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# 3<sup>rd</sup> International Conference on Dosimetry and its Applications



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## Message from the Conference Chairs:

Dear Colleague,

Welcome to Lisbon!

We are very pleased to host the 3rd International Conference on Dosimetry and its Applications (ICDA-3) in the premises of the Congress Center of Instituto Superior Técnico (IST), the leading Portuguese University of Engineering, Science and Technology.

The previous ICDA Conferences were held in Prague (ICDA-1, 2013) and Surrey (ICDA-2, 2016). Building on the success of the previous Conferences, ICDA-3 is a major gathering of experts from several tens of countries, worldwide. It addresses a broad range of dosimetry topics. The involvement of experts from Portuguese and foreign or international institutions has been of paramount importance for the success of this organization. Special thanks are due to the members of the Scientific Committee and all those who helped shaping the Conference Programme, the Workshops and Refresher Courses, as well as to the sponsoring institutions, organizations and corporations.

In these challenging times for Radiation Protection and Dosimetry, we anticipate that ICDA-3 will be a memorable event, rich of achievements, from the scientific as well as from the social point of views and formulate our best wishes that you profit from the Portuguese hospitality and the charming atmosphere of Lisbon.

Enjoy your stay in Portugal!

***Pedro Vaz  
Isabel Lopes***



Conference Programme  
Scheme

Sunday May, 26		Monday May, 27		Tuesday May, 28		Wednesday May, 29		Thursday May, 30		Friday May, 31				
8:30 – 9:15		Poster Session 1 (all day)		Poster Session 2 (all day)		Poster Session 3 (all day)		Poster Session 4 (all day)		Poster Session 5 (all day)				
		Neutron dosimetry and measurement techniques Room 2.2	Development of dosimetric quantities and units, as reflected in recommendations Room 2.1	Externally dosimetry Room 2.1	Internal Dosimetry Room 2.2	Animating computational human phantoms using 3-D motion-capture data and the use of personal dosimetry Room 2.1		Establishment and use of DRLs Room 2.1	Dosimetry audits in Radiotherapy Room 2.2	The New ICRU Recommendations for Neutron Dose Coefficients and the impact of neutron reassessments Room 2.1				
			REGISTRATION			Plenary session 12 Radiation Protection and Dosimetry in Medicine Auditorium		Plenary session 14 Low dose radiation effects and Radiobiology Auditorium		Plenary session 15 Hot Dosimetry topics I Auditorium				
9:20 – 11:00	Workshop I (starting time 10:00) Room V41	Opening & Plenary Session II Auditorium		Radiation Protection and Dosimetry in Medicine Auditorium		Plenary session 12 Radiation Protection and Dosimetry in Medicine Auditorium		Plenary session 14 Low dose radiation effects and Radiobiology Auditorium		Plenary session 15 Hot Dosimetry topics I Auditorium				
Coffee-Break														
11:00 – 11:20														
11:20 – 13:00	Workshop I (cont.) Room V41	Plenary session II (cont.) Auditorium	Radiation Protection in Medicine III Auditorium	Environmental Dosimetry, radioactivity and monitoring I Room 1.1	Monte Carlo and hybrid methods in Dosimetry I Room 2.1	Radiation Protection in Medicine V Room 2.1	Environmental Dosimetry, radioactivity and monitoring II Room 1.1	Monte Carlo and hybrid methods in Dosimetry II Room 2.1	Dosimetry of radon exposures Room 1.1	Computational Dosimetry and Phantoms II Auditorium	Monte Carlo and hybrid methods in Dosimetry III Room 2.1	Dosimetry in space applications Room 1.1	Radiation Protection in Medicine VI Auditorium	Dosimetry in radiological and nuclear emergencies and accidents II Room 2.1
Lunch-Break														
13:00 – 14:15														
14:15 – 15:55		Radiation Protection in Medicine I Auditorium	Micro and Nanodosimetry I Room 2.1	Internal Dosimetry and Biokinetic models I Room 1.1	Radiation Shielding and Dosimetry at Accelerators I Room 1.1	Radiation Shielding and Dosimetry at Accelerators II Room 2.1	Biodosimetry, Radiobiology, Retrospective Dosimetry Room 2.1	Radiation Shielding and Dosimetry at Accelerators II Room 2.1				Micro and Nanodosimetry II Auditorium		
15:55 – 16:15														
16:15 – 17:55	Workshop II (cont.) Room V41	Radiation Protection in Medicine II Room 1.1	Neutron Dosimetry I Auditorium	Individual Dosimetry Monitoring I Room 2.1	Radiation Protection in Medicine IV Room 2.1	Dosimetry in radiation and nuclear emergencies and accidents I Auditorium	Individual Dosimetry and Monitoring II Room 1.1	Radiation Protection and Dosimetry in Medicine VI Auditorium		Radiation Protection and Dosimetry in Medicine VII Room 1.1		Neutron Dosimetry II Room 2.1		
18:00 – 20:00														
20:00 – 23:00	Workshop II (cont.) Room V41													
REGISTRATION														
Conference Dinner														

# Conference Programme

## Sunday May, 26

Time	Content	Speaker
10:00 – 12:45	New Trends in Imaging for Proton Therapy	
10:00 – 10:15	Introductory remarks	João Seco
10:15 – 11:00	4D imaging for 4D adaptive proton therapy	Antje Knopf
11:00 – 11:45	MRI for Proton therapy	Maria F. Spadea
11:45 – 12:00	Coffee-Break	
12:00 – 12:45	Modeling approaches for imaging simulation and applications to proton therapy	Marco Riboldi
12:45 – 13:15	Round Table discussion	
13:15 – 14:00	Lunch-Break	
14:00 – 15:40	4 <sup>th</sup> International BioQuaRT Workshop "From Micro- and nanodosimetry to biological effectiveness"	
14:00 – 14:30	Introduction / Review of recent European proposals	Hans Rabus
14:30 – 15:05	Radiobiology: Recent progress in radiobiology	M. Hill
15:05 – 15:40	Experimental micro / nanodosimetry: State of the art of micro and nanodosimetry	V. Conte
15:40 – 16:05	Coffee-Break	
16:05 – 16:40	Computational approaches: Towards a gold standard for Monte Carlo	C. Villagrasa
16:40 – 17:10	Linking into clinics: Clinical needs on radiation effectiveness	A. Carabe-Fernandes
17:10 – 17:40	Round Table discussion	
18:00 – 20:00	Welcome Drink	

REGISTRATION

# Conference Programme

## Monday May, 27

Time	Poster Session 1 (all day)		
8:30 – 9:15	<b>REGISTRATION</b> (8:00 – 9:00)	Neutron dosimetry and measurement techniques (M. Silari)	Development of dosimetric quantities and units, as reflected in the ICRU recommendations (L. Musilek)
9:20 – 11:00	<b>Opening &amp; Plenary Session I1 – Computational Dosimetry</b> <i>Session chairs: Pedro Vaz, Isabel Lopes</i>		
	<b>OPENING</b> (25min)		
	I1.1 – Jenia Vassileva: IAEA Views (25 min)		
	I1.2 – Werner Rühm: EURADOS Views (25 min)		
	I1.3 – Shaheen Dewji: Grand Challenges in the American Nuclear Society: Resolutions by 2030 (25 min)		
11:00 – 11:20	Coffee-Break		
11:20 – 13:00	<b>Plenary session I1 (cont.) – Computational Dosimetry</b> <i>Session chairs: Pedro Vaz, Isabel Lopes</i>		
	I1.4 – David Bradley: IRPS: approaching 40 years of existence (25 min)		
	I1.5 – Nolan Hertel: Radiation Protection Dosimetry Research: A View From the USA (25 min)		
	I1.6 – George Xu: The impact of phantoms, realtime Monte Carlo simulation, and machine-learning on radiation dosimetry (25 min)		
	I1.7 – C.H. Kim: ICRP mesh-type reference computational phantoms and high-fidelity deformation for body-size and posture change (25 min)		
13:00 – 14:15	Lunch-Break		
14:15 – 15:55	<b>Radiation Protection in Medicine I (Radiotherapy)</b> <i>Session chairs: Antje Knopf, Joana Santos</i>	<b>Micro and Nanodosimetry I</b> <i>Session chairs: Carmen Villagrasa, Alessio Parisi</i>	<b>Internal Dosimetry and Biokinetic models I</b> <i>Session chairs: M.A. López, Pedro Teles</i>
	O1.1 – Gonzalo Garcia (20 min)	O1.1 – Carmen Villagrasa (15 min)	O1.1 – Sergei Tolmachev (15 min)
	O1.2 – Gabriele Magugliani (20 min)	O1.2 – Alessio Parisi (15 min)	O1.2 – M.A. López (15 min)
	O1.3 – Grazia Gambarini (20 min)	O1.3 – Juan Prieto-Pena (15 min)	O1.3 – Anna Pántya (15 min)
	O1.4 – Andreia Oliveira (20 min)	O1.4 – Davide Mazzucconi (15 min)	O1.4 – Gumersindo Verdú (15 min)
		O1.5 – Davide Bortot (15 min)	O1.5 – Pedro Teles (15 min)
		O1.6 – Anna Bianchi (15 min)	O1.6 – Hsin-Hon Lin (15 min)
15:55– 16:15	Coffee-Break		
16:15 – 17:55	<b>Radiation Protection in Medicine II (Radiotherapy)</b> <i>Session chairs: Manuel Bardiès, M.C. Lopes</i>	<b>Neutron Dosimetry I</b> <i>Session chairs: Stefano Agosteo, Carles Domingo</i>	<b>Individual Dosimetry and Monitoring I</b> <i>Session chairs: Ladislav Musilek, Lawrence Hudson</i>
	O2.1 – Francisco Henriquez (20 min)	O1.1 – Carles Domingo (20 min)	O1.1 – Larry Hudson (20 min)
	O2.2 – Natália Alves (20 min)	O1.2 – A. Devienne (20 min)	O1.2 – Miroslav Voytchev (20 min)
	O2.3 – Ana Cravo Sá (20 min)	O1.3 – Carles Domingo (20 min)	O1.3 – Inmaculada Sierra (20 min)
	O2.4 – Francisco Henriquez (20 min)	O1.4 – Grazia Gambarini (20 min)	O1.4 – Fabio Pozzi (20 min)

# Conference Programme

## Tuesday May, 28

Time	Poster Session 2 (all day)		
8:30 – 9:15	Extremity dosimetry (F. Vanhavere)	Internal Dosimetry (P. Teles)	
9:20 – 11:00	Plenary Session I2 – Radiation Protection and Dosimetry In Medicine Session chairs: Jenia Vassileva, Eliseo Vaño		
	I2.1 – Jenia Vassileva: Patient exposure monitoring in medical imaging: why and how? (25 min)		
	I2.2 – Eliseo Vaño: Automatic patient dose registry and help in the optimisation and audit of interventional procedures (25 min)		
	I2.3 – Manuel Bardiès: Patient-specific dosimetry in Molecular radiotherapy (25 min)		
11:00 – 11:20	Coffee-Break		
11:20 – 13:00	<b>Radiation Protection in Medicine III (Radiotherapy)</b> Session chairs: Jenia Vassileva, Ana Cravo Sá	<b>Environmental Dosimetry, radioactivity measurement and monitoring I</b> Session chairs: J. Francisco Navarro, José Rodénas	<b>Monte Carlo and hybrid methods in Dosimetry I</b> Session chairs: Christopher Chantler, Luis Peralta
	O3.1 – Emily Russell (15 min)	O1.1 – Aina Noverques (20 min)	O1.1 – Catherine da Silva (20 min)
	O3.2 – Lorenzo Isolan (15 min)	O1.2 – Maksym Luchkov (20 min)	O1.2 – Manon Jacquemin (20 min)
	O3.3 – Keida Kanxheri (15 min)	O1.3 – Natalie Heracleous (20 min)	O1.3 – Richard Hugtenburg (20 min)
	O3.4 – Ouiza Moussous (15 min)	O1.4 – José Corisco (20 min)	O1.4 – André Gomes Otero (20 min)
	O3.5 – E. Tomarchio (15 min)		
	O3.6 – Alessio Parisi (15 min)		
13:00 – 14:15	Lunch-Break		
14:15 – 15:55	<b>Radiation Shielding and Dosimetry at Accelerators I</b> Session chairs: Marco Silari, Yuriy Romanets	<b>Computational Dosimetry and Phantoms I</b> Session chairs: George Xu, Shaheen Dewji	<b>Biodosimetry, Radiobiology and Retrospective Dosimetry</b> Session chairs: João Seco, Octávia Monteiro Gil
	O1.1 – A. Devienne (20 min)	O1.1 – Daiki Satoh (20 min)	O1.1 – João Seco (15 min)
	O1.2 – Radu Alin Vasilache (20 min)	O1.2 – Jonathan Dean (20 min)	O1.2 – Géraldine Gonon (15 min)
	O1.3 – Victoria Corregidor (20 min)	O1.3 – Takuya Furuta (20 min)	O1.3 – N.T. Tavares (15 min)
		O1.4 – Elisabeth Hansen (20 min)	O1.4 – P. Costa (15 min)
		O1.5 – Joana Vale (20 min)	O1.5 – Jose Chimeno (15 min)
			O1.6 – Ana Belchior (15 min)
15:55– 16:15	Coffee-Break		
16:15 – 17:55	<b>Radiation Protection in Medicine IV (Imaging)</b> Session chairs: Eliseo Vaño, Eric Shirley	<b>Dosimetry in radiological and nuclear emergencies and accidents I</b> Session chairs: Luís Neves, Daiki Satoh	<b>Individual Dosimetry and Monitoring II</b> Session chairs: Filip Vanhavere, Isabel Lopes
	O4.1 – Luís Peralta (20 min)	O1.1 – Shaheen Dewji (20 min)	O2.1 – Ladislav Musilek (20 min)
	O4.2 – Francisco Henriquez (20 min)	O1.2 – José Ródenas (20 min)	O2.2 – Filip Vanhavere (20 min)
	O4.3 – Fernanda Santos (20 min)	O1.3 – J. Francisco Navarro (20 min)	O2.3 – Sabina Yasmin (20 min)
	O4.4 – Pedro Teles (20min)	O1.4 – Olivier Van Hoey (20 min)	

# Conference Programme

## Wednesday May, 29

Time	Poster Session 3 (all day)		
8:30 – 9:15	Animating computational human phantoms using 3-D motion-capture data and their applications in personal dosimetry (M. Abdelrahman)	Use of computational human phantoms in medical applications (G.Xu)	
9:20 – 11:00	Plenary Session I3 – Hot Dosimetry topics I Session chairs: Hans Rabus, Filip Vanhavere		
	I3.1 – Hans Rabus: Nanodosimetry – past, present, future (25 min)		
	I3.2 – João Seco: Think Like a Proton .... Stay Positive: Cutting Edge Ideas in Proton Therapy (25 min)		
	I3.3 – Filip Vanhavere: Radiation-induced lens opacities among interventional cardiologists (25 min)		
	I3.4 – Christopher Chantler: Quantification of X-ray methodologies and extraction of reliable and new insight (25 min)		
11:00 – 11:20	Coffee-Break		
11:20 – 13:00	<b>Radiation Protection in Medicine V (Imaging)</b> Session chairs: David Bradley, Maria Carmen Sousa	<b>Environmental Dosimetry, radioactivity measurement and monitoring II</b> Session chairs: Pasquale Fulvio, Maria José Madruga	<b>Monte Carlo and hybrid methods in Dosimetry II</b> Session chairs: Richard Hugtenburg, Ana Belchior
	O5.1 – Teodoro Rivera-Montalvo (15 min)	O2.1 – Vladimir Mares (20 min)	O2.1 – Ladislav Musilek (15 min)
	O5.3 – Hugo Schelin (15 min)	O2.2 – C.A. Federico (20 min)	O2.2 – José Ródenas (15 min)
	O5.4 – Chien Yi Ting (15 min)	O2.3 – Sadia Assad (20 min)	O2.3 – Débora António (15 min)
	O5.5 – Hugh Wilkins (15 min)	O2.4 – Maria José Madruga (20 min)	O2.4 – Georgina Benítez (15 min)
	O5.6 – Agnieszka Szumska (15 min)	O2.5 – Aina Noverques (20 min)	O2.5 – Maria Pinilla (15 min)
			O2.6 – Jorge M Sampaio (15 min)
13:00 – 14:15	Lunch-Break		
14:15 – 18:00	SOCIAL PROGRAMME		
18:00 – 20:00			
20:00 – 23:00	CONFERENCE DINNER		

# Conference Programme

## Thursday May, 30

Time	Poster Session 4 (all day)		
8:30 – 9:15	Establishment and use of DRLs (J. Vassileva)	Dosimetry audits in Radiotherapy (M.C. Lopes)	
9:20 – 11:00	<b>Plenary Session I4 – Low dose radiation effects and Radiobiology</b> <i>Session chairs: Werner Rühm, Liz Ainsbury</i>		
	I4.1 – Werner Rühm: Recent Work of ICRP Committee 1 on Radiation Effects – From Low-Dose and Low-Dose-Rate Effects to Individual Radiation Response (25 min)		
	I4.2 – Liz Ainsbury: Interdisciplinary dosimetry research supporting medical (and wider) uses of ionising radiation (25 min)		
	I4.3 – Susana Constantino: Low doses of ionizing radiation: where do we stand now? (25 min)		
	I4.4 – Shaheen Dewji: A Roadmap to a Roadmap: Perspectives on Recent Low Dose Initiatives in the United States (25 min)		
11:00 – 11:20	Coffee-Break		
11:20 – 13:00	<b>Dosimetry of radon exposures</b> <i>Session chairs: Alain Rannou, Mário Reis</i>	<b>Computational Dosimetry and Phantoms II</b> <i>Session chairs: C.H. Kim, Mahmoud Abdelrahman</i>	<b>Monte Carlo and hybrid methods in Dosimetry III</b> <i>Session chairs: David Broggio, Jorge Fernandez</i>
	O1.1 – Maria Lurdes Dinis (15 min)	O2.1 – J.F. Benavente (20 min)	O3.1 – Ricardo Augusto (20 min)
	O1.2 – Alcides Pereira (15 min)	O2.2 – Hans Rabus (20 min)	O3.2 – M.N. Kinakin (20 min)
	O1.3 – Yoenlis Prata (15 min)	O2.3 – Salvatore di Maria (20 min)	O3.3 – Rong-Jiun Sheu (20 min)
	O1.4 – Mário Reis (15 min)	O2.4 – Weishan Chang (20 min)	O3.4 – Tiago Ribeiro (20 min)
	O1.5 – Yoenlis Prata (15 min)	O2.5 – Ana Denis-Bacelar (20 min)	O3.5 – David Redondo (20 min)
	O1.6 – Luis Peralta (15 min)		
13:00 – 14:15	Lunch-Break		
14:15 – 15:55	<b>Radiation Shielding and Dosimetry at Accelerators II</b> <i>Session chairs: Werner Rühm, Diego Di Francesca</i>	<b>Micro and Nanodosimetry II</b> <i>Session chairs: Hans Rabus, Alejandro Carabe-Fernandes</i>	
	O2.1 – Richard Hugtenburg (20 min)	O2.1 – Valeria Conte (15 min)	
	O2.2 – Diego Di Francesca (20 min)	O2.2 – Florian Heimbach (15 min)	
	O2.3 – Gabriele Zorloni (20 min)	O2.3 – Anna Selva (15 min)	
	O2.4 – Masafumi Akiyoshi (20 min)	O2.4 – Hans Rabus (15 min)	
		O2.5 – Volker Dangendorf (15 min)	
		O2.6 – Aleksandr Bancer (15 min)	
15:55 – 16:15	Coffee-Break		
16:15 – 17:55	<b>Radiation Protection in Medicine VI (Staff dosimetry)</b> <i>Session chairs: M. Francesca Spadea, Marta F. Dias</i>	<b>Radiation Protection and Dosimetry in Industry &amp; NORM</b> <i>Session chairs: Frank Becker, Maria de Lurdes Dinis</i>	<b>Neutron Dosimetry II</b> <i>Session chairs: Nolan Hertel, Michał Kuć</i>
	O6.1 – Katharina Bairlein (20 min)	O1.1 – Jovica Atanackovic (20 min)	O2.1 – E. Tomarchio (20 min)
	O6.2 – Hayo Zutz (20 min)	O1.2 – Christopher Chantler (20 min)	O2.2 – Michał Kuć (20 min)
	O6.3 – Oliver Hupe (20 min)	O1.3 – Frank Becker (20 min)	O2.3 – R. Méndez-Villafañe (20 min)
	O6.4 – Cristian Candela-Juan (20min)	O1.4 – Thomas Quirk (20 min)	
	O6.5 – Cristian Candela-Juan (20min)	O1.5 – Marina Sáez-Muñoz (20 min)	

# Conference Programme

## Friday May, 31

Time	Poster Session 5 (all day)		
8:30 – 9:15	The New ICRU Recommendations for Neutron Dose Coefficients and the impacts of neutron resonances (N. Hertel)		
9:20 – 11:00	<b>Plenary Session I5 – Hot Dosimetry topics II</b> <i>Session chairs: Eduardo Gallego, Alain Rannou</i>		
	I5.1 – Eduardo Gallego: Dosimetry issues in Radiological and Nuclear Emergency Preparedness and Response (25 min)		
	I5.2 – Alain Rannou: RADON DOSIMETRY- Biological, internal dosimetry and radiometric issues (25 min)		
	I5.3 – Marco Silari: Dosimetry at Accelerators - State-of-the-art and challenging issues (25 min)		
	I5.4 – José Ródenas: Application of dosimetry to estimate activity in irradiated samples (25 min)		
11:00 – 11:20	Coffee-Break and Poster Session 5		
11:20 – 13:00	<b>Dosimetry in space applications</b> <i>Session chairs: Vladimir Mares, Amir Bahadori</i>	<b>Radiation Protection in Medicine VII</b> <i>Session chairs: Linda Caldas, Salvatore di Maria</i>	<b>Dosimetry in radiological and nuclear emergencies and accidents II</b> <i>Session chairs: Eduardo Gallego, Isabel paiva</i>
	O1.1 – Amir Bahadori (20 min)	O7.1 – Abdelmoneim Suleiman (20 min)	O2.1 – Joyce Silvestre (20 min)
	O1.2 – Ana Luisa Casimiro (20 min)	O7.2 – Wiam Elshami (20 min)	O2.2 – Marina Sáez Muñoz (20 min)
	O1.3 – Marco Pinto (20 min)	O7.3 – Leonello Servoli (20 min)	O2.3 – J.F. Navarro (20 min)
	O1.4 – Rong-Jiun Sheu (20 min)	O7.4 – Salvatore di Maria (20 min)	O2.4 – Ámille Erbe (20 min)
13:00 – 14:15	<b>WRAP-UP &amp; CLOSING</b>		

# Conference Programme

## Poster Session 1 – Monday May, 27

Radiation Protection and Dosimetry in Medicine	Author	Poster Number
PATIENT DOSIMETRY OF PEDIATRIC ICU DURING CHEST RADIOGRAPHY	Ana Paula Bunick	P1.1
Dose profile study in mammographic exposition using radiochromic film	Fernanda Santos	P1.2
Calculation of the typical values of reference levels for a hospital facility in the city of Medellín	Carolina Viloria Barragán	P1.3
Quality control and entrance skin dose evaluation in a pediatric CT scanner	Danielle Filipov	P1.4
Patient Radiation Dose and Image Quality in Plain Radiography: An assessment of Certain Common Procedures in Ten Capital Hospitals in Sudan	Esameldeen Babikir	P1.5
Evaluation of Physical Spaces of Nuclear Medicine Services	Gládis G. Reimemberger	P1.6
Local DAP and Effective Dose values during Pacemaker Implantations	Gabriela Cardoso	P1.7
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Biodosimetry, Radiobiology and Retrospective Dosimetry	Author	Poster Number
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Assessment of imaging protocol and patient radiation exposure in pediatric computed tomography angiography	Ali Aamry	P1.2
Dose Evaluation of a 137-cesium source exposition using a solid water phantom	Fernanda Santos	P1.3
Feasibility study on quality assurance of THOR-BNCT performed with TEPC	Fang-Yuh Hsu	P1.4
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Analysis of Hp(0,07) readings measured above the lead apron	Cristian Candela-Juan	P1.6
Evaluation of the mean glandular dose and irradiation parameters in digital mammograms of patients with breasts with sparse fibroglandular densities	Irene Nakano	P1.7
Nuclear medicine in the Russian Federation at last decade: structure and doses	Irina Zvonova	P1.8
An extrapolation chamber for the establishment of a primary radiation standard in <sup>85</sup> Kr and <sup>147</sup> Pm beta radiation beams	Linda Caldas	P1.9
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DOSetrace Research capabilities for radiation protection dosimeters: Training actions	Oliver Hupe	P1.11
Comparative evaluation of image quality and dose between 2D full field digital mammography and digital breast tomosynthesis	Yi-Shuan Hwang	P1.12

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The Impact of CT-density conversion curve for VMAT plans in Monaco Monte Carlo TPS: case of head and neck cancers	El haffari said	P3.2
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Optically and thermally stimulated luminescence in LaAlO <sub>3</sub> :Dy <sup>3+</sup> beta irradiated	Angélica de León	P5.1
Design and implementation of a gamma spectrometry mobile unit using LaBr <sub>3</sub> detectors	Elena Prieto Butillé	P5.2
APPLICABILITY OF AIR VEHICLES ON RADIOLOGICAL AND NUCLEAR MONITORING – A LITERATURE AND HISTORICAL REVIEW	Joyce Silvestre	P5.3
Use of ceramic $\alpha$ -Al <sub>2</sub> O <sub>3</sub> detectors for discriminate beta and photon fields	Luiz Claudio Meira Belo	P5.4

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Dosimetric Measurement of Scattered Radiation for Simulated Head and Neck Radiotherapy with a Hand-Made Oral Prosthesis	Chia-Chun Lu	P1.2
Dosimetric characterization of 3D printed phantoms at different infill percentage for diagnostic x-ray energy range	Daniel Villani	P1.3
Radiation dose assessment to caregivers of the out-patients treated with iodine-131 for thyroid	Fang-Yuh Hsu	P1.4
Treatment of mixtures of lead and barite powders in ceramic materials for the shielding of ionizing radiation by the thermal spray process	Gladis G. Reiserberger	P1.5
Dosimetric characterization of high-linearity bone radiation detector exposed to gamma-rays	Linda Caldas	P1.6
Concrete analysis for radiological protection	Caroline K. Bandeira	P1.7
Dose conversion coefficients for medical diagnostic imaging with the Chinese reference phantoms	Rui Qiu	P1.8
Establishment of diagnostic X-ray air kerma standard in Taiwan	Yi-Chun Lin	P1.9
A Novel Method to Improve Learning Efficiency of Artificial Neural Network Algorithm to Estimate Dose Distribution for Radiation Treatment	Yong Nam Kim	P1.10

Monte Carlo and hybrid methods in Dosimetry	Author	Poster Number
Preclinical Dosimetry in the Development of New Radiopharmaceuticals through Monte Carlo Simulation	Catherine da Silva	P2.1
Comparison of the Response Between Different Dosimeters in Clinical Beams: A Monte Carlo Study	Ney Souza	P2.2
Activation study of a 15 MeV LINAC via Monte Carlo simulation	Sara Vichi	P2.3

Individual Dosimetry and Monitoring	Author	Poster Number
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Energy dependence of an individual dosimeter: Experimental and PENELOPE-Monte Carlo simulation results	Patricia Nicolucci	P3.2
A Snapshot of Occupational Radiation Dose in Veterinary Radiology	Wiam Elshami	P3.3
Development and verification of a new OSL-eye-lens dosimeter and algorithm	Fang-Yuh Hsu	P3.4
Occupational exposure doses in a Nuclear Medicine Department	Vanessa de Sousa	P3.5
Type testing of 7Li211B4O7:Cu finger thermoluminescent dosimeters for the assessment of Hp(0.07)	J.F. Benavente	P3.6
Assessment of patient's and occupational exposure from PET/CT with Fluoro-D-Glucose (18F-FDG)	Hassan Salah	P3.7
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Environmental impact assessment relevant to accidental events during nuclear reactor plants decommissioning activities	M. Giardina	P4.3
Radiation Shielding and Dosimetry Accelerators	Author	Poster Number
Transmission properties of X-ray radiated from Crookes tube used in teaching of science	Do Duy KHIEM	P5.1
Induced activity measurements in Cu target for Ne and C ions	Hiroshi Yashima	P5.2
Radiation monitoring network at ALBA Synchrotron	A. Devienne	P5.3
Comparing Measurement Methods and Monte-Carlo Simulations to assess dose levels in the irradiation rooms during treatment in the MedAustron hadron therapy center	Lukas Jaegerhofer	P5.4
Comparison of response of passive and active dosimetry systems at laser-based facility	Vojtech Stransky	P5.5
Nuclear Data and Evaluation	Author	Poster Number
Neutron spectrum determination of accelerator-driven d(10)+Be neutron source using the multi-foil activation technique	Milan Stefanik	P6.1
RADIATION DOSE TO MALAYSIAN POPULACE VIA THE CONSUMPTION OF COFFEE	David Bradley	P6.2
Dosimetry in space applications	Author	Poster Number
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Alanine Pellets Comparison using EPR Spectrometer suitable to be use in Quality Assurance of Gamma Knife System in Romania	Catalin Tuta	P1.2
Evaluation of the dose distribution of tomotherapy using polymer gel dosimeters and optical computed tomography with ring artifact correction	Cheng-Ting Shih	P1.3
Absorbed and Effective Doses evaluation in a pediatric PET/CT scan	Fernanda Santos	P1.4
Dose estimation per Occupationally Exposed Individual for the burden of eighty patients per week considering doses of preparing room, radioisotope injection, hall circulation, and command room according to AAPM 108	Heber Simões Videira	P1.5
Measurement and Reconstruction of High Energy Photon Beam Spectra using Compton Spectrometry	John Peter O. Manrique	P1.6
Comparative dosimetric study between the Acuros XB and AAA algorithm for treatment of lung tumor with RapidArc technique	Lucas Delbem Albino	P1.7
Quality control in "Intensity Modulated Radiation Therapy-IMRT" using thermoluminescent dosimeters	Leticia Rodrigues	P1.8
EVALUATION OF DOSE AND DIAGNOSTIC IMAGE QUALITY USING BRAZILIAN BREAST PHANTOM	Fernanda Santos	P1.9
Personal dose equivalent of $^{18}\text{F}$ -FDG PET assessed using a semiconductor personnel dosimeter to protect workers from radiation	Yasuyuki Takahashi	P1.10

Computational Dosimetry and Phantoms	Author	Poster Number
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Determination of interaction quantities of radiation with dosimeters through PENELOPE code	Mirko Salomón Alva Sánchez	P2.2
A comparison of age-dependent organ depth distributions: stylized versus voxel phantom series	Shaheen A. Dewji	P2.3

Monte Carlo and hybrid methods in Dosimetry	Author	Poster Number
3D dosimetry based on SPECT/CT: Evaluation for Lutetium Therapy using Monte Carlo simulation and the NEMA phantom	Gumersindo Verdú	P3.1
Mammographic density assessment with the LIBRA software	Hugo Schelin	P3.2

Environmental Dosimetry, radioactivity measurement and monitoring	Author	Poster Number
PLASMA REACTOR TO VIABILIZE THE VOLUMETRIC REDUCTION OF RADIOACTIVE WASTES	Ademar J.P. Junior	P4.1
Optically stimulated luminescence dosimetric characteristics $\text{TiO}_2\text{:Ce}$	Teodoro Rivera-Montalvo	P4.2
Radioactive waste management in a Nuclear Medicine Department	Vanessa de Sousa	P4.3



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Evaluation of the FTIR technique for the linearity assessment of commercial soda-lime glass irradiated with gamma radiation	Linda Caldas	P5.2
Comparison of doses, secondary particle yields and LET spectra between semiconductor reliability testing using protons and neutrons	Yueh Chiang	P5.3

Micro and Nanodosimetry	Author	Poster Number
Influence of ionizing radiation on photo-thermo-stimulated exoelectron emission spectra of Gd <sub>2</sub> O <sub>3</sub> nanoparticles and films	Marina Romanova	P6.1
Microdosimetry modelling for evaluation of the therapeutic effect of different radionuclides in various cell and micrometastasis geometries	Roar Skartlien	P6.2
Silicon photonics for micron-scale dosimetry and calorimetry of industrial and radiotherapy beams	Ronald E. Tosh	P6.3
Measurement of correlations between two nanometric volumes in the track structure of <sup>241</sup> Am alpha particles	Gerhard Hilgers	P6.4



Monday May, 27



### IAEA Views

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## EURADOS Views

### Werner Rühm

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The European Radiation Dosimetry Group (EURADOS) is a self-sustainable network of more than 60 European institutions including about 600 scientists active in the field of radiation dosimetry. The mission of the network includes promotion of European cooperation in research and development in the dosimetry of ionizing radiation and its implementation in routine practice. EURADOS Working Groups are active in various dosimetric fields and cover a wide range of dosimetric applications. Working Group topics include harmonization of individual monitoring, environmental dosimetry, computational dosimetry, internal dosimetry, dosimetry for medical applications (diagnostics and therapy), retrospective dosimetry, and dosimetry in high-energy radiation fields. Education and training are also important activities for EURADOS.

As a major topic across all Working Groups, EURADOS has recently published a Strategic Research Agenda “Visions on Dosimetry of Ionising Radiation” which is used by the European Commission to identify future research needs in radiation dosimetry in Europe. Currently this Strategic Research Agenda is being updated by a cross-cutting effort involving all EURADOS Working Groups.

The present paper introduces the network and presents strategic views on the future of dosimetry in Europe including also education and training aspects. More details can be found on the EURADOS website ([www.eurados.org](http://www.eurados.org)).

## **Grand Challenges in the American Nuclear Society: Resolutions by 2030**

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In order to identify technical nuclear challenges that need to be resolved by 2030, the American Nuclear Society embarked on the identification of core “Grand Challenges”. The objective of the Grand Challenges initiative was to identify and help solve some of the economic, sociological, or political issues that we face as a society. From some 300 recommended submissions and following a consolidation process, nine core “Grand Challenges” were recommended. From within the entire American Nuclear Society community, establishing a scientific basis for modern low-dose radiation regulation was identified as one of the top challenges faced by the Society. This Grand Challenge outlines that the Linear-No-Threshold (LNT) model is based on high dose rate nuclear weapons data and its application to nuclear reactor, medical, and irradiation applications is tenuous at best. New evidence in radiation and chemical toxicity fields is suggesting that LNT models are likely overly conservative, and the way in which they are used makes this conservatism inordinately expensive. Today, the principle of As Low As Reasonably Achievable (ALARA) has in many cases lost the “reasonable” aspect, as nuclear power plants micromanage every milliroentgen (mR) of worker dose in order to meet metrics of dose reduction. Unnecessary fear of low doses of radiation has adversely impacted safety and enabled cumulative costs to build up within the U.S. nuclear energy industry such that building and maintaining plants is now overly cumbersome and expensive. The progress and activities addressing this Low Dose and other synergistic Grand Challenges within the American Nuclear Society will be discussed.

## IRPS: approaching 40 years of existence

**D. A. Bradley**

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The International Radiation Physics Society (IRPS) was the brainchild of Ananda Mohan Ghose (PhD supervisor of the present speaker, 1982-1985) and John Hubbell, the formation of the Society being something the two agreed to work towards during the 1<sup>st</sup> International Symposium on Radiation Physics (ISRP-1, 1974). Last October saw ISRP-14. The Society now sponsors three series of meetings, encompassing the International Topical Meetings on Industrial Radiation and Radioisotope Measurement Applications (IRRMA), IRRMA-X (Chicago, 2017) being the most recent of these and the ICDA series. As such the Society now holds events every calendar year and to-date conferences, symposia and meetings have been held in 24 cities across five continents. The Conference arrangements provide for the coverage of the various radiations, encompassing nuclear instability, atomic arrangements and emissions together with the entire range of peaceful applications and impacts wherever such matters arise. In the present talk, the speaker will provide a brief vignette of key developments of the Society and of its aspirations, with some ability to mention just a very few of those who have played major roles in sustaining the Society. In addressing ICDA-3 interests, the speaker will also provide a brief reflection of his own current involvements in radiation dosimetry, work that may lead to what one may eventually call defectoscopy.



## **Radiation Protection Dosimetry Research: A View From the USA**

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In the summer of 2017, the Center for Radiation Protection Knowledge, the Oak Ridge Associated Universities, and the Health Physics Society (HPS) sponsored a workshop to assess what the principal research needs for radiation protection in the USA were. A HPS radiation protection research task force was subsequently formed and will complete their recommendations for a United States radiation protection research program this summer. This presentation will review those recommendations as they exist to date and link them to similar efforts by other international organizations. Many of the issues that are at the forefront involve improvements in radiation protection dosimetry.

## The impact of phantoms, realtime Monte Carlo simulation, and machine-learning on radiation dosimetry

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Radiological physics principles governing radiation dosimetry have not changed in the past 60 years during which computer information technologies advanced drastically. The research field of anatomical modeling for the purpose of radiation dose calculations has experienced an exponential growth in activity in the past two decades. Such an exciting advancement is due to the feasibility to create 3D geometric details of the human anatomy from tomographic imaging and to perform Monte Carlo radiation transport simulations in increasingly fast and cheap personal computers. The advent of a new type high-performance computing hardware in recent years, especially the graphics processing units (GPUs), has made it possible to carry out time-consuming Monte Carlo calculations in near “realtime” speeds. However, despite the impressive recent development by the machine-learning community involving convolutional neural networks (CNN), how such a technology will affect aspects of radiation dosimetry is not obvious to many. This paper introduces the history of three generations of computational human phantoms (the stylized MIRD-type phantoms, the voxelized tomographic phantoms, and the BREP deformable phantoms) and new development on the GPU-based Monte Carlo radiation dose calculations. Examples are given for research projects using computational phantoms and a GPU-based Monte Carlo code, ARCHER for problems in radiation protection, imaging and radiotherapy. Two on-going projects to accelerate Monte Carlo dose calculations by denoising and to derive patient-specific CT organ doses by automatic multi-organ segmentation, both using CNN-based deep-learning algorithms, are also reported. Finally, the talk discusses challenges and future research opportunities.

## ICRP mesh-type reference computational phantoms and high-fidelity deformation for body-size and posture change

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Recently the Task Group 103 of International Commission on Radiological Protection (ICRP) developed mesh-type reference computational phantoms (MRCPs) for adult male and female by converting the ICRP 110 reference phantoms into high-quality mesh format. The MRCPs include all source and target regions needed for estimating effective dose, even the  $\mu\text{m}$ -thick target regions in the respiratory and alimentary tract, skin, and urinary bladder, assimilating the supplemental stylized models. The MRCPs can also be directly used in Monte Carlo codes without voxelization, fully maintaining the fidelity of the mesh phantoms. In the presentation, the MRCPs will be first introduced highlighting the advantages of the MRCPs phantoms over the voxel-type ICRP 110 reference phantoms. Then, one of the main advantages of the mesh phantoms, deformability, will be discussed in two directions – (1) phantom deformation to change body size, which leads to a library of phantoms with different body sizes, and (2) phantom deformation to change posture, which leads to realization of 4D Monte Carlo dose calculation with moving phantoms.



## Neutron dosimetry, shielding and radioprotection studies in Compact Proton Therapy Centers (CPTC) using MCNP6 Monte Carlo code

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### Introduction

Proton therapy uses accelerated proton beams with energies between 70 and 230 MeV. Compact Proton Therapy Centers (CPTC) are facilities with a single treatment room. From a radioprotection point of view the leading concern in CPTC are high-energy neutrons that are produced from proton interactions with mechanical elements and patients. The goal of this work is to carry out neutron dosimetry and shielding studies by estimating ambient dose equivalent  $H^*(10)$  around a CPTC facilities, aiming to protect the radiation workers and the public. Experimental measurements were compared with values obtained with Monte Carlo calculations.

### Methods

$H^*(10)$  due to stray neutrons in CPTC was calculated using Monte Carlo methods through MCNP6 code and CAD designs. The facility modeled consists of a superconducting proton accelerator room and a treatment room with a rotating gantry. Several models of the radiation sources and the facility were simulated, starting from the manufacturer's model, with conservative assumptions, followed by models recently published with more realistic assumptions, and finally by models with more efficient shielding materials against neutron radiation. Experimental measurements will be carried out with extended range rem meters, WENDI-2 and LUPIN types, and also with conventional LB 6411 detector.

### Results

Using the conservative assumptions of the manufacturer the maximum  $H^*(10)$  value obtained is 0.4 mSv/year around the accelerator room. With models based on more realistic and accurate assumptions, the results are even lower. Absolute responses of extended range rem meters, which will be used in the experimental measurements, have been characterized in previous works.

### Conclusions

The shielding effectiveness against diffuse neutron radiation in CPTC facilities has been verified with MCNP6, using different models, materials and assumptions of radiation source. In any case, results achieved are below internationally accepted dose limits. These results should be verified soon by carrying out experimental measurements in a CPTC facility.

## Characterization of Fricke-gelatin dosimeters for Intraoperative Radiation Therapy dosimetry

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### Introduction

IntraOperative Radiation Therapy (IORT) is a cancer treatment strategy that relies on the delivery of therapeutic dose during surgical intervention with the aim of inhibiting local tumor recurrence. To this goal, dedicated accelerators were designed to output electron beams characterized by very high values of dose-per-pulse and steep dose gradients. Due to the harsh irradiation conditions, suitable dosimetric systems for accurate and precise dose distribution measurements are fundamental. In this perspective, the use of tridimensional dosimetric tissueequivalent phantoms would be of great interest for both the evaluation of dose profiles and for machine calibration.

This study was aimed at evaluating the applicability of Fricke-gelatin dosimeters to IORT. A characterization of the dose response was performed, followed by a preliminary evaluation of transverse dose profiles.

### Methods

For this preliminary study, samples - in form of spectrophotometer cuvettes and layers of 3 mm thickness - were irradiated with Novac7 (9 MeV nominal energy, 0÷40 Gy) at reference conditions, as defined by IAEA code of practice. Samples were optically analyzed with previously validated procedures. Uniformly irradiated cuvette samples were employed to evaluate the dose response properties in terms of sensitivity and dose resolution, reproducibility and stability. Through the use of layers, transverse dose profiles were acquired.

### Results

A linear response up to 35 Gy, with a dose resolution < 0.5 Gy, was observed. Moreover, a calibration protocol was developed to ensure reproducibility (< 3%), and a good stability (< 4%) in terms of sensitivity up to 3 days post-irradiation. Transverse dose profiles were compared to ionization chamber data and a good agreement within 2% in the dose plateau region was observed.

### Conclusions

Fricke gel system proved to be suitable candidates for application in IORT dosimetry. Studies are ongoing to test gel phantoms for use in 3D dose measurements.

## Experimental studies of in-water broadening and depth-dose profiles of pencil beams for Hadron Therapy

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### Introduction

The purpose of this work is the achievement of parameters describing the broadening versus depth in water of pencil beams (PBs) of charged particles, such as protons and carbon ions, used for Hadron Therapy, to improve a method for amending measured dose values affected by error due to the variation in the dosimeter sensitivity with the radiation LET variation.

### Methods

Measurements were performed by means of Gafchromic films, suitably placed in solid-water phantoms and exposed to proton or carbon ion beams at the Synchrotron of CNAO (Pavia). Images of optical absorbance were attained by means of a laboratory-made instrumentation. The films were suitably placed in a water phantom. The transversal distributions of the measured absorbed doses were fitted by means of a single Gaussian approximation for protons and a double Gaussian for carbon ions. The surfaces obtained with the fit procedure give information of the PB broadening, deduced by evaluating the section area at half height of the fitting surfaces and also allow to estimate the entity of the sensitivity quenching, by applying a properly developed procedure of comparison between measured and calculated dose values.

### Results

From the measured images of the dose in planes perpendicular to the PB axis, the area at half height of the Gaussian fit, the total dose in the same plane and the dose at the PB center were evaluated. Mathematical procedures describing the PB broadening v.s. depth as a function of the initial PB energy were found for both kinds of particles. For protons, also the formulation of in-depth dose profiles, as a function of the PB energy was achieved. For carbon ions a general in-depth dose profile formulation is still in development. Functions describing the sensitivity quenching versus depth were achieved for both particles.

### Conclusions

The obtained results are a consistent improvement of the information in the fields of both PB broadening and dosimeter sensitivity quenching.

## A Large Area GEMPix detector for treatment plan verification in hadron therapy

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### Introduction

The most advanced radiation modality for treating cancer is hadron radiotherapy, which at present uses protons and carbon ions. This is mainly because hadrons have the unique feature of increasing energy deposition with penetration depth, with a maximum at the end of the range followed by a sharp decrease (Bragg peak). However, treatment with hadrons requires not only an extremely accurate dose calculation, but also verification with high spatial and dosimetric accuracy. A promising tool is GEMPix, a detector recently developed by CERN Radiation Protection group, which combines two CERN technologies: a triple GEM (Gas Electron Multiplier) detector and a quad Timepix ASIC as highly pixelated readout.

### Methods

In this presentation, we will introduce the idea of a larger area GEMPix, the LaGEMPix detector, with active area of the order of  $20 \times 20 \text{ cm}^2$ . LaGEMPix will allow for the monitoring of large-area radiation fields associated with clinical treatments and will also allow the precise evaluation of the dose distribution despite the spread out of the beam with depth.

### Results

The status of this project in terms of engineering development and physics analysis will be reviewed. Various studies performed by our team have shown that the GEMPix (active area of  $28 \times 28 \text{ mm}^2$ ) is capable of providing two-dimensional images of the beam with high spatial resolution, the Bragg curve and the three-dimensional energy deposition. The results are very promising; however, room for improvement has also been demonstrated. Therefore, the continuation of these studies using a larger area detector will be presented.

### Conclusions

The development of a highly innovative detector technology allowing more accurate dose measurements while minimizing the limitations of the technologies presently used in hadron therapy is essential for the treatment plan verification to demonstrate that the required dose is delivered exactly where needed and no healthy tissue is unnecessarily irradiated.



## BENCHMARK ON MONTE CARLO CALCULATIONS FOR MICRO- AND NANODOSIMETRY: ASSESSING THE CONTRIBUTION OF CROSS-SECTIONS TO THE RESULTS' UNCERTAINTY

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### Introduction

Monte Carlo (MC) simulation techniques are often used to study particle track structure in different target volumes linked to biological effects of different radiation qualities.

To this end, dedicated track-structure MC codes have been developed and some general-purpose MC codes have recently been upgraded to enable the simulation of energy depositions in microscopic or nanometric volumes.

These MC codes include different cross-section data tables or models and computed results are known to strongly depend on the cross-sections data used to describe the individual inelastic interactions of charged particles, in particular electrons of very low energy.

Therefore, an estimation is needed of the uncertainty in microdosimetric spectra or frequency distributions of ionizations in nanometric volumes due to the use of different cross-section data in MC codes.

### Methods

EURADOS Working Group 6 “Computational Dosimetry” launched a two-step exercise. In the first step, participants using different MC codes were asked to calculate microdosimetric spectra in a 10  $\mu\text{m}$  diameter water sphere using a given electron source spectrum and three geometrical configurations on the one hand as well as ionization cluster size distributions (ICSDs) in 3 nm and 8 nm diameter target spheres on the other hand. The second step is to perform a sensitivity analysis on the dependence of the simulated results on the cross-section data.

### Results

Comparison of microdosimetric spectra shows a general good agreement in the resulting mean values and general shape for two of the three configurations.

For ICSDs results, the differences are larger and mean values can differ up to 40%.

### Conclusions

A preliminary sensitivity analysis was performed using the MC code Geant4-DNA with different cross-section data tables available. Results indicate that interaction cross-sections for low energy electron interactions may have associated uncertainties in the order of 100%.

## The Microdosimetric d(z) Model for the assessment of the response of luminescent detectors to different radiation qualities: development, benchmark and applications

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### Introduction

Luminescent detectors are commonly used for dose measurements in space and hadron therapy facilities. Therefore, it is of fundamental importance to completely characterize the efficiency of these detectors for measuring a wide range of particles and energies.

The experimental relative efficiency determination through irradiations in calibrated particle accelerators is time consuming and very expensive. Furthermore, due to technical limitations it is often not possible to irradiate the detectors with energies above 1 GeV/u or with less common isotopes. In addition, the efficiency determination at low energies is biased with associated large uncertainties in range, LET and dose.

Therefore, the goal of this work was to develop a model that allows predicting the relative efficiency of luminescent detectors for different radiation qualities.

### Methods

The recently developed Microdosimetric d(z) Model assesses the relative efficiency of luminescent detectors for measuring different radiation qualities by convoluting the simulated specific energy dose probability distribution in nanometric targets with an experimentally determined response function.

### Results

The model was tested for LiF:Mg,Ti and LiF:Mg,Cu,P thermoluminescent detectors in case of charged particles from  $^1\text{H}$  to  $^{132}\text{Xe}$  in the energy range 3 to 1000 MeV/u and to photons in the energy range 12 to 1250 keV. A comparison with experimentally determined efficiency data showed a very good agreement in case of calculations performed in targets of 40 nm. As a consequence, the model has been used to predict the efficiency of these detectors for ions up to  $^{222}\text{Rn}$  and lighter particles such as electrons, positrons, muons, pions, and kaons.

### Conclusions

The Microdosimetric d(z) Model can be reliably used to assess detector efficiencies to exotic particles, unavailable radiation qualities and energies at ground level accelerators or complex mixed fields.

## **Limitations of solid-state devices for microdosimetry applications**

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#### **Introduction**

Use of solid-state sensors for measuring microdosimetric quantities has been increasing recently due to advantages such as its size, portability and its lack of high voltage biasing to work properly. However, these devices do not lack drawbacks; drift and diffusion phenomena affect partial charge collection, modifying the microdosimetric spectra depending on the geometry of the site, operation conditions and readout electronic noise.

#### **Methods**

Drift and diffusion processes are very relevant when micrometric active sites are considered. A perturbation in the pulse height detected spectrum respect to the ideal imparted energy within the considered site geometry is produced. Effects in silicon micro-dosimeters built by IMB-INM (CSIC, Spain) were evaluated. To parametrize the charge collection efficiency an IBIC test at CNA (Seville, Spain) was performed and results were compared with TCAD simulations. The device model used together with FLUKA Monte Carlo simulations has been compared with experimental micro-dosimetric spectra of a clinical  $^{12}\text{C}$  ion beam at Fondazione CNAO (Pavia, Italy).

#### **Results**

Smeared Monte Carlo spectra reproduce the main features of the experimental spectra taken with the silicon microdosimeters affected by partial charge collection events. The perturbation on the frequency and dose averaged lineal energy as a function of micro-dosimeter size was evaluated. Additionally, the minimum detectable lineal energy for no intrinsic gain devices was evaluated considering a general model of readout electronics as a function of the fluence averaged mass thickness of solid-state micro-dosimeters.

#### **Conclusions**

Solid-state devices can be employed to measure microdosimetric spectra, but large collection and electronic noise pose limitations on their performance. The perturbation on the microdosimetric spectra has been evaluated in this work to set a general benchmark for the expected performance of a micro-dosimeter depending on geometry and sensitive media.

## A wall-less Tissue Equivalent Proportional Counter as connecting bridge from microdosimetry to nanodosimetry

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### Introduction

The effectiveness of a radio-therapeutic treatment is strictly related to the pattern of the interactions of the radiation at cellular and sub-cellular level that induces the biological response. The study of the cell inactivation requires a detailed physical knowledge of the local energy deposition of the therapeutic beam. This goal can be achieved through different approaches: microdosimetry and nanodosimetry.

### Methods

A new Tissue Equivalent Proportional Counter capable of simulating site sizes down to a few tens of nanometers was constructed for finding a bridge between microdosimetry and nanodosimetry. The TEPC has a cylindrical sensitive volume and consists of three independent electrodes: a central anode wire, a cathode shell and a helix for confining the avalanche. An accelerated ion beam can interact directly with the gas sensitive volume through a hole, drilled in the cathode. In this way, the same particle beam can cross the TEPC and the STARTRACK nanodosimeter (INFN, Italy) sensitive volumes at the same time allowing the comparison between the TEPC spectra and the corresponding nanodosimetric one.

### Results

Preliminary irradiations employing an <sup>241</sup>Am source have demonstrated the capability of the device in measuring in nanometric sites. Alpha spectra in the range 300-25 nm in simulated site size were acquired employing both propane and DME as tissue equivalent gases. Monte Carlo simulations were carried out using ad hoc codes for studying: the pattern of ionizations at DNA level and the electronic avalanche inside the TEPC. Such simulations have demonstrated the capability of reproducing the detector response under different operating conditions.

### Conclusions

Preliminary numerical and experimental characterizations of the TEPC give confidence about the capability in finding a bridge between microdosimetry and nanodosimetry. Irradiations with <sup>7</sup>Li ions are foreseen in the near future to perform the direct comparison with the STARTRACK nanodosimeter.

## A new TEPC for nano-microdosimetric investigation of therapeutic hadron beams

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### Introduction

In the last decades, hadrontherapy has been spreading worldwide for cancer treatment. As a new approach, its application requires novel methods for physical characterization of the beam. The tissue equivalent proportional counter (TEPC) is the most accurate device for measuring the microdosimetric properties of hadron beams, nevertheless no detailed information on the track structure can be obtained, since the lower operation limit of standard TEPCs is around 0.3  $\mu\text{m}$ . This work describes an innovative low-pressure avalanche-confinement TEPC capable of measuring microdosimetric distributions of hadron beams in nanometric-equivalent sites.

### Methods

The cylindrical chamber of the new TEPC is defined by three electrodes biased independently which subdivide the sensitive volume into an external drift zone and an internal multiplication region. Two aligned cavities embed a removable alpha source and a miniaturized photodiode for calibrating the TEPC for different simulated site sizes. A transportable gas flow system allows a continuous replacement of tissue equivalent gas inside the chamber.

### Results

The TEPC response against different hadron beams, in particular protons (therapeutic beam for eye melanoma), helium ions and carbon ions was experimentally assessed for different simulated site sizes in the range 500 – 25 nm at several points across the depth dose distribution. Moreover, measured spectra were compared with Monte Carlo simulations performed with the FLUKA code. The obtained results show a satisfactory agreement. The behaviour of dose-averaged lineal energy values measured at different site sizes and at different depths is discussed.

### Conclusions

A systematic comparison between microdosimetric distributions at nanometric scale and nanodosimetric measurements will allow to investigate the feasibility of unfolding the nano-microdosimetric spectrum into a track-structure information, which is more relevant for the description of the induced radiation damage.

## First Microdosimetric measurements with a sealed mini-TEPC at the clinical proton SOBP of CATANA

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### Introduction

Radiation therapy with charged particles is spreading worldwide because of the favourable depth-dose distribution with respect to conventional radiotherapy.

Although the relation between physical interactions and biological effect is still difficult to establish, it is known that an accurate treatment requires a detailed physical knowledge of the local energy deposition of the beam at the subcellular scale. To this respect, experimental microdosimetry offers a valuable aid. Tissue-Equivalent Proportional Counters (TEPC) are the reference devices.

### Methods

A miniaturized TEPC (mini-TEPC) has been developed in Legnaro National Laboratories (LNL) of the Italian Institute of Nuclear Physics (INFN) to cope with high-intensity clinical beams such as those delivered in active scanning modality. The cylindrical cavity has a diameter of only 0.9 mm, as compared to the 12.7 mm of the Far West LET-1/2. Several microdosimetric measurements have been performed with the mini-TEPC over years, working the detector in a gas-flow modality in order to minimize the aging effects due to gas deterioration. However, a sealed detector working in gas-steady modality would be attractive for practical use in clinics, in particular a sealed mini-TEPC will overcome the limitation of the necessity of introducing a bulky gas flow system in the clinical treatment room.

A prototype of a sealed mini-TEPC was irradiated in the 62 MeV clinical proton beam of CATANA (LNS-INFN), using a half-modulated SOBP.

### Results

Following an appropriate cleaning and gas filling procedure, several measurements were performed at different depths within the proton SOBP and at different beam currents. The spectra measured at different times were very well superimposable, emphasizing the stability of the detector even in the gas-steady modality.

### Conclusions

The stability of the microdosimetric response even at high beam currents paves the way to the design of a new miniaturized TEPC that works in steady-gas modality.

## Plutonium in human brain: Is more biokinetic detail needed for dosimetry?

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### Introduction

Biokinetic model for systemic plutonium is used to estimate internal radiation doses to organs and tissues. The brain is not included explicitly in the model but is aggregated into a pool called *Other tissue* in which activity is assumed to be uniformly distributed. Explicitly identified tissues are liver, bone, bone marrow, kidneys, and gonads. Due to increasing interest in potential adverse effects of radiation on the brain, efforts are underway within the Million Person Study to improve brain dosimetry for both internal and external radiation sources.

The purpose of this study was to assess potential improvements in brain dosimetry for incorporated plutonium from explicit modelling of brain kinetics.

### Methods

The most relevant data available for modelling brain kinetics of plutonium are autopsy data for individuals occupationally exposed to this element. The U.S. Transuranium and Uranium Registries (USTUR) has studied the biokinetics and tissue dosimetry of actinides in nuclear workers. Plutonium (<sup>239</sup>Pu) activities in brains were measured for 70 individuals. In 31 cases, Brain/(Liver+Skeleton) activity ratios were estimated to modify plutonium systemic model by explicitly adding brain compartment. Plutonium brain dosimetry was evaluated for two alternate versions of the systemic biokinetic model: (a) with the brain as an implicit mass fraction of *Other tissue* and (b) with explicit modelling of brain kinetics. Dose coefficients for <sup>239</sup>Pu based on both versions of the biokinetic model were calculated and compared.

### Results

<sup>239</sup>Pu activity concentrations in brain tissue of occupationally exposed individual ranged from 0.0003 to 4.4 Bq kg<sup>-1</sup> with a median of 0.027 Bq kg<sup>-1</sup>. A median value for these individuals, the brain contains ~0.2% as much <sup>239</sup>Pu as liver and skeleton combined. A single compartment representing brain was added to the plutonium biokinetic model, and parameter values were set to yield a long-term total activity ratio Brain/(Liver + Skeleton) of 0.002.

Dose coefficient for brain for acute <sup>239</sup>Pu input to blood was 0.022 mSv Bq<sup>-1</sup> based on biokinetic model with brain included in *Other tissue* and 0.026 mSv Bq<sup>-1</sup> based on modified version with an explicit brain compartment. The dose coefficient based on the modified model with an explicit brain compartment is 0.96 times the value based on the model with implicit brain.

### Conclusions

The results of the study to this point suggest that explicit biokinetic modelling of a brain pool for plutonium is not likely to result in significant difference in estimated dose to the brain.

## Internal Dosimetry of Uranium Workers exposed during the Nuclear Fuel Fabrication Process in Spain

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### Introduction

Workers in the Juzbado Plant of ENUSA in Spain are exposed to intakes of low enriched uranium during the fabrication of nuclear fuel elements for Spanish Nuclear Plants. CIEMAT established in 2014 an individual monitoring program consisting in bioassay measurements of uranium in urine by alpha spectrometry and a methodology of dose assessment based on current ICRP models and recommendations, ISO 27048 standard and IDEAS Guidelines V2.

### Methods

Results of routine monitoring data of 24h urine samples (creatinine normalization, MDA= 0.5 mBq/sample of each uranium isotope) of Juzbado workforce confirmed low level of chronic intakes of uranium oxides in the Plant, combined with acute intakes when incidents took place. IMBA software (v4.1.6, PHE, UK) permitted the dose assessments of internal exposures in complex intake regimes of occupational inhalation of Type S compounds (ICRP 78/68). Uncertainties were evaluated for monitoring data using the Scattering Factor approach (ISO27048) for the Intake calculation and to test the fitting of measurements results with the prediction of the excretion uranium model under the internal exposure frame described above. Intake and dose E(50) are obtained separately for <sup>234</sup>U and <sup>238</sup>U when activity concentration (Bq/d) is above MDA. Total Intake and dose of low enriched uranium is estimated afterwards.

### Results

A total of 200 workers at risk of internal exposures in the Juzbado facility in Salamanca (Spain) were included in different individual monitoring programs (routine, special, confirmatory, task-related) established by CIEMAT Internal Dosimetry Service. Annual chronic intakes were assessed for 106 workers with results > MDA; doses E(50) > 1 mSv/year were detected in 50% of these cases. Maximum annual intakes corresponds to long term exposed staff (30 years of chronic exposure) with E(50) = 5 mSv/year (Lopez et al, HEIR2018). Incidents occurred in the plant resulted in doses E(50) < 1 mSv so far. Results of Annual intakes with doses E(50) > 0.2 mSv are reported to workers. Individual monitoring program is complemented with workplace monitoring using Static Air Samplers (SAS) at the Juzbado facility.

### Conclusions

Internal dosimetry of uranium workers exposed during the nuclear fuel fabrication process was carried out by CIEMAT Internal Dosimetry Service. Bioassay results confirm low level of chronic intakes of enriched uranium in the Juzbado plant. The preliminary study of the impact on the dose assessment using the new uranium model according to ICRP Publication 137 (OIR Part III) is also presented here.



## Investigation of dose estimation uncertainties for uranium exposure

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### Introduction

For most radionuclides, the internal dose is estimated in two steps. First, the activity in the body is determined with direct or indirect monitoring methods at a given time after intake. By direct measurements, the radioactivity in the whole or part of the human body can be determined (in-vivo), while by the indirect method, the radioactivity of biological samples taken from the body (e.g.: urine) is assessed (in-vitro). In the second step, from measured data, considering a scenario of exposure (time and route of intake, chemical form etc.), the intake value and the radiation dose can be estimated. The uncertainty of measurement data can be determined with application of well-known methods. But there is no existing general formula to specify the uncertainty of dose estimation since a number of possible assumptions may be applied regarding the circumstances of intake.

### Methods

In this study, the permutable parameters and their effect on internal dose estimation for 3 workers exposed to uranium are presented. Using the data of the workers, reference dose assessments were performed by assigning default assumptions to each parameter and sensitivity analyses were conducted by changing the parameter values

### Results

As a result of this study, we identified the parameters influencing the most the dose estimation following uranium exposure.

### Conclusions

The sensitivity analysis may also contribute to guidelines to estimate doses for epidemiological studies and for compensation claims.

## Comparison of the biokinetic models of lutetium and iodine, and validation

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### Introduction

The biokinetics and behavior of radioisotopes that can be incorporated into the body by different ways are described in various ICRPs (100, 129, 130).

There is a lot of interest in trying to calculate the internal dose in different organs when a radiopharmaceutical is supplied. Different software with different methods have been developed to theoretically calculate the doses in the different organs, according to the biokinetics of the radionuclide.

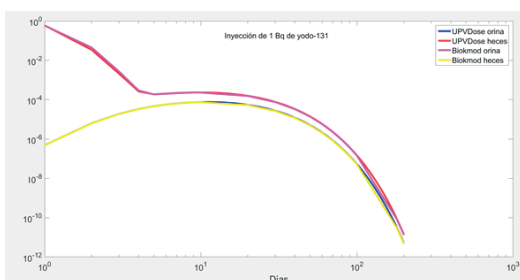
In the Universitat Politècnica de València, the UPVDose software has been developed based on the guidelines of the ICRP. In this work, the application of this code for the calculation of the dose of the Lutetium-177 and iodines (131 and 123) intakes, is shown.

### Methods

The software has been developed in MATLAB<sup>®</sup>, by the symbolic calculation module. The program uses the compartmental model that solves systems of ordinary differential equations. The biokinetic models described in the ICRPs (66,78,100,129 and 130) have been implemented. With these models it can be calculated the dose by injection and ingestion, for nuclear medicine applications of the lutecium and iodine. The results obtained will be compared with other softwares such as the 'Biokmod' and the 'IDAC\_Dose'. The dose of each organ are calculated according to their biokinetics.

### Results

In the graph below, the evolution of iodine-131 activity in urine and feces can be seen.



### Conclusions

It can be concluded that the comparison with other programs of calculation of internal dosimetry have given acceptable results.

The comparison of the data with the clinical results will validate the understanding of the biokinetic models provided.

## Specific absorption fraction estimation in a voxel phantom model of a mouse for use in new radiopharmaceutical developments.

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In radiopharmaceutical applications, whether it is to study new metabolisms or to reduce the exposure of human patients and professionals to absorbed dose, tests on small animals are paramount. A correct radiopharmaceutical dosimetry in these animals is thus of great importance. This can be done using Monte Carlo methods and the MIRD methodology.

In this work, the MCNPx particle transport software and the DIGIMOUSE voxel phantom were used to calculate the self-absorption fractions in the kidneys, with both photons and electrons using monoenergetic sources in an energy range of 10 keV to 4 MeV. The results were favorably compared with other studies, validating the computational model. After validation, a  $^{99m}\text{Tc}$  source was defined in various organs to determine specific absorption fractions (SAFs) in 21 organs. These values were converted into S-Factors.

In the case of electrons, for energies between 10 keV and 4 MeV, the self-absorption factors ranged from 0.99 to 0.15, while for the photons ranged from 0.66 to 0.006. Finally, the results obtained for the S - factors are generally in agreement with the previously published results. The obtained differences are due to variations in the mass of the organs of the mice, as well as the distance between the source and target organs and the constitution of the organs and tissues that separate them.

This work will help create a database that will be used by the Grupo de Proteção e Segurança Radiológica, of C<sup>2</sup>TN to study new radiopharmaceuticals that have  $^{99m}\text{Tc}$  as radionuclide.

## Three-dimensional Personalized Monte Carlo Dosimetry for Treatment Planning for Selective Internal Radiation Therapy with Yttrium-90 Microspheres using GATE

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### Introduction

Y-90 radioembolization is a well-established therapy for the treatment of refractory primary or metastatic liver tumors. Compared with organ-based dosimetry, three-dimensional (3D) and image-based dosimetry better accounts for radionuclide distribution and anatomic patient variability. GATE is a unique Monte Carlo (MC) platform allowing for the simulation of theranostic scenarios dedicated to imaging and therapeutic applications such as image-based dosimetry. The purpose of the study is to develop a workflow for radiation dose prediction of Y-90 microsphere selective internal radiotherapy (SIRT) for liver tumors using GATE.

### Methods

A data group of 21 patients undergoing SPECT/CT imaging of intra-arterial hepatic <sup>99m</sup>Tc macroaggregated albumin (<sup>99m</sup>Tc-MAA) scan before Y-90 SIRT were collected. 3D distribution of cumulated activity was generated from <sup>99m</sup>Tc-MAA SPECT data. The 3D absorbed doses were then generated from the GATE software. The VOIs of tumor and organs at risk (OAR), including right lung, left lung, non-tumor liver and gallbladder, were drawn on CT images using ITK-SNAP software. The maximum-injectable activity (MIA) for tolerance criteria based on OAR mean absorbed doses ( $D_{\text{mean}}$ ) and OAR dose-volume histograms (DVHs) were determined. Those MIAs were compared with the one suggested by the conventional partition model (PM) with  $D_{\text{mean}}$  tolerance criteria.

### Results

The MIA determined by  $D_{\text{mean}}$  tolerance criteria from the MC method is 50.1% lower than that using the PM method. However, the MIA based on DVH using the MC method simulation is 11.8% lower than the conventional partition model. The computing time of the simulation per case is ~18 hours.

### Conclusions

We have demonstrated the feasibility of the workflow for Y-90 SIRT dosimetry based on the MC method into clinical practice. The MIA recommended by the MC method is significantly different from the conventional PM method. Further investigation of the clinical impact needs is needed.

## Enhanced analysis of Dynamic Multileaf Collimator performance with EPID

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### Introduction

Dynamic MLC performance is assessed by detection of landmarks in the image (picket), and linear fits of the leaf positions are used as the reference to find deviations of individual leafs. Therefore, faulty leafs could affect the reference values themselves and cause an inconsistency. Robust statistical methods help overcome this difficulty.

### Methods

Data from images taken in 6 linacs, collected in a 2 year period, have been used. Linacs were all Varian, TrueBeam and C-series, two of them equipped with a high definition MLC. The python module Pylinac ([//github.com/jrkerns/pylinac](https://github.com/jrkerns/pylinac)) was used to extract picket positions from the images. R statistical software was utilized to write scripts performing the analysis. Test plans provided by Varian for RapidArc QA were used.

Robust central tendency measures, dispersion, tests and linear regression were used to fit robust models, providing measurements for gravity effect, MLC leaf accuracy and dynamic MLC delivery.

### Results

We found that it is possible to discriminate differences between picket fence results at different gantry angles of 1mm, and misplacement of the leaves from 1mm. Yuen t-tests for two dependent groups were used ( $p < 0.05$ ) for this analysis.

Leaf fits based on trimmed means were consistent with the estimates obtained with robust linear models including all relevant variables (leaf pair, gantry angle, picket number).

### Conclusions

This study shows that Robust Statistics provide tools to safely and accurately analyze the performance of DMLC for RapidArc, utilizing all the information contained in the images. Leaf performance can be assessed taking away the effect of confounders like imager sag, gravity and accuracy of other leaf pairs. The sensitivity of these tests is well above the requirements for a very tight tolerance level. This analysis is fast and accurate and its sensitivity and accuracy is independent of the result, as errors in a limited number of leaf pairs will not change results for the other ones.

## Do a priori expectations of plan quality offset planning variability in head and neck IMRT?

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### Introduction

Radiotherapy planning is still a rather biased and planner dependent process, presenting large output variability. This work aims to evaluate whether PlanIQ software by SunNuclear contributes to a significant improvement in IMRT plan quality for head and neck patients in Tomotherapy and if it leads to greater homogeneity across different planners.

### Methods

28 head and neck clinical cases distributed by 3 different planners (A,B,C) were planned: 1) without the use of PlanIQ version 2.2 and 2) using as guidelines to the OAR's DVH the feasibility DVH (fDVH) with feasibility level  $f=0.1$ . The closest fDVH to the relative DVHs (rDVH) obtained by each planner with and without PlanIQ, as well as the corresponding feasibility level were calculated. The closeness between each DVH curve pair was assessed through Dice index. Planned values were crossed with OAR prescription dose constraints and with target coverage, for each of the planners. To assess for statistical significance of the results with and without PlanIQ the Wilcoxon signed paired rank test was performed. Finally a validation of the results by SPIDERplan (<http://dx.doi.org/10.1016/j.rpor.2016.07.002>) scores was carried out.

### Results

For planner A, 3 out of 17 OARs showed statistically significant lowering of the mean  $f$  value with PlanIQ. As for planner B, only 1 OAR achieved this result. Planner C had the greatest improvement with 12/17 OARs showing significant differences. For the total mean score there were 9/17 OAR's with significant improvement without significant penalty of PTV coverage. This results were corroborated by the SPIDERplan scores.

### Conclusions

For planners A and B the usage of PlanIQ didn't show a great improvement in the sparing of OARs whereas for planner C it made a major difference. In any case, PlanIQ contributed to improve the homogeneity between planners as the global mean SPIDERplan scores with PlanIQ had lower standard deviations compared to without PlanIQ.

## Monte Carlo assessment of out-of-field doses in radiotherapy treatments of paediatric patients

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### Introduction

Out-of-field doses are of concern in radiotherapy, where doses below 3 Gy are considered low doses and neglected in radiotherapy treatment planning. Radio-carcinogenesis is the most severe side effect that may be caused by exposure of healthy tissues due to out-of-field doses. It is therefore of cornerstone importance to evaluate them, namely in paediatric patients. The aim of this study is to create a Monte Carlo (MC) model to assess out-of-field doses in radiotherapy treatments of paediatric patients.

### Methods

The computational model of the linear accelerator (Linac) Clinac Varian 2100 CD head operated at 6MV was implemented in MCNP6, including main components and secondary shielding. To perform the validation of this model concerning the in-field and out-of-field doses, measurements of dose profiles and percentage depth doses curves, for different field sizes, were undertaken in clinical settings with an ionization chamber and compared against MC simulations using the Linac model. Out-of-field organs doses measurements were performed using a CIRS 5 years old anthropomorphic phantom on the Linac using brain fields. Thermoluminescent detectors were placed on the thyroid, spine, heart and lungs. A CT scan was carried out on the anthropomorphic phantom. The CT images were segmented to create a voxel phantom and to perform MCNP6 calculations, to determined the organ doses.

### Results

The MC simulation results of the Linac showed good agreements with the clinical measurements, namely  $\leq 2\%$  for in-field and  $\leq 5\%$  for out-of-field doses. Therefore a good agreement between the clinical measurements and the MC simulations was obtained for the organ doses in the paediatric phantom.

### Conclusions

Our study provides a model that could be used in clinical research, namely in the assessment of out-of-field doses in paediatric patients; the obtained dosimetric results can be used, applying appropriate risk models, to estimate the development of secondary cancers, of utmost relevance namely for paediatric patients.

## A novel method for the evaluation of volume averaging effects in dosimetry of flattening filter-free photon beams.

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### Introduction

This work describes a novel practical method to assess the effect of the averaging of non uniform fluence across a thimble ion chamber in flattening filter-free beams. This procedure can be carried out with equipment available in any clinical facility. It is based on in-air measurements at different SSDs. The non uniform profile of a FFF beam has negligible effect on scattering in this setup, and all the variation is either geometric or ion recombination, as the dose per pulse changes with SSD.

### Methods

In air measurements at different distances (80 to 125 cm SSD) were performed. This way, the magnitude of the averaging effect changes in a controlled manner, and an estimate of an upper bound of the effect is obtained by comparison of the measurements carried out with different beam qualities: with and without flattening filter.

Measurements have been performed with a FARMER type ion chamber (NE 2571) and a small volume PinPoint 3D chamber (PTW 31016), connected to a Sun Nuclear PCE electrometer. A Varian TrueBeam linear accelerator was used for the irradiations. For each SSD, readings were corrected for ion recombination using the two voltage technique.

### Results

The range of the effect on measured dose of volume averaging has been estimated for 6 FFF (0.2% - 0.7%) and 10 FFF (0.6% - 1.5%) for the FARMER ion chamber, for the above measured range of SSDs. The PinPoint ion chamber shows negligible effect for 6 FFF and it ranges 0.1% - 0.3% for 10 FFF.

### Conclusions

Radiotherapy departments can apply this method to make estimates of the volume averaging effect, commission detectors for FFF beams and, in any case, add evidence of the volume averaging effect to procedures described in the literature to deal with the increased dose rate and the spectral difference with flattened beams.



## Neutron spectrometry at the ALBA Synchrotron Light Laboratory

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### Introduction

Synchrotron light is produced at ALBA from electrons at 3 GeV in a storage ring of about 270 m circumference. Electrons are initially accelerated by a LINAC up to 110 MeV, then transferred to the booster where they are accelerated to 3 GeV, and are finally transferred to the storage ring where they produce the synchrotron radiation used at the experimental stations. Transfer lines between LINAC and booster and between booster and storage are the most likely places where electrons may interact with beam elements. Although cross sections for neutron production from electrons are small, a considerable amount of neutrons may result from these interactions given the relatively high beam intensity.

### Methods

An experimental campaign was performed to measure the spectrum of the neutrons resulting from the interaction of beam electrons with the horizontal scraper at the BTS (booster to storage) transfer line in a dedicated run. Measurements were done with the UAB Extended Range Bonner Sphere Spectrometer (BSS), able to detect neutrons from the thermal energy region up to 1 GeV. Measurements took place in a point at 149 cm from the scraper, inside the shielding tunnel, and in a point close to this position but outside the tunnel, in the experimental hall. In addition, neutron production was simulated using FLUKA. Spectra are obtained from unfolding the BSS measurements with the FRUIT code in numeric mode, using the simulated spectrum as the initial guess.

### Results

Spectra obtained in both measurement points, as well as global dosimetric quantities (neutron fluence and ambient dose equivalent, fluence fractions in different energy ranges and energy averaged in fluence and in dose) will be presented. Results at the point inside the tunnel are representative of the neutron “source” term in the unlikely situation of a beam loss during operation, while results at the point in the experimental hall are useful for radioprotection purposes.

### Conclusions

Results from this campaign will allow to extend the operational range of our BSS up to 3 GeV.

## Calibration of neutron dosimeters for radiation protection use at the ALBA synchrotron experimental hall

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### Introduction

Bright beams of synchrotron radiation are produced from a 3 GeV electron accelerator at the Spanish synchrotron facility ALBA. The electron acceleration and storage mechanisms lead to complex secondary radiation fields. These fields include electrons, photons and neutrons of a wide energy range, and have an important pulsed behaviour and very significant spatial variations. In order to perform correct dose assessments for radiation protection purposes, it is necessary to measure separately electrons, photons and neutrons. In the case of neutron dosimetry, given the strong dependence with energy of the radiation weighting factor and of the fluence to ambient dose equivalent conversion coefficient, it is necessary to have some spectrometric information to correctly assess dose.

### Methods

Neutron dosimeters designed at UAB, based on PADC (Poly Allyl Diglycol Carbonate) track detectors covered with a set of adequate converters to make them sensitive to a wide range of neutron energies, were exposed in different places of the ALBA experimental hall. After exposure, the detectors were electrochemically etched using the standard UAB procedure and tracks were counted taking images with a photographic scanner and using a counting software based on MATLAB. As to date no calibration facility provides neutron fields similar to those found at ALBA, ambient dose equivalent was originally evaluated with conversion factors obtained from calibration at an Am-Be neutron source.

### Results

The neutron spectrum and total fluence at specific places in the ALBA experimental hall is known from a separate work. Comparing the tracks recorded at the PADC detectors at a given place with the neutron fluence determined at the same place, it is possible to obtain the calibration factor for this particular neutron field. From this calibration factor, results of the neutron ambient equivalent dose at the remaining points of the ALBA experimental hall will be presented in this work.

### Conclusions

Using PADC based track detectors for neutron dosimetry at the ALBA experimental hall, combined with prior knowledge of the neutron spectra and fluence at specific points, allow calibrating the detectors for determination of neutron ambient dose equivalent at the premises.

## The EURADOS inter-comparison exercise on neutron spectra unfolding in Bonner spheres spectrometry

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### Introduction

The “International comparison on neutron spectra unfolding in Bonner spheres spectrometry” was launched by the EURADOS Working Group 6 “Computational Dosimetry”. The purpose of the exercise is not establishing which unfolding procedure is best, but surveying how the computerized unfolding methods are handled in practice by real users. It is expected that the exercise allows pointing out the most common difficulties found by users and the possible mistakes related to them. The exercise focused on aspects such as the pre-information required for unfolding the spectra, the uncertainties and the type of convergence algorithm used.

### Methods

Participants were provided with the response matrix of an idealized Bonner Spheres Spectrometer (BSS), the sphere counts and uncertainties obtained in four different idealized scenarios: a medical accelerator 25 MV GE Saturne 43 situated in the centre of a 7x7x3 m<sup>3</sup> room, a workplace field consisting of an ISO <sup>241</sup>Am-Be source moderated by a water tank, an irradiation room with an ISO <sup>241</sup>Am-Be source in the centre of an iron sphere and a skyshine scenario.

The considered BSS included an idealized <sup>3</sup>He detector and a set of 13 spheres: bare, 2”, 2” + 1 mm Cd, 3”, 3.5”, 4”, 4.5”, 5”, 6”, 7”, 8”, 10” and 12”. The response matrix and the reference neutron spectra were calculated using MCNP5 and ENDF/B-VII cross sections with thermal scattering treatment, S(a,b) for polyethylene at room temperature. The counts for each sphere in the proposed scenarios were calculated by folding the simulated neutron spectrum with the response matrix and perturbed using a Poissonian distribution to simulate realistic uncertainties.

Participants were asked to determine the neutron spectra and relevant spectrum-integrated quantities, using the unfolding code they normally use, and to provide information about how they reached the solution.

### Results and conclusions

The solutions presented by the participants will be depicted in this communication, classified by the different categories of the unfolding codes used, and compared to the reference solutions for the spectra and integral dosimetric quantities. Some relevant physical effects related to the perturbation of the field by the Bonner spheres is shown to change the unfolded field relative to the detector absent field, thus affecting systematically the unfolding process..

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## Role of the energy spectrum in epithermal neutron dosimetry

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### Introduction

The dosimetry in radiation fields generated by epithermal neutrons is still a challenging topic. Several dose components contribute to the total absorbed dose and each of them has its spatial distribution and relative intensity. These spatial distributions and relative intensities depend not only on the chemical and isotopic composition of the irradiated material, but on its shape and size too. With particular interest for tissue or water equivalent materials, the main dose components are: (a) the dose due to recoil nuclei, mainly protons, caused by elastic scattering of epithermal or fast neutrons, mainly with hydrogen nuclei, (b) the  $\gamma$  dose coming from the reactions of thermal neutrons with hydrogen nuclei in tissue or water and, in tissue, (c) the dose of protons emitted in the reactions of thermal neutrons with nitrogen. If isotopes having high cross section for thermal neutrons are introduced in tissue or water, also the resulting dose (d) must be taken into consideration.

### Methods

Monte Carlo simulations have been developed to investigate the neutron spectrum variations in water phantoms of different sizes and shapes and the doses both from charged particles and from photons. The phantoms were made of pure water, water containing an amount of nitrogen near that in human tissues and water containing isotopes with high cross section for thermal neutrons.

### Results

The results have shown how, in each position of the irradiated volume, the dose components (a), (c) and (d) depend on the neutron fluence and spectrum, which in turn depend on shape, size and isotopic composition of the irradiated volume. The dose component (b) has shown a stronger dependence on these parameters, which has been interpreted.

### Conclusions

The results give a useful estimate of the extent of the variations of each dose contribution following changes in the various characteristics of the irradiated volume.

## Proposals to Improve the Accuracy of Calculating Reference Effective Dose in ANSI N43.17 (Security Screening of Persons)

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In today's world, people are intentionally exposed to ionizing radiation for the purpose of security screening. In the US, the national standard that provides guidelines and specific limits to the radiation-safety aspects of the operation of these systems is ANSI N43.17: Radiation Safety for Personnel Security Screening Systems Using X-Ray or Gamma Radiation. System designs include backscatter and transmission portal systems, multi-source systems, vehicle scanners with human occupants, and the use of radioisotope sources of radiation.

The ANSI N43.17-2009 standard is undergoing formal revision. The current standard provides a simple formula for "reference effective dose" ( $E_{\text{REF}}$ ) and limits for  $E_{\text{REF}}$  on a per screening and annual basis. While the formula has the virtue of being simple to use, in real-world applications it has often underestimated the effective dose by up to 30 % relative to more sophisticated methods of estimating dose to persons. We identify four underlying causes for these inconsistencies and propose a new formulation for  $E_{\text{REF}}$  that greatly improves the agreement while still trying to maintain a simple recipe for estimating exposures. Based upon our measurements and calculations, these are:

1. Rather than relying on a single proprietary Monte Carlo package, we propose to apply the relatively new ICRP Publication 116 which uses a much more accurate anthropomorphic phantom (CT based) and averages results over multiple simulation packages, presumably yielding more accurate results.
2. Currently the  $E_{\text{REF}}$  formula is based upon a piecewise linear approximation of estimated dose vs. HVL for a wide variety of beam qualities. We propose to replace it with a piecewise cubic or quadratic approximation, greatly improving the agreement between modeled and calculated doses.
3. Rather than averaging AP and PA exposures (the equal AP/PA assumption), separate formulas will be provided for each irradiation geometry. The contribution to the total effective dose from each irradiation geometry can then be summed to match whatever screening is actually performed.
4. The data used to generate the  $E_{\text{REF}}$  formula suffered from large scatter between beams of low and high filtration. We show that this effect can be greatly reduced by plotting the modeled effective doses against the Quarter Value Layer instead of the HVL.

## IEC standards for active dose (rate) meters and monitors and passive dosimetry systems

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### Introduction

The International Electrotechnical Commission (IEC) is the world's leading organization that prepares and publishes international standards for all electric and electronic devices and systems. The paper presents the standards developed by IEC Subcommittee 45B "Radiation protection instrumentation" concerning the active pocket and portable dose (rate) meters and monitors and passive dosimetry systems.

### Methods

The dosimetry systems with integrating passive detectors for individual, workplace and environmental monitoring of photon and beta radiation are covered by IEC 62387 (2012, currently being revised, expected publication in 2020). The active personal and ambient meters and monitors for photon and beta radiation are covered respectively by IEC 61526 (2010, revision started to update and add  $H_p(3)$ ) and IEC 60846-1 (2009). The neutron ambient dose equivalent (rate) meters are subject to IEC 61005 Ed. 3 (2014, revision envisaged). All these standards were transposed as European EN standards.

### Results

The IEC standards describe the performance requirements and the functional criteria along with the test methods for evaluating the performance of the applicable instrumentation. The standards specify the general characteristics, the general test procedures, the radiation characteristics, as well as the environmental, mechanical, electromagnetic and electric characteristics.

### Conclusions

The criteria and compliance test methods in the standards discussed in this paper are the result of an optimization, compromise and consensus among the participating experts from many countries searching for acceptable detection performance that reflects the positions of the national regulatory agencies, scientific and technological progress of the industry, testing laboratories capabilities and end user needs. These standards provide manufacturers with internationally acceptable requirements and provide consistent test methods for compliance with the stated performance requirements.

## Comparison of Uranium Activity Results Obtained by Alpha Spectrometry and ICP-MS from Workers Exposed to Enriched Uranium.

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### Introduction

Individual monitoring of uranium radioisotope intakes in workers exposed to enriched uranium is mandatory, especially due to their radiotoxicity. Alpha Spectrometry (AS) is the technique most common used in in-vitro bioassay. AS features allow the uranium isotopic quantification with an excellent accuracy although require a long and complex treatment of sample. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) has an optimal accuracy, requires low sample volume and allows fast analysis, though it is not sensible enough to quantify  $^{234}\text{U}$  isotope. The aim of this work is to evaluate if ICP-MS could supply the information obtained by AS, using an estimative method for  $^{234}\text{U}$  quantification.

### Methods

24h urine samples were analyzed by both techniques and the results have been compared.. For ICP-MS determination an aliquot of 5 mL was taken and diluted to 10 mL with 4% nitric acid. The rest of the sample was analyzed by AS technique, using a 5-day radiochemical treatment based on four different processes to isolate uranium isotopes from inactive substances and other radionuclides: precipitation, incineration, solid phase extraction and electrodeposition. Finally, a counting time of 3.5 days was required.

### Results

105 urine samples from occupationally exposed workers were analyzed.  $^{235}\text{U}$  activity results were only quantified in 7 samples by AS (0.07-0.3 mBq/d). However, ICP-MS could quantify  $^{235}\text{U}$  in most of the samples.  $^{238}\text{U}$  activity was quantified in 88 samples by both AS and ICP-MS obtaining a wide range of results (0.11-2.4 mBq/d). However,  $^{234}\text{U}$  activity results measured by AS (0.15-7.6 mBq/d) and the  $^{234}\text{U}/^{238}\text{U}$  isotope ratios were highly variable (range from 1.1-6.4).  $^{234}\text{U}$  estimation was done using the average of the obtained isotope ratios. Significant differences between the  $^{234}\text{U}$  estimated ICP-MS results and the ones obtained by AS were explained.

### Conclusions

Uranium activity results and the isotopic compositions found were extremely variable. The great sensibility of ICP-MS allows the easier and faster quantification of  $^{238}\text{U}$  and  $^{235}\text{U}$  activities in more cases than AS. However, due to the variability of its isotope ratios and the lack of historical data, the estimation of  $^{234}\text{U}$  from ICP-MS values was not satisfactory, since the poor stable information about uranium enrichment inhibits it scaling.

## Radiation protection and dosimetry challenges for nanolab, a new laboratory for the production of uranium nanoparticles at CERN

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### Introduction

At ISOLDE, radionuclides are produced via spallation, fission, or fragmentation reactions in thick targets (~60% of which are made of uranium carbide), irradiated with the 1.4 GeV proton beam (up to 2  $\mu$ A) from the Proton Synchrotron Booster. The volatile nuclear reaction products are released from the high temperature target into an ion source and extracted as radioactive ion beams for a variety of physics experiments. As of 2021, a new laboratory, nanolab, will house the production of targets made of micro- and nano-particles (~100 nm) of uranium, the installation for their carburization and a temporary storage for radioactive waste from ISOLDE (e.g. irradiated targets sorted in containers). The use of uranium nano-particles is a new frontier that will enhance the production of radioisotopes and the target lifetime but will introduce new radiological and chemical challenges. Therefore, a comprehensive study was performed to assess the main radiation protection aspects and constraints of this project.

### Methods

Nanolab will follow the recommendations of the Swiss Radiation Protection Ordinance in terms of ventilation, quality assurance and fire resistance requirements. Situations involving radiological risks (e.g. transfer of nuclear materials) were analyzed and specific mitigation measurements implemented. Dosimetric evaluations were carried out for failure scenarios (e.g. accidental inhalation of micro- and nano-particles of uranium). The shielding material and thickness of the storage area for radioactive waste were assessed by means of FLUKA simulations. The radiological area classification, personal protective equipment, screening measurements for intake, and radiation and environmental monitoring were also studied and defined.

### Conclusions

The presentation will show the radiation protection aspects of nanolab, justify the RP measures and underline radiological risks related to the manipulation of radioactive nanomaterials.



## PATIENT DOSIMETRY OF PEDIATRIC ICU DURING CHEST RADIOGRAPHY

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### Introduction.

The radiosensitivity of pediatric patients and the increase in the radio-induced carcinogenic risk, mainly due to the longer life expectancy of children, are the cause of concern with the dose of radiation received by these patients due to radiographic procedures. In the case of pediatric ICU patients, the number of radiographic examinations is large and there are few studies on the radiation dose received by these patients. The objective of this study is to estimate the entrance skin dose into the patient and the dose-area product during the acquisition of chest radiographs in a Pediatric ICU.

### Methods.

The entrance skin dose was estimated using MCP-N thermoluminescent dosimeters (TLDs), previously calibrated with a diagnostic X-ray beam. The dosimeters were packaged three to three and positioned on the children's skin in the center of the radiation field. The dose-area product was estimated through a diamentor, positioned at the exit of the X-ray tube whose uncertainty is equal to 8%. Both measurements were performed concomitantly. Radiographic examinations of the thorax were performed in the AP projection and the following data were collected from the children: gender, age, weight, height, thickness and radiographic parameters adopted by the technician at the moment of the examination.

### Results.

496 radiographs were performed in children aged 0 to 15 years and weight varying between 2.4 kg and 77.9 kg. The mean values of voltage and current x time were respectively  $(49.7 \pm 0.2)$  kV and  $(2.6 \pm 0.0)$  mAs. Focus-skin distances ranged from 50 to 130 cm. The results showed that the mean value of the skin entrance dose was  $(114.9 \pm 2.5)$   $\mu$ Gy, with maximum and minimum values equal to  $(421.3 \pm 112.5)$   $\mu$ Gy and  $(26.9 \pm 22.4)$   $\mu$ Gy, respectively. The estimated mean dose-area area was equal to  $(57.68 \pm 6.14)$  mGy.cm<sup>2</sup>, with maximum and minimum values equal to  $(281.24 \pm 22.50)$  mGy.cm<sup>2</sup> and  $(5.99 \pm 0.48)$  mGy.cm<sup>2</sup>, respectively. In the majority of the exams the absence of collimation was verified and also the clinical justification for the accomplishment of the procedure.

### Conclusions.

The results of this study present higher values than those found in international references indicating the need for optimization of procedures and investments in the training of radiological protection of medical staff and technicians.

## Dose profile study in mammographic exposition using radiochromic film

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### Introduction

According to the 2018 Cancer Incidence Estimate in Brazil, conducted by the National Cancer Institute José Alencar Gomes da Silva, 59,700 new cases of breast cancer were expected in the country. Two-dimensional mammography plays an important role in the early detection of breast cancer, however, in some cases it may be difficult to detect malignant lesions due to breast tissues overlapping. Mammography is considered to be the most effective technique for identification of breast cancer.

### Methods

A breast compressed phantom was developed for use in mammographic tests. This phantom is made in PMMA and it is composed of three plate model, one external with 2 cm and two central, with 1 and 0.5 cm. The complete set is composed by six plates, two from each model. This configuration allows obtain compressed breast from 4 to 7 cm in steps of 0.5 cm thickness. The phantom was used for observe the air kerma distribution profile in the central area and the entrance skin air kerma (ESAK) in the superior surface. To record profile doses it was used radiochromic film sheets. The experiments were made in a device Selenia, Dimensions model, using the automatic exposition control to define the optimized acquisition protocol to produce a mammogram.

### Results

The compressed breast phantom made in PMMA was developed with three different plates, an external and two middle plates. In the mammographic exposition was used an assembled phantom with thickness of 5 cm. The ESAK profile obtained from the film sheet placed on the superior surface and irradiated with the optimized protocol. This profile permits observe that higher values happened in the anterior region. Considering the anterior region of the breast phantom the ESAK average value was 5.96 mGy.

### Conclusions

In this work a breast compressed phantom was developed using PMMA plates. The developed phantom may be used to dosimetry and mammographic equipment's through two-dimensional and three-dimensional techniques. The use of radiochromic film allowed demonstrating the air kerma distribution variations in the central area and the ESAK in the superior surface of the phantom.

## Calculation of the typical values of reference levels for a hospital facility in the city of Medellín

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### Introduction

The use of diagnostic images in the population has increased significantly in recent decades. X-ray images are the oldest type of image, but one of the most used, since they are inexpensive, fast and have low risk [1]. The risks associated with the use of radiation for X-ray images, where the effects depend on the type of radiation, the amount and distribution of doses, and that its use is justified only if through its application it is possible to obtain better results for detection early of diseases. It is important to evaluate the use of such equipment and its quality control to verify that its performance during commissioning is kept within certain tolerance limits, in relation to the values defined as a baseline in medical practice. since their sensitivity, specificity and predictive value are not always the desired due to inadequate technique, insufficient exposure or errors in the position and cooperation of the patient, also, the accuracy of the radiography is limited by the capabilities of the technology and the variability of the observer [2].

Each time a patient receives an x-ray, he receives a dose of radiation. The radiation levels received by patients, occupational workers and the public have been analyzed for a long time. In terms of radiological protection, the International Commission for Radiological Protection (ICRP) has provided practical information on the application of diagnostic reference levels for different types of images in its publication 135 [3].

For a particular medical imaging task and a patient size group, a DRL is typically established at the 75th percentile (third quartile) of the distribution of dose values associated with clinical practice. DRLs are not dose limits or thresholds. Rather, they serve as a guide to good practices without guaranteeing optimal performance. The radiation doses higher than expected are not the only concern; the lower than expected are also lower, because they are associated with inadequate or low-quality diagnostic information [4]. Facilities can characterize their own radiation dose practices in terms of "local" reference levels, that is, medians or means of distribution dose index values. Local reference levels should be compared with regional or national diagnostic reference levels, when they are available, even when they are not available, as is the case we have in our country, tracking dose rates within an Installation can be valuable to help identify exams with doses that are far from their usual ranges. Such comparisons are essential for quality improvement activities.

Therefore, this study establishes the typical reference levels for a hospital in the city of Medellín, which has a large volume of patients, this being a public institution.

### Methods

Following the recommendations of publication 135 (ICRP), the reference levels of the institution were calculated for patients undergoing examinations in the conventional X-ray equipment, which has a high flow of patients of approximately 10 patients / day. The calculations were made based on the performance values of the equipment, obtained from the quality control tests carried out previously; and from a database obtained from patients who underwent the main diagnostic tests performed at the institution, in addition to those with higher radiation

doses such as Thorax, Pelvis and Column. A database of patients was collected, this consists of the patient's age, sex, equipment parameters for each test such as the tube tension (kV) and the load (mAs), the distance to the entrance surface and the type of projection. The Kerma in air at the patient's entrance surface ( $K_{a,e}$ ) was the dosimetric magnitude estimated. For the values obtained, the median of the data was calculated as the typical value of the reference level for each of the examinations evaluated. The SSPS software was used for the statistical analysis, the significance was established in  $p < 0.5$  for the statistical tests. Finally, given that the country does not have values of established reference levels for any diagnostic test, these were compared with the values refilled in the literature.

## Results

The results of the evaluation carried out to obtain the dose reference levels in the patients submitted to the diagnostic tests are close to the values reported in the literature. For the patient sample, the results of the  $K_{a,e}$  are close to the dosimetry reference level values for thorax and pelvis exam.

## Conclusions

It is essential to define the typical values of the reference levels in each one of the institutions to optimize the quality of the services provided. The values obtained contribute to the estimation of local and national reference levels, given that currently these established values are not available. Finally, the relevance of identifying and reducing the number of unjustified high or low values in the distribution to promote good practices for the use of diagnostic medical imaging equipment.

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## Quality control and entrance skin dose evaluation in a pediatric CT scanner

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### Introduction

In a computed tomography equipment, as in all modalities of diagnostic radiology, it is indispensable a quality control program that guarantees the good performance of the equipment and the quality images produced. In addition, the service must ensure that the radiation doses comply with the dose reference levels (DRLs). In Brazil, the DRLs for brain, abdomen and lumbar spine protocols CT are, respectively, 50 mGy, 25 mGy and 35 mGy. However, these values are for a typical adult, and there are no pediatric indexes. In this way, the aim of the present work is to perform the quality control tests in a CT scanner and to determine the values of the entrance skin dose (ESD) of the pediatric brain, abdomen and lumbar spine CT protocols.

### Methods

The ESD and the quality control tests (collimation analysis; table alignment relative to the gantry; longitudinal displacement of the table; gantry slope; noise, accuracy and uniformity of the CT number; high-contrast spatial resolution and cutoff thickness determination) followed the methodology and used the materials disposed by the Brazilian Health Regulatory Agency.

### Results

The quality control tests results were mostly positive, except for the table alignment test (approximately 50% higher the limit) and the CT number accuracy for the brain protocol (12% above the limit). However, it is noted that the quality of the images is not affected by these two non-compliant results. The ESD values for brain, abdomen and lumbar spine CTs were, respectively, 28 mGy, 23 mGy and 45 mGy. It is noted that, for the pediatric lumbar spine protocol, the dose was 29% higher than the adult DRL and the dose from pediatric abdominal protocol was 92% of the adult DRL.

### Conclusions

It is noted that, although the results of two tests were higher than the recommendation, the quality of the images produced is not being affected. However, the ESD values are similar to the adult DRLs, which means that an optimization protocol is necessary.

## Patient Radiation Dose and Image Quality in Plain Radiography: An assessment of Certain Common Procedures in Ten Capital Hospitals in Sudan

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### Introduction

Radiation exposure from x-ray imaging studies can be controlled by several strategies with keeping the image quality at a level that supports the diagnostic information. This study aimed to assess the main factors affecting the radiation dose and the image quality for selected routine common radiography procedures in ten capital hospitals in Sudan, to establish guidelines for maintaining the expected quality while keeping the patient radiation doses as low as possible.

### Methods

Entrance surface air kerma (ESAK) and radiography image quality for a total of 866 patients undergoing chest, abdomen and pelvis x-rays in ten X-ray departments were assessed using the European Image Criteria method. Equipment Basic quality control (QC) testing was performed based on international standards.

### Results

The mean percentage and range of good quality images were 71.3 (56-86.1) for chest postero-anterior (PA), 76.1 (65-91) for abdomen anteroposterior (AP) and 70.7 (35.7-92.6) for pelvis antero-posterior (AP). The corresponding ESAK (mGy) were  $0.6 \pm 0.4$ ,  $3.6 \pm 1.7$  and  $3.5 \pm 1.5$  for each procedure, respectively. Faulty X-ray machines, suboptimal patient communication and instructions prior to imaging along with insufficient clinical referral information were the main factors responsible for interfering the patient dose and the radiographic quality.

### Conclusions

This study provides essential data for patient dose levels and image quality for abdominal, pelvis and chest radiography in the hospitals where the studies were carried. The image quality findings reveal wide variations within each hospital and across hospitals. The ESAK values for patients undergoing abdominal and pelvic X-rays showed comparable values in relation to the international diagnostic reference levels (DRLs), while they were twice as high for chest X-rays. These findings reflect the necessity of an ongoing quality control program to confirm that doses are minimized to a level.

## Evaluation of Physical Spaces of Nuclear Medicine Services

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**Introduction:** Nuclear medicine is a medical specialty applied to diagnosis and therapy that uses unsealed radioactive sources for image formation. A nuclear medicine service should include a physical structure that provides security and facilitates in the flow processes of radioactive materials in order to avoid unnecessary exposure to the radiation of professionals and other people who transit in the service. This study presents the evaluate the projects installation of nuclear medicine service in Southern and North Paraná State of Brazil.

**Methods:** Five nuclear medicine services were analyzed, regarding radioprotection (shields) requirements and the dimensions of their environments according to the standard RDC No. 50/2002 - ANVISA, and the existence of necessary dependencies required related to the standard CNEN-NE-3.05. Data were collected in surveys into nuclear medicine clinics, through analysis of architectural designs and radioprotection plans of the services.

**Results:** The results show that one of the five nuclear medicine services evaluated is not according to the rules of ANVISA, and that none all the services have all essential physical dependencies to the working routines of nuclear medicine as exclusive sanitary for ergometry and the inhalation room. Furthermore, one of the services did not present all the minimum dependencies required by CNEN.

**Conclusions:** The architectural designs of nuclear medicine services need to be improved and periodically monitored in order to meet the specifications required by Brazilian laws. The other nuclear medicine services in Brazil need to be evaluated so that we can verify their quality and provide greater assurance for all who use these sites.

## Local DAP and Effective Dose values during Pacemaker Implantations

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### Introduction

Pacemaker implantation is the gold standard method for management of cardiac electrical disorders. During the procedure, patients are exposed to ionizing radiation. The aim of this study was to evaluate Dose Area Product (DAP) and Fluoroscopy Time during pacemaker procedures, executed in a cardiac catheterization room with a biplane C-arm. The mean DAP value was then compared with the recommendations published by Public Health England (PHE). Mean effective dose (ED) was also calculated.

### Methods

A retrospective analysis, including 26 procedures performed on a Siemens Artis Zee biplane system, from April 2017 to December 2017, submitted to Pacemaker implantation was done. For each patient, weight, height, sex, fluoroscopy time (FT), total DAP was collected. Mean DAP and FT values were compared with the reference values (PHE) and relative errors were calculated. The ED was estimated multiplying DAP by a conversion factor. For comparison purposes, patients were divided in 3 categories according to BMI published by World Health Organization (WHO).

### Results

The collected sample had a median DAP value of 4.60 [P25: 0.86; P75: 3.30] Gy.cm<sup>2</sup> and a median FT value of 2.40 [P25: 1.70; P75: 2.70] min. Comparing these values with the recommendations of PHE we found relative errors of -34.23% for DAP and -53.13% for FT. Median ED for the three BMI sub-categories were 0.38 mSv (normal), 0.42 mSv (pre-obesity) and 2.07 mSv (obesity).

### Conclusions

The observed differences in DAP are related to the implementation of corrective measures regarding the reduction of radiation doses, and the use of protocols of low dose as well as the movement of the patient without an additional exposure. As expected, ED increases along with BMI.

Establishment of regulatory standards and an adequate radiation protection plan aiming compliance to a safety culture leads to a decrease in dose values.



## Dosimetric applications of borate glass matrix ( $\text{MgB}_4\text{O}_7$ and $\text{MgB}_2\text{O}_4$ ) doped with Cerium and Dysprosium and co-doped with Lithium for study as OSL dosimeter.

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### Introduction

A growing research for new dosimetric materials is the focus of many studies currently. New materials are constantly proposed and tested for a variety of applications, such as personal, medical, space and accident dosimetry. While most of the investigated materials are crystalline, this research developed a glass matrix, here called MBO, based on two known borate crystals: magnesium diborate ( $\text{MgB}_2\text{O}_4$ ) and magnesium tetraborate ( $\text{MgB}_4\text{O}_7$ ). The purpose is improving the understanding on behavior of borate glasses and their dosimetric capabilities, as ionizing and non-ionizing radiation. The known luminescence of rare earth elements (REE) plays a key role in such glasses because the REE provides singular optical properties. In particular, this research examined the viability of these materials doped with Cerium and Dysprosium and co-doped with Lithium for optically stimulated luminescence dosimetry.

### Methods

The structural characterization of the glasses was made using X-ray diffraction, optical absorption and emission. The dosimetric behavior of the glass matrix was examined after irradiations with calibrated beta and photon (Ultraviolet, X-ray and Gamma) beams. To this, small pieces of glass and some pellets were used.

### Results

The samples showed great response for beta and gamma irradiations, as well as the OSL signal fading did not was accentuated. The dose response tests presented a good behavior for low doses range for MBO:Ce,Li and high doses range for MBO:Dy,Li. The glasses showed a good absorption for UV spectrum, indicating some application as UV dosimeter and a scintillator.

### Conclusions

For both glasses, features such as reproducibility, linearity, lower detection limit and fading were analyzed. The cerium composition presented higher sensitivity for low doses, and dysprosium composition is more sensitive for high doses.

## Quality control of solar protection films via design of experiments

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### Introduction

Solar radiation reaching the earth surface is broadly divided into infrared, visible and ultraviolet radiation (UVR). Individual dosimetry and monitoring of the sun rays in humans and environments is of interest since in homes, shops and cars the effects of UVR radiation can bring irreparable damage to the skin and eyes. The efficacy of solar protective films has been recognized as an important public health product. The objective of this work was the quality control of solar films using the UV-Vis spectroscopy technique via 2<sup>k</sup> Experimental Factor.

### Methods

Four types of solar protective films were tested: G05, G20, G35 and WB (Windom Blue), which follow the blocking of UVR rays by 95%, 80%, 65% and 0% (76% transparent). The samples had dimensions of 1.0 x 3.0 cm<sup>2</sup> and the readings were taken on a GENESYS™ 10S UV-Vis Spectrophotometer with an optical step of 1 nm from 190 nm to 400 nm. The absorbances were used in a 2<sup>k</sup> Experimental Factor, in which the four films were read individually and also with overlap (two films together). It was possible to obtain results of all the interactions among the films, with or without overlap.

### Results

The results about the absorption of the sunscreen films were modeled from the 2<sup>k</sup> Experimental. This factor indicates that the best regions of the spectrum are blocked and/or where they produce a better quality control of these materials. The region studied in this work was where the ultraviolet radiation dosimetry can be of interest. The proposed spectrophotometric method is rapid, simple and cost effective for the evaluation on quality control of protection films.

### Conclusions

The results provide information on ultraviolet radiation and they can be useful for the medical physics community. The proposed methodology may be useful as a rapid quality control tool. It can be used during the production process, in the analysis of the final product, and can offer important information for the scientific community.

## Assessment of Patient Radiation Dose from Cardiac Computed Tomography Procedures

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### Introduction

The Recent technical advancements in CT have resulted in a remarkable growth in the use of CT imaging in clinical practice. Offering faster acquisition, CT scanners have increased availability of CT cardiac imaging and expanded its clinical indications. The objective of this study was to measure patient dose during cardiac CT procedure from four different hospitals equipped with CT of 128 slices patients and to compare dose length product (DLP) based estimates of effective dose.

### Methods

A total of 84 patients were investigated in this study with different clinical indications. Multislices CT 128 slices were used in all four hospitals. Effective doses were also calculated from the respective DLPs using published conversion coefficients that depend only on body region.

### Results

The mean patient age (years), weight (kg), and body mass index (BMI(kg/m<sup>2</sup>)) were 48.7±11, 81.9±12, 31.3±6, respectively. The tube voltage (kVp) and tube current were ranged between 100 to 140 and 50 to 850, in that order. The overall mean and range of patients' dose values of CTDIvol and DLP were 34.8±15 (3.7-117) , 383.8±354 (46.0-3277.0). The mean and the range of effective dose was 5.4±5 (0.64-45.9).

### Conclusions

Patient dose showed wide variation between different hospitals and even in the same hospital. The dose in one hospital is almost double the patient doses at other three hospitals these variations in patients suggest the need to optimize the radiation doses and established diagnostic reference levels (DRL).

## Monte Carlo study for development of a radiation field simulating secondary neutrons produced in carbon-ion radiotherapy

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### Introduction

The risk of radiation-induced secondary cancer is of great concern to long-term cancer survivors receiving radiotherapy and people involved in radiotherapy. The risk estimations for conventional radiotherapy have been reported based on epidemiologic studies. By contrast, the epidemiologic approach is not realistic yet for more modern radiotherapies such as proton and carbon-ion radiotherapies, and then the approach using RBE-based risk model has a key role.

In carbon-ion radiotherapy (CIRT), secondary neutrons with high LET are produced, leading to high RBE and whole-body exposure. As is well known, RBE of neutrons depends on energy, so it is ideal to perform biological experiments with cells and animals in the radiation field of interest. But, experiments in the treatment room would be limited mainly by constraints of time and biological hazard. Therefore, the development of a radiation field simulating well the neutron energy spectrum in the real treatment room will contribute to the RBE evaluation. This study aims at reproducing neutron energy spectra produced during CIRT in the HIMAC treatment room by using monoenergetic carbon beam with Monte Carlo simulations.

### Methods

The PHITS code was used throughout this study. At first, the neutron energy spectra at patient positions during CIRT in the HIMAC treatment room were calculated. From the characteristics of the neutron energy spectra, various combinations of neutron production targets and spectrum-shaping materials were investigated.

### Results

As a result, it was shown that the combination of iron target and iron and polyethylene filters can reproduce well the neutron energy spectra in the HIMAC treatment room during CIRT by taking advantage of angular dependence of neutrons produced in the target bombarded by primary carbon beam.

### Conclusions

This Monte Carlo study showed that the development of a radiation field simulating secondary neutrons produced in CIRT is feasible.

## Evaluation of the Dose Length Product in skull tomographic exams of patients with traumatic brain injury and decompressive craniectomy

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### Introduction

Patients with cranioccephalic trauma (TBI) and decompressive craniectomy need to perform several tomographic examinations of the cranium (CT) for medical monitoring and scheduling of a possible cranioplasty. Despite the benefits, these tests may represent a risk due to the high doses of radiation sequentially. The objective of this study was to evaluate the technical parameters of exposure used in CT performed in patients with TBI, in order to determine the value of the Dose Length Product (DLP). From this study it is expected to obtain data of the estimation of the effective dose, establishment of reference values and the optimization of the CT exams.

### Methods

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### Results

The patients' age ranged from 17 to 71 years (mean of 34 years  $\pm$  16.9), all male, number of exams performed were 4-16 exams (mean of 10 exams). Technical Parameters were: kVp 120, mA 290-300, scanning extension range of 17-20cm (mean of 18.18cm  $\pm$  1.98), CTDIvol with values of 51.31 to 72.98 mGy (mean of 67.28  $\pm$  10.35mGy), DLP with measurements ranged from 923.63 to 1477.77 mGy \* cm (mean of 1357.19  $\pm$  252.89 mGy \* cm).

### Conclusions

Higher CT DLP values were found in the study compared to the recommended reference values of the American College of Radiology and European Guidelines for Multislice Computed Tomography. It is recommended the optimization of CT protocols for patients with TBI in evolutionary follow-up after decompressive craniectomy.

## Development of Inverse Planning Strategy Using Volumetric Arc Therapy for Intensity Modulated Radiation Treatment for Prostate Cancer

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### Introduction

When we consider intensity modulated radiation therapy(IMRT), inverse optimization process requires a substantial amount of time. It is very effective to make a planning strategy, which considers a trade-off between target coverage/homogeneity and normal organ saving. This study intended to make an optimization strategy for IMRT planning for prostate cancer. A novel approach was proposed, which is based on the history of optimization process, named "history-based optimization".

### Methods

Firstly, we considered a step-by-step approach to obtain a clinically acceptable plan. In the first step, we obtained the best target coverage and homogeneity by using dose constraints of highest priority, regardless of radiation damage of critical organs. In the next steps, the constraints of the critical organs were increased step by step, based on the dose volume histogram(DVH) data of the previous step. Considering a trade-off between the target coverage/homogeneity and the critical organs damage, we selected an optimal plan as the reference. As a novel approach, we deleted all the fluences of the reference plan and proceeded optimization process with the constraints sets of the reference plan which has been obtained from the step-by-step approach. Both plans were compared with the DVH data and dose distribution. The ECLIPSE planning system was used.

### Results

The planning performances were compared with the DVH data. It showed that the history-based optimization had the better plan quality in terms of target coverage and homogeneity. The doses to rectum and bladder significantly decreased in the plan with history based optimization method. Even though the dose to the left femur head increased, the magnitude is negligible in the sense of dose tolerance of femur head.

### Conclusions

From this study, we developed the novel approach by employing a history based optimization method for inverse planning for volumetric arc therapy for prostate cancer.

## Commercial filament testing for use in 3D printed phantoms

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### Introduction

With the popularization of 3D printing, many areas of knowledge are using this technology to create products and diminish costs, even in health segment. Commercial phantoms are expensive and hard to obtain in development countries. As alternative, 3D printed phantoms can be the way to produce inexpensive and reliable simulators aimed for dosimetry and teaching. That said, the objective of this study is to determine which of the available commercial filaments can be used in 3D printing to mimic human tissue for use in 3D printed phantoms.

### Methods

Fourteen 3D printing filaments (ABS, ABS premium, PLA, PLA+Bone, PLA+aluminum, PLA+brass, PLA+cooper, SILK, HIPS, PETG, PVA, Wood, TPU and TPE) commercially available in Brazil had their attenuation tested, using computed tomography. Each material was printed as 2 centimeters edge cube with rectilinear pattern and 60, 80 and 100 percent infill. The cubes were scanned in a Philips CT Brilliance 6 with 120 kV, 200 mA, 2mm slices and standard reconstruction. At the center of each cube, an  $\sim 120 \text{ mm}^2$  region of interest were set to measure the mean Hounsfield Unit (HU) and the standard deviation value. For each material a graphic was plotted and the curve equation determined.

### Results

The HU of the tested materials ranged from  $-516,2 \pm 7,3$  to  $329,8 \pm 18,9$ . All human tissues could be mimetized with these materials, except bone (mainly cortical bone). Considering the curve equation, the most promising filament was PLA+Cooper, due to the multiple infill configuration that allows the resulting HU range to represent from adipose and skin tissue to marrow bone. With a two extruder printer may be possible add lung tissue to the model and make a 3D phantom more complex and accurate.

### Conclusions

With these tested materials, is possible to construct various phantoms, simulating a wide range of tissues. However, any simulator with cortical bone is impaired because none filament achieve the required HU value (at least over 800 HU).

## Development of Chinese Pediatric Reference Phantoms Series and Application in X-ray Radiography Dose Assessment

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### Introduction

X-ray Radiography is the most frequently used medical examination with radiation exposure. As children are more susceptible to radiation, it is important to establish the Chinese reference pediatric phantoms for different ages and assess the X-ray radiography dose.

### Methods

A series of Chinese pediatric reference phantoms including 3 months, 1 year, 5 years, 10 years, 15-year-male and female were constructed. The organs were obtained from the CT data by threshold segmentation and artificial segmentation. The volume of the organs and bones were adjusted to consist with the reference data. Finally, established organs and bones were assembled into a complete phantom. The Monte Carlo method was applied to simulate the X-ray radiography. The X-ray energy spectrums were generated by the Xcomp5r software. The X-ray source was simulated as conical beam emission from point source. Square collimators were constructed and the sizes were adjusted to obtain the accurate irradiation field on the patient surfaces. In-phantom dose measurements using TLD were carried out to verify the accuracy of the method and simulation calculation. The developed series pediatric phantoms were applied to calculate the organ dose conversion coefficient and the effective dose conversion coefficient in different radiography conditions.

### Results

The heights, weights and the organ mass of the six established phantoms were consistent with the reference value. Each phantoms contains all radiation-sensitive organs proposed by the latest ICRP. The database of the pediatric chest postero-anterior projection and abdominal antero-posterior projection were obtained, and the results were compared with the data in the literature.

### Conclusions

The established Chinese reference pediatric mesh-type phantoms can be applied in the studies of radiation protection and clinical medicine. The simulation results of this work can provide important reference for the dose assessment of the pediatric X-ray radiography.



## Using micro silica glass bead TLDs in HDR brachytherapy

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### Introduction

Brachytherapy (BT) is a cancer treatment modality utilising sealed radioactive sources. It is characterised by rapid dose fall off near the sources governed mainly by inverse square law. Micro silica glass bead TLDs with special dosimetric characteristics such as small size (1-2mm), inert nature, high sensitivity and a large dynamic dose range with high linearity, have the potential to be used in steep dose fall off fields in BT. The aim of this study was to investigate the feasibility of using glass beads TLDs as in vivo dosimeters.

### Methods

An antropomorphic female phantom was designed and constructed to allow assembly of the clinical treatment applicator (Eckert & Ziegler GmbH) and bead TLDs within the relevant organs. 458 calibrated TLDs were positioned at different clinically relevant distances from the BT applicator and irradiated with a <sup>60</sup>Co HDR source with 7Gy prescribed to ICRU38 defined A-points. A TOLEDO TL system was used to read the TLDs. The TLDs were divided according to their distances from the source and mean absolute dose difference of TLD readouts were compared to the treatment planning system (TPS).

### Results

The results showed that the mean absolute dose difference of TLD measurements compared to the TPS calculations were  $9 \pm 42$ ,  $10 \pm 10$ ,  $7 \pm 8$  and  $13 \pm 6$  cGy for 2-3cm, 3-5cm, 5-8cm and 8-16.5cm distances from the center of external os as the origin respectively. These doses are  $1.1 \pm 5.1\%$ ,  $2.7 \pm 2.8\%$ ,  $4.8 \pm 5.8\%$  and  $26.8 \pm 12.8\%$  of TPS mean doses. The mean doses of TLD reading was higher than calculated by the TPS in all cases and the percentage increase is stronger at larger distances which may arise from moving the beads between CT scan and treatment room and bead positioning uncertainty. In the low dose region (<1Gy), the attenuation coefficient of the bead TLDs and their energy response at far distances from the source may also need more investigation.

### Conclusions

Our result show that glass bead TLDs are reliable dosimeters in the high dose region (>2Gy) in BT.

## THUBrachy: a fast Monte Carlo code for brachytherapy dose calculation

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### Introduction

Brachytherapy is an important radiotherapy method for cancers by placing radiation sources inside or next to the volume requiring treatment. TG-43 method is widely used in clinical dose calculation. However, it is not accurate as it uses uniform water phantom to represent the patient. Monte Carlo method could give accurate dose but requires a large amount of computing source. The development of heterogeneous computing provides new options to accelerate Monte Carlo code. This work developed a fast Monte Carlo code, THUBrachy, using heterogeneous hardware accelerators to achieve accurate dose calculation within clinically acceptable time.

### Methods

The code THUBrachy can simulate photons which energy are less than 3 MeV and it takes photoelectric effect, Compton scattering, Rayleigh scattering and pair production into account. It can deal with heterogeneous materials voxel phantom. By modifying the code according to several parallel programming model such as OpenMP, OpenACC and CUDA, THUBrachy could execute on multicore CPU, GPU, Intel Phi and other accelerators to speedup. For accuracy test, THUBrachy was benchmarked against TG-43 method using water phantom and validated with Geant4 using real patient cases. Performance test was also performed using two clinical cases.

### Results

In accuracy test, parameters generated by THUBrachy is consistent with TG-43 report. And for real cases, dose in most voxels are consistent with Geant4 within the difference less than 3%. Dose of target area and organs at risk are also consistent with result of Geant4. In performance test, it takes only 5s to simulate  $10^7$  primary photons using THUBrachy in a GTX 1080Ti GPU for clinical cases, while Geant4 requiring several core·h.

### Conclusion

This work developed a fast brachytherapy dose calculation code THUBrachy. It is able to use different types of hardware accelerators to achieve fast Monte Carlo dose calculation. There is great potential to use this code in clinical application.

## Fluence rate and dose from cosmic-ray-induced neutron inside the aircraft

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### Introduction

The radiation environment at flight altitude is composed of cosmic-ray-induced particles (CRIP). Neutrons are responsible for 40% for the effective dose and they are also the main cause of radiation effects in avionics systems during flight route. There are differences between the radiation field inside and outside the aircraft, so it is important to apply any dosimetry method to evaluate the fluence rate and dose inside the aircraft.

### Methods

A simplified computer model of aircraft was developed for Monte Carlo simulation using MCNP6 code considering the aircraft structures, fuel and passengers in order to evaluate the radiation behavior inside the aircraft. The radiation source was also modeled using data from a previously developed computation platform, which generates the energy and angular distributions of the CRIP along atmosphere. In this work, we evaluated the influence of structures and aircraft materials on the radiation field, studying the factors that provide greater internal radiation levels and thus may affect both the susceptibility to failure of avionics devices and differences in the estimated dose received by aircrew members at different positions along aircraft fuselage.

### Results

This study was made for different conditions of altitude, latitude, longitude and solar potential. As part of the results, we determined the fluence, angular and energy distribution of the neutrons at different positions inside the aircraft. The thermal fluence varies more than one order of magnitude along aircraft, and the fluctuations in the neutron fluence rate above 1 MeV can exceed 20%, depending on position.

### Conclusions

These data could be useful to estimate dose in crews and also to predict radiation effects in avionics systems. The results from simulations suggest the position and angular orientation of the device could be key factors to optimize the radiation protection of an embedded electronic, and this approach could benefits the safety of the aircraft.

## A Monte Carlo Variance Reduction Method for Small Detectors outside the Reactor Core

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### Introduction

In the reactor shielding calculation, the fluxes of small detectors outside the reactor core are often need to be calculated. It has the characteristics of large source region, small detector and deep penetration. The mainstream variance reducing technique for this problem is the Consistent Adjoint Driven Importance Sampling (CADIS) method. Compared with deterministic adjoint calculation, the Monte Carlo (MC) adjoint calculation driven CADIS method has the advantage of using only one program. However, because the adjoint calculation is still deep penetrating, the parameters obtained are not ideal. The Auto-Important Sampling (AIS) method is a new MC variance reduction technique proposed by Tsinghua University for deep penetration problems, which introduces virtual surfaces to divide the space into multi-layer subspaces, and the virtual particles are generated on the virtual surfaces as the source of the next subspace transport.

### Methods

In this paper, the MC adjoint calculation was used to generate source biasing parameters. The AIS method was used to reduce the statistical error of the adjoint flux at the point far away from the detector, ensuring the quality of the source biasing parameter. In the forward calculation, the source biasing method, AIS method and point flux method were used comprehensively. These methods were implemented in the self-developed MC program called MCSHIELD. A real reactor model was calculated. The fast neutron fluxes at some points in the pressure vessel and the main steam line were tallied and compared with the weight window method and experimental measurements.

### Results

The results show that the difference between the results of our method and the measured results is within 30%, which is similar to the result of the weight window method.

### Conclusions

The method in this paper has the accuracy comparable to the weight window method. Nevertheless, it only needs MC program and has low requirements on the user's experience.

## Integration of Radon Suppressed Function to Low Background Gamma-ray Spectroscopy System: Monte Carlo Simulation Approach

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### Introduction

Low-background gamma-ray spectrometry has been developed for many years and widely applied in different fields such as fundamental physics researches and conventional sample investigations [1]. Low-background HPGe gamma spectrometers are playing an increasingly important role in material selections for rare event experiments and measurements of environmental samples [2-4]. One of the main challenges of all ultra-low background germanium spectroscopy is the presence of radon isotopes in air. In order to reduce the effects of radon isotopes inside the spectrometry volume, there are several approaches and flushing the spectrometry volume with nitrogen to actively remove the radon isotopes is one of its. Maintain constant overpressure by continuous flushing to suppress radon diffusion. In this study, the Monte Carlo simulation based on MCNP6 code [5] has been applied to perform this approach with several configurations of the HPGe spectrometry in the NAA lab (KAERI, Republic of KOREA).

### Methods

A series of measurements of radon activity levels and gamma background counting rates been performed to quantify and understand the evolution of these background components. To quantify the gamma background a set-up was prepared, consisting of a coaxial ORTEC HPGe detector (model number - GMX40-76) and the energy of events up to ~3 MeV was continuously registered.

The simulated background source can be modeled based on the advantaged features of MCNP6 that introduced a generic background source of neutrons and photons from a background. dat source file. The background.dat file consisting of generic terrestrial soil emission spectra (from K, U, Th, etc. decay) include not only air to ground transport effects but also ground reflection effects.

The simulation background with and without nitrogen flushing are shown in Figure I.

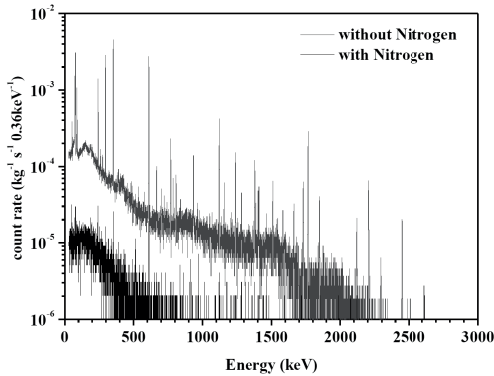


Figure 1: Background spectra of HPGe spectrometry with (blue) and without (red) N2 flushing by simulation.

## Conclusions

$^{222}\text{Rn}$  in the air around the detector contributes significantly to the remaining background and attention will be paid to the radon concentration, especially inside the sample chamber. The reduction of  $^{222}\text{Rn}$  contributions was performed by using Monte Carlo simulation with some distinct conditions and showed significant improvements were possible by its removal.

## Acknowledgement

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## Determination of initial electron parameters by means of Monte Carlo simulations for the Siemens Artiste Linac 6 MV photon beam

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### Introduction

It is essential to define all the characteristics of initial electrons hitting the target i.e. mean energy and full width of half maximum (FWHM) of the spatial distribution intensity, which is needed to run Monte Carlo simulations. In this study, we have investigated initial electron parameters of Siemens Artiste Linac with 6 MV photon beam using the Monte Carlo method.

### Methods

Linac head geometry was modeled using BEAMnrc code. In BEAMnrc, the number of history of Monte Carlo calculation was  $6 \times 10^8$  particles (Total particles in phase space file are nearly 25 million). Monte Carlo simulations were performed for monoenergetic beams ranging from 6 to 6.4 MeV and FWHM varied from 0.28 to 0.32 cm for 6 MV beam. The phase space files were used as input file to DOSXYZnrc simulation to determine the dose distribution in water phantom. We have obtained percent depth dose curves and the lateral dose profile. All the results were obtained at 100 cm of SSD and for  $10 \times 10$  cm<sup>2</sup> field. For correct PDD and lateral dose profile; Quality Index (QI), gamma index criteria and maximum dose depth have considered.

### Results

We concluded that there existed a good conformity between Monte Carlo simulation and measurement data when we used electron mean energy 6.3 MeV and 0.30 cm FWHM value as initial parameters. We have observed that FWHM values effect very little on PDD and we see the electron mean energy and FWHM values effect on lateral dose profile. However, these effects are between tolerance values.

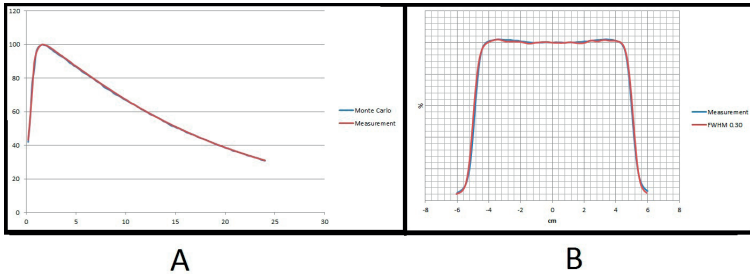


Figure 1: Compare of Monte Carlo and Measurement results for PDD and profile.

### Conclusions

The important components were defined about Siemens Artiste Linac head. Then, the significant parameters were obtained. A small change in electron parameters creates strong effects on the dose. The phase space file which was obtained from Monte Carlo Simulation for linac can be used as calculation of scattering, MLC leakage, to compare dose distribution on patients and in various researches.





## Radioactivity and Background Radiation in the Production Area of Hokutolite in Taiwan

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### Introduction

Geothermal Valley hot spring area (GV) in Taiwan is famous for discovery of Hokutolite. Due to abundant U- and Th-series radioisotopes (RI), the background radiation (BR) in GV is higher than elsewhere in Taiwan. Many residences and hotels stand here; however, environmental radiation dose is not clear. Thus, RA of major naturally occurring radioactive materials, <sup>220</sup>Rn and <sup>222</sup>Rn activity concentrations (ACs), BR and external dose (ED) were investigated in this study.

### Methods

Water samples were measured for the pH, redox potential (Eh), anion concentration and concentrated for  $\gamma$ -spectrometry analysis or distilled for analyzing <sup>3</sup>H. The soil, sludge and plants were dried before analysis. Theyemmiters were determined with an HPGe detector, and gross  $\alpha$  and  $\beta$  activities (GAs) in water were measured with a proportional counter. Environmental dose rates (DRs) were measured with a  $\gamma$  radiation monitor. ACs of Rn were determined with a radon and thoron monitor.

### Results

Acidity, gamma RA and concentration of major anions (Cl<sup>-</sup> and SO<sub>4</sub><sup>2-</sup>) in water decreased from the GV toward downstream PC. Indicated by Eh, the water is oxidizing. In water, maximum ACs of <sup>226</sup>Ra and <sup>228</sup>Ra were respectively 0.34±0.04 and 1.55±0.08 Bq/kg, but <sup>3</sup>H was undetected. Maximum ACs of <sup>40</sup>K, <sup>238</sup>U and <sup>232</sup>Th were respectively 543±15, 56.5±1.4 and 67.4±3.0 Bq/kg in soil, and were respectively 549±21, 243±5 and 3356±30 Bq/kg in sludge. In plants, <sup>7</sup>Be was maximum 21.0±1.0 Bq/kg, yet <sup>137</sup>Cs, <sup>238</sup>U and <sup>232</sup>Th were undetected. The <sup>137</sup>Cs was 1.3±0.3~4.4±0.5 Bq/kg in soil but undetected in sludge. Maximum DR was 0.340±0.014  $\mu$ Sv/h and maximum ED from soil was 0.060  $\mu$ Sv/h at GV. In water, maximum GAs were respectively 3.6±0.9 and 15±1 Bq/L. The AC of <sup>220</sup>Rn and <sup>222</sup>Rn was maximum 77.7±21.8 and 114.7±18.4 Bq/m<sup>3</sup>, respectively.

### Conclusions

Obviously, the RA and AC of the RIs are higher at some sites than those investigated previously elsewhere in Taiwan. However, the BR and ED are similar to those of the global average.

## Neutron activation analysis of meteorites at the VR-1 training reactor

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### Introduction

Low-power nuclear reactors provide useful research techniques utilizable for monitoring of natural environment and investigation of environmental, biological and geological samples, historical items and archaeological artefacts. For study of sample composition, impurities and trace elements compositions, the neutron activation analysis (NAA) utilizing the thermal neutron field delivered by research reactor is employed.

### Methods

This contribution deals with the detailed study of meteorites by means of instrumental NAA at the VR-1 nuclear reactor of the Czech Technical University in Prague. Fragments of Moldavite (tektite glass formed by a meteorite impact) and two iron meteorites (Muonionalusta and Sikhote-Alin) were irradiated by thermal neutrons ( $\varphi = 2 \times 10^9 \text{ cm}^{-2}\text{s}^{-1}$ ) in the experimental channel at nominal reactor power (80 W), and irradiated samples were analysed using the nuclear gamma-ray spectroscopy method (semiconductor HPGe detector); saturated activities of observed radionuclides were obtained, and subsequently the composition of the meteorites was determined (qualitative and quantitative analysis).

### Results

Using the NAA, the presence of Al, K, Mg, Fe, Mn, V, and Na was revealed in Moldavite. Muonionalusta meteorite contains Fe, Ni, and Na; and Sikhote-Alin meteorite consists of Fe, Ni, and Co. Concentration of Ni reached the value of 7.9% in Muonionalusta meteorite, and 5.8% in Sikhote-Alin meteorite. Obtained results will be discussed in detail.

### Conclusions

The results presented in this paper show clearly that the low-power research reactor VR-1 is excellent tool for the neutron activation analysis experiments. It will be discussed how data provided by this nuclear analytical method can be useful for interdisciplinary research.

## Concentration of cesium 137 activity in soils of the state of Espírito Santo, Brazil

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### Introduction

The state of Espírito Santo is located in the southeastern region of Brazil, between the meridians 39° 40' and 41° 55' of longitude and the parallels 17° 45' and 21° 24' of South latitude. The samples were collected within the Low Density Geochemical Survey Project conducted by the Company of Research of Mineral Resources (CPRM)

### Methods

A total of 66 soil samples were collected, with a distance of approximately 25 km by 25 km. The soil samples were collected in Horizon B, with depth of collection varying from 10 cm to 50 cm, were homogenized, dried in a oven at 40 °C, sieved and conditioned in 250 ml polyethylene pots. To analyze the samples, a semiconductor detector of pure germanium of 30% efficiency was used.

### Results

The Cs-137 artificial radionuclide was found in 14 of the 64 soil samples analyzed. The concentration of activity ranged from 0.20 Bq / kg to 0.47 Bq / kg, with a geometric mean of 0.34 Bq / kg.

### Conclusions

Only 14% of the samples presented the radionuclide presence, and with low activity concentration values due to the methodology used to collect soil samples, which considered samples at horizon B.



## Use of biological dosimetry to confirm radiation overexposure - case study

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### Introduction

In Portugal the notification of a radiological accident/incident is very rare. The present study was conducted after a suspected occupational overexposure to ionizing radiation by a radiologist. The thermoluminescent personal dosimeter (TLD) had registered a value of the effective dose that exceeded both the mandatory reporting level, and the maximum annual dose limit allowed by Portuguese Decree-Law no. 222/2008, set at 20 mSv/year for exposed workers. As a first step, a verification of the facility where the accident occurred was carried out in order to verify the radiation safety conditions in situ on the use of the equipments source of radiation. No problem was detected as a result of the verification. The second step consisted of inquiries to the dosimetry service provider, to discard the possibility of damage or incorrect reading of the TLD. Having found no indication that this was the case, and taking into account the magnitude of the dose, the third step consisted in the biological dosimetry study of the affected person.

In the event of a radiation accident, biological dosimetry is essential for determination of the radiation dose to the exposed individuals. Biological dosimetry, used to estimate the absorbed dose, is commonly used as a complementary study in case of lack of information about the radiation exposure (dose, time of exposure, place, etc.) in order to confirm the exposure dose from the thermoluminescent personal dosimeter. Cytogenetic dosimetry applied in this study allows to know the accidental dose of radiation by analyzing the level of chromosomal damage - dicentric chromosomes, since they are specific biomarkers of exposure to ionizing radiation

### Methods

The dose estimation was carried from the frequency of dicentric chromosome aberrations observed in peripheral blood lymphocytes, by comparison with an appropriate *in vitro* dose-response calibration curve.

### Results

500 cells were observed for chromosomal aberrations. The biological dose confirmed that the worker was overexposed to ionizing radiation.

### Conclusions

Through biological dosimetry is possible to confirm if any exposure/overexposure has occurred and validate the dose of thermoluminescent personal dosimeter when the suspected doses are high enough.

## Evaluation of Patient Radiation Dose in Routine Radiographic Examinations in Saudi Arabia

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### Introduction

X-ray examinations have been increased over the last decade in Kingdom of Saudi Arabia and consequently the responsibility of protecting the staff and patients from radiation risk. Protecting patients during diagnostic procedures is an important feature that obliges radiologic staff to maintain levels of radiation, to keep it as low as reasonably possible. The aim of the current study was to evaluate the entrance skin dose (ESD) in most radiographic X-ray examinations in Taif City, Saudi Arabia.

### Methods

The study was conducted in 3 different hospitals in Taif City. These hospitals are indicated in this study as I, II, and III. In total, 221 images were acquired at the aforementioned hospitals by using two different techniques of dosage calculation, DosCal software and the routine thermo-luminescence (TL) method. A data collection sheet was designed to record technical factors (kVp and mAs) and patient bio-data. Also x-ray machines specifications have been recorded and machines calibrated as well as TLDs chips before study investigation started.

### Results

The average finding of ESD for all examinations was 1.67 mGy for both methods, while the average tube voltage was 64.6 kVp. Additionally, the highest ESDs were associated with the lumbar-spine and pelvis at 7.4 and 6.3 mGy, respectively. The two methods of dose calculation were compared and related with a correlation coefficient  $R^2 = 0.93$ .

### Conclusions

Although this study concluded that the ESDs obtained in all examinations were lower than those mentioned in most previous studies, more studies in radiation dose field are required to make a diagnostic reference level available.

## Estimation of radiation doses in the area of the NPP after a reactor accident

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### Introduction

The theme of the prediction of the progress of severe nuclear accidents at nuclear power plants has been very often discussed recently. One of the important aspects is to be able to estimate dosimetry quantities (i.e. dose rates) derived from distribution of leaked radionuclides into the containment area after a nuclear reactor accident.

### Methods

To estimate dose rates in selected locations (and as well as out) of NPPs main production block a modeling approach has been chosen. Monte Carlo code MCNP (v 6.2) has been employed. The main inspiration for a building geometry was the construction of the NPP Temelín installed in the Czech Republic (Central Europe). A fixed source term – a homogeneous distribution of radionuclides in the individual compartments of the main production block – was considered. The energy emission spectrum of the source term was calculated on the basis of a proportional representation of individual radionuclides in the mixture as well as the yields of photons produced during their decay.

### Results

Based on input data and designed simulation geometry and source term definition, dose rates were estimated in selected locations (backup control room, entrance gate, etc.) of NPP. The results were evaluated from the point of view of the possibility of occupation of the intervening personnel in these areas.

### Conclusions

Knowledge of dose rates values in some places of NPPs main production block is very important for staff radiation protection because of the need of intervention after an accident. The technique of estimation of these values presented in this paper is generally applicable to different types of nuclear power plants.





## Herbs and spices like suitable material for retrospective dosimetry - photo and thermo stimulated luminescence study from low to high radiation dose

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### **Introduction**

The evolution of the absorbed dose is of great significance in the onset of an emergency conditioned by a radiological incident. The methods for detection of irradiated food using photo and thermo stimulated luminescence, and their long-term application have determined that herbs and spices contain silicate minerals which are highly sensitive to high doses. Their availability makes them suitable for use as accidental dosimeters.

### **Methods**

This research uses raw materials (some herbs and spices) for optical and pulsedphoto stimulated luminescence, as well as their extracted silicate minerals for thermoluminescence testing. The preparation of samples and their measurement is done according to EN 13751 and EN 1788 standards, and certain modifications.

### **Results**

A study of herbs and spices and their extracted silicate mineral from herbs in the dose range 1 Gy to some kGy. Depending on the method used, different samples observe linearity and supralinearity at different dose ranges. Most of the samples have repeatability of the measurement results. This indicates that these materials may be appropriate for accidental dosimetry.

### **Conclusions**

Most of the tested samples produce promising results for use in retrospective dosimetry at low and high doses. In most of the examined samples, the dependence of the luminescent response on the dose was reported. However, some of the herbs and spices have a greater difference in the response in repeated measurements. Further research should be undertaken in order to precisely determine the minimum detectable dose as well as, the applicability of the method.

## The impact of detection thresholds in automatic scoring of radiation-induced and background DNA damage foci

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### Introduction

To study the dependence of DNA damage induction on radiation quality, HUVEC cells were irradiated at the ion microbeam facility of PTB with by 8, 10 and 20 MeV alpha particles and 3 MeV protons. The ions were targeted perpendicular to the observation plane in a quincunx pattern chosen such a to make foci forming at the loci of different tracks distinguishable.

### Methods

Fluorescence microscope images of irradiated and sham-irradiated cells were analyzed using the software CellProfiler (CP) for identification of cell nuclei and counting of foci per nucleus. The data retrieved from CP were post-processed applying filters on nuclei size as well as size and intensity of the foci and then fitted by parametric model functions describing the probability distributions of background foci and radiation-induced foci, respectively. For irradiated cells, a convolution of the background distribution and a relative frequency model of radiation-induced foci derived from the experimental conditions of the microbeam irradiation was used.

### Results

Data analysis of the sham-irradiated samples gave foci number frequencies that could not be satisfactorily described by a Poisson distribution. The heuristic formula  $f(k) = (1-b) \times b^k$  was found to better represent the observed frequency distribution of background foci, where the goodness of fit was sensitive to the choice of threshold values used for filtering the CP data. Using the same filter criteria also for analyzing the irradiated cell samples and fitting the data with aforementioned model, the key model parameter  $p$  (probability for a track being observed as a focus) was found to have values below 0.7, while the fit could not fully reproduce the data within the estimated experimental uncertainties.

### Conclusions

To enable parameter  $p$  to be obtained with lower uncertainty, the data filtering procedure needs to be further improved. The low values of  $p$  are consistent with recent findings of Gonon et al. (PloS Comp. Biol., under review).

## Study of the effectiveness of low-densely ionizing radiation as a DNA-damaging anticancer treatment in different cancer cell lines

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### Introduction

Radiotherapy (RT) remains one of the main approaches for the treatment of many cancers, whether used alone or in combination with chemotherapy. However, tumoral cells often develop resistance to traditional anticancer treatments, which limits their efficacy, leading to higher mortality and morbidity, and to an increased economic burden of the disease. Different types of radiation sources are currently used for cancer treatment, enabling the killing of proliferating cancer cells, while limiting the effects on healthy tissues. In general, RT works by causing cellular genomic damages, either directly by interacting and injuring biological targets, mainly DNA, or indirectly by inducing the formation of Reactive Oxygen Species (ROS) that may alter DNA structure or cause lipid peroxidation.

### Methods

The present study aims to explore the radiobiological effects induced by photons (X-rays) in several cancer cells lines exhibiting different radioresistance profiles. For that, radiation produced at the DKFZ facility will be used to investigate how different radiation doses affect bladder, brain, breast, and lung cancer cell lines. Phosphorylated H2AX ( $\gamma$ -H2AX) will be used as a marker for DNA double-strand breaks, in order to evaluate the effectiveness of photons as a DNA-damaging anticancer treatment.

### Results & Conclusions

The results obtained in this work highlight the different radioresistance of the cancer cell lines under study. Furthermore, the results obtained on the dose-response curves of  $\gamma$ -H2AX in the different cell lines exposed to radiation were correlated with their survival upon exposure to the same dose of radiation, assessed using the clonogenic assay. It is expected that this study will contribute to better bridge the gap in knowledge between the clinical doses routinely used and the effective biological effects that are exerted by the treatment on tumoral cells.

## The effect of temperature on $g$ -values of soda-lime samples irradiated at different doses

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### Introduction

Electron spin resonance (ESR) dosimetry aims to investigate different materials for the purpose of reconstruction of the dose absorbed by the victims of radiological and nuclear accidents. Soda-lime glass has been proven to have very good performance as an ESR dosimeter in the dose range above 2 Gy by using the readout of ESR signal amplitudes. In the dose range below 2 Gy ESR signal of radiation induced radicals overlaps with the intrinsic ESR signal. Recently it was shown that in this range, the method of using  $g$ -effective values of irradiated samples provide good results.

### Methods

The soda-lime glass samples were chosen from different batches with chemical composition defined and certified according to European standards. The samples were cut in the plates of the same size. The irradiations were performed at a calibration Co-60 unit, Alcyon. ESR spectra were recorded using Varian E-9 spectrometer equipped with Bruker ER 041 XG microwave bridge working at X-band. A standard Bruker ER 4111 VT temperature controller with a nitrogen gas flow was used to control the temperature within 1 °C.

### Results

All irradiated soda-lime samples exhibit ESR spectra that can be decomposed to inhomogeneous background signal (BKS) with associated  $g_{\text{BKS}}$  value, and homogeneous radiation induced signal (RIS) with associate  $g_{\text{RIS}}$  value. The effective  $g$ -value of the irradiated sample is combination of these two. In this study, the dependence of  $g$ -effective value on the dose, temperature and fading of the ESR signal was monitored. The  $g$ -effective value has exponential dependence on the dose as shown before. It is independent of the temperature and the value stabilizes 2 hours after the irradiations.

### Conclusions

The  $g$ -effective value exhibits strong dependence on the dose in soda-lime glass samples, and yet its value remains unchanged with the temperature and 2 h after irradiation. According to the results,  $g$ -effective value approach is useful tool in dose reconstruction.

## Study of the influence of humidity degree into the adsorption capacity of radon by means of granular activated carbon used in the canister device

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### Introduction

Radon is a radioactive gas that comes from the radium decay. Due to its gaseous nature and its high solubility in water, it emanates from soil and water, reaching the air, penetrating into buildings and accumulating in closed spaces. When it is inhaled, it is deposited in the lungs as small particles that cause cell damage; in fact, it is the second cause of lung cancer. Therefore, the Directive 2013/59/EURATOM sets action plans and limit values for radon exposure for buildings and workplaces in order to minimize radon inhalation. As activated carbon is demonstrated to be a very good adsorbent, it can be used as a measurement method for radon exhalation from the soil and as an air purification technique.

### Methods

The objective of this work is to study the radon adsorption capacity of different activated carbons, both mineral and vegetal origin, and analyze the influence of the activated carbon humidity degree on it. For this, it has been designed a deposit, impermeable to radon, which contains soil and a pitchblende stone. Above it, a high density plastic chamber is placed containing a canister with the sample of activated carbon to test, so radon exhaled from the soil will be adsorbed by it. For the measurements, the canister will be exposed to radon exhalation during a 3-day exposure period. To study the influence of humidity content in activated carbon, this parameter will be monitored and changed preparing carbons with different humidity degrees. With this purpose, carbon will be dried in an oven at 100°C to reach dryness, and after will be soaked in distilled water to reach different humidity degrees (till 100 % humidity) After each experiment the canister will be analyzed by gamma spectrometry using a scintillation detector. Radon concentration in air will be measured with RAD7.

### Results

Results of radon adsorption will be compared between the different activated carbons to evaluate the radon adsorption capacity and the influence of humidity degree in the adsorption process.

## Study of the adsorption capacity of radon by means of granular activated carbon of vegetal and mineral origin used in the canister device

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### Introduction

Radon is a radioactive gas that comes from the uranium and radium decay. Due to its gaseous nature and its high solubility in water, it emanates from soil and water, reaching the air, penetrating into buildings and accumulating in closed spaces. When it is inhaled, it is deposited in the lungs as small particles that cause cell damage; in fact, it is the second cause of lung cancer. Therefore, the Directive 2013/59/EURATOM sets action plans and limit values for radon exposure for buildings and workplaces in order to control and minimize radon inhalation by people. As activated carbon is demonstrated to be a very good adsorbent for radon, it can be used as a measurement method for radon exhalation from the soil and as an air purification technique.

### Methods

The objective of this work is to study the radon adsorption capacity of different activated carbons, both mineral and vegetal origin, and analyze the influence of the specific surface, the iodine number and the methylene blue number on it. For this purpose, it has been designed a deposit, impermeable to radon, which contains soil and a pitchblende stone. Above it, a high density plastic chamber is placed containing a canister with the sample of activated carbon to test, so radon exhaled from the soil will be adsorbed by the carbon. For the measurements, the canister will be exposed to radon exhalation during a 3-day exposure period. To study the influence of the parameters of the activated carbon, its origin, specific surface, iodine number and methylene blue number will be previously known or characterized. After each experiment, the canister will be analyzed by gamma spectrometry using a scintillation detector. Radon concentration in air will be measured with RAD7.

### Results

Results of radon adsorption will be compared between the different activated carbons to evaluate the radon adsorption capacity and the influence of its origin, specific surface, iodine number and methylene blue number in the adsorption process.

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## Patient exposure monitoring in medical imaging: why and how?

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International Safety Standards require medical facilities to monitor radiation exposure of patients for the medical imaging procedures they perform. The monitoring process includes recording of relevant patient exposure and dose related data at the facility, their collection and analysis. The amount of information and the method of recording and collecting depend on the purpose, modality and technical capabilities. Collected data from different patients, modalities, and units are combined and processed to perform relevant statistical analysis and establish diagnostic reference levels (DRLs). This can be done at local, regional, national or international level. Established DRLs are then used to benchmark local practice in each facility as a tool for optimization. Samples based on specific examination, patient group or acquisition conditions should be well defined. Availability of a good coding system of examination and protocol nomenclature is crucial, as well as selection of examinations based on clinical indications. Data quality evaluations should be conducted at all steps. Another use of dose monitoring is for tracking exposure history of individuals that is useful to avoid performing redundant radiological examination and optimize the overall patient care. A dose data management infrastructure may deploy an integrated electronic system, which interface and functionalities depend on the intentional user groups. Ideally, it should be integrated with the general patient information systems. If properly implemented, the patient exposure data management contributes to the improvement of radiation protection and patient care.

## Automatic patient dose registry and help in the optimisation and audit of interventional procedures

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Obtaining sufficient diagnostic information during interventional procedures is a priority, but optimisation also requires considering patient radiation doses. This work presents the experience using a homemade automatic patient dose registry ("Dose On Line for Interventional Radiology" DOLIR) for optimisation.

Automatic patient dose registries allow collecting data for all the radiation events (when the Radiation Dose Structured Reports –RDSR– are available) and auditing the protocol of the examinations and their different imaging acquisition modes: fluoroscopy, cine, DSA and CBCT events. A continuous comparison (using samples of 30 procedures) with Diagnostic Reference Levels (DRLs) allows suggesting corrective actions when appropriate. The Medical Physics Service carries out periodic validation of patient dose quantities managed by the system.

The system used in a large university hospital during the last two years is currently connected to the interventional systems of other 6 hospitals, so as to jointly manage the patient dose values and arrange intercomparison of protocols. The current number of interventional procedures available in the system is about 40.000. Kerma Area Product, kerma at the patient entrance reference point and some calculated skin dose maps (and peak skin doses) are included in the system.

The use of the automatic patient dose registry allowed an easy auditing process of the individual patient dose values (in case of potential skin radiation injuries) and obtaining median patient dose values for groups of procedures (with the same or similar clinical indications). The easier comparison with DRLs helped suggest corrective actions when appropriate.

## Patient-specific dosimetry in Molecular radiotherapy

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Radiopharmaceutical dosimetry can be sorted out according to clinical applications. As 90% of nuclear medicine is in diagnostics, model-based dosimetry has been developed for decades, mostly in order to get authorities approval before putting a new (diagnostic) radiopharmaceutical on the market.

Targeted radionuclide therapy, or Molecular radiotherapy (to better emphasize the fact that this is a kind of *radiotherapy*) has long been mostly dealing with the treatment of thyroid diseases with radioactive iodine ( $^{131}\text{I}$ ). New generations of radiotherapeutic drugs are being developed and tested in a clinical environment. Some radiopharmaceuticals have obtained FDA or EMA approval and are now available for patient therapy. In that context, patient-specific dosimetry is not only a legal requirement (EURATOM Directive 2013/59), but a means to document and optimise the treatment delivered.

Patient-specific dosimetry requires the determination of the number and localization of radioactive sources. This is usually obtained via quantitative imaging, even though other means to get activity in different compartments of the patient can be implemented. Time-activity curve are integrated to derive cumulated activity (Bq.s), i.e. the number of sources present in the patient during the therapeutic procedure. Absorbed dose calculation then requires the determination of how emitted radiation propagates and is eventually absorbed in patient tissues.

The different steps that characterise clinical dosimetry will be reviewed. The growing availability of commercial dosimetric software represents a major challenge for professionals involved in clinical dosimetry. On one hand, the promise to get tools that allow performing clinical dosimetry within reasonable time frames is appealing. On the other hand, the variety of available codes and the fact that they not necessarily address the same parts of the clinical dosimetry chain call for a standardised appraisal of their capabilities.



# Dosimetry for investigations of the effect of strong magnetic fields on radiobiological response

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## Introduction

In support of MR-guided radiotherapy, the National Physical Laboratory (NPL) has positioned an electromagnet (up to 2T) adjacent to a clinical linac (Fig. 1). Bespoke phantoms are placed between the magnet poles for *in vitro* investigations, varying radiation and magnetic fields. Dosimetry must consider the electron return effect (ERE), due to the Lorentz force acting on electrons moving perpendicular to a magnetic field, making ionisation chambers inaccurate. Hence, dosimetry was performed using EBT3 Gafchromic film and Alanine.

## Methods

Gafchromic films were placed in the phantom at the cell position to determine the dose per monitor unit (MU) at varying magnetic field strengths. Measurements were validated in the high dose range using alanine which has been reported to be negligibly affected by the magnetic field. Placing Gafchromic films at different depths, impact of the magnetic field on the dose-depth curve was also estimated.

## Results

With 100 MU/Gy at reference conditions (95cm SSD, 5cm in water, 10x10cm field), the dose per monitor unit calculated using Gafchromic film at a depth of 47mm in PMMA (the depth that cells would be placed) for magnetic field strengths of 0T and 1.5T were  $0.0952 \pm 0.0045$  cGy/MU and  $0.0989 \pm 0.0045$  cGy/MU respectively. The difference in dose is due to magnetic fields shifting the dose-depth curve, altering the dose at a given depth. Film data is in good agreement with the Alanine measurements, ( $0.0985 \pm 0.0021$  cGy/MU for 1.5T). Although both Gafchromic films and alanine should not be affected by magnetic fields, the Alanine proved more consistent (Table 1), which has been used to determine the dose *in vitro*.

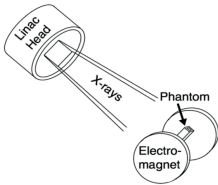


Figure 1: Schematic diagram of experimental setup at NPL.

Table 1: Results of Dose per monitor unit for this experimental setup, for Gafchromic film and Alanine dosimetry.

Magnetic Field (T)	Dose (cGy) / MU	
	Gafchromic Film	Alanine
0.0	0.0952 ± 0.0045	0.0963 ± 0.0004
1.0	0.0950 ± 0.0038	0.0992 ± 0.0023
1.5	0.0989 ± 0.0045	0.0985 ± 0.0021

## Conclusions

Dosimetry was performed for a variety of methods, considering magnetic fields, using Gafchromic film and Alanine which are unaffected by the ERE. The dosimetry allows for radiobiological *in vitro* experiments for this setup and has indicated the most accurate method for calculating the dose per MU received by cells.

## Application of a magnetic quadrupole for focusing the electron beams emitted by a Plasma Focus device

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### Introduction

A Plasma Focus (PF) is a device that allows the production, during the pinch phase, of high intensity electron beams, in the order of  $10E+15$  particles in a few tens of ns. One of the issues in using these beams in industrial and medical applications is that their self-collimated behavior at the emission can be partially lost during the traveling between the pinch volume (microns) and the interaction target for X-ray pulses production, due to the Coulomb repulsive interaction. This aspect is of strategic relevance in dose control for the radiotherapy proposed applications. One possible solution is to implement a magnetic focusing device able to drive the beams in spot in the order of hundreds of  $\mu\text{m}$ . This could enhance the performances of the PF devices.

### Methods

A dedicated computational model of this aspect of the PF device has been studied using the Comsol® Multiphysics software, including the geometry of the hollow anode, the presence of low-pressure (0.4 mbar) nitrogen filling the plasma chamber, the extraction electron channel, the support for the quadrupoles and the permanent magnets used for focusing. The electron spectra used as source for the simulations came from experimental results. A first project solution has been found thanks to the simulations and a preliminary prototype of the magnetic lens has been implemented. The beam shape has been detected using the Gafchromic® HDV2 film dosimeters.

### Results

A parametric analysis for the setup of shape and intensity of the required magnetic field generated by the quadrupole has been performed. Under that field, the charged particle beam has been simulated starting from the pinch phase and the focusing effectiveness verified. The performances of a magnetic lens prototype have experimentally checked.

### Conclusions

The design of a magnetic lens for focusing the ultra-short and intense electron beams produced by a PF device has been performed and a first prototype of the system developed.

## Diamond detectors with 3D graphitic electrodes for medical dosimetry

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### Introduction

The capability of diamond films to act like medical dosimeters due to their excellent properties, has been widely demonstrated. To this purpose, polycrystalline chemical vapor deposited (pCVD) diamond substrates are obtained creating graphitic conductive paths in the diamond bulk, using a pulsed laser technique. Main advantages of such solution are the low voltage working point, the all-carbon material, the large sensitive volume compared to the planar devices and the higher signal. In this work we present a customized matrix of 9 diamond pixel units, with a 0.5 mm pitch, which could represent in the future after optimization a solution for the verification of small size high intensity modulated stereotatic treatments and for linac QA.

### Methods

Diamond dosimeters with 3-dimensional structures are produced by using laser pulses which create conductive paths inside the diamond bulk. Before testing the devices with clinical beams, laboratory tests were needed to evaluate each pixel performance. Tests at the Florence Hospital were made to calibrate the device with a standard field of 6 MeV photon maximum energy. An inter-calibration among all pixels was needed to take into account the different responses due to non-uniformities in the substrate and in the graphitization process.

### Results

The device was characterized in terms of short and long term stability and repeatability, dependence on dose and dose rate showing good time stability, repeatability and linear dependence from dose rate. Measurements of small field profiles (less than 3cm<sup>2</sup>) and output factor as function of field size was carried out. Comparison was made with other detectors used in clinical routine, in order to identify limitations and issues to be addressed in the future.

### Conclusions

The good spatial resolution obtainable with the 3D geometry will significantly increase the understanding of dosimetry of small clinical photon beams, overcoming the drawbacks and issues of the available dosimeters.

## Investigation of Ferrous-Agarose-Xylenol Gel (FAX) Dosimeter developed at SSDL irradiated with $^{60}\text{Co}$ g-rays therapy unit

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### Introduction

Over recent decades, modern protocols of external beam radiotherapy and radiation techniques such as intensity-modulated radiotherapy (IMRT) have been developed. These methods are extremely sensitive to errors in treatment delivery, so that it is essential to apply a high resolution 3D dosimetry system that has high sensitivity and is capable of measuring and verifying the complex delivery. The ferrous-agarose-xylenol orange (FAX) gels the material properties of which are changed when irradiated have been suggested for such use.

In this study the proprieties of FAX gel dosimeter such as precision, linearity, dependency on dose rate and potentiality to measure output factors for different field sizes for  $^{60}\text{Co}$  were examined.

### Methods

FAX gel was prepared using 1 mM (FAS),  $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$  of analytical grade, 25 mM  $\text{H}_2\text{SO}_4$  98%, 0.165 mM (XO) xylenol orange-sodium salt, 1% by weight of agarose gel powder and the remaining mass of the solution being ultra pure water. FAX gels were exposed to doses in the range of 1–25 Gy using  $^{60}\text{Co}$  g- rays beam by an Eldorado-78 therapy unit. The home built PMMA phantom used for irradiation. Some general characteristics of FAX such as optical absorbance-dose relationship, sensitivity, precision were analyzed. The FAX potentiality to measure output factors for different field sizes of  $5 \times 5 \text{ cm}^2$ ;  $7 \times 7 \text{ cm}^2$ ;  $8 \times 8 \text{ cm}^2$ ;  $10 \times 10 \text{ cm}^2$ ;  $12 \times 12 \text{ cm}^2$ ;  $15 \times 15 \text{ cm}^2$  and  $20 \times 20 \text{ cm}^2$ , was also investigated.

The output dose rate to PMMA was measured previously using a  $0.35 \text{ cm}^3$  reference ionization chamber PTW # 329 connected to a PTW UNIDOS 10002 electrometer. All irradiations were performed according to the IAEA Code of Practice TRS-398.

### Results

Results indicate FAX has a linear optical response in the range 1-15 Gy. Little dependency on dose rate (1%), a good reproducibility (< 2%), In the present work, dosimetric use of FAX system for relative output factor measurement in PMMA phantom for  $^{60}\text{Co}$  teletherapy unit was also investigated. For this purpose, results obtained from FAX system under identical irradiation conditions, have been intercompared with those published in the literature. A good agreement was observed between the two results

### Conclusions

In conclusion, the small volume studies presented in this work indicate FAX as developed in our secondary standard dosimetry laboratory (SSDL) presented a good performance.



## An innovative dosimeter based on a floating Gate sensor

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### Introduction

This work describes the development of a new method for recording radiation exposure by using a passive dosimeter based on a Floating Gate CMOS sensor.

The floating Gate sensors based on the MOS structure discharge allow the construction of compact and cost-efficient dosimeters, realized in VLSI CMOS technology, for use in integration mode in various applications, in particular in radiotherapy.

### Methods

A monolithic rad-hard dosimeter has been designed starting from a standard six metal levels CMOS technology with lithography at 180nm. The radiation sensor (C-sensor) is based on a non-volatile memory cell with floating-gate which, once loaded, can provide a measure of the absorbed radiation on the basis of its threshold discharge. Since the memory cell is mainly a transistor the greater is the current flowing into the channel the greater is the dose of radiation received by the sensor. The output current of the transistor is processed by a current-voltage converter (IV converter) and interfaced to an analog-digital Flash converter (ADC) with a resolution of 5 bits. To ensure the re-use of the device both the current-to-voltage converter and the ADC have been designed to be resilient to radiation (rad-hard) to avoid a degradation of the internal circuitry that can affect the measure of the absorbed dose.

### Results

Ten dosimeter samples have been designed, integrated and tested under gamma irradiation at the IGS3 gamma-ray irradiator of DEIM Department of Palermo University to verify their performances. Dosimeters have been irradiated with a dose-rate of 1.44 Gy/min (Si) and in a dose range between 3 and 10 Gy(Si) and a linear relation between dose and response has been detected. Following the reading the dosimeters were reprogrammed and irradiated again to verify their re-use.

### Conclusions

The results confirm that, in this first version, the dosimeter is reprogrammable and able to detect a dose up to 10 Gy (Si) with temperatures that can go from 0 to 85°C.

## Assessment of the increasing RBE at the distal edge of a proton therapy SOBP by using solid state detectors and an in-vitro cell survival study

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### Introduction

The higher RBE of protons used for cancer radiotherapy is currently considered in the treatment planning by using a fixed value of 1.1 relative to photons. However, recent evidence suggests the inadequacy of using a constant factor, especially in the distal edge region. The goal of this study was to investigate the RBE change within a clinical proton SOBP. Measurements with solid state detectors were used in combination with biophysical models to correlate physical quantities with the radiation-induced cell death. The obtained results were compared with computer radiation transport simulations and the results of an in-vitro cell survival study.

### Methods

Couples of differently doped thermoluminescent detectors (TLDs), the MicroPlus silicon microdosimeter and Chinese hamster ovary (CHO) cells were exposed at different depths within a proton SOBP in the therapy room of iThemba LABS (South Africa). The measured physical quantities were correlated with the RBE by respectively using a proton LET vs RBE phenomenological model and the modified microdosimetric kinetic model (MKM). In addition, simulations of irradiation setup were performed with the GEANT4 Monte Carlo code.

### Results

The LET was assessed with the TLDs by means of a new methodology based on the Microdosimetric  $d(z)$  Model and it was found to increase from approximately 1 keV/ $\mu\text{m}$  at the entrance plateau to 6 (fluence mean  $\text{LET}_f$ ) and 8 keV/ $\mu\text{m}$  (dose mean  $\text{LET}_d$ ) at the distal edge. Similarly, the  $y_f$  and  $y_d$  measured with the MicroPlus ranged from 2-3 keV/ $\mu\text{m}$  up to 6 and 10 keV/ $\mu\text{m}$  respectively. Using this physical information as input to the biophysical models, the RBE for a clinical dose of 2 Gy was calculated. In both cases, maximum RBE values of 1.9-2.0 were obtained, in good agreement with the results of the clonogenic survival study.

### Conclusions

The results of this study confirmed the presence of significant RBE changes in therapeutic proton beams and the feasibility of RBE assessment with solid state detectors.

Analysis of the influence of moisture on the soil in the concentration of exhaled radon

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Introduction

Radon gas, produced by radium decay, is considered as a carcinogenic element by the World Health Organization due to its progeny <sup>214</sup>Po and <sup>218</sup>Po. Both descendants are solid particles that could be inhaled and deposited in the lungs.  
The radon hazardous led in 2013 the Directive 59/2019/EURATOM which stablishes new radon limit levels in air. Furthermore, it was included for the first time the obligation to measure radon exhalation, strongly influenced by weather and soil conditions.

Methods

This work analyzes the effect of soil moisture during the exhalation radon process which is an advance in radon behavior knowledge for different measurement conditions. A passive measurement system based on electretes connected to an accumulation chamber has been used. Moreover, in order to evaluate the precision of the method, the standard deviation of the results obtained will be studied.  
Additionally, an experimental equipment which contained a pitchblende stone, has been designed allowing the variation of the moisture content in soil through a sprinkler system.

Results

The results using an H chamber connected to an electret are shown in Table 1. For each test the mean values are shown.

Table 1. Results obtained during the exhalation radon process for different soil moisture

Test	Soil moisture (%)	Rn concentration (Bq/m³)	Exhalation rate (Bq·hr/m²)
Test 1	2.10	4131 ± 207	71.84 ± 3.40
Test 2	1.90	4081 ± 205	70.97 ± 3.40
Test 3	2.09	4541 ± 228	78.97 ± 3.97
Test 4	28.37	6099 ± 306	106.06 ± 5.32
Test 5	33.79	7753 ± 432	134.82 ± 7.51
Test 6	36.26	9470 ± 538	164.68 ± 9.35

Conclusions

It is confirmed that the exhalation rate is increased the greater the content of water retained in the soil. The permeability of the experimental does not allow the amount of water to evaporate. The liquid captures the radon atoms due to its free half path in water.  
Moreover, the methodology of adding water in the container has been optimal. No impervious barrier has been created of the surface of the ground.

## Development of a UAV based spectro-dosimetric system

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In the framework of the EMPIR project 16ENV04 “Preparedness”, PTB is developing a spectrometer based dosimetric system that can be operated while attached to an unmanned aerial vehicle (UAV). This is a consequence of the basic safety standards of the EU which demand the “Health protection of emergency workers”. The importance is evident for a radiological emergency situation where UAV can cover a large area much faster than a ground squad, therefore minimizing the workers’ exposition to ionizing radiation.

The dosimetric system consists of a  $\text{CeBr}_3$  scintillation detector which records spectra every two seconds into a database and converts them to dose rate information. The conversion function from spectra to dose was derived with a Monte Carlo simulation (GEANT4) of the detector. The system also measures global position, height above ground and can send this information to a ground base where additional data treatment is possible.

The paper presents the results from a ground measurement campaign on PTB’s premises, where an uncollimated free field irradiation facility was operated. The artificial dose rate increase at the reference point was ranging from 60 to 400 nSv/h. The standard deviations of the measured dose rates in 2 s intervals are in the order of 10-30 % and the results agree well with the reference values.

The remarkable performance of the dosimetric system demonstrates the ability of metrologically accurate two-second long dose rate measurements with the well-characterized spectro-dosimeter. The next step will be the testing of the dosimetric system in an aerial measurement campaign against well-known radiation fields. Finally, the system needs to be able to calculate surface activity concentrations from the recorded spectra.

## A wireless network for radiation monitoring in waste at CERN (W-MON)

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**Introduction** Radiation Protection and Environmental monitoring at CERN is of great importance in order to ensure a controlled and radiologically safe workplace. Monitoring is one of the most important requirements in controlling and limiting the exposure of CERN personnel, as well as of the general public, to ionizing radiation.

**Methods** The W-MON project aims to deploy a fully automated, remotely controlled monitoring system for radioactivity in ordinary waste containers at CERN. The system will provide better sensitivity, better uniformity and increased reliability at lower costs than the current operator-driven procedure. The goal is to equip approximately 100 ordinary waste containers with a series of wireless radiation sensors in order to monitor the radiation level on a continuous basis.

**Results** A suitable radiation detector (D-shuttle) from Chiyoda in the form of a personal dosimeter was chosen at the initial stage and was modified for our purposes. In this presentation, we will give an overview on the current developments on the collection of the dose data from the sensors and transmission to a back-end server for data archiving and visualization, using long range wireless technologies. Tests were performed on different system configurations of data transmission according to the required power consumption, data transfer size and frequency etc. The LoRaWan infrastructure has been developed and is being optimized to increase the autonomy and range of the device.

**Conclusions** The development of a fully automated radiation monitoring system for radioactivity in waste containers at CERN is of paramount importance and will eliminate current reliability and uniformity issues introduced by the human operator and manual data logging. Such a system can also serve in the future in different applications such as personal dosimetry for the general public, environmental monitoring, automatic tracking of radioactive sources and tracking of transport of radioactive materials.

## Radiation dose assessment in plants and mosses growing on a phosphogypsum stockpile in Portugal

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### Introduction

Phosphogypsum (PG) is a phosphate industry sub product with enhanced concentrations of NORM. A PG stockpile remains near a suburban area in the south bank of Tejo estuary. Herbaceous plants and moss have been covering the PG surface, so this stockpile can be used as a natural laboratory to quantify the transfer of radionuclides to the vegetal biota and assess the absorbed dose resulting from exposure to ionizing radiation.

### Methods

Studied materials consisted in herbaceous plants (*Plantago coronopus*), moss (*Bryum argenteum*) and the PG from the root system. The determination of the natural radionuclides activity concentrations was carried out by gamma spectrometry (HPGe). Dose assessment was performed using the ICRP reference wildgrass coupled with the Monte Carlo code MCNPX.

### Results

Main contributors to radiation exposure are <sup>40</sup>K, <sup>210</sup>Pb, <sup>226</sup>Ra and <sup>228</sup>Ra. Herbaceous plants have higher concentrations of <sup>226</sup>Ra (141 Bq kg<sup>-1</sup>) and <sup>210</sup>Pb (260 Bq kg<sup>-1</sup>) in roots than aerial parts. Moss has 3 - 4 fold higher concentrations of <sup>226</sup>Ra (2900 Bq kg<sup>-1</sup>) and <sup>210</sup>Pb (4000 Bq kg<sup>-1</sup>) than the underlying PG. Total estimated doses in *Plantago* (8.34E-09 Gy d<sup>-1</sup>) and *Bryum* (9.53E-09 Gy d<sup>-1</sup>) are very similar.

### Conclusions

Dosimetric calculations show that internal doses are similar to external doses in herbaceous plants but can exceed 2 orders of magnitude in moss. The estimated doses are in the order of the natural background for ICRP reference wildgrass (< 0.01mGy d<sup>-1</sup>).

## Dosimetry in Radionuclide Therapy with Ra-223 for the Treatment in Bone Metastases

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### Introduction

According to estimates, in Brazil, between 2018 and 2029, prostate and breast cancer will be the most frequent. About 90% of patients with advanced prostate cancer have developed bone metastases that can cause pain, disability, and deterioration in the patient's quality of life. Ra-<sup>223</sup>Ra-Dichloride (Xofigo®) is indicated for patients with bone metastases in castration-resistant prostate cancer. Currently, <sup>223</sup>Ra is administered according to standard fixed administrations: 50 kBq/kg. Some studies suggest that Ra-223 could also be applied to osteolytic bone metastases in breast cancer in women. The aim of this work is evaluate a dosimetric study of Ra-223 to obtain the S-values and the Absorbed Doses through the Monte Carlo simulation for the male and female standards.

### Methods

The Monte Carlo simulation was performed using the GATE with a male and a female 4D Extended Cardiac-Torso (XCAT) models to extract the S values. The decay chain of Ra-223 includes four alpha particles and two beta particles. Using the <sup>223</sup>Ra-Dichloride (Xofigo®) biodistribution and the S values obtained, absorbed as doses were calculated for more than 30 organs in the human body.

### Results

The absorbed doses were divided for doses by alpha, beta and gamma particles. The highest doses were found in the bones and intestine, because it is the means of excretion of the radionuclide. This study calculated the dose in the following parts of the bone separately: yellow marrow, bone marrow and bone surface.

### Conclusions

The S values obtained and the Dose coefficients obtained in this work using the Monte Carlo method is the first stage for the development of a personalized treatment and a patient-specific dosimetry for individual patients.

## Multi-cellular dosimetry of cells labelled with $\beta^+$ -emitting radionuclides for PET imaging

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**Aim:** *In vitro* labeling of cells with  $\beta^+$ -emitting radionuclides combined with nuclear medicine imaging is a potential method for *in vivo* cell trafficking analysis with PET imaging. The labeling-associated exposition of cells to high levels of activity still raises some concerns. Although there are some studies on the subsequent cellular effects, they are often carried out without dose assessment. This work aimed to develop a realistic multi-cellular dosimetry and to apply the model to labeling experiments with  $^{18}\text{F}$ -FDG.

**Materials and Methods:** A 3D cellular model taking into account the realistic conditions of labeling was developed to calculate the mean absorbed dose to cells. The cells were assumed to be packed in a cubic lattice or uniformly distributed within the studied volume, while the cell density and the proportion of activity incorporated by the cells were varied. With the aim of achieving as accurate as possible results while managing a very large number of cells, a hybrid method was developed, combining Monte-Carlo (MNCP6 code) and an analytical approach implemented in Python. This approach was based on the use of radial distribution function  $g(r)$  derived from the molecular dynamic software LAMMPS. Comparison with the standard approach, based on the explicit summation of cell-to-cell dose contributions, was done. Then, calculations were done for  $^{18}\text{F}$ -FDG-labeled cells assuming parameters used in 8 different publications, *i.e.*, cell density, added activity concentration, incubation time and labeling efficiency.

**Results:** The cell absorbed doses calculated with the two methods agreed well. LAMMPS-based indirect approach was showed to be more effective and less time consuming than the standard approach. Results also showed that the absorbed dose was not significantly impacted by the type of cell distribution considered, but strongly dependent of the cell density and labeling efficiency. Application of the model to  $^{18}\text{F}$ -FDG labeling to different experimental conditions showed that a same activity per cell can result in significantly different absorbed doses, reinforcing the crucial role of the absorbed dose, as the reference, for studying the cellular effects rather than the added activity.

**Conclusions:** Through the development of a new calculation approach, our multi-cellular dosimetry provided a generic and robust method to estimate the cell absorbed dose and better understand the influence of key labeling parameters.



## Monte Carlo modelling of microbeam radiotherapy

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### Introduction

Microbeams have extraordinary tissue-sparing properties that could be exploited to deliver high doses to radiation resistant tumours. Microbeams are typically 50 micron in width and measurements are challenging, therefore Monte Carlo is used to infer clinical parameters associated with the dose distribution on the micron scale. In particular the ratio of the dose in the microbeam to the dose between microbeams is an important clinical parameter referred to as the peak-to-valley-ratio (PVDR).

### Methods

Monte Carlo modelling using simplified geometries of dose in water and bone phantoms has been performed using three well known photon and electron codes, EGSnrc, GEANT4 and PENELOPE. Challenges include needing accurate electron transport to determine the dose in the microbeam and for the diffuse dose generated by Compton scattering photons and long-range photoelectrons. Results are compared between the codes as well as with recently published experimental data.

### Results

Significant discrepancies for the PVDR parameter in the range of 2-6% are shown to occur between the PENELOPE Monte Carlo code and the two other codes. The difference is thought to be due to the normalisation screening correction applied to the photo-effect cross-section in PENELOPE, but not EGSnrc and GEANT4. Results from measurements were found not to be sufficiently accurate to distinguish between the Monte Carlo models and cannot yet provide support for either theoretical approach.

### Conclusions

The differences reported in this study are potentially clinically significant, as there remain difficulties in measuring the diffuse dose between microbeams, likely to be the limiting factor in patient treatments. Calculations will continue to be compared to the latest measurements, where the most promising results arise with the use microdiamond detectors and radiochromic film, though excellent tissue-equivalence and spatial resolution.

## Applying Deep-learning in gamma-spectroscopy for radionuclide identification

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### Introduction

Neural networks, particularly deep neural networks, are used nowadays with great success in several tasks, such as image classification, image segmentation, translation, text to speech, speech to text, achieving super-human performance. In this study we explore the capabilities of deep learning on a new field: gamma-spectroscopy analysis.

Using a well-known deep neural network architecture with gamma spectroscopy data, we successfully identify the radionuclides (Am-241, Ba-133, Cd-109, Co-60, Cs-137, Eu-152, Mn-54, Na-24 and Pb-210) contained in several experiments.

This neural network is also capable to identify different mixed radionuclide in the same source, demonstrating that deep neural networks can be successfully applied on gamma-spectroscopy analysis.

### Methods

Using a HPGe detector to acquire several gamma spectra, from different sealed sources, we created a dataset that was used for the training and validation of the neural network.

We created our deep neural network using python as programming language, alongside with *Keras*, a deep learning framework. Applying the VGG19 network architecture, except by the last layer which using *softmax* as activation function, we used sigmoid in order to allow classification of not mutually exclusive classes in the same instance.

### Results

After 250 epochs of training the classification error on the training and test datasets reached a minimum, the same occurred with accuracy.

As a final test we used a spectrum from a triple sealed source, containing Am-241, Cs-137 and Co-60. As this kind of data was never seen by the network before we expect that the network generalizes well and correctly classify the spectra as containing the three isotopes.

When applying the new data, the model correctly classified the spectra as containing the tree radionuclide.

### Conclusions

The model successfully classifies different spectra with different radionuclides and his performance is good on never seen before data (the triple source sealed) demonstrating that deep learning can be used on a new domain.

## Shielding calculations for the design of new Beamlines at ALBA Synchrotron

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### Introduction

ALBA is a Spanish synchrotron facility generating bright beams of synchrotron radiation from a 3 GeV electron accelerator. Electrons are first accelerated in a 110 MeV linear accelerator and then injected in Booster ring which increases the energy up to 3GeV. Finally, the electron beam is stored in a synchrotron Storage Ring with a current up to 400 mA emitting a bright beam of synchrotron radiation. Both the Booster and the Storage Ring are located inside the same concrete building called Tunnel, while the LINAC is located in a separated concrete building called Bunker. Outside the Tunnel, and tangentially to the Storage Ring, are located the experimental research laboratories named Beamlines, where scientists receive synchrotron light for a wide variety of experiments. At present ALBA has 8 Beamlines installed, 3 Beamline under construction, and 1 Beamlines in the design stage.

### Methods

This paper details the design of the shielding elements of the new Beamlines under construction called LOREA, NOTOS and XAIRA. The first one is a soft X-ray and the other two are hard X-ray beamlines. Shielding calculations are performed using FLUKA Monte Carlo code and aim at quantifying the total dose produced by the different sources of radiation at the Beamline in operation. In particular, it studies the dose generated by the gas bremsstrahlung radiation resulting from the interaction of the 3 GeV electron beam with the residual gas of the storage ring vacuum chamber, and compares it to the dose generated by the insertion device radiation flux.

### Results

The objective of the FLUKA simulations performed in this work is to establish the requirements for all the beamline shielding elements (walls, roof, shadow shielding, collimators and beam stops) to ensure a public dose (dose rate lower than 0.5  $\mu\text{Sv/h}$ ) outside the shielding during Beamlines operation.

### Conclusions

Results from the simulations will allow establishing the requirements for all the beamline shielding elements.

## Proposal of a FLUKA-based radiation monitoring system for the laser driven electron acceleration area at ELI-NP

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### Introduction

In the present paper we use FLUKA simulations to design a dosimetry monitoring system for the typical electron acceleration experiments in the E6 area of the ELI-NP building. We propose solutions for some practical issues: proper choice of the detector type and proper detector positioning in accordance with the characteristics of the radiation field (pulse duration, components, energy ranges).

### Methods

A complex FLUKA geometry of the E6 experimental area was built by using data extracted from the latest available version of the corresponding Catia file, including all the building and beamline transport elements. With FLUKA we calculated  $H^*(10)$  in a Cartesian binning over E6 and neighbouring areas. The doses per hour and per pulse were obtained by normalising the results to a number of  $8.61 \times 10^{10}$  primary electrons per pulse, for a maximum frequency of 1 pulse/min. The dose per pulse values are particularly important, as they can point to rather high instantaneous dose rate values that can exceed regulatory limits. The fluence rates of the secondary prompt radiation field components generated by the 38 GeV Gaussian electron source term at E6 were mapped throughout this experimental area. These results were used to determine which is the most important contributor to the dose and in which areas, as well as what would the optimal zoning be for the areas adjacent to the experimental hall.

### Results

We used the FLUKA results to propose the adequate types of detectors and their positioning for each field component. We evaluated the detector response to high energies, starting from the known energy response and investigating the additional errors at higher energy values.

### Conclusions

The results returned by FLUKA highlight the difficulties inherent to the dose monitoring system for the ELI-NP project: the extremely short pulses that need to be accurately measured, the mixed radiation fields and the wide energy range which make detector calibration impossible in the existing metrology labs.

## Economic evaluation of a radiotherapy shielding design as a function of treatment techniques

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### Introduction

The benefits of using external radiotherapy (RT) to treat cancer are well known mainly due to the deterministic effects provoked on cells. On the other hand, the stochastic effects (or tissues reactions) provoked under low dose of radiation exposure are not well understood. In this last scenario are found the workers of RT departments and visitors. In order to limit this exposure to acceptable levels, vaults with proper barrier thickness should be constructed, taking into account the RT techniques intended to use.

The main objective of this work is to evaluate the barriers' dimensions of a vault as a function of the RT techniques (3D-CRT, IMRT, SRS and TBI) and correlate with the economic impact on the budget.

### Methods

The NCRP 151 methodology was followed to calculate the thickness of barriers, including the door. The selected beam energies were 6 and 15 MV and then, neutrons should be taken into account.

The external dimensions of a planned ideal vault have been maintained constant, while the number of treatments delivered with different RT techniques have been changed, resulting thus, in different barrier thickness.

### Results

Barrier thicknesses were compared with those obtained for the 3D-CRT technique for which the primary and the leakage workload have the same value. The increment of the barriers' thickness is mostly due to the leakage workload, which is related with the RT technique employed. Results show that if 50% of the treatments performed are IMRT, the leakage workload increment (about 2.1 times) results in a volume of the secondary barriers increment of about 30 m<sup>3</sup> of ordinary concrete, increasing the cost about 13 %.

If TBI is used in 4% of the treatments, the leakage workload increment is about 10 times and the secondary barrier contiguous to the primary will increase in 0.10 m, increasing the cost about 400 €.

### Conclusions

Considering the results obtained, existing vaults should be reassessed if the RT techniques and/or the number of patients being treated with them change along the years.



## A computer code for dose estimation from external exposure to radioactive plume

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### Introduction

To protect the public against radiations from radionuclides released into the environment, we have been developing a dose-estimation system for both internal and external exposures. In this presentation, we introduce a computer code that is a part of the system and can estimate the external doses from a radioactive plume.

### Methods

The behavior of the radioactive plume is traced by a local-scale atmospheric dispersion model using large-eddy simulation (LOHDIM-LES) in a three-dimensional space segmented with cubic grids. For a quick and accurate dose estimation, we use response functions which are dose contributions from one grid containing radionuclide with a unit radioactivity to neighboring grids. The response functions were evaluated for  $^{85}\text{Kr}$ ,  $^{131}\text{I}$ ,  $^{132}\text{I}$ ,  $^{133}\text{I}$ ,  $^{132}\text{Te}$ ,  $^{134}\text{Cs}$ ,  $^{136}\text{Cs}$ , and  $^{137}\text{Cs}$  on the ground and in the air using the Particle and Heavy-Ion Transport code System (PHITS). According to the radioactivity distribution outputted from the LOHDIM-LES, the dose distribution is calculated by multiplying the radioactivities by the response functions. In addition, the code can treat the undulations of the ground and the dose reduction by buildings and houses.

### Results

The dose distribution was calculated using the response functions based on the results of radioactive-plume dispersion by the LOHDIM-LES in a target region of  $240 \times 240 \times 150 \text{ m}^3$  with the grid size of  $1 \times 1 \times 1 \text{ m}^3$  which contains concrete buildings of  $24 \times 24 \times 24 \text{ m}^3$ . The calculated results were compared with those calculated by the PHITS to examine its accuracy and calculation speed. It was found that our code has the ability to predict dose distribution with a comparable accuracy and a 100 times faster calculation speed as compared with the PHITS.

### Conclusions

The computer code has been developed to estimate the external doses from radioactive plume, and its accuracy has been verified through the comparisons with the PHITS results. The code will be distributed free of charge as open source software.

## Absolute energy of the K emission spectrum of Scandium

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### Introduction

The absolute energy of Sc K $\alpha$  has not been measured in over 50 years (since [1]). The standard uncertainty was estimated to be 100ppm. However, we report a Sc K $\alpha_1$  energy of 4090.773eV and a Sc K $\alpha_2$  energy of 4086.253eV, uncertainties of 2.5ppm and 4.4ppm respectively. Recent works reporting on the *relative* energy of Sc K $\alpha$  (such as [2, 3, 4, 5, 6]) all cite [1] as the energy reference.

The K $\alpha$  spectral line is a doublet labelled K $\alpha_1$  and K $\alpha_2$  for the  $2p_{3/2} \rightarrow 1s_{1/2}$  and  $2p_{1/2} \rightarrow 1s_{1/2}$  transitions respectively. From QM, it's expected that the intensity ratio  $I(K\alpha_2):I(K\alpha_1)$  is 0.5. However, this increases with Z, known as the anomalous Z-dependence. Further anomalies are asymmetries, being representative of a dominant transition with several nearby satellites of disputed origin.

### Methods

A 20 keV electron gun bombards samples of elements Z=21 to Z=25 creating K $\alpha$  fluorescence. A Ge(220) curved crystal Bragg diffracts a beamline towards the detector. Results are only recorded when pressure was less than  $10^{-7}$  Torr. The angle was measured by gravity referenced clinometers requiring precise calibration.

A multi wire proportional counter (MWPC) with backgammon geometry detects the X-rays. The detector was filled with P10 (10% methane in argon) gas at approximately 1060Torr.

### Results

The Sc K $\alpha_1$  energy of 4090.773eV and a Sc K $\alpha_2$  energy of 4086.253eV with standard uncertainties calculated as 2.5-4.4ppm. The component positions of 6 Voigts are fitted. The data represented in Figure 1.

### Conclusions

This work shows reliability of curved crystals in diffraction experiments for spectrometry. Similar analytical techniques may reach 1ppm accuracy. The results give potential for novel theoretical calculations to be tested to new precision.

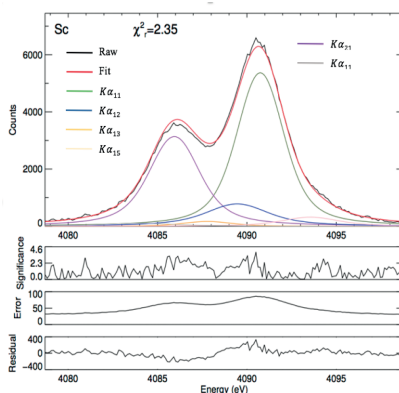


Figure 1: The raw data with the overall fit from 6 Voigts



## Development of a scalable and deformable stylized eye model and its application to the standard radiation exposure geometries

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### Introduction

Assessment of radiation exposure of the eye is important in many occupational and medical situations. There are several studies to evaluate the radiation exposure of the eye using a realistic eye model coupled with Monte Carlo (MC) transport calculation. Although there are a large variety in size and shape for individual eyes, the eye model of one standard eye size and shape was adopted in most of those studies.

### Methods

We developed a stylized eye model that is both scalable (allowing changes in eye size) and deformable (allowing changes in eye shape). The model is based on the geometric equations as functions of measurable ocular dimensions and the updated parameters adopted from recent literature data. We prepared 5 sample eye models: standard, large, small, myopic and hyperopic eye models, with the variation of the size and shape parameters of the eye model. Using these models, we performed the radiation transport calculation with the MC transport code PHITS for mono-energetic beams of electrons, photons, and neutrons in the standard ICRP radiation geometries.

### Results

Electron dose coefficients (DCs) were found to vary with changes to both eye size and shape, while no strong dependence upon eye size or shape was found for photon and neutron dose coefficients. The variation of the electron DCs was due to difference in the depth location of the ocular structures with the size and shape changes against the build-up peak positions of electrons at each energy.

### Conclusions

We confirmed that only a trivial dependence of DCs on the eye size and shape, namely variation of the depth location of the ocular structures, was observed for radiation exposure in the standard ICRP broad radiation geometries. Our next target is to study influence of the variation of the eye size and shape for focused radiotherapy beams in practical situations such as stereotactic x-ray radiotherapy for age-related macular degeneration and ion therapy for uveal melanoma.

## Dosimetry for dose-effects studies at the FIGARO facility

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### Introduction

The FIGARO <sup>60</sup>Co gamma irradiation facility (Lind et al. 2018) at the Norwegian University of Life Sciences (NMBU) is dedicated to the study of effects on living organisms from acute or chronic ionizing radiation exposures, either alone or in combination with other stressors such as UV radiation, metals or radionuclides. Here, we report on our experiences from supporting dose-effect studies at FIGARO with dosimetry, involving the development of a framework of working guidelines and computer software for FIGARO (Hansen et al. 2018).

### Methods

The software includes a Geant4 (<http://geant4.web.cern.ch/>) Monte Carlo radiation transport model of the FIGARO exposure hall and source, along with applications for dose planning (under development) and for dose recording and reporting. The Geant4 model can be updated with the geometries of concrete experimental setups.

### Results

The framework encourages users to devote adequate resources to planning of exposures and calls attention to the type of data that should be recorded so that exposures can be reproduced. Users are also strongly encouraged to present their effects data against whole-system or whole-body absorbed dose rates and accumulated doses, and with information on the type of exposure, in published work. When this information is missing, it is difficult to interpret results from exposures, to compare results with literature data and to put these results into context.

### Conclusions

Several recent publications have pointed out the need for improved dosimetry in radiobiological or radioecological work, including improved reporting of dosimetry in papers. The dosimetry framework for FIGARO aims to give regular and expert users the tools required for adequate planning, recording and reporting of exposures in order to ensure good dosimetry and to make the work reproducible.

### Citations

Ole Christian Lind, Deborah Helen Oughton & Brit Salbu (2018): The NMBU FIGARO low dose irradiation facility, *International Journal of Radiation Biology*, DOI:10.1080/09553002.2018.1516906

Elisabeth Lindbo Hansen, Ole Christian Lind, Deborah Helen Oughton & Brit Salbu (2018): A framework for exposure characterization and gamma dosimetry at the NMBU FIGARO irradiation facility, *International Journal of Radiation Biology*, DOI:10.1080/09553002.2018.1539878

## Monte Carlo vs Pencil Beam – Film Gamma Analysis for Cyberknife® treatment delivery

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### Introduction

*Precision* treatment planning system (TPS), by *Cyberknife®* Accuray™, provides the option of using either a modified Pencil Beam (Ray-Tracing) or a Monte Carlo (MC) algorithm for optimization and final dose calculation.

The purpose of this work was to evaluate the dose implications of Monte Carlo treatment planning and to quantitatively compare the MC dose calculation algorithm with the Ray-Tracing in two different tumor locations with high inhomogeneity interfaces.

### Methods

For each of a simulated lung, paraspinal and mediastinum treatment volume, two treatment plans were created in *Precision* TPS, using Monte Carlo (MC) and modified Pencil Beam (Ray-Tracing) algorithms

We irradiated a *CIRS®* IMRT thorax phantom model 002LFC with a *GafChromic™* EBT3 film on an axial plane.

EBT3 film was scanned with *Epson®* Perfection 800V two hours after irradiation.

A home-made gamma analysis algorithm was created in *MathWorks®* MATLAB R2018a to compare film and TPS dose distribution. A gamma analysis criterion of 2.00 mm DTA 2% Dose 20% threshold was used.

### Results

For lung volume, Ray-Tracing shown 88.25% Area Gamma passing rate, a Maximum Gamma of 2.58 and Average Gamma of 0.65 while MC shown 97.81% Area Gamma passing rate, a Maximum Gamma of 2.26 and Average Gamma of 0.42.

For paraspinal volume, Ray-Tracing shown 96.89% Area Gamma passing rate, a Maximum Gamma of 1.82 and Average Gamma of 0.49 while MC shown a 98.95% Area Gamma passing rate a Maximum Gamma of 1.35 and Average Gamma of 0.42.

For mediastinum volume, Ray-Tracing shown 99.72% Area Gamma passing rate, a Maximum Gamma of 1.23 and Average Gamma of 0.38 while MC shown a 99.57% Area Gamma passing rate a Maximum Gamma of 1.33 and Average Gamma of 0.40.

### Conclusions

In daily practice, patient point dose QA in homogeneous phantom with ionization chamber does not detect the differences in dose distribution. Film dosimetry allow us to see that MC is a more suitable algorithm for dose calculation in high inhomogeneity regions.



## Title: The Role of Lipid Metabolism in Radiation Resistance

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### Introduction

Despite all recent advances in the detection and therapy of cancer, it still remains as the 2<sup>nd</sup> highest cause of deaths all around the world. Radiotherapy (RT) is one of the most important and non-invasive treatment method, commonly used either as primary modality or in conjunction with other treatments. Unfortunately radioresistance and subsequent recurrence in the disease occurs in numerous patients that have received radiotherapy. A small population of cancer cells known as cancer stem cells (CSCs) are responsible for radioresistance in various types of cancer. To date, the mechanism that confers radio-resistance to CSCs is still unclear. In the last years, altered lipid metabolism and lipid droplets (LDs) accumulation have been recognized to have an important role in CSCs tumorigenicity. To this regards, our study aims to understand the LD expression and role in radioresistant breast and lung cancer cells.

### Methods

Radiation clonogenic assays were performed for all cell lines involved in the study: MCF-7 (breast), H460 (lung), H4 (neuro-glioma), PC3 (prostate) and T24 (bladder). The cells were irradiated with a 6MV linear accelerator (LINAC) with a field size of 20cm by 20cm. Reactive oxygen species (ROS) and LDs double staining was performed on the various cancer lines using Nile red and CM-H2CFDA. Fluorescence activated cell sorting (FACS) was used to sort cells into two populations (LD<sup>High</sup> and LD<sup>Low</sup>), to study the impact of lipid metabolism in cancer cells radiation resistance. Gene expression analysis was assessed by real-time PCR using the cDNA obtained from T24, MCF-7, H460, H4 and PC3 for irradiated and non-irradiated cells.

### Results and Conclusions

Our data show that radioresistant cells present a common lipid alteration, specifically an increase in LD contents, representing high lipid metabolism. This upregulation correlates with a CSC phenotype. Interestingly, the highest clonogenic potential was mainly shown by the LD<sup>High</sup> sorted subpopulation.

## DNA damage yields after microbeam irradiation and comparison to MC simulations

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### Introduction

The growing use of hadrons in oncology entails the need to establish more specific dosimetry concepts adapted to their biological efficacy. This requires more information on the likelihood of subcellular effects, mainly DNA damage (double-strand breaks), according to the details of how energy is deposited within cells by ionizing particle tracks. Monte Carlo track structure simulation provides a powerful tool for investigating this relation. However, the reliability of simulation results can only be assessed by comparison with dedicated biological data.

### Methods

Experiments were conducted on a single-ion microbeam. Primary human cells were exposed to  $\alpha$  particles of different energies with respective LETs of about 36, 85 or 170 keV $\cdot\mu\text{m}^{-1}$  at the cells' center position, or to protons (19 keV $\cdot\mu\text{m}^{-1}$ ). Statistical evaluation of nuclear foci formation (53BP1/ $\gamma$ -H2AX) observed by immunofluorescence and related to a particle traversal was undertaken in a large population of cell nuclei. The biological results were adjusted for factors leading to experimental bias and compared with results from Geant4-DNA simulations modeling the ionizing particle interactions on a virtual phantom of the cell nucleus with the same geometry and DNA density as the cells used in the experiments.

### Results

Observed relocation/modification of DNA damage signaling proteins and simulations both show an initial increase of the relative frequency of induction of DNA damage with increasing LET of the projectile. For  $\alpha$  particles of LET ranging from 80-90 to 170 keV $\cdot\mu\text{m}^{-1}$ , a constant DNA damage-induction frequency was found where 10-30% of the particle traversals did not lead to foci formation indicating DNA damage.

### Conclusions

These findings allow studying the relationship between the topology of energy deposition from particles of different LET and early cell damaging, obtaining an accurate estimate of the probability of interactions which induce foci formation after DNA damage.

## Cell survival models: A personalized approach counteracting the establish for EBR

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### Introduction

Nowadays radiotherapy (RT) is recognized as essential for of an effective cancer treatment. In RT, using X-rays, the protocols are based and extrapolated from *in vitro* results obtained from clonogenic assay, the gold standard technique to determine cell reproductive death after treatment with ionizing radiation (IR) is the ability of a single cell to grow into a colony. Considering this, there is a lack of data to adjust the external beam radiotherapy (EBR) protocol according with cancer biologic features. Therefore, the aim of this work is to contribute to personalize EBR therapy based on tissue characteristics, characterizing the X-ray radiation effects on different cell lines from different types of cancer with different embryonic origins and with different biological characteristics and genetic profile.

### Methods

Eight cancer human cell lines were exposed to single-shot doses of IR from 0.5-12Gy. Standards of the International Code of Practice for Dosimetry, TRS-398, published by International Atomic Energy Agency (IAEA) were assumed as references for calibration and dose calculations. Clonogenic assay assesses the capacity of cells to produce colonies and allowed to mathematically modeling cell survival curves. The best fitting model, half lethal dose ( $LD_{50}$ ) and surviving fraction at 2 Gy ( $FS_2$ ), were determined.

### Results

The best fitting model was the linear for the Y79 and MNNG-HOS and the linear quadratic for the other six cell lines (LnCap, PC3, HT1376, OE19, HSC3 and BICR-10).

Table 1 – Parameters determined for the eight human cancer cell lines studied.

Cell line	$\alpha$	$\beta$	$LD_{50}$	$SF_2$
LnCap	0.33	0.046	1.68	0.43
PC3	0.37	-0.015	1.75	0.51
HT1376	0.20	0.0074	3.09	0.65
MNNG-HOS	0.30	-	2.30	0.55
Y79	0.59	-	1.18	0.31
OE19	0.24	0.016	2.47	0.58
HSC3	-0.53	0.38	2.23	0.64
BICR-10	0.24	-0.0078	3.17	0.63

### Conclusions

The major interest in survival curves data is to predict radiation effects on humans. It is important to consider tumor biologic features to adequate survival models from which clinical doses are defined.



## How to set-up a laboratory for advanced preclinical studies of biological effects of ionizing radiation: our experience

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### Introduction

Biological effects of ionizing radiation (IR) are one of the current concerns in scientific community, and there still is a lack of evidence about biological effects of low doses. In addition, there are several limitations being pointed to biological models of study being used. In such context, our group is working on the improvement of preclinical models to be used in the study of biological effects of low doses of IR. This paper aims to disseminate the design and implementation of a laboratory for these advanced preclinical studies.

### Methods

Our laboratory has around 25m<sup>2</sup>, divided in 2 areas - aquaculture and cell culture - dedicated to preclinical studies of IR effects.

3D cell cultures mimic better *in vivo* environments. However, it remains unclear the best techniques to use, reason why we are working on the optimization of our models (e.g.: alginate encapsulation, culture of spheroids in agar/agarose and/or under rotation).

On other hand, Zebrafish small size significantly reduces costs and space required, being the researchers able to create their own flexible system, which is what we did.

### Results

It is primarily aimed to share all the process of planning and implementation of our lab and all challenges involved. In addition, some results of preliminary experiments could be cited: i) correlation between cellular effects and cell culture techniques used, being identified an acute tendency for decrease in proliferation rate that is recovered shortly after; ii) direct correlation between zebrafish' offspring DNA damage and radiation dose, differential responses in damage biomarkers by males and females, and different protein expression levels.

### Conclusions

The optimization of our new laboratory, along with the knowledge and experience acquired by the involved team, should enable future investigations in Radiobiology to study complex effects and phenomena such as bystander or other complex interactions, using our advanced models.

## Dicentric chromosome assay as a tool for biodosimetry in the treatment of high risk neuroblastoma $^{131}\text{I}$ -mIBG in children

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### Introduction

The aims of this study were to estimate the whole-body absorbed dose (WBD) for patients treated with  $^{131}\text{I}$  - metaiodobenzylguanidine for neuroblastoma with the Dicentric Chromosome Assay (DCA) and to assess the correlation between biological and physical dosimetric methodologies.

### Methods

Three children with relapsed high-risk neuroblastoma were treated to a prescribed whole-body absorbed dose of 4 Gy delivered over two administrations. The first administration (ranging in activity from 8980 MBq to 14345 MBq) was used as a *tracer* in order to calculate the activity needed in a second infusion (8521 MBq – 12997 MBq) to achieve the prescribed dose. Equivalent dose-rate measurements were taken every few hours at a fixed position two meters away from the patient in order to calculate the retained activity and to apply the MIRD procedure. To assess toxicity in bone marrow, blood samples were also drawn every 2-to-3 days. Blood samples were obtained previously and seven days after first infusion allowing to obtain an estimate of WBD due to the first infusion using biodosimetry.

### Results

Whole-body absorbed dose one week after the first administration was estimated with MIRD procedure to be 1.45 (1.03-1.87) Gy, 1.33 (0.98-1.68) Gy and 0.87 (0.65-1.10) Gy for the three patients. On the other hand, DCA obtained corresponding doses of 2.24 (1.44-2.85) Gy, 1.71 (0.79-2.28) Gy and 1.96 (1.00-2.54) Gy. All patients developed thrombocytopenia grade 3 after both infusions and neutropenia grade 3 and grade 4 (based on Common Terminology Criteria for Adverse Events - CTCAE 4.0) during respective phases one month after treatment.

### Conclusions

Our study reports the estimation of WBD for children with relapsed neuroblastoma treated by  $^{131}\text{I}$ -mIBG by means of the DCA and the MIRD protocols. For high-risk neuroblastoma treated with  $^{131}\text{I}$ -mIBG, the number of studies related to biodosimetry applied to targeted radionuclide therapy is relatively small. We consider that refinement and a larger cohort of the DCA are needed to define the role of biodosimetry in clinical situations. Further comparisons between image-based (SPECT) dosimetry and biodosimetry obtained with DCA and the correlation of these magnitudes to blood toxicity and tumor response, would allow the optimization of  $^{131}\text{I}$ -mIBG treatment for neuroblastoma.

## Assessment of the Energy Deposited and Biological Damage Induced by DNA-targeted $^{99m}\text{Tc}$ -complexes

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### Introduction

Recently, it has been shown that the *in vitro* DNA damage caused by a new family of  $^{99m}\text{Tc}$ (I)-tricarbonyl complexes, bearing an acridine orange (AO) DNA targeting unit, is strongly dependent on the length of the linker between the Auger emitter ( $^{99m}\text{Tc}$ ) and the AO moiety. Among them,  $^{99m}\text{Tc-C}_3$  places the radionuclide at appropriate distance to DNA and produces important double strand breaks (DSB) yields in plasmid DNA, showing that  $^{99m}\text{Tc}$  can efficiently induce DNA damage. Here in, the studies were extended to human cancer cells, and the early and late biological effects in PC3 prostate cancer cells were quantified for two of these  $^{99m}\text{Tc}$ -complexes,  $^{99m}\text{Tc-C}_3$  and  $^{99m}\text{Tc-C}_5$ , which place the  $^{99m}\text{Tc}$  atom at a distance of 10 and 12 Angstrom from the central axis of DNA, respectively.

### Methods

PC3 cells were incubated with several activities of  $^{99m}\text{Tc-C}_3$  and  $^{99m}\text{Tc-C}_5$  for 24 h at 37 °C. Their capacity to associate and/or to enter the PC3 cells and nucleus was evaluated by quantitative gamma-counting measurements. The ability to induce *in vivo* DSBs was assessed using the  $\gamma$ -H2AX assay. The late biological effects were studied using the micronuclei and clonogenic assays. A cellular dosimetric study was made by using both MIRD formalism and MCNP6 Monte Carlo simulations, aiming at determining the cytoplasm and nuclei doses of  $^{99m}\text{Tc-C}_3$  and  $^{99m}\text{Tc-C}_5$ .

### Results

The results show a significantly decrease of the early biological effects induced by  $^{99m}\text{Tc-C}_5$  when compared with  $^{99m}\text{Tc-C}_3$ . Also the number of micronuclei and survival fractions reveal a decrease on the late biological effects induced by  $^{99m}\text{Tc-C}_5$ . A comparison with the two-calculation methods (MC and MIRD) showed a difference of the energy deposited, both in the nucleus and in cytoplasm, of about one order of magnitude.

### Conclusions

The results herein obtained suggest that the Auger-electrons play a crucial role on the radiation-induced biological effects, which are strongly dependent on the  $^{99m}\text{Tc}$ -DNA distance.



## Study of scintillating fibers response to low energy protons

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**Introduction:** The range uncertainty in proton therapy (PT) adds an additional degree of freedom to treatment planning. Uncertainties in the exact position of the distal dose arise from organ motion, setup and anatomical variations, dose measurements, and biological effects. Reducing these uncertainties allows a better use of the advantages of protons, minimizing their risks [1]. For measurements of proton depth-dose distributions, the gold standard is the use of plane-parallel ionization chambers (PPIC) [2]. A fundamental requirement for PT dosimetry is that these detectors have a very good spatial resolution. With PPIC this is of the order of few mm. In this work, we present a study of scintillating fibers response to protons with the goal of developing a fiber-based system for PT dosimetry. Such a system can, in principle, achieve sub-mm resolutions.

**Methods:** PSF (Plastic scintillating fibers) from Kuraray will be tested for scintillation response in the Bragg peak energy range. A setup has been designed to allow the scanning of the proton energy impinging on a single fiber through proton energy loss in air. First tests will be performed with 2 MeV protons at the C<sup>2</sup>TN/IST (Lisbon) facilities. Fibers with sub-mm diameter will be coupled to a PMT read by an electrometer.

**Results:** It is known that for high-LET (that is, in the Bragg peak region) fields scintillating fibers exhibit a saturation of the light yield, due to the increased number of excited molecules along the track that cannot be resolved. We will address this quenching effect for these specific fibers using Monte Carlo simulations. The energy deposited along the fibers will be simulated using the code FLUKA [3] and the code pMC developed within the group, and compared with the measured results.

**Conclusions:** Comparisons with recent results with doped optical fibers [4] will be performed. These results show promising results for the future design of more complex spatially resolved beam monitoring and QA systems.

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Study of Acuros XB algorithm performance with an extended CT density range

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Introduction

Varian Acuros XB algorithm is based on the solution of the linear Boltzmann transport equation. This algorithm improves calculation accuracy in heterogeneous media, especially when high density materials are present, such as metal implants.

This work addresses the calculation differences between Acuros XB 13.6 using two CT configurations: 16 bits depth one leading to an extended CT density range and 12 bits depth saturating at 3071 HU. The use of an extended CT density range allows the use of realistic HU estimates when metal implants are present. AAA 13.6 calculations were also analyzed.

Methods

A Philips Brilliant Big Bore CT scanner has been used to scan phantoms with different inserts mimicking different metal implants. Different image sets were acquired, both, with 12 bits and 16 bits reconstruction enabled. Head and Neck VMAT and conformal plans were prepared and optimized in Varian Eclipse TPS. Coverage and dose figures of merit were assessed, and DVH curves compared between different experimental setups.

Results

Reporting dose to water in Acuros XB, results show, for our standard two full arcs VMAT Head and Neck plan. As an illustration, the following results (PTV60) were found for Ti dental implants (insert) along the mandible:

	Maximum dose (%)	Mean dose (%)
12 bits	111.0	84.9
16 bits	138.2	97.3

Conclusions

The results of this study show that using Acuros XB with both CT configurations lead to statistically significant differences between 12 bits and 16 bits depth configurations (Student's T test,  $p = 0.05$ ). The use of an extended HU range density helps to assess PTV coverage and surrounding OAR's doses when metal objects are present. The need for accurate computation when metal implants are present is essential in order to obtain properly optimized dose distributions. Extended range of HU helps achieve this aim.

The use of AAA algorithm also leads to differences but not as pronounced as with Acuros XB, the use of an extended CT range would also be advisable.

## Dose Evaluation of Head Computed Tomography Scans Using a Male Anthropomorphic Phantom

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### Introduction

The Computed Tomography (CT) has been one of the most used exam for radiologic diagnostic in medicine. The increase of CT is a global concern due to high doses of radiation. The head CT scans helps to diagnose disorders that affect the brain, including tumors, infarction, bleeding within the brain, hematoma and other diseases. The aim of this work is to reduce the absorbed dose in the head CT scan with the use of bismuth shielding and with the head tilted.

### Methods

A anthropomorphic male phantom model Hamley Atom were used to do a head CT scan, from the cervical vertebra C1 to the top of skull, using an Toshiba CT scanner, Prime Aquillion model with 80 channels. Radiochromic films strips were used to evaluate the doses in the organs such as lenses, thyroid, hypophysis, spinal cord, breasts, salivary and parotid glands. Were conducted three heads CT scan using the same protocol, with the phantom in supine position with and without bismuth shielding and in supine with the head tilted without the bismuth shielding.

### Results

The results of this experiment show absorbed doses from 1.16 to 47.16 mGy. The highest dose of 47.16 mGy were in the lenses without bismuth shielding and with bismuth shielding were 33.01 mGy. Also, the dose with the head tilted were 20.42 mGy. Record doses were lower with the head tilted for all organs, mainly in the lenses. The analysis of noise in the image of the head central slice presented acceptable values for soft tissues, less than 1%.

### Conclusions

Dose values were significantly reduced and they suggested that the use of bismuth shielding or the head tilted would be, in some cases, a proper procedure for protection as the conditions used for all scans were the same.

## Estimation of the collective dose in the Portuguese population due to radiodiagnostic and nuclear medicine exams

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There has been an increasing use of ionizing radiation in medical procedures in the last decades which have led to a rise in the collective dose in the population.

This work studied the exposure of the Portuguese population to ionizing radiation due to radiodiagnostic and nuclear medicine exams, using a well-established methodology. In order to determine the total collective effective dose and per caput dose due to nuclear medicine exams, a survey to 39 nuclear medicine centers was undertaken. The estimated total collective dose due to nuclear medicine exams was of 0.088 mSv per person in 2013 and 0.090 mSv per person in 2017. In the case of radiodiagnostic exams a survey was undertaken to the 5 Health Regional Administrations (ARSs) concerning the top 20 radiodiagnostic exams which account for 75-90 % of the total effective dose due to these exams, and a survey to the National Health Service Hospital system is underway. The estimated average annual effective dose of the population due to radiodiagnostic exams was 0.79 mSv per person in 2013 and 0.91 mSv per person in 2017.

The obtained results will provide input to the NRD Portugal project, which will establish National Diagnostic Reference Levels (DRLs) in Portugal for the first time. This work stresses the importance of performing the estimation of the collective dose due to medical exams on a periodic basis.



## Estimation of External Contamination and Exposure Rates Due to Fission Product Release

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### Introduction

The release of fission products with ensuing external contamination presents a challenge for triage assessment by emergency response personnel. Reference data for exposure rate and skin absorbed dose rate coefficients were computed for photon-emitting fission products that externally deposit on a receptor.

### Methods

To determine fission products of concern, a radionuclide inventory was generated modeling a pressurized water reactor following 3 burn-up cycles and final decay times a 30-day period. Simplified mathematical skin phantoms were created using surface area and height specifications from International Commission on Radiological Protection Publication 89. Simulations were conducted using Monte Carlo N-Particle 6.1 radiation transport code using newborn, 1-, 5-, 10-, 15-year-old, and adult phantoms. Skin contamination was simulated as a 1 $\mu$ m thick homogeneous deposition layer for 22 photon-emitting radionuclides. Skin dose and exposure rate coefficients were computed at 2-in., 1-, 2-, and 3-ft. distances from the midline of each phantom.

### Results

Assuming the exposure rate from a nuclide at 1 ft., 1.74 $\times 10^6$  Bq of <sup>140</sup>Ba produces 10 mR/hr at 1 ft. for the adult male, which produces a skin exposure rate of 18 mrem/hr. For <sup>137</sup>Cs/<sup>137m</sup>Ba, 5.19 $\times 10^5$  Bq produces 10 mR/hr at 1 ft., with a skin exposure rate of 5 mrem/hr. For <sup>131</sup>I, 8.15 $\times 10^5$  Bq produces 10 mR/hr at 1 ft., with a skin exposure rate of 8 mrem/hr. For these 3 radionuclides, the exposure rate in mR/hr at 1 ft. compares within a factor of ~2 to the skin dose rate in mrem/hr.

### Conclusions

The 22 considered radionuclides represent > 50% of the fission product inventory at > 5 days post-reactor shutdown. Skin dose was dominated by electron (beta) emissions though photon contributions determined exposure rate coefficients. This data provides reference coefficients to be used with release/deposition fractions and specific fission product inventories to determine dose/exposure rates for emergency response.

## Screening approach for $\gamma$ -spectrometry in nuclear and radiological emergencies using a Monte Carlo model of a BEGe detector

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### Introduction

In the frame of accidents in nuclear and radioactive facilities, actual regulations inquire adapting environmental radiological surveillance to contemplate emergency situations. In this frame, the Laboratorio de Radiactividad Ambiental (LRA) of the Universitat Politècnica de València (UPV) is developing logistic procedures of  $\gamma$ -spectrometry with semiconductor detectors for the characterization of high activity samples.

### Methods

One of the problems when measuring such high activities is the fact that the detector could be saturated. It is possible to calculate the allowed counting rate for a given conditions, setting a maximum dead time and knowing the resolution time of the detector. The counting rate could be controlled by varying the sample-to-detector distance as well as by using different measuring geometries. In this frame, a Monte Carlo model of a BEGe detector is performed to analyze the system efficiency response for several measurement configurations. The BEGe crystal has been characterized through the SALSA method (Salamanca Lyso-based Scanning Array).

### Results

The efficiency curve for all the possible configurations is obtained using a Monte Carlo code for an energy range between 59.5 and 1836 keV. The simulations have permitted to estimate the admissible sample activity for some geometries (petri boxes and Marinelli beaker), matrices (water, sands, soils, etc) and sample-to-detector distances to avoid the detector saturation. Results leads to achieve a compromise between geometry, distance and measuring time for a certain conditions in emergency situations.

### Conclusions

The Monte Carlo method allows knowing if the sample needs some pretreatment and the optimal configuration of measurement. Therefore, the response time of the laboratory as well as the risk of contamination would decrease.

## CALIBRATION OF A SPECT/CT GAMMA CAMERA WITH CHILD AND ADULT THYROID-NECK PHANTOMS FOR IN VIVO MONITORING OF EXPOSED POPULATION IN CASE OF NUCLEAR EMERGENCY

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### Introduction

The need for quantifying the uptake of  $^{131}\text{I}$  in thyroid of exposed population and workers in nuclear or radiological emergencies is one of the main concerns to take into account. Due to the high volatility and rapid intake of  $^{131}\text{I}$ , it is very important a rapid identification of exposed individuals to know their level of internal contamination from the estimation of the committed effective dose, in order to establish action protocols and countermeasures. Gamma cameras locate at nuclear medicine services could be used as an alternative method in order to provide support in the emergencies response. This work describes a methodology to calibrate this kind of equipment using anthropometric neck phantoms for the measurement of  $^{131}\text{I}$  in the thyroid of exposed population.

### Methods

A dual-headed gamma camera without collimator was calibrated taking into account that a realistic geometry ( $d=10$  cm GC-phantom distance) and a rapid screening ( $T_c=300$  s) of individuals is necessary in early response. Calibration phantoms consist of a set of Thyroid Neck phantoms for children (1, 5, 10 and 15 years old) designed according to ICRP89 recommendations and, and in case of adults, a thyroid neck phantom following specifications of the ANSI n13.44 standard. Thyroid glands were simulated using cylindrical vials filled with a homogeneously distributed liquid solution of  $^{133}\text{Ba}$  and  $^{137}\text{Cs}$  as a surrogate of  $^{131}\text{I}$ .

### Results

The calibration factors obtained for  $^{131}\text{I}$  vary with thyroid size being in the range of 0,0459 to 0,0541 cps·Bq $^{-1}$ . The MDA also varies with the thyroid size of the phantoms (from 67 to 79 Bq). Validation of the methodology has been carried out by participating in an international intercomparison exercise (CATHYMARA project, EC-OPERRA 2016-2017) for the  $^{131}\text{I}$  thyroid measurement to the exposed population in emergencies. An estimation of minimum detectable effective dose for children (E(70)) and adults (E(50)) has been carried out assuming a scenario of acute inhalation of  $^{131}\text{I}$  by members of the public. Results obtained allow estimating doses far below 1 mSv three days after the intake.

### Conclusions

A calibration methodology has been developed for the in vivo measurement of  $^{131}\text{I}$  in the thyroid of exposed population using gamma cameras in case of nuclear emergency. The usage of different calibration phantoms for adults and children allows a greater reliability in the calculation of  $^{131}\text{I}$  activity in thyroid, improving the response in the early stage of the accident. Results obtained are in good agreement with other publications on this matter. Therefore this methodology may be used not only in emergency scenarios but also in triage monitoring programmes of exposed workers for screening purposes and may be also extended to others Nuclear Medicine Centers in Spain.

## Uncertainty evaluation of organ dose reconstruction with optically stimulated luminescence on mobile phone resistors after a radiological incident

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### Introduction

During a radiological incident or terrorist attack citizens can be exposed to high doses. Rapid dose assessment is then needed to identify people requiring treatment. Optically stimulated luminescence (OSL) on mobile phone resistors is very promising in this context. Previous studies showed good dosimetric properties and dose reconstruction protocols were optimized in the MULTIBIDOSE project.

In this work it was investigated how different factors influence the dose reconstruction, how one can correct for these and how much they contribute to the uncertainty. The investigated factors include calibration, zero dose signal, reproducibility, dose response, fading, red light exposure, storage temperature, energy response and conversion from resistor dose to organ doses.

### Methods

Accident scenarios with increasing complexity were setup to investigate above mentioned factors. In the final scenario a Rando Alderson anthropomorphic phantom equipped with thermoluminescent detectors, for assessing the reference organ doses, and with mobile phones at different positions was irradiated with a small <sup>137</sup>Cs source at 1.5 m. Dose reconstruction was performed after 1 week. Most conversion factors from resistor to organ doses were available from previous work, factors specific for the last scenario were assessed by MCNPX simulations.

### Results

Uncertainty and detection limit were found to depend strongly on dose level, delay and accident scenario. For typical scenarios, detection limits of 50 and 70 mGy were found for delays of respectively 1 day and 1 week. For doses around the detection limit the zero dose signal dominates the uncertainty, while for higher doses fading and conversion from resistor to organ doses are dominant giving uncertainties about 44% ( $k=2$ ). For mono-directional exposure and unknown phone position uncertainties can increase to about 110% ( $k=2$ ).

### Conclusions

The found detection limits and uncertainties are acceptable for accident dosimetry.

## **Dosimetry in the light of the development of dosimetric quantities - more art than science?**

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### **Introduction**

The long development of dosimetric quantities and units, originally motivated by the need to measure the amount of radiation emitted by medical X-rays, has led to the gradual modification and refinement of definitions since the founding of the ICRU in 1925. Gradually, an ever more complex and detailed system of quantities and units was created, up to the current ICRU 85 recommendation.

### **Methods**

The paper compares the various sequentially modified systems in terms of their suitability and usability in the field of dosimetry for radiation protection. At the same time, it considers the possibilities of measuring these variables and their uncertainties in terms of interpretation for limitation of radiation load and development of methods of personal dosimetry and interpretation of measured values.

### **Results**

The main milestones in this development are highlighted and their contribution to the current radiation protection practice has been evaluated. On the other hand, it should be noted that some recommendations made the situation more complicated without significant practical benefits.

### **Conclusions**

If we evaluate current radiation protection dosimetry practice, including dosimetric methods and instrumentation, it is possible to say that we are still far from satisfactory situation, and we are working on estimates rather than on realistic values. The question of where to go is in the light of existing practice and needs open.

## EURADOS Neutron Personal Dosimeter Intercomparisons: Overview, and history, differences between 2012 and 2017

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### Introduction

EURADOS has run a series of b/g personal dosimeter intercomparisons, but ran its first neutron dosimeter intercomparison in 2012 (IC2012n). That intercomparison provided a rare opportunity to see how neutron dosimeters perform: the results showed some relatively large biases. 31 Individual Monitoring Services (IMS) entered 34 dosimetry systems in IC2012n. The high level of interest and variable results led EURADOS to conduct a repeat exercise. The lessons learned from IC2012n are discussed and related to how IC2017n has been performed.

### Methods

IC2012n: dosimeters were exposed on ISO water-filled slab phantoms using bare & moderated <sup>252</sup>Cf sources and a 250 keV field. Strict procedures were put in place to ensure that the participating IMSs could not know in advance the doses received nor the fields used. However, some dosimetry systems required pre-information on the field, so IMSs could choose to modify their results when the fields were categorized by hardness. IC2017n has used a slightly different set of fields, with no monoenergetic neutrons, <sup>241</sup>Am-Be and a mixed n/g field being used. A tailored online platform was used for the management of the intercomparison.

### Results

Some large biases were recorded, mainly underestimates, especially for the 250 keV monoenergetic field. When the results of IC2012n were analyzed, there were no applicable performance standards for neutron personal dosimeters, but since then ISO14146:2018 updated the previous version, including neutron dosimetry and ISO 21909 was updated. Such opportunity was a general agreed need highlighted by IC2012n. Now results can be reviewed according to performance criteria given in international standards.

### Conclusions

There is a demonstrated need for neutron personal dosimeter intercomparisons. Evaluation of the results is aided by the availability of performance standards for neutron personal dosimeters. Results are still inconsistent, and systems can rely heavily on “pre-information”. Because of the diverse dosimeter types, some of which have restricted fields of application, structuring the intercomparison requires careful consideration.

## Study on thermoluminescence properties of commercial glasses used in Bangladeshi dwellings for accidental dosimetry

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### Introduction

Commercial glasses used in Bangladeshi dwellings were analyzed by the thermoluminescent (TL) technique, to verify the prospect of their use as dosimeters for measurements of accidental radiation exposures, due to their easy handling, low cost and moisture protection. Therefore, the investigated samples were studied in terms of their dosimetric characteristics: energy and dose response, glow curve and reproducibility in typical irradiation procedures.

### Methods

All the powdered glass samples and TLD-100 were annealed for a period of 1 hour and irradiations were made using X-ray and gamma beams, from an ERESO 200 MF4 and a conventional Gamma cell-220 <sup>60</sup>Co respectively. X-ray mean photon energies from 20 keV to 185 keV and gamma dose of range 10 Gy to 50 Gy were used in this study. The sample TL measurements have been carried out using a Harshaw 3500 TLD reader (USA) supported by WinREMS software. The TLD reader was set up as following the preheat temperature of 50 °C, heating rate of 10 °C.s<sup>-1</sup> and maximum temperature for data acquisition of 400 °C.

### Results

The glasses under this study showed linear TL response with gamma dose range 10 Gy to 50 Gy, glow peaks were between 150° C and 300° C. In energy range 20 keV to 120keV the TL response of the investigated glasses partially followed the trend of TLD-100. Reproducibility of TL response was estimated to have a maximum variation of 5.0%. The fading rate of the glass response at room temperature is small.

### Conclusions

These results demonstrate the potential use of commercial glass as TL dosimeters to determine radiation dose (for 'retrospective' case) following catastrophic, large-scale radiological events.





## GeB Flat Fibre TL dosimeters for *in-vivo* measurements in radiosurgery

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### Abstract

Noting a rising demand for procedures involving clinical radiosurgery we seek to develop a high spatial resolution thermoluminescence dosimeter (TLD) to allow conduct of *in vivo* dose verification measurements. An associated need is for a dynamic dose range exceeding that of the well-established LiF (Mg,Ti) phosphor TLD-100, the latter being limited in particular at the elevated doses seen in radiotherapy. The work investigates the performance of a novel GeB co-doped Flat Fiber (GeB-FF) fabricated using the modified chemical vapour deposition (MCVD) process, the hollow capillary optical fibres (COF) produced from this being collapsed down into flat fibres (FF) to create strain-related defects. This process has already been demonstrated to increase the low dose sensitivity of optical fibres, notably at diagnostic x-ray potentials, with Minimum Detectable Dose (MDD) values of down to 0.1  $\mu\text{Gy}$  [1]. The intent of present work has been to examine and compare the performance of the two forms of TL dosimeter, GeB-FF and TLD-100, measuring scattered radiation resulting from cranial cavity radiosurgery procedures. The dosimeters were placed on the neck, chest and pelvis of fourteen patients. Using both types of dosimeter, raw dose values at each site show general accord ( $\pm 3$  mGy at  $1\sigma$ ), covering mean doses ranging from some 10 mGy to less than 1 mGy, representing doses of  $< 1\%$  to  $< 0.1\%$  of prescribed dose at the treatment site. While GeB-FF results uncorrected for energy response show absorbed doses greater than that using TLD-100, by factors of some 1.5, 1.3 and 1.4 for the pelvis, chest and neck respectively, energy corrections provide for the expected closer agreement.

[1] Amjad Alyahyawi et al. (2018). Appl. Radiat. Isot. 138, 45-49.

## Maximum dose to the thyroid organ assessment with APD Unfors EDD-30 in mammography screening examinations

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### Introduction:

We characterized the active personal dosimeter EDD-30 (dose and dose rate linearity, energy dependency, reproducibility and angular dependency) and used it in the assessment of the maximum equivalent dose to the thyroid organ ( $H_T$ ) in patients submitted to mammography screening examinations.

### Methods:

Set up for characterization: two UNFORS dosimeters (reference  $^{40}\text{K}$  detector and EDD-30), set together on the surface of a Perspex phantom irradiated with the x-ray beam of a mobile and mammography units. Set up for  $H_T$  assessment: EDD-30 readings,  $R$  obtained in AOP-STANDARD mode using the EDD-30 in the surface of NM thyroid phantom placed on top of the trunk of the anthropomorphic phantom Alderson-RANDO and using CIRS BR12 slabs (50% glandularity) to simulate compressed breast thicknesses ( $t$ ) in range 20-80mm; Geometry: cranium caudal (CC) view; Mean incident air kerma at the entrance surface of the neck in the thyroid location, is given by  $K_a$  ( $F_a$  are correction factors and  $J$  converts  $H_p(10)$  to incident air kerma); Mean incident air kerma in thyroid organ,  $K_T$ , obtained using  $K_a$ ,  $x=0,8\text{cm}$ ,  $\mu_{\text{PMMA}}$  - linear attenuation coefficient of PMMA for scattered beam energy. To obtain the maximum equivalent dose to the thyroid organ,  $H_T$  in a screening exam, we considered the approximations:  $\geq$  ; Medio-lateral-oblique (MLO) view with the same  $H_T$  and 10% increase in mean glandular dose (MGD), relative to CC view.

### Results:

EDD-30 is linear in the dose rates interval 13 mSv/h - 2.0 Sv/h with relative response,  $r = 1.22 \pm 6\%$  ( $k=2$ ). Energy response and angle dependence are in accordance with manufacturer data,  $r \approx 1.2$  in the energy range 28-40 keV;  $r \approx 0.8$  for angles above 60 degrees. Maximum equivalent dose in thyroid for a CC view:  $H_T^{\text{CC}}$  range 0.17 – 3.87  $\mu\text{Gy}$ ; ( $H_T^{\text{CC}}/\text{mAs}$ ) range: 0.006–0.024  $\mu\text{Gy}/\text{mAs}$ ; For the bilateral exam,  $H_T$  normalized to the mean glandular dose ( $H_T/\text{MGD}$ ) range: 0.02-0.11%.

### Conclusions

We reproduced the results obtained by Monte Carlo Simulation, and TLD readings. Thyroid organ dose for a mammography screening examination of an average breast ( $t=55\text{mm}$ ) is very low (3.3  $\mu\text{Gy}$ ) corresponding to approximately 30 minutes of exposure to natural radiation. No thyroid protection is recommended.

## Dosimetry of Testicular Dose Measurements in Radiotherapy: A Study Using Thermoluminescent Dosimeter and Optically Stimulated Luminescent Dosimeter

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### Introduction

In radiotherapy for rectal cancer, control of the testicular dose for young patients is important, since exposure of the testis could lead to temporary or permanent infertility. Although the testis is located out of the treatment field for patients receiving radiotherapy, the testis is inevitably exposed to scattered radiation resulting from the interaction between primary beams and patients and collimators. In this study, the dosimeters were used to measure the testicular dose with and without a testicular shielding to verify the effect of shielding.

### Methods

The anthropomorphic phantoms representing a human were used to estimate the doses absorbed in testicular and total body studies. The anthropomorphic phantom was irradiated according to the treatment protocol of rectal cancer. Measurements were made using a thermoluminescent dosimeter (TLD, composed of lithium fluoride) and a optically stimulated luminescent dosimeter (OSLD, composed of carbon-doped aluminum oxide) having characteristics suitable for radiotherapy dosimetry studies. The both dosimeters were used to measure the testicular dose with and without a testicular shielding. A set of TLDs and OSLDs were placed in small plastic bags and then attached to different organs of the model. Both dosimeters were also placed surround the shielding to estimate scatter dose. Before and after irradiation the TLDs and OSLDs were placed in a 2.5-cm-thick lead container to prevent exposure from occasional sources. The doses absorbed by each organ were calculated by averaging the values obtained for each corresponding TLD and OSLD. These values were used to evaluate the effective dose (ED) following guidelines described in ICRP report number 103.

### Results

The testicular dose was about 57~83 cGy when a dose of 4500 cGy was given to the whole pelvic. The testicular dose was reduced to 32~48 cGy when the testicular shielding was used.

### Conclusions

For patients of reproductive age, the use of testicular shielding is still necessary.

## Assessing personnel doses induced by the veterinary X-ray diagnostic inspections in Taiwan

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### Introduction

The number of veterinary hospital is growing rapidly in recent two decades in Taiwan. Due to the helper, usually the pet breeder or assistant in the veterinary hospital, usually needs to accompany the pet inside the X-ray room during the X-ray inspection in most cases, the helper in the X-ray room is also exposed to the scattered X-ray radiation. The purpose of this study is to investigate the exposed doses of the helpers inside the X-ray inspection room during veterinary diagnostic inspection procedures, and also investigates the characteristics such as radiation leakage and the total filtration of X-ray tubes.

### Methods

A plastic scintillation survey meter (Atomtex AT1121) was used to measure the doses at the position of the helper stand in the X-ray room and also used to measure the leakage of X-ray tube. Besides, the pen dosimeters with different thickness of Al shielding rings were used to assess the total filtration of X-ray tubes.

### Results

Over 250 veterinary hospitals were inspected on-site in this study. By means of setting the survey meter at the position of the helper's body which is assumed at a distance of 50 cm from X-ray field center, and considering the conditions of wearing with/without lead apron respectively, the ambient dose is measured by the survey meter and then transfer into effective dose by considering the conversion factors. The effective doses at the helper's positions in cases of without wearing lead apron during the x-ray inspection are in the range of  $2.49 \times 10^{-1} - 1.35 \mu Sv$  per animal care, and the effective dose with lead apron are in the range of  $4.0 \times 10^{-8} - 3.8 \times 10^{-2} \mu Sv$ .

### Conclusions

In addition to assess the doses of the helper, this study also indicated the results of qualities of diagnostic X-ray equipment used in veterinary in Taiwan.

## Dose evaluation in patients submitted to chronic thrombo-embolic pulmonary hypertension treatment with Balloon Pulmonary Angioplasty

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### Introduction

Balloon pulmonary angioplasty (BPA) is an option for treating patients with inoperable or residual/persistent post-surgery chronic thrombo-embolic pulmonary hypertension (CTEPH). This interventional therapeutic is a complex procedure, which increases the radiation exposure. The purpose of this study was to evaluate the patient Dose Area Product (DAP), Fluoroscopy Time (FT) and Peak Skin Dose (PSD) in the diagnosis and treatment of BPA.

### Methods

Eight patients with complete treatment (total of 38 BPA sessions), were included in the study. All patients were submitted to right heart catheterisation (RHC) and diagnostic pulmonary angiography (DPA) before BPA treatment. Patient's demographic data were collected. PSD was estimated according to Guidelines for Patient Radiation Dose Management method. The suggested trigger levels from SIR and CIRSE guidelines (PSD>3 Gy, DAP>500 Gy·cm<sup>2</sup> and FT>60 minutes) were compared with the values of the patients included in the study.

### Results

The mean number of sessions per patient was 4.8 (range 2 – 8). The calculated mean values for DAP and FT were 1150.0±532.5 Gy.cm<sup>2</sup> and 290.9±138.3 min per patient (including RHC, DPA and BPA), respectively. It was verified that 4 patients exceeded DAP and 3 patients exceeded PSD trigger levels, considering the procedures RHC and DPA. For the 33 treatment sessions with DAP values higher than 50 Gy.cm<sup>2</sup>, the PSD mean value was 1.08±0.36 Gy. FT was greater than 60 min in 42% of the 38 treatments.

### Conclusions

Since this technique was recently implemented in the institution, professionals are still optimizing protocols in order to reduce exposure doses without impairing image quality. Although no acute radiation induced dermatitis was observed, a longer follow up time is required in order to detect skin injuries, suggesting the implementation of an institutional trigger level from which a follow-up should be made. A data base with patient dose reports should also be implemented for optimization purposes.

## Optical absorbance analyses of PVA-GTA based Fricke gel dosimeters

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### Introduction

The recent development of Fricke gel dosimeters (FGs) based on poly(vinyl alcohol) (PVA) and glutaraldehyde (GTA) enabled a significant improvement in the stability over time of the spatial radiation dose patterns. In PVA-GTA crosslinking reaction kinetics, possible effects of temperature and pH on the degree of cross-linking may occur. Aim of this study is to test if such effects have consequences also on the dosimetric properties of these systems. Therefore, possible variations in the dose-response and  $\text{Fe}^{3+}$  diffusion rate of PVA-GTA-FGs prepared using different amounts of sulfuric acid (SA) and different gelation temperatures (GT) were investigated.

### Methods

FGs with PVA and GTA concentrations of 9.1% w/w and 26.5mM, respectively, were prepared using different amounts of SA (18-100mM) and gelation temperatures from 6°C to 42°C. FGs in spectrophotometry cuvettes were uniformly irradiated with a  $^{137}\text{Cs}$  source.

FGs in form of layers were irradiated with a steep dose gradient. Light transmittance images of these layers were acquired at regular intervals up to 6 hours post-irradiation in order to derive the  $\text{Fe}^{3+}$  diffusion coefficient.

### Results

The results demonstrated that the amount of SA determines both the sensitivity of the PVA-GTA-FGs to dose, and the interval of dose response linearity. Although effects of temperature and pH on the degree of PVA-GTA cross-linking may occur, no significant consequences on diffusion properties of PVA polymer network were observed. Indeed, ferric ions diffusion rates measured in all investigated samples were found to be very similar and less than half of those achievable in FGs prepared with gelatin and agarose, confirming the higher stability of PVA over traditional gel matrices.

### Conclusions

These characteristics, together with the independence of the dose response curve of the PVA-GTA-FGs of the gelation temperature over a wide temperature range, supports the potential of these gels for the manufacture of large phantoms for 3D-dose mapping.

## National survey of radiation dose in computed tomography in Taiwan: a distribution from 2009 to 2018

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**Introduction:** Radiation dose of computed tomography (CT) examinations in diagnostic radiology contributes primarily to medical exposure. There are four times of the survey since 2009 to 2018 (round 1: 2009-2011; round 2: 2012-2013; round 3: 2014-2016; round 4: 2017-2018). The dose distribution of single-detector row CT (SDCT) and multi-detector row CT (MDCT) can be investigated continuously with a national survey. The purpose of our study is to investigate the long-term distribution of radiation dose for diagnostic CT scanners in Taiwan.

**Methods:** The CT radiation dose were conducted with an on-site measurement for each CT scanner in diagnostic radiology for all the hospital. Typical practices, *i.e.* adult head and abdomen protocols, for the four surveys have been characterized by mean values of the standard dose indices volume CT dose index ( $CTDI_{vol}$ ).

**Results:** There was 35.2% of SDCT and 67.5% of MDCT of the round 1 survey. The  $CTDI_{vol}$  was  $57.3 \pm 22.1$  mGy of adult head protocol and  $15.5 \pm 7.0$  mGy of adult abdomen protocol. An increase of MDCT scanners was observed from round 2 to round 4. MDCT scanners are about 98% of round 4. The mean  $CTDI_{vol}$  values of adult head protocol are  $57.3 \pm 22.1$ ,  $52.4 \pm 13.9$ ,  $56.2 \pm 11.2$ , and  $57.9 \pm 10.3$  mGy for round 1 to round 4, respectively. The mean  $CTDI_{vol}$  values of adult abdomen protocol are  $15.5 \pm 7.0$ ,  $13.1 \pm 5.2$ ,  $12.9 \pm 4.2$ , and  $13.1 \pm 4.1$  mGy for round 1 to round 4 survey, respectively. The fail rate of the CT dose for those two protocols was reduced since the regulation of the CT dose limit (adult head: 80 mGy; adult abdomen: 30 mGy) has been launched in 2011.

**Conclusions:** A longitudinal analysis of radiation dose of CT scan for adult head and abdomen examinations was conducted during the four times national surveys in Taiwan. MDCT scanners are the majority in Taiwan. The effect of the legislation in quality assurance for diagnostic CT scanners is significant because the fail rate of CT dose for those protocols was reduced.

## Study of Patient Doses in Conventional Diagnostic Radiology in Ukraine

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### Introduction

In Ukraine there are above 10500 X-ray units for conventional diagnostic radiology on which about 40 million X-ray diagnostic procedures are carried out annually. The values of patient effective doses from X-ray Diagnostic examinations were established by Order of Ministry of Health in 2001, but these doses do not correspond to real patient's doses because do not consider the type of X-Ray units and parameters of diagnostic techniques.

### Methods

The entrance surface doses (ESD) for adult patients in different diagnostic Radiology departments were studied by direct TLD measurements and indirect method from measurements of radiation output of X-Ray units and data of parameters of diagnostic procedures for fluorography, 12 types of radiographic studies and mammography.

### Results

It was established that for most types of X-ray examinations ESDs differ up to 10-50 times between different X-Ray units. The national diagnostic reference levels were determined and accepted by Regulatory Body. Practically for all types of examinations the national DRLs exceed in 1.3 – 2.0 times the recommended levels of IAEA BSS.

For mammography screening the X-ray units type MADIS are wide used in Ukraine. It was shown that patient's average gland doses (AGDs) on this type of mammography unit were about 1.5–2.5 mGy for single project that less than acceptable level in according EU recommendations but the quality of the diagnostic images on the criteria of the EU Guidance and the IAEA were not satisfactory.

### Conclusions

Introduction of indirect methods of patients' doses estimation using the results of radiation output checking allows to study the patients' doses for the most common X-ray examinations practically in each X-ray diagnostic units and to compare them with values established as national Diagnostic Reference Levels. It will give the chance to carry out the target actions directed on optimization of medical exposure and decrease of collective population doses in Ukraine.



## A study preliminary a new methodology of QA in Computerized Tomography

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### Introduction

Computerized tomography (CT) images have a high resolution, allowing the distinction between different densities of the tissues about the order of 0.5%. To ensure CT image quality, the equipment quality assurance (QA) is performed. QA is a set of tests which are part of a quality assurance program. There are several guidelines for QA's. Every equipment has its own QA phantom and the respective manual (with all the requirements, instructions and acceptable limits). The main objective of this research is to consolidate a methodology of QA tests by using only one type of phantom instead of each manufacturer phantoms.

### Methods

The data were collected at a Porto Alegre's hospital. Three types of CT devices were used: GE Brightspeed Edge 8-Slice, Toshiba Aquilion One TSX-301A, and Phillips Brilliance CT 16 Power. The performed tests were uniformity, noise and accuracy using the respective CT phantoms and comparing with the measurements made in all the CTs with the Gammex 464 (with the unification proposal), always following the instructions from each equipment manual.

### Results

Measurements results from the manufacturer phantom and Gammex for GE's and Toshiba's CTs were inside the acceptable limits. However, for Phillips the 3, 6 and 9 o' clock measurements from the Gammex measurements were out of the respective limits.

### Conclusions

The Phillips's results can be assigned to the use of the manufacturer protocol in the tests with the equipment's own phantom and with the Gammex. The manufacturer's limits are more restrictive than the limits from the Gammex manual probably due to the large range of parameters and equipment specificity. The QA program unification using only one simulator should be adjusted to the parameters heterogeneity such as the acceptance limits. It is recommended to perform tests using the Gammex manual and compare the data with the present results.

## Estimation of Absorbed Dose on Eye Lens for Patients Undergoing a Chest CT

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### Introduction

Computed Tomography (CT) has become an important tool for medical purposes such as exploration; diagnosis and even treatment leading to a better life quality to patients. Nevertheless, the use of ionizing radiation of these devices may induce damage to high radiosensitive tissues due to the high dose with which the patients are exposed on these studies. The eye lens is one of the most radiosensitive tissues and according to IAEA, cataracts may appear at 0.5 Gy.

### Methods

A non-invasive prototype was designed, validated and built to have a reliable measure without altering the image quality. TLD-100 thermoluminescent dosimeters were previously calibrated according to the norm ISO 12794 and used in the measurement. A total of 44 patients were involved on this research project. 22 studies were realized on a Siemens Somatom Emotion 6 (SE6) and 22 on a Siemens Perspective 128 (SP128).

### Results

The prototype was validated using MCNP. The conditions of charge-particle equilibrium were satisfied according to the simulation.

The average absorbed dose found on a simple CT scan performed on a SE6 was  $2.99 \text{ mGy} \pm 1.03$  meanwhile the same study performed on a SP128 was  $12.66 \pm 1.3 \text{ mGy}$ . On the other hand, the averaged absorbed dose on a contrast CT scan performed on a SE6 was  $3.06 \pm 1.02 \text{ mGy}$  while the studies performed on a SP128 had an averaged absorbed dose of  $7.6 \pm 6.63$ .

### Conclusions

Through statistical analysis, it was shown that there are important differences in the absorbed dose, mainly in those performed in the Siemens Perspective. Although the radiation dispersed is relatively low, it is widely recommended to take actions for the radiological protection of the patient. This last point is since cataracts are a deterministic effect that occurs at low exposures.

It should be remembered that radiodiagnostic equipment is not the only exposure factor. So, these small contributions should be taken account for the annual exhibition.

## An efficient treatment planning approach for diminishing critical organ dose in volumetric modulated arc therapy technique for synchronous bilateral breast cancer patients

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### Introduction

Treatment plans for synchronous bilateral breast cancer (SBBC) patients pose a challenge due to complex treatment volumes. To diminish both high-dose and low-dose volume of heart and lungs, we proposed an efficient and simple strategy for the VMAT (volumetric modulated arc therapy) treatment plans in this study.

### Methods

Five SBBC patients were enrolled for this research. We utilized two pseudo block planning structures to diminish high dose volume of whole lungs and heart, and confined low dose area in normal organs for VMAT plans. Prescription was 45 Gy in 25 fractions to the whole breast. VMAT treatment plan was consist of two partial arcs.

### Results

In terms of whole lungs, the average  $V_{5Gy}$ ,  $V_{10Gy}$ , and  $V_{20Gy}$  in the VMAT-B (plans with two pseudo planning block structures) plan for five patients was  $34.8 \pm 7.2\%$ ,  $23.4 \pm 5.0\%$ , and  $14.8 \pm 3.0\%$ . For the VMAT-NB (plans without two pseudo planning block structures) plan, the average  $V_{5Gy}$ ,  $V_{10Gy}$ , and  $V_{20Gy}$  was  $38.6 \pm 6.8\%$ ,  $27 \pm 5.9\%$ , and  $18.4 \pm 4.0\%$ . As for heart, the average  $V_{5Gy}$ ,  $V_{10Gy}$ ,  $V_{20Gy}$ , and  $V_{30Gy}$  in the VMAT-B plan was  $19.6 \pm 3.1\%$ ,  $7.0 \pm 2.5\%$ ,  $2.2 \pm 1.2\%$ , and  $0.7 \pm 0.7\%$ . The mean  $V_{5Gy}$ ,  $V_{10Gy}$ ,  $V_{20Gy}$ , and  $V_{30Gy}$  in the VMAT-NB plan was  $26.2 \pm 6.3\%$ ,  $11.3 \pm 3.9\%$ ,  $3.9 \pm 1.8\%$ , and  $1.5 \pm 1.1\%$ .

### Conclusions

We presented an approach to diminish both high-dose and low-dose volume by utilizing some pseudo planning structures in the VMAT treatment plans. The dosimetric results of this research represents that "Ref\_block" structures have potential to reduce the risk of radiation pneumonitis and heart disease, while may preserve same tumor control rate.

## Patient dose optimization for computed radiography using physical and observer-based measurements as image quality metrics

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Radiation protection of patients undergoing diagnostic x-ray examinations requires practical evaluation of doses and image quality under clinical conditions. On this subject, optimization of the dose-image quality relationship plays key role in order to achieve this goal. In this study, patient dose optimization was implemented for a computed radiography (CR) system used in general x-ray examinations, considering physical and observer-based measurements as image quality metrics. An anthropomorphic phantom was used to simulate the patient under clinical conditions of chest and abdominal x-rays. Entrance skin doses (ESDs) were measured using a solid-state dose detector positioned at phantom entrance surface during simulated x-rays with different combinations of tube potential (kV) and tube current-time product (mAs), including the kV-mAs used clinically. Agfa's CR System with CR12-X digitizer and a set of 35x43cm cassettes and imaging plates (IP) were employed to capture digital images. Contrast-to-noise ratio (CNR) determined for different regions in the images obtained from phantom was used as physical measurement of image quality. The images were also assessed by two experienced radiologists with regard to the acceptable noise. The relationship between calculated CNR and ESD measured for each exposure setting in association to the acceptable images by radiologists were employed as optimization strategies: maximize CNR for a constant dose, minimize dose for a constant CNR and, finally, maximize the figure of merit (FoM) that relates CNR and dose. Prior to the dose and image quality optimization, standardized exposure index (EI) from clinically accepted images and its associated deviation index (DI) were collected for one month. Outcomes point that the association between quantitative and qualitative image quality measurements along with dose can be an efficient and practical way to achieve optimization in digital imaging systems.

## Monte Carlo study of out-of-field exposure in carbon-ion radiotherapy: Organ doses in pediatric brain tumor treatment.

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### Introduction

Ion-beam radiotherapy can reduce the entrance dose because of their physical characteristics called the Bragg peak. In addition, CIRT offers physical and biological advantages over proton beams. These advantages in CIRT lead to high-dose localization in the target volume with minimal damage to the normal tissue, thereby indicating favorable outcomes. Meanwhile, the radiation-induced second cancer risk of patients receiving radiotherapy is a major concern, especially in children, as is increasing the effectiveness of the radiotherapy and extending life expectancy. The second cancer risk depends on the volumes of both the high-dose region in the irradiation field and the low-dose region outside the field. The aim of the study is to use Monte Carlo simulations with an anthropomorphic phantom to estimate the secondary dose in CIRT with the beam parameters of a typical pediatric brain tumor treatment.

### Methods

The target disease of this study was pediatric cerebellar ependymoma. We estimate the out-of-field organ absorbed dose, dose equivalent and equivalent dose for each radiation type during CIRT for typical pediatric cerebellar ependymoma treatment using Monte Carlo simulations using the Particle and Heavy-Ion Transport Code System (PHITS). Because the CIRT out-of-field dose depends on the beam parameters, the typical values of the parameters were used. Both methods of passive beam and active scanning beam were calculated.

### Results

The results showed that the dose equivalent decreased with distance from the target, ranging from 1.3 mSv/Gy(RBE) in the thyroid to 0.05 mSv/Gy(RBE) in the bladder. The neutron equivalent doses per treatment dose in organ were lower than passive scatter proton therapy. When increasing distance from the target volume, contribution from external secondary charged particles decreases and contribution from external neutrons increases.

### Conclusions

The typical out-of-field organ dose during CIRT in pediatric cerebellar ependymoma were shown.

## Protocol optimizations of chest Computed Tomography scans using pediatric and adult chest phantoms

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### Introduction

Computed Tomography (CT) has become an important tool for diagnosing cancer and to obtain additional informations on different clinical issues. The radiation dose values in computed tomography depends on the scan acquisition protocol. Today, it is a very fast, painless and noninvasive test that can be performed high quality images. Therefore, it is indispensable to improve protocols, seeking smaller doses, without impairing the diagnostic quality of the image. The doses received are related with risks of stochastic effects.

### Methods

In this study, a cylindrical chest phantom made of polymethylmethacrylate (PMMA) and a second chest phantom of the same material was developed in oblong shape including the axillary regions, based on the dimensions of the patient's chest of 8 years old. They were used representing an adult and an 8 years old chest.

The oblong phantom was built based in the chest cut section, including axillary region, with the same cut area of the cylindrical phantom. A comparative study of chest phantoms was performed in a Toshiba scanner, Aquillion model with 80 channels.

Placed in the CT scanner isocenter the central slice of the two chest phantoms were irradiated successively to obtain measurements using a pencil chamber. On the basis of the measurements, dose indexes (CTDIvol) were obtained considering the scan of 10 cm of the central area for each phantom in every tests. The scanning of the adult chest phantom was performed using the routine service protocol with a voltage of 120 kV. Optimized acquisition protocols were tested for the pediatric chest phantom, they were performed with voltages of 120, 100 and 80 kV and the image noise was controlled lower than 1%.

### Results

The volumetric dose indexes obtained using the routine protocol for the adult chest phantom was 13.02 mGy and 16.94 mGy for paediatric chest phantom. Optimized acquisition protocols for pediatric chest phantom protocols produce volumetric dose indexes of 3.39 mGy, 2.58 mGy and 2.74 mGy for voltage of 120 kV, 100 kV and 80 kV, respectively.

### Conclusions

The study of optimized protocols for pediatric patients promoted a considerable reduction in patient absorbed dose. The use of the optimised acquisition protocol of 100 kV has presented the lowest dose index for the pediatric chest phantom with the shape and size studied. This work allowed to observe the dose variation absorbed by the pediatric chest phantom with the variation of the value of the tube supply voltage and adjust of the other parameters.

## Determination of the detective quantum efficiency of a digital dental X-ray imaging devices: intrinsic performance study

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### Introduction

According to the International Electrotechnical Commission (IEC) 62220 series, part1-1: determination of the detective quantum efficiency-detectors used in radiographic, part1-2 : detectors used in mammography, part1-3 : detectors used in dynamic imaging, we studied the image quality and radiation dose for dental X-ray imaging devices. This study discusses the method for the determination of the DQE of dental X-ray imaging devices which were made by National Chung-Shan Institute of Science and Technology in Taiwan. We designed the devices for the purpose of replacing the imported commodities. It only needs 20% of dose for instant imaging compared to other products.

### Methods

This study applied the edge method to acquire the fine sampling edge spread function and then calculated presampling modulation transfer function. The method was created to fit the conditions of digital dental X-ray imaging devices. First, determination of the linearization and noise power spectrum had been done before evaluation of modulation transfer function (MTF). Furthermore, the detective quantum efficiency was estimated based on the MTF feature. The programming language, MATLAB(R2018a) produced by The Math Works™, was adopted for analysis and calculation of measured data.

### Results

The results assist in the establishment of standards of dental medical electrical equipment-characteristics of digital dental X-ray imaging devices. The relationships between doses and pixelvalues in the dental imaging and its noise power spectrum in vertical and horizontal direction can be shown in figures. The edge spread function in samples of the image shifted to the center. Then, we obtained the line spread function by differentiating the edge spread function. Next, the modulation transfer function by fast fourier transformation of line spread function was gotten. At the end, the detective quantum efficiency that combined effects of signal and noise performance of a dental imaging system was estimated. The results attested that the dental X-ray imaging devices made by National Chung-Shan Institute of Science and Technology had a 29.4% DQE at 0 line pair per millimeter.

### Conclusions

This study was to establish the standards of dental medical electrical equipment-characteristics of digital dental X-ray imaging devices made by National Chung-Shan Institute of Science and Technology. The coefficient of determination for doses and pixelvalues in the dental imaging is 0.9826 and it shows a good curve-fitting. The DQE determination could describe the ability of preservation of signal to noise ratio from radiation field to digital image. The result of this method could describe the dose efficiency of digital dental X-ray imaging devices and recover the truth quality of the digital dental X-ray imaging device.

## Measurement of the Stopping Power of liquid water for carbon ions below 6 MeV

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### Introduction

The stopping power of water for carbon ions,  $S_{\text{H}_2\text{O,C}}$ , is a crucial parameter to determine the range of projectiles in human tissue. It is evident that a precise knowledge of this quantity reduces the range uncertainty which allows to avoid energy deposition in the healthy tissue/critical organs behind the target volume. In addition, experimental data for carbon ions [1] in water indicate an increasing relative biological effectiveness for linear energy transfers prevailing in the so-called Bragg-peak. However, experimental data for  $S_{\text{H}_2\text{O,C}}$  in this energy regime is sparse.

### Methods

The Inverted Doppler-shift Attenuation Method (IDSAM) is applied to the decay of the  $2^+$  in  $^{12}\text{C}$  state at 4.4 MeV ( $\tau = 61\text{fs}$ ) to measure  $S_{\text{H}_2\text{O,C}}$  for projectiles with kinetic energies below 6 MeV. Prompt gamma-rays were detected with an array of BGO-shielded HPGe detectors. The experimental data is analyzed by a comparison to simulated spectra generated with a dedicated Geant4 simulation tool.

### Results

Results of the first experimental run using a provisional experimental setup [2] agree with the recommendation of the ICRU report 73 errata [3] and recent theoretical results [4] but the experimental uncertainty of 12% is comparably large. Preliminary results of the experiment employing the full experimental setup will be shown.

### Conclusions

The IDSAM is a powerful tool to investigate the stopping power of liquids for projectiles at energies for which the conventional transmission method cannot be applied. The present work triggered the preparation of a follow-up experiment using the same method, which will increase the projectile energy up to 25 MeV. This enables the connection to the Bethe-Block theory and allows to investigate the mean ionization potential of liquid water.

[1] Friedrich *et al.* in J. Radiat. Res. **54**, 494 (2013)

[2] Rahm *et al.* in Phys. Med. Biol. **59**, 3683 (2014)

[3] Sigmund *et al.* in J. ICRU **5**, 1 (2006)

[4] Friedland *et al.* in Sci. Rep. **7**, 45161 (2017)



## Construction of X-ray source model of various recent CT scanners and comparison of exposure dose using voxel phantom and Monte Carlo simulation

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### Introduction

X-ray CT (Computed Tomography) is very popular as a useful diagnostic method, so it is important to assess high exposure dose of CT in terms of justification and optimization. WAZA-ARI version 2 (WAZA-ARiv2, <https://waza-ari.nirs.gst.go.jp/>) is the web-based open system for X-ray CT dose calculation. The organ doses of various CT exposures were calculated using Monte Carlo simulation and voxel phantoms. The selectable CT scanners in WAZA-ARiv2 are still not enough despite the continuing addition of CT scanners because the CT developers deliver a steady stream of new products. In this study, in order to construct X-ray source model of recent CT scanners, the measurements of radiation quality and distribution were carried out, and exposure dose by its source models were compared.

### Methods

The measurements of radiation quality and dose distribution of newer CT scanners made by Canon, GE and Philips using Piranha model 657 (RTI Electronics AB) were carried out. Assuming that the bowtie filter is made of aluminum, the shape of the filter was estimated from the results of the radiation quality and dose distribution. The organ doses in CT exposure were calculated using Monte Carlo code, PHITS and Japanese adult voxel phantoms developed by JAEA.

### Results

The constructed sources model well reproduced the measurement results. Each CT scanner was equipped with one or more bow-tie filters, and the estimated filter shape of each CT scanner showed a characteristic shape for each manufacturer. Assuming a scan of the thoracoabdominal range, the effective dose per value of CTDI free air correlated with the effective energy of the source model.

### Conclusions

In order to construct X-ray source model of recent CT scanners, the measurements of radiation quality and distribution were carried out, and exposure dose by its source models were compared. The effective dose per value of CTDI free air correlated with the effective energy of the source model.



## Monte Carlo design of a moderator to produce a thermal neutron source from a $^{241}\text{Am}/^9\text{Be}$ source

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### Introduction

Neutron Activation Analysis (NAA) is an analytical method usually carried out through the use of high intensity neutron sources. For low-intensity neutron fields, the thermal neutron flux impinging on the analysed sample must be at least around  $10^3 \text{ cm}^{-2} \cdot \text{s}^{-1}$ . With this purpose, a neutron moderator device called FANT –Spanish acronym of Enhanced Thermal Neutron Source (*Fuente Ampliada de Neutrones Térmicos*)– has been designed using Monte Carlo methods.

### Methods

The MCNP6 code has been used to optimise the design, including moderator and detection system. FANT is made of high density polyethylene (HDPE). It consists of a parallelepiped of  $90 \times 70 \times 70 \text{ cm}^3$ , with a cylindrical irradiation chamber of  $32 \text{ cm } \varnothing \times 70 \text{ cm}$  long, a  $111 \text{ GBq } ^{241}\text{Am}/^9\text{Be}$  neutron source inside the chamber and a NaI(Tl)  $3'' \times 3''$  detector. Neutron fluence rates were estimated inside and outside the irradiation volume, as well as 222 energy-groups neutron spectra. In the calculations  $10^8$  histories were used to get uncertainties lower than 5%; the ENDF/B-VII cross section library was used. For the simulation of low-energy neutrons transport in polyethylene the  $S(\alpha, \beta)$  treatment was included.

### Results

Depending on the irradiation plane, the fractional thermal component increasing up to about 70%. The largest thermal neutron flux obtained was  $500 \text{ cm}^{-2} \cdot \text{s}^{-1}$ , being constant along a line of 5 cm. Our results are in agreement with the thermal neutron flux reported for similar assemblies. The ambient dose equivalent rate  $H^*(10)$  was also calculated; the largest doses are reached at 50 cm and are reduced with distance from the neutron source. The ambient dose equivalent rate of FANT at 1 m is less than  $10 \text{ } \mu\text{Sv/h}$ .

### Conclusions

Using a  $^{241}\text{Am}/^9\text{Be}$  neutron source and a HDPE assembly, FANT produces a thermal neutron field that could be used in applications like NAA. Monte Carlo calculations have been very useful to optimise its design.

## pMC a fast-low energy proton simulation program

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### Introduction

The major contribution for proton stopping power come from the electronic component [1]. For low energy (up to a few MeV) where most pn and pp channels are not open, absorbed dose is essentially due to proton interaction with atomic electrons. In situations where secondary particles contribution to absorbed dose can be neglected, a good estimation can be obtained from proton direct energy deposition.

### Methods

The proton tracking program, pMC, is based on AlfaMC [2], the alpha particle fast Monte Carlo simulation program. Deposited energy is computed from lookup stopping power tables adapted from NIST ASTAR/PSTAR tables [1]. For speed, the Fermi low angle multiple scattering model is adopted. The program uses modular geometry building, adding flexibility for use in complex setups.

For benchmark purposes, pMC results in selected setups have been compared with results from well-established SRIM [3] and FLUKA [4] programs.

### Results

Depth dose profiles (Bragg curve) and transverse profiles have been obtained with pMC and compared to results obtained from SRIM and FLUKA for air, water and PMMA in energy range from 2 to 20 MeV. All results show a good agreement. pMC proved to be 10 to 100 times faster than any of these two programs.

### Conclusions

pMC can be a valuable tool for fast evaluation of proton energy deposit in matter. The program is easily set even for fairly complex geometries.

### References

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- [2] AlfaMC: A fast alpha particle transport Monte Carlo code, NIM A 737 (2014) 163-169.
- [3] SRIM - The stopping and range of ions in matter (2010), NIM B 268 (2010) 1818-1823.
- [4] The FLUKA Code: Developments and Challenges for High Energy and Medical Applications, Nuclear Data Sheets 120, (2014) 211-214

## **Dosimetry of narrow, high-energy x-ray sources typical of cargo screening systems**

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### **Introduction**

Screening at borders and entry points is increasingly applied to cargo containers and vehicles. The sources being used have evolved from radio-isotopic sources such as Cs-137 and Co-60 to bremsstrahlung x-ray sources with accelerating potentials. If one wishes to determine air kerma or dose to cargo, ionization chambers may be used. However, the photon sources used for calibrating these chambers are typically lower in energy and use broader beams than encountered in the field.

### **Methods**

We investigate these situations using a two-pronged approach. We first made measurements in several laboratory beams ranging from calibration fields to those designed to mimic conditions encountered in the field. We performed these measurements with commercial ionization chambers and with a specially designed ionization chamber. Then we simulated these measurements via Monte Carlo calculations using the codes MCNP, EGSnrc and Penelope. These transport codes were utilized both for direct simulation of the experimental situations and to determine the dosimetric quantities via corrections to measured current/charge (e.e. wall corrections).

### **Results**

The perturbative approach, performed using the specially designed ionization chamber did not reproduce a known air kerma to reference accuracy. The detailed calculations are underway and will be complete and analyzed by the time of the meeting.

### **Conclusions**

It is too early at this timer to draw definitive conclusions from this work. These conclusions will be made after all calculations are complete and will be presented at the meeting.

## The Latest Backgammon Detector Technology

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### Introduction

The meander wire backgammon technology has high levels of flux and spatial linearity across a wide range of energies. One of the attractive features of these detectors is the stability of response and robustness under long X-ray exposure, the compactness and portability. We present the specifics of the latest University of Melbourne backgammon type multi-wire gas proportional counter (UM backgammon detector).

### Methods

A key problem historically has been the limited range of count-rate for processing to the optimum resolution. We report dramatic advances in this area through a flux linearity test, using a rotating anode generated Cu K $\alpha$  X-ray spectrum. Using the same experimental setup, the spatial linearity of the new detector was also examined. The performance of the detector was then highlighted through an investigation into the K $\alpha_{1,2}$  spectra of titanium and chromium. The Ti and Cr spectrum were measured using a Johann-type curved crystal X-ray spectrometer and the spectra fitted with the current best parameterisation in the literature.

### Results

The outcome of the flux linearity test shows the count rate is linear from 7 Hz up to at least 17 kHz. The spatial linearity test gave a regional non-linearity of 1  $\mu\text{m}$ , corresponding to an energy

accuracy of order 2 ppm or less and an improvement on previous designs. The X-ray spectra, measured using the Johann-type spectrometer, displayed quality fitting of data using the best available parameterisations and provided an estimated resolution of 240(20)  $\mu\text{eV}$ , again improving on earlier designs.

### Conclusions

Experiments striving to probe phenomena at increasingly high levels of sensitivity rely on corresponding detectors. The collected data for the K $\alpha$  splitting of copper, chromium, and titanium, and the capacity to make critical tests of quantum electrodynamics, demonstrate that the University of Melbourne Backgammon detector is capable of recording highly accurate X-ray spectra over a wide range of energies.

## Radiation dose due to natural radionuclides in soils of the state of Rio de Janeiro (Brazil).

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### Introduction

The main source of external irradiation of human body is due to the presence of the primordial radionuclides <sup>40</sup>K, <sup>238</sup>U and <sup>232</sup>Th and their daughter nuclides in soil. Located in the south-western part of Brazil, the state of Rio de Janeiro is geotectonically contained within a complex structural province. An extensive radiological characterization of soils of Rio de Janeiro State was undertaken.

### Methods

Two hundred and fifty-nine surface soil samples were collected in non-impacted areas that encompassed the state and represent the major types of soils. Samples were identified, processed and analysed by gamma spectrometry with hyper pure germanium detector

### Results

The obtained results pointed out median values of 114 Bq.kg<sup>-1</sup> for <sup>40</sup>K, 32 Bq.kg<sup>-1</sup> for <sup>226</sup>Ra and 74 Bq.kg<sup>-1</sup> for <sup>228</sup>Ra. The total external dose values ranged from 0.03 and 2.16 mSv.year<sup>-1</sup>, which surpassed the worldwide range, but the highest values were concentrated in small hotspots. The main contributor to the dose rate is the Th decay series, which accounted for 59% and was followed by the U-series and <sup>40</sup>K at 12% and 11%, respectively.

### Conclusions

The external radiation dose indicates that the state has a background radiation level within the natural range.

## The latest development and the new extended capabilities of the GENII-LIN soil transfer model

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### Introduction

GENII-LIN is a health physics code under development at the University of Bologna. The aim of the project is to provide a computational framework with capabilities for calculating radiation dose and risk to individuals or populations from radionuclides released to the environment, and from pre-existing environmental contamination.

The code has capabilities to handle: acute and chronic releases to air from ground and elevate sources; acute and chronic releases to water; chronic releases to deep soil from waste form degradation; pre-existing contamination soil, surfaces, and environmental media. The radionuclide environmental concentrations are calculated over time by modeling appropriate transfer processes through air, deep and surface water, deep and surface soil, and biotic transport.

### Methods

The nuclide transfer model through soil was originally conceived for evaluating exposure to residual contamination from long term activities and from waste form degradation. Short life nuclides were intended absent or at equilibrium with long life parents. In a previous work [1], we introduced a new soil transfer model, that accounted short life nuclide contributions correctly. This model was at an early stage of development and could be applied only to non-agricultural soils. In these years, the model has been further developed and its capabilities significantly extended to cover agricultural and residential scenarios. The number of soil layers and compartments has been increased and both physical and numerical modeling of the transfer processes have been deeply revised.

### Results

The new soil transfer module is perfectly working and well interfaced with the other modules of the GENII-LIN computational framework.

### Conclusion

The GENII-LIN capabilities have been remarkably extended to cover a wider number of contamination and exposure scenarios.

[1] Teodori, F., 2017. A new nuclide transport model in soil in the GENII-LIN health physics code, *Radiat. Phys. Chem.* 140, 146–149.



## Application of deconvolution technique on the airborne gamma spectrometry data analysis

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### Introduction

Deconvolution of scintillation spectrometry data, based on the Monte Carlo calculated detector response matrix, can be used for calculation of air kerma rates energy distributions and/or radionuclide concentrations in terrestrial environmental monitoring, where detector size/weight and time of acquisition are not important limiting factors as in airborne monitoring using spectrometer carried by drone. Requirements for small detector weight (i.e. size/efficiency) and short time of single spectra acquisition (typically 1s scan to achieve good space resolution) result spectra with poor statistics. Deconvolution technique application on such spectra and possibilities to improve stability and statistics of results are discussed.

### Methods

Deconvolution of airborne spectra were tested on spectra from twin 2"x2" NaI(Tl) airborne spectrometer detector and obtained from 1s scans. Response matrix was calculated by the MC method and deconvolution made by Scofield-Gold iterative method. Methods of poor statistics impact reduction were studied and method of improvement of measured spectra statistic by the calculation of most probable spectrum on the basis experimental spectra statistical processing was designed.

### Results

Method was successfully used for processing of data collected by airborne spectrometer (see above) used for mapping area affected by the uranium ore mining using drone. Air kerma rate spectral distributions calculated by the deconvolution enables, despite larger fluctuations, to identify the main contaminants on the monitored area.

### Conclusions

Poor statistic is specific problem processing scintillation spectra from airborne monitoring using drones with limited load. The tests carried out show that poor statistics deteriorate in particular the fluctuations in the energy distributions of quantities determined by the deconvolution, but little is reflected in their integral value. On tested data (more than 3000 spectra), the validated method proves applicability at least for emergency monitoring.

## The Environmental Level Multi-Source Air Kerma Rate Calibration System

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### Introduction

Since the accident of Fukushima Daiichi nuclear power plant, the environmental radiation dose has been an emphasized global issue. The public is very sensitive to the amount of environmental radiation, but the environmental radiation detector is quite low in accuracy and the various radiation protection instruments are to have a large difference of response to environmental radiation levels. The dose range of radiation detectors calibrations is from several mSv/h to 10  $\mu$ Sv/h; the lowest dose is about 50 times of the background values. To test the accuracy of general radiation detectors when measuring natural background dose intensity, the Institute of Nuclear Energy Research (INER) established an environmental-level radiation dose calibration system. It can improve the quality and accuracy of radiation dose measurement, and guarantee the radiation safety and protection in the field of low dose rate environmental radiation, as the basis for calibration services.

### Methods

The system was verified to meet the needs of measurement and calibration through evaluations and comparisons. It was assessed using ISO 4037-1 criteria (ISO 4037, 1988). The multi-source environmental-level air Kerma calibration standard system, which is composed of americium-241, cesium-137 and cobalt-60, and with the environmental-level irradiation device, movable cone, backscatter baffle, nitrogen assist device system, circuit isolation device and other devices constructed, the overall system equipment distribution. The energy range of the environment radiation is simulated by multiple energy distributions. The radioactive sources, being stopped by filter of three different thicknesses, produced radiation fields of three different strengths.

### Results

According to the above evaluations, we can estimate the relative dose rate from the environmental-level and up to radiation protection. In this study, we obtained the radiation field, in increments of a few decimal by using the conventional dosimeter, ion chamber. The air kerma measurement and calibration is defined as that under strict conditions, the standard ionization chamber is applied in the measurement of free in air, and when proceeding the calibration, the standard ionization chamber is to be replaced by the to-be-calibrated ionization chamber for comparisons. This method is valid when the conditions are known with accuracy, such as beam homogeneity, air gap distance, and air composition and temperature. The expanded uncertainties were respectively: 1.34 % - 5.77 %.

### Conclusions

The National Radiation Standard Laboratory established an environmental-level dose rate multi-source air kerma rate calibration system and set it up in the Building 035 of INER to respond to the measurement and calibration needs in Taiwan. It can also be used as an origin of domestic traceability in calibration. The environmental-level dose rate measurement and calibration system provides a total of nine standard radiation fields with intensity ranges from 1746.6  $\mu$ Gy/h to 0.092  $\mu$ Gy/h. The calibration capability of INER reaches 0.092  $\mu$ Sv/h which equals the general environment radiation. The environmental-level dose rate measurement and calibration system is of low-dose rate; the signal is weak, and the measurement is difficult, although there are initial efforts being given, there is still a lot to be improved.

## Quantification of the biological effects induced by low doses of X-radiation in non-tumor cells of the breast.

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**Introduction:** With the increasing use of high-precision techniques for radiation therapy, there has been also an increased requirement for imaging techniques to assist in treatment planning and verification. Image-guided radiotherapy offers advantages of accurate targeting of dose to the tumor due to the verification imaging performed using cone beam CT (CBCT) procedures. Although the dose from these procedures is considered low, the concomitant dose administered to the patient has been raised as a potential concern, because of an increase in stochastic effects to the anatomic region subjected to the imaging dose. The aim of this study was to investigate the biological effects of radiation in non-tumoral breast (MCF 10A) cells, induced by CBCT procedures.

**Methods:** The experimental validation of the physical phantom used as setup to support the cell cultures during the *in vitro* irradiations was performed using an ion-chamber. The induced biological effects in MCF10A cells exposed to low doses of x-radiation were evaluated using established cytogenetic and molecular methods; g-H2AX assay, Micronuclei and Clonogenic assays.

**Results:** Herein, we report the evaluation of the early and late biological effects with dose values. In this study, the dependence of the DNA repair kinetics and the concomitant dose, administered to a patient, was also investigated.

**Conclusions:** The benefits of imaging in radiotherapy are clear. These include avoiding geographic miss and minimizing the dose to healthy tissue thereby improving the therapeutic ratio. Changes in tumour position on a daily basis, or even within a treatment period drive the need for imaging before, during and following treatment. This investigation will provide a deeper insight into the radiobiological effects of x-ray exposure, which is very important in order to assess the effect of using CBCT during radiotherapy and their possible trigger function for potential carcinogenic effects on normal breast cells and stem cells.

## Auger therapy of prostate carcinoma: $^{99m}\text{Tc}$ -labelled Acridine Orange derivatives targeting Bombesin receptor

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**Introduction:** Theranostics is one of the main focus on cancer treatment because it allows to do diagnosis and treatment with the same radiocompound, decreasing the dose to the patient and potentiate new treatments for cancer.  $^{99m}\text{Tc}$  is one of the most interesting radionuclides used for theranostics, because decays by gamma radiation (imaging) and emits auger electrons (therapy). Recently, we shown that  $^{99m}\text{Tc}$ -complexes incorporating a DNA intercalator, acridine orange (AO) derivatives, were able to easily enter the cell, penetrate the nucleus and promote several damages in the DNA. However, such complexes internalized in either tumoral as non-tumoral cells. Therefore, we aim to synthesise  $^{99m}\text{Tc}$ -AO complexes bearing a bombesin derivative (BBNder) to specifically bind the BBN receptor (BBNr) overexpressed in prostate tumor cells, and to evaluate those  $^{99m}\text{Tc}$  multifunctional complexes for auger therapy of prostate carcinoma.

**Methods:** We radiolabelled BBNder-bearing conjugates with  $\text{fac-}[^{99m}\text{Tc}(\text{CO})_3]^+$  and their BBNr-targeting properties were evaluated in PC3 prostate cancer cells. In order to evaluate the release of the peptide from the  $^{99m}\text{Tc}$ -AO complex, enzymatic metabolic studies were performed using cathepsin B. DNA damages induced by auger-emitting  $^{99m}\text{Tc}$ -complexes were assayed by  $\gamma\text{-H2AX}$ .

**Results:** Herein, we report on the synthesis and characterization of peptide conjugates containing a pyrazolyl-diamine chelator with or without the AO unit. The labeling of both conjugates with  $^{99m}\text{Tc}(\text{I})$  and their metalation with Re are also described. Metabolic studies of  $^{99m}\text{Tc}/\text{Re}$ -BBNder complexes are presented. Preliminary results of *in vitro* (prostate cancer cells) BBNr-targeting, nuclear uptake and DNA lesions of  $^{99m}\text{Tc}$ -AO-BBNder and  $^{99m}\text{Tc}$ -BBNder are also reported.

**Conclusions:** The BBNr-targeting is a huge step towards the specificity of  $^{99m}\text{Tc}$ -AO complexes for prostate carcinoma cells. Those findings opens the perspectives for using  $^{99m}\text{Tc}$ -complexes for cancer theranostics.

## Comparative analysis of changes in the reproductive system of male rats caused by exposure to external radiation in doses of 0.5 and 2.0 Gy

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### Introduction

Due to the high sensitivity of the male reproductive system to ionizing radiation, it is interesting to conduct a comparative analysis of changes in the testes and epididymis of male rats caused by external irradiation at doses of 0.5 and 2.0 Gy.

### Methods

The study was conducted on male Wistar rats. External single irradiation of animals at a dose of 0.5 and 2.0 Gy was performed at the IGUR unit ( $^{137}\text{Cs}$ , dose rate 43 cGy/min). The experiments were performed on the 8<sup>th</sup> and 37<sup>th</sup> days after irradiation. The state of some parameters of the reproductive system of male rats (absolute and relative weight of testis and epididymis, the spermatogenic cell types counted at various stages of differentiation, the epididymal sperm count, their viability and DNA fragmentation level) after irradiation was studied.

### Results

It was established that on the 8<sup>th</sup> day after irradiation at a dose of 0.5 Gy changes in the studied parameters, except for the fall of epididymal sperm viability, is not observed, while on the 37<sup>th</sup> day revealed a discoordination of cellular tissue composition of the testis and fall of sperm count and reduced viability. The dose of 2.0 Gy significantly increases the negative effects of radiation, which can be seen largely in the remote period including the loss of testicular tissue. On the 37<sup>th</sup> day after the exposure at this dose, the absolute tested weight decreased almost twice, there is a marked intensification of the initial stage of differentiation of spermatogenic cells in the step preleptotene and spermatocytes 1<sup>st</sup> order and elongating spermatids in severe inhibition of production of round and elongating spermatids. The sperm count extracted from the epididymis irradiated rats on the 37<sup>th</sup> day after exposure decreased by 40% ( $P < 0.05$ ), their viability was significantly reduced.

### Conclusions

These data indicate the specific features of tissue response seminiferous epithelium; radiation damage is manifest in a greater degree in the initial and in the remote period after irradiation.



## Quantification of DNA damages by Real-time PCR Reactions and Its Application to Radiation Monitoring System

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### Introduction

A biological dosimeter that directly reflects cellular responses to ionizing radiation in living organisms would be useful for protecting human health against exposure. We are developing a novel dosimetric system using DNA molecules as a radiation sensor. DNA molecules are irradiated and the resulting DNA damage is quantified by a real-time polymerase chain reaction (quantitative PCR, qPCR).

We investigated the DNA lesions caused by gamma or carbon ion particle irradiation and revealed that the extent of DNA amplification is negatively correlated with the magnitude of LET of exposure to radiation.

### Methods

The DNA fragment for the dosimetry system was formed using the PCR technique (amplification of 804 base pairs of *URA3* gene DNA fragment of yeast).

- Gamma-ray (From  $^{60}\text{Co}$ , LET 0.2 keV/ $\mu\text{m}$ ); Chiyoda Technol Corp., Japan and Osaka Univ.)
- Carbon ion beams (290 MeV/u, LET 50 keV/ $\mu\text{m}$  and 220 MeV/u, LET 107 keV/ $\mu\text{m}$ ); by HIMAC (NIRS, Japan) and TIARA (JAEA, Japan).
- Neon ion beams (260 MeV/u, LET 428 keV/ $\mu\text{m}$ ); by HIMAC (NIRS, Japan).

The real-time PCR was used to amplify a 200 bp region of the *URA3* gene. We used EcoTM Real-TimePCR System (illumina). The template amount is 0.1ng (1 $\mu\text{l}$ : 0.1 $\mu\text{g}/\text{ml}$ ). The amplification leads to an increase in fluorescence intensity which allows measurement of DNA concentrations. 8-oxoG is one of the main mutagenic modifications induced in DNA by oxidative stress.

The amount of 8-oxoG in the model is estimated by 8-oxoG Check ELISA kit. Absorbance in 450nm was measured using iMark microtiter tray reader (BIO-RAD, Japan), and quantity of 8-oxoG was evaluated. Calf thymus DNA was used as Model DNA.

### Results

We obtained the result that amplifiable template by the polymerase chain reaction decreased in proportion to gamma-ray irradiation

This means that DNA lesions such as strand breaks caused by ionising radiation inhibit the DNA polymerase reaction using irradiated DNA fragments.

While ionizing radiation elicits not only DNA strand breaks but 8-hydroxy-2'-deoxyguanosine (8-OHdG) production, the levels of 8-OHdG produced by high- and low-LET gamma irradiation were similar, demonstrating that 8-OHdG production was not affected by the magnitude of LET.

### Conclusions

- (1) The real-time PCR assay for the irradiated DNA is useful to measure the irradiated dose.
- (2) The detection sensitivity for DNA lesions will improve by enlarging a region performing DNA synthesis.

## LUMINESCENCE PROPERTIES OF NATURAL DEAD SEA SALT PELLET DOSIMETRY UPON THERMAL STIMULATION

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### Introduction

The liberation of charge carriers (e.g. electrons) from ground state to higher state can be caused by irradiation. If the subsequent recombination is radiative, thermoluminescence (TL) takes place upon heating, the emitted light intensity corresponding directly to the rate at which the system returns to equilibrium. In the event of a radiological accident or attack it is important to measure and assess the absorbed ionising radiation dose to the population. Present investigation has been to examine the TL properties of natural salt collected from the Dead Sea in Jordan and exposed using <sup>60</sup>Co gamma irradiation to entrance doses ranging from 2 to 10 Gy, providing desirable luminescence features of fast optical bleaching. Natural Dead Sea NaCl are produced in pellet form, achieved with 0.1 and 0.3 cm sized salt grains and a compression force of  $5.0 \pm 0.1$  tonnes. With the proposed NaCl pellets, linear dose reponse has been achieved, producing intense TL yield for a 0.1 cm thick layer compared to that of 0.3 cm thickness. It is also noted that impurities present in the phosphor may affect the sensitivity. The combination of thermoluminescence activator, sensitiser and quenching presence from the natural salt elements affects the output and is expected to result in characteristic TL. It is therefore to be considered an excellent candidate for complementary emergency dosimeter in radiological accident situations. Supplementary thermoluminescence characterisation of the salts investigated have included; dose response, energy response, fading, reproducibility, sensitivity and kinetic parameters of the deconvolved glow curve. It has also been found that moisture, pre irradiation annealing and particle size influence the TL properties

### Methods

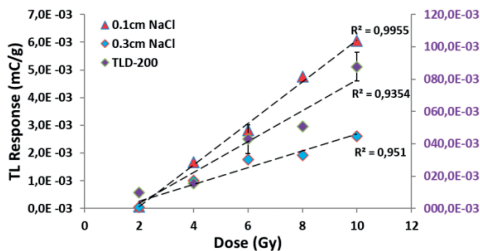
The natural Dead Sea NaCl used in present investigation has been provided by the University of Jordan. The samples have been prepared in pellet form, with thickness of 0.1 and 0.3 cm, and retained in containment together with silica gel to control the moisture content. Prior to irradiation, the sample have been annealed at 250 °C for a period of 1 hour in order to remove any residual irradiation memory, emptying the high temperature traps or interstitials. All samples have been irradiated at the Radiation Laboratory, Department of Physics, University of Malaya using a <sup>60</sup>Co gamma source; doses from 2- up to 10 Gy were delivered. After irradiation, NaCl samples have been stored in a black light-tight containment in order to minimize exposure to light. The TL was readout using a Harshaw TLD Reader Model 3500, 24 hours post-irradiation. Nitrogen gas was flowed through the sample chamber during the readout process in order to suppress light stimulation froiroxygen in aur and also to reduce the oxidation of the heating element and surface of the NaCl pellets. The time-temperature profile used in this readout



process was as follows: preheat temperature of 180°C for 5s; readout temperature is 400°C for 6 s with the heating cycle rate of 35°C/s

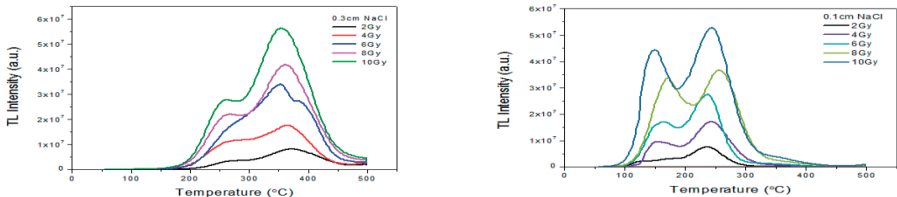
Results

In present study, increase in TL yield with dose remains linear over the range 2 Gy to 10 Gy (Fig. 1). Over the dose range 1-10 Gy for 0.1 cm thick NaCl irradiated with the <sup>60</sup>Co source, the TL light yield (in counts per second per unit mass of fibre, x 10<sup>-3</sup>) shows that the dose dependency is given by [(0.75 x absorbed dose, measured in Gy)-1.44], being 3 times greater than that of the 0.3 cm thick sample. It is also evident that TLD200 provides the basis for sensitive dosimetry throughout this range, producing a significant TL yield of 15% and 36% compared to that 0.1 and 0.3 cm thick NaCl, respectively.



**Figure 1** Observed dose response for natural Dead Sea NaCl of thickness 0.1 and 0.3 cm, in comparison with TLD 200 (with uncertainties quoted in terms of the standard error of the mean). The solid lines are least square fits to the data, obtaining correlation coefficients of 0.996, 0.951 and 0.935 respectively. (Note: the y-axis to the right represents the TL yield of TLD200; the error bars are smaller than the data points)

Figure 2 demonstrates the glow curve measured from 0.3 and 0.1 cm thick natural Dead Sea NaCl, respectively with two distinctive peaks. As expected the glow curve for 0.1 cm thick NaCl begins to rise at a temperature of 100 °C while requiring twice that value to initiate release of trapped electrons in the 0.3 cm thick sample. This shift in glow peak towards greater temperature for the 0.3 cm thick sample suggests need for the TL process to be interpreted in terms of second-order kinetics based on the one-trap one-recombination centre model, in which the electrons in traps are most probably re-trapped before final recombination.



**Figure 2** TL glow curves of 0.3 and 0.1 cm thick natural Dead Sea NaCl, respectively.

Conclusions

The natural Dead Sea NaCl are seen to offer favourable thermoluminescence performance, with dose delivery using a <sup>60</sup>Co source. Linearity in response is noted in the investigated range from 2 to 10 Gy. The medium offers a cheap method for production of a retrospective dosimetry system.

## Characterization of the Radioluminescence Response of P-doped Silica Optical Fibers under kilovoltage and Megavoltage X-rays

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### Introduction

Radioluminescence response of a P-doped silica optical fibre under kilovoltage and megavoltage X-ray radiation has been investigated. Doped silica glass provides significant radiation-induced luminescence to become effective dose-rate and total dose monitors. When drawn into fibres of sub-mm diameters, they provide excellent spatial resolution, particularly for applications in small-field radiation.

### Methods

P-doped silica optical fibers were fabricated using the Modified Chemical Vapour Deposition (MCVD) process in three concentrations of P-content in the core (1.30, 3.10, and 5.27 wt%). The radiation sensitive fiber strand (1cm length) was attached to 20m long PMMA (of 1mm diameter) plastic optical fiber, the arrangement being terminated at a remote readout unit. Measurements were made for exposure to 6MV and 10MV X-ray produced by Elekta-Synergy LINAC. The same were exposed to a 60 kV to 120 kV by Toshiba Rotanode diagnostic radiology X-ray. Data acquisition times (gate time) of 200ms and 500 $\mu$ s were used to capture real-time and time-resolved data from LINAC respectively. Gate time of 1ms was used during radiology X-ray exposures.

### Results

For LINAC, response to dose rates varying from 75MU/min to 600MU/min was observed to be linear ( $R^2=0.99$ ). Lowest concentration of P-content 1.30 wt% provided the highest light yield. Pulse-by-pulse dose measurements were successfully made for pulse rate frequencies (prf) 50, 100, 200, and 400 Hz. Energy dependence was observed for response at 10 MV, declining by ~4% from that at 6MV. For diagnostic radiology exposures, the energy dependence was much significant, but linear. Good agreement of the inverse square law for varying source-to-object distance was also observed.

### Conclusions

P-doped silica optical fiber is radiation sensitive over a wide range of energy from kV to MV of ionizing radiation. The linear response for dose-rate and energy variations ( $R^2>0.95$ ) make it a good candidate to be used with a fiber-coupled real-time dosimeter system.

## Study of a new multisphere neutron spectrometer printed on a 3D printer using ABS filament material

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### Introduction

Bonner sphere spectrometers (BSS) are widely used to measure neutron spectrum. BSS consist of a set of moderating high density polyethylene (HDPE) spheres of varying thickness with an active or passive thermal neutron detector in its center. 3D printers have allowed the fabrication of printed devices or objects at a very low cost. Filaments normally used in these printers are high hydrogen and carbon content materials, which can be used as neutron moderators. The aim of this work was to investigate the use of the acrylonitrile butadiene styrene (ABS) filament used by a commercial 3D printer, to manufacture a BSS system.

### Methods

The Monte Carlo N-Particle radiation transport code MCNPX, version 2.7.0, with ENDF/B-VII.0 nuclear data library was used to calculate the response functions of the BSS system printed with ABS filament material: ABS is  $(C_8H_8 C_4H_6 C_3H_3N)_n$  with a density of 1.02 to 1.07 g/cm<sup>3</sup>. We compared these response functions with those obtained with a previous Monte Carlo model of a BSS system manufactured by LUDLUM Measurements Inc., Model 42-5 with a <sup>6</sup>LiI(Eu) scintillator.

### Results

The mean values and interquartile ranges (IQR) of the response ratios HDPE/ABS were close to 3.7 for the spheres 2" and 3" and near 1.9 for sphere 5". For the spheres 5", 8", 10" and 12", the response functions from 1E-08 MeV to 1E+00 MeV are almost flat, which is a desirable behavior in the case of designing a neutron area monitor. Additionally, for the spheres 8", 10" and 12" there are not a so pronounced peak close to 1 MeV, as for the HDPE. These observations can be attributed to the lower hydrogen content of the ABS compared to HDPE.

### Conclusions

The response functions of spheres made with ABS have lower moderation performance in comparison with spheres made of polyethylene. However, results show the viability of producing low cost BSS system or neutron area monitors using 3D printers and adequate high hydrogen and carbon content material filament.



Wednesday May, 29



## Nanodosimetry – past, present, future

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The basic concept of nanodosimetry as a tool for the characterization of charged particle track structure dates back to 1975 [1]. With the advance of computational techniques, investigations of track structure in the 1990s were dominated by simulation approaches [2, 3], until around the beginning of this century experimental methods were developed that allowed track structure details to be measured in gas counters simulating target sizes of nanometric dimensions [4].

In the context of the European project BioQuaRT [5], an intercomparison of the three gas-counter nanodosimeters existing in Europe was performed and led to the discovery of a universal relation among the statistical parameters of the frequency distributions of ionization cluster sizes in different nanometric target volumes [6]. This universal curve showed also a close relation with the dependence of the yield of biological endpoints observed in cell irradiations by ions [6, 7]. Within BioQuaRT as well as in parallel, independent research, so-called multi-scale approaches encompassing micro- and nanodosimetry [5, 8, 9] have been investigated and the application of nanodosimetric track parameters in treatment planning has been explored [10, 11].

The current development of experimental nanodosimetry is characterized by endeavors to develop condense-phase nanodosimetric detectors [12], to measure correlations of track parameters for several nanometric targets in spatial proximity [13], and to extend microdosimetric measurements into the nanometer regime [14]. On the simulation side, the focus is on extending the concepts of nanodosimetry for use in clinical situations, e. g. by considering multi-target situations [15] or by developing 3D models of particle tracks from simulations [16]. An overarching challenge is the establishment of uncertainty budgets for nanodosimetric track structure parameters obtained by measurement [17] or simulation [18].

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## Think Like a Proton .... Stay Positive: Cutting Edge Ideas in Proton Therapy

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Proton beam therapy has many potential advantages over photon therapy for treatment of cancer therapy. The entrance dose is low, the exit dose is almost nonexistent, and most of the beam energy is deposited at a specified depth. But do these theoretical advantages translate into practical clinical ones? We will overview the pros and cons of proton therapy, and how “thinking positive” helps maintain a long-term perspective for better patient quality of life post radiation therapy. In addition, novel cutting edge techniques will be presented and how they benefit and improve proton therapy and reduce side effects of radiotherapy.

### *List of the Pros of Proton Therapy*

1. It provides precise radiation therapy. Proton therapy can provide extreme targeting of cancer cells that would normally be difficult to appropriately treat. It provides an option to treat tumors that are near vital organs or children who need their developing structures to be preserved.
2. It treats a comprehensive range of cancers. Compared to other treatment options, proton therapy is more of a universal option for those diagnosed with cancer. It is used to precisely target tumors and the match treatments to the exact size of the tumor.
3. It has a short life. Proton therapy has a low radiation risk compared to other radiotherapy treatment methods for cancer. After a treatment session, a patient can leave their treatment room without exposed others to radiation.
4. It can allow people to maintain an active lifestyle. Most people are able to maintain their activities while being treated with proton therapy. That includes being able to maintain their employment.

### *List of the Cons of Proton Therapy*

1. There are no comparative studies. No studies exist that appropriately compare proton therapy to traditional therapy options for treating cancer. In 2010, a report issued by the ECRI Institute concluded that proton therapy was only appropriate in about 15% of all cancer cases.
2. Dosing levels can be inconsistent. Individuals have different treatment needs. The lack of data with this treatment option is another concern. There are few best practices available with proton therapy simply because optimal dosing must come through a trial and error process.
3. It is costly. New proton centers cost between \$30million and \$225 million. The average cost of a facility that has 4-5 rooms can cost \$150 million. Even a single-suite option is upwards of \$30 million.



## Radiation-induced lens opacities among interventional cardiologists

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Low dose radiation effect on the eye lens has been an area of interest in numerous epidemiological studies. The radiation-induced risk has been assessed for different populations and in some cases, an attempt was made to determine a dose-response relationship. The European epidemiological study, EURALOC, was conducted between 2014 and 2017 with the objective to investigate a possible dose-response relationship by targeting a sufficiently large study population with reasonably high exposure levels, namely interventional cardiologists (ICs). In total, 393 subjects have been successfully recruited in the exposed group, they have completed study questionnaires on work history and risk factors for lens opacities and received an ophthalmological examination. As for the control group, 243 subjects have been recruited, completing the same questionnaire on risk factors for lens opacities and ophthalmological examination. Large efforts have been made to develop 2 approaches to assess retrospectively the cumulative eye lens doses of the recruited cardiologists. The first approach is based on the individual work history in combination with published eye lens dose data, while the second approach is based on individual routine whole body dosimetry and its conversion to eye lens dose. More than 200 dose measurements have been performed in clinical practice to validate both calculation approaches and this study demonstrated that the 1st approach resulted in the most satisfactory results with an average ratio between measured and calculated eye lens dose value of 0.96 [95%CI: 0.87-1.09] for the left eye and 0.50 [95%CI: 0.44-0.56] for the right eye. The added value of the EURALOC dosimetry approach is that for each IC, not a single dose value, but an individual cumulative eye lens dose distribution has been used as input for the statistical analysis of the risk of radiation-induced lens opacities. Innovative approaches have been used for the statistical analysis by using a mixed linear regression and polytomous logistic regression approach, which permit a correct modelling of the lens opacities by taking into account the correlation of the scoring outcomes of both eyes in the radio-induced risk estimation as well as dose estimation uncertainties. The analyses established a significant impact of radiation dose in the occurrence of PSC opacities with a relative risk for ICs of OR=2.41 (95%CI 1.23-4.69). A linear no threshold model provided the better fit of the lens opacities dose-response relationship with an excess relative risk per Gy equal to 0.88 (95%CI 0.15-2.01).

The research leading to these results has received funding from the European Atomic Energy Community's Seventh Framework Programme FP7/2007-2011 under grant agreement no 604984 (OPERRA: Open Project for the European Radiation Research Area).

## Quantification of X-ray methodologies and extraction of reliable and new insight

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X-ray standards have an extraordinary rich and long history, but there is need both for new standards and new applications of standards. Key markers historically have been Characteristic X-ray Spectra ( $K\alpha$ ,  $K\beta$  et seq.); Absorption K, L Edges; X-ray Absorption Near Edge Spectroscopy and X-ray Absorption Fine Structure. Applications have included for routine calibration and checking, for alignment and correction of systematics, for exotic high-accuracy experiments at advanced facilities, and for fundamental parameters work including for PIXE, EXSA and related applications. Recently critical needs and applications have been learned for Inelastic Mean Free Paths of electrons for electron microscopy, LEED, EELS, overlayer experiments and related fields, for stopping power and Monte Carlo transport codes and for Dosimetry. This presentation will give a brief overview of classes of knowledge which are needed, how to achieve the new understanding and methodologies, and a selection of what types of new insight can be reliably extracted. Effective dose is dependent upon this new understanding. This discussion and dialogue should be a core work, future endeavour and it should be a coordinated collegiate effort across Europe, Americas, Asia and Australia for example with both a coordinated drive and coordinated support both for laboratory facilities, standards facilities and exotic facilities.

## Patient dosimetry in neurointerventional procedures

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**Introduction.** Neurointerventional radiology procedures often require a long time to perform. Patient radiation dose is an important issue due to hazards of X-ray radiation. The aim of this work was to measure the entrance surface dose (ESD) in the patient during interventional neurologic procedure.

**Methods.** A batch of solid state dosimeters were used by mean of thermally stimulated luminescence (TSL) phenomena. Dosimeters were firstly calibrated being used. DTLS were placed around the patient head during interventional procedures. The entrance surface dose in the patient head was measured.

**Results.** The entrance surface dose in the patient head was measured, the higher dose is attributed the long fluoroscopic time spent during interventional radiological procedure. We fund high radiation dose on patient underwent treatment procedures.

**Conclusions.** Entrance surface radiation dose value should assist to develop guidelines on patient radiation dose levels and can be proposed for interventional neurological procedures. The results suggest the necessity of adopting strategies for radiation dose optimization during neurologic interventional procedures.

## Impact of imaging techniques on radiation dose during paediatric barium meal examinations

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### Introduction

Paediatric barium meal (BM) procedure is an examination that employs ionizing radiation and implies radiation exposure of children with doses that can be rather high. It is possible to reduce the dose values optimizing the technical parameters of the equipment that usually is not configured for paediatric imaging. The present work studied how the total dose received by the patient depends on frame rate, number of radiographic images, dose received in radiographic image production, kVp and mAs.

### Methods

This study was performed at one of the largest paediatric hospitals in Brazil. The procedures of 49 different patients (age: 0–16 years) were studied. The dose-area product was measured for each examination.

### Results

The dose-area product dependences on frame rate, number of radiographic images, dose received in radiographic image production, kVp and mAs during the fluoroscopy were constructed. These dependencies were compared with theoretical calculations.

### Conclusions

The frame rate is not a dominant factor in the dose increase. The number of radiographic images and the dose received during their production should be considered as a dominant factor in the dose increase. The radiographic techniques (kVp and mAs) should not be considered as a dominant factor in the dose increase.

## Evaluation reduction radiation dose of children with pelvic X-ray protection shieldings

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### Introduction

Lead is commonly used to shield children's gonad area during radiography; however, the image can be too obscure by lead gonadal shields to obtain sufficient diagnostic information so that re-taking the image is usually required. Therefore, bismuth shielding was evaluated for radiation protection, especially over pelvis radiography in this study.

### Methods

Optically stimulated luminescence dosimeters (OSLD) and CIRS ATOM Dosimetry Verification Phantoms were used to measure radiation dose. Pelvis radiographs with different shieldings both in materials and thicknesses were acquired and compared with those without shielding to explore the influence on image quality and the reduction of radiation dose.

### Results

Statistical analysis of the results indicated that 67.45% of radiation dose was reduced by traditional lead gonadal shielding whereas the reduction by one layer of bismuth shielding was 73.85%. The reduction increased to 81.06% after two layers of bismuth shielding were applied. When the gonad was shielded by three and four layers of bismuth shielding, respectively 86.50% and 97.68% of radiation dose were reduced. It is clear that the more layers of bismuth applied, the lower the radiation dose can be achieved. However, the image quality should be equally concerned in radiography. In this research, all the images were viewed and evaluated by three pediatric orthopedic practitioners separately. After carefully examined, the images with both one layer and two layers of bismuth shielding were confirmed to provide adequate diagnostic information whereas those with three layers or four layers of bismuth shielding failed to do so.

### Conclusions

In this study, application of bismuth shielding was found superior than lead shielding over gonad area during clinic radiography in providing better image quality and reducing the repetition of radiographic examination.

## A cautionary tale of an RPE raising concerns with hospital managers about doses to patients from x-ray medical exposures

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### **Introduction**

It is important that medical exposures, by far the largest artificial source of exposure of the world's population to ionising radiation, are justified and optimised. The European Basic Safety Standards Directive defines a "radiation protection expert" (RPE) as having the knowledge, training and experience needed to give effective radiation protection advice. This talk describes experiences of an RPE who was unfairly dismissed by hospital managers after raising concerns, after dose audits showed that radiation doses to patients from common x-ray procedures were substantially higher than national benchmarks.

### **Methods**

The RPE, in quietly raising these concerns through internal hospital channels, was seeking to promote the IAEA/WHO Bonn Call for Action, which seeks to improve radiation protection in medicine. He was seeking to introduce a dose management system, so as to be able to harvest digital dose information automatically, to significantly improve dose audits and support optimisation programmes for diagnostic x-ray exposures.

### **Results**

Newly-appointed relatively junior managers considered the RPE a troublemaker for raising these concerns. An employment dispute was engineered against him resulting in his dismissal. An employment tribunal confirmed that he had been unfairly dismissed. Both regulatory inspection and external review corroborated the concerns raised by the RPE. Nevertheless, despite this vindication, he has not been reinstated and has lost his career.

### **Conclusions**

This case illustrates the dangers of concerns about radiation doses being filtered and suppressed by managers with no scientific qualifications or relevant knowledge of radiation safety matters. The latent period between exposure and manifestation of biological effects and the statistical nature of stochastic effects increase the difficulty that RPEs may face when trying to improve radiation safety culture in an organisation resistant to messages that improvements are needed.

## IMPLEMENTATION OF EYE-LENS DOSIMETRY IN POLAND

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### Introduction

The eye lens is one of the most sensitive organ for radiation injury and exposure leads to radiation induced cataract. It has been seven years from the ICRP Statement on tissue reactions containing the recommendations for an equivalent dose limit for the lens of the eye of 20 mSv in a year for workers, and has been 6 years since Laboratory of Individual and Environmental Dosimetry provided eye lens doses measurement. Reduction of the limit for occupational exposure for the lens of the eye needs adequate approaches for eye protection and eye dose monitoring.

### Methods

The most accurate method for monitoring the equivalent dose to the lens of the eye is to measure the personal dose equivalent  $H_p(3)$  with a dosimeter worn as close as practicable to the eye. To measure eye lens doses in terms this quantity a dedicated dosimeter and the appropriate method has been developed in the largest dosimetry service in Poland. In measurements MTS-N (LiF: Mg,Ti) thermoluminescence detectors were used.

### Results

Results of measurements of  $H_p(3)$  from eye lens dosimeters (over 3000 readouts), issued in the years 2012–2017 were reported.

The frequency distribution of eye lens dose measurements performed using special dedicated dosimeters, via their  $H_p(3)$  operational values, over 3-month periods, after subtraction of natural background in 72% cases are below 0.1mSv. In case new operational quantity  $H_p(3)$  the percentage of workers, which exceed the new limit are 2%.

Our data show great differences on ratio between eye lens doses and doses on skin.

### Conclusions

The obtained dosimetry data could be used for epidemiological studies to assess retrospectively eye lens dose.

No meaningful correlation could be established between eye lens doses and skin doses.

Eye-lens dosimetry was introduced and implemented in Poland as a routine and accredited measurement for the PN-EN-ISO/IEC 17025 standard and became a routine method with fulfilled new requirements.





## Influence of environmental parameters on secondary cosmic ray neutrons at high-altitude research stations at Jungfraujoch, Switzerland, and Zugspitze, Germany

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### Introduction

The secondary cosmic ray (CR) neutron spectra in the atmosphere do not include many thermal and epithermal neutrons at energies below several eV. In contrast, close to the Earth's ground surface many more of those neutrons are present, due to albedo neutrons backscattered from the ground. The number of albedo neutrons is mainly determined by soil moisture and by snow cover.

To investigate this effect in detail, in June 2016 and September 2018 measurement campaigns were carried out at the High Altitude Research Station Jungfraujoch, Switzerland, in cooperation with the University of Bern. During these campaigns the energy distributions of secondary CR neutrons were measured at two different positions with different environmental conditions. The measurements were made at two different locations: under the cupola of the astronomical observatory in the Sphinx building (3,571 m a.s.l.) and below the shelter roof of the research station (3,466 m a.s.l.). Close to each of these two locations two neutron monitors (NM64 and IGY) are operated by the University of Bern.

Moreover, since 2004 continuous measurements of the energy spectrum of neutrons from the secondary CRs have been performed at the Environmental Research Station (UFS Schneefernerhaus; 2,650 m a.s.l.) close to the summit of the Zugspitze Mountain, Germany.

### Methods

An Extended Range Bonner Sphere Spectrometer (ERBSS) system was used which includes Ø 3.3 cm spherical <sup>3</sup>He proportional counters (type SP9, Centronic Ltd.) within 15 polyethylene spheres with different diameters from 2.5 to 15 inch acting as moderators and showing therefore specific energy responses to neutrons. Furthermore, two additional 9 inch spheres were used that include lead shells of different thickness to increase the response for high-energy neutrons ( $E > 20$  MeV).

### Results

The results of these measurement campaigns are presented and compared with those obtained at the UFS Schneefernerhaus. The different environmental conditions at the chosen measurement positions allow quantification of environmental conditions which affect the neutron spectral distribution in the whole neutron energy range from a few meV up to GeV. With this spectral information, it is also possible to derive detailed information about the neutron ambient dose equivalent ( $H^*(10)$ ) at these altitudes and geomagnetic latitudes.

### Conclusions

The ERBSS measurements at ground level presented here have shown that snow cover affects the fluence rate of secondary neutrons. This effect could be explained by seasonal changes of the amount of ground albedo neutrons (from thermal energies to several MeV) depending on the amount of snow and water in the environment surrounding the detectors.

## A statistical evaluation on the cosmic radiation doses on aircrews flying over South America and Caribbean regions

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### Introduction

There are substantial researches on the cosmic radiation doses received by aircrew on their typical flight workload. Most part of these studies was made by measurements onboard aircrafts of some specific companies in established routes. A recurrent question from countries over South America and Caribbean regions is related on the significance of doses accumulated by aircrews over this region and if those magnitude justifies a specific radiation protection procedure.

### Methods

The evaluation was made by statistical analysis using CARI-6 aircrew radiation dose code and the data are derived from comprehensive records of registered flights performed in the South America and Caribbean airspace between 29,000 and 41,000 feet, performed from March 7 to 20, 2009. The analysis of this sample was composed of 80,548 route calculations totalizing 53,163 hours of real flights, by means of calculation of each track performed by aircrafts between aeronautic navigation waypoints.

### Results

The analysis identifies that the typical group of flight crew operating over this region receives mean dose rates ranging from 2.65  $\mu\text{Sv/h}$  to 2.95  $\mu\text{Sv/h}$  depending on the solar cycle. This distribution, integrated over typical workload from Brazilian aircrews results on annual doses ranging from 1.45 mSv to 1.67 mSv.

### Conclusions

The results demonstrate that the typical aircrew flying over this region exceeds the annual radiation limit for public (1 mSv). The statistical analysis also shows that this is the case of more than 96% of the aircrew flying with this flight routine and workload. The presented results can be used by local authorities of countries over this region as a basis to evaluate the convenience on adoption the recommendation from ICRP Publication 132 regarding radiation protection recommendations for aircrews.

## Prediction of Light Pulses' Number Caused by Cosmic Radiations at Aircraft Flight Altitudes

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### Introduction

Part of the air framers daily work is to focus on improving the aircraft reliability, safety, energy efficiency, and reducing the aircraft weight. One of the reasons why these goals are important to achieve is that the aerospace industry is going towards more electrical aircraft, as well as composite fuselage. Moreover, aircraft systems' electronic components are more and more miniaturized, making them more sensitive to any type of radiations; one of which is cosmic radiations. In order to ensure that future systems remain protected against cosmic radiations (single events), aircraft manufacturers must collect in-flight cosmic radiations data that will help certification authorities to come with new requirement for systems qualification against that threat. Those data will also contribute to develop a global strategy for real-time processing, and help the pilot to make the right decisions in case of unusual high cosmic radiation exposure during the flight. In that perspective, Bombardier has launched a cosmic radiation measurement campaign. A plastic scintillator is used to measure the cosmic radiation particles based on the aircraft geographical position. Those measured particles are then used to predict the number of induced light pulses.

### Methods

This article compares two different prediction models for real time analysis. The first one is based on a linear function called Arimax (Box-Tiao), while the second one uses a non-linear, neural-networks based function. The methodology of predication for the complete flight route relies mainly on the light pulses that were calculated based on the recorded altitude, latitude, and longitude positions of the aircraft early flight route. These calculations should be processed in real time.

### Results

The presented results have shown that both prediction models are quite acceptable when compared to the entire set of measurements, leading to a coefficient of determination value of more than 90 %.

### Conclusions

The results show that the proposed methodology is accurate enough to predict the number of light pulses caused by cosmic radiation at different aircraft altitude, latitude, and longitude.

## Internal radiation dose assessment for the public based on the environmental radioactivity data in Portugal

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### Introduction

To verify compliance with Articles 35 and 36 of the EURATOM treaty, Portugal as Member State, undertakes a radiological environmental monitoring programme to determine the radionuclides concentration in environmental media (air, water, soils, etc.) and foodstuffs and to provide information and data for dose assessment to the population, through the exposure pathways (external and internal). To assess the dose due to internal exposure it is necessary to know the radionuclide concentration that is incorporated into the human body by inhalation (air) and ingestion (water and foodstuffs). The annual effective dose due to inhalation and ingestion of artificial radionuclides in these components for three age categories (infant, child and adult) of the Portuguese population was estimated and was compared with the dose limit to the public.

### Methods

Aerosol samples (filters), drinking water and foodstuffs were collected, prepared in the laboratory and the radionuclide activity concentrations determined by gamma-ray spectrometry (<sup>137</sup>Cs), gas flow proportional counting (<sup>90</sup>Sr) and liquid scintillation counting (<sup>90</sup>Sr, <sup>3</sup>H). The effective dose was assessed taking into account: i) the concentration of the radionuclide in each matrix; ii) the inhalation rate or the annual consumption rate; iii) the inhalation or the ingestion dose coefficient of the radionuclide considering the category of the member of the public.

### Results

The results for the year 2017 shows that the activity concentrations for <sup>137</sup>Cs, <sup>90</sup>Sr and <sup>3</sup>H in the different components are in general very low being the majority of the results below the minimum detectable activity (MDA). Taking into account a conservative perspective for the effective dose calculation, the maximum value, which could corresponds to the higher MDA value, of each radionuclide in each component was used. As an example, dose values lower than 1.9, 1.2 and 0.8 µSv/year were obtained for <sup>137</sup>Cs and <sup>90</sup>Sr in infant, child and adult respectively, due to milk ingestion.

### Conclusions

The annual effective dose due to inhalation and ingestion of artificial radionuclides for three age categories (infant, child and adult) corresponds to less than 1% of the dose limit for public exposure, 1 mSv/year.

Study of the influence of radon in water on radon levels in air in a closed location

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Introduction

Radon is a radioactive gas that comes from radium decay. It is considered the first cause of lung cancer in non-smokers, classified as a carcinogenic element by the WHO. Due to its gaseous nature it comes from the soil and it is transferred to water and air where radon could reach high concentrations in closed locations. The main objective of this work is to analyze the possibility that radon in water diffuses into air and how this process occurs.

Methods

Initially sampled water had been enriched from a radon source by a hermetically sealed equipment. When stable concentration values have been achieved, the experimental equipment is extended and a free space is left inside it for the air. Measurements for radon in air and in water are taken simultaneously through continuous monitors in order to know if there is a correlation between both and in what proportion it diffuses from one medium to the other. All results are compared with the field measurements. Likewise, all of them are contrasted with legislative limits set at Directive 2013/51/EURATOM.

Results

Obtained results are shown in the following Table 1.

Table 1. Measured values for radon concentration in water and in air

Code	Radon concentration in water (Bq·L <sup>-1</sup> )	Radon concentration in air (Bq·m <sup>-3</sup> )
P1	27 ± 1.9	4702 ± 249
P2	41.5 ± 2.8	677 ± 34
P3	34 ± 2.2	634.30 ± 43
P4	20.9 ± 4.2	292.30 ± 27.38
P5	14.9 ± 3.5	273.80 ± 26.65
P6	17.6 ± 3.8	251.60 ± 24.80
P7	14.6 ± 3.2	240.50 ± 24.42

There is a possible correlation between radon concentration in water and in air for a closed location.

Conclusions

From radon samples in water and air it is verified that there is a correlation between both. Radon concentration in water, even below the legislative limit, imply radon values in air above the permissible levels set at Directive 2013/59/EURATOM.

These results demonstrate prove the need to continue making new measurements in order to allow knowing in what proportion radon is transferred from water to air.



## Determination of X-ray tubes radiation beam characteristics with silicon semiconductor detectors

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### Introduction

X-ray tubes belong among the most important sources of ionizing radiation and are used in various applications and methods, i.e. investigation of materials, diagnostics in medicine, irradiations, etc. The exact properties of X-ray sources or their X-ray beams must be known also when Monte Carlo simulations of experimental setups are considered with the aim of optimization or calibration of X-ray systems. These properties are X-ray spectra, beam profiles, divergence and homogeneity of beams.

### Methods

Properties of low power X-ray tubes with the maximum voltage up to 50 kV were investigated in this study. These X-ray tubes included small laboratory X-ray tubes with collimated X-ray beams and microfocus X-ray tubes with polycapillary focusing optics. Spectral characteristics of X-ray beams were determined with silicon drift detectors (SDD), whereas beam shape features were reconstructed from a silicon pixel detector response.

### Results

The pixel detector was inserted into X-ray beams at different distances from X-ray sources which were operated at different voltages. Beam 2D profiles were obtained and since the pixel detector works in a single event detection mode, approximate energy of individual photons can be measured besides the position of their detection. X-ray spectra were also measured with a standard SDD.

### Conclusions

We have described and demonstrated, how several parameters of X-ray beams can be determined using one common semiconductor detector (SDD type). When detailed profile of the beam is required, the silicon pixel detector can provide this information. It has high resolution in the order of tens of micrometres, but its abilities to determine spectral properties of the beam are worse in comparison with the SDD.

## Characterization of a TLD100-HARSHAW in the low energy range using the Monte Carlo method

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### Introduction

TLD100 are widely used for personal dosimetry with reliably results for Hp(10) and Hp(0.07) in mixed photon/electron fields. In the Universitat Politècnica de València (UPV) the TLD100 is used to assess the official personal dosimetry of the professionally exposed workers. One of the most important characteristics of these dosimeters is the energy and the angular dependence (response function).

### Methods

The MCNP6 code has been used to implement a Monte Carlo model of the TLD100-HARSHAW including a collimated point source and a water phantom. Tallies F4 (particle fluency, 1/cm<sup>2</sup>), F6 (Energy deposition in a cell, MeV/g) and \*F8 (Energy, MeV) have been applied to calculate the air kerma and the equivalent dose. This model allows obtaining the relative response energy (RRE) function normalized to <sup>137</sup>Cs. Furthermore, the RRE functions are affected by the incident beam angle. The validation of the model is carried out by comparing simulated and experimental data using different X-ray beam qualities (N-40, N-80, N-100, <sup>137</sup>Cs, <sup>241</sup>Am and <sup>60</sup>Co) according to the ISO-4037-3.

### Results

A detailed analysis of the crystal response in an energy range between 30-1000 keV is performed. Accordingly, RRE functions for different quality beams and incident angles are obtained. Using tallies F6, F4 and \*F8, the air Kerma and the dose have been calculated for Hp(10) and Hp(0.07). Results show different behavior when analyzing the ratio Hp(0.07)/Hp(10), normalized to <sup>137</sup>Cs, for energies lower and higher than 100 keV. Moreover, it has been noted that the reproducibility in the experimental measurements is not well established in the energy range 50-100 keV. The MCNP6 code along with experimental measurements is used to analyze this behavior.

### Conclusions

The MCNP6 allows obtaining the response functions of the TLD100-HARSHAW for different irradiation conditions, being a powerful tool to study the reproducibility of the experimental measurements for energies lower than 100 keV.



## Dose assessment and reconstruction algorithm optimization in simultaneous breast and lung CT imaging

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### Introduction

Cancer is the second leading cause of death in the world, and therefore, there is an undeniable need to ensure early screening and detection systems worldwide. The aim of this project was to study the feasibility of a Cone Beam Computed Tomography (CBCT) scanner for simultaneous breast and lung lesion imaging. Additionally, the development of reconstruction algorithms and the study of their impact to the image quality was considered.

### Methods

Monte Carlo (MC) simulations were performed using the PENELOPE code system. A geometry model of a CBCT scanner was implemented for energies of 30 keV and 80 keV for hypothetical scanning protocols. Microcalcifications were inserted into the breast and lung of the computational phantom (ICRP Adult Female Reference), used in the simulations for dose assessment and projection acquisition. Dosimetric and imaging performances were evaluated through Computed Tomography Dose Index and Catphan phantoms, respectively. Reconstructed images were analyzed in terms of Contrast-to-Noise Ratio (CNR) and dose calculations were performed for two protocols, using a normalization factor of 2 mGy in the breast and another with 5 mGy in the lungs.

### Results

MC geometry model and reconstruction algorithm were validated by means of on-field measurements and data acquisition in a clinical center. Results indicate that for both protocols, the absorbed dose in both organs is the same, allowing the optimization of protocol strategies regarding radiosensitive organs. The best implementation of the reconstruction algorithm was achieved with 80 keV, using linear interpolation and hanning filter. More specifically for a spherical lung lesion ( $r = 7$  mm) a 30% CNR gain was found when the number of projections varied from 12 to 36 (corresponding to a dose increase of a factor of 3).

### Conclusions

This study suggests the applicability of a CBCT modulated beam scanner for imaging simultaneously breast and lung lesions while ensuring dose reduction without compromising image quality as a possibility.

## Determination of absorbed dose in eye lens due to therapy of I-131 using MCNP5

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### Introduction

I-131 is a radioactive isotope used as an internal radiotherapy treatment for thyroid cancer, which is most common in woman. In this therapy I-131 circulates throughout the bloodstream where cancer cells absorb the iodine to finally be eliminated by the radiation action. However, critical organs are also affected, so it is necessary to perform internal dosimetry in order to analyze the risks and benefits for the patient. Consequently we simulate the transport of radiation to determine the absorbed dose in lens due to its high radiosensitivity and proximity to the thyroid.

### Methods

In this work we used a mathematical phantom for head and neck based in the phantom BOMAB, and Monte Carlo code MCNP5 to simulate a source of I-131 located in the thyroid in order to calculate the absorbed dose in the lens through the Tally \*F8.

### Results

The results of the simulation show that the lens receives an absorbed dose of  $30 \pm 4\%$  mGy for an irradiation of 8 hours with 150 mCi in I-131 treatment. These results are in agreement with those reported by other authors.

### Conclusions

The dose absorbed by the lens is within the limits established by the ICRP. However, it is necessary to improve the model to obtain results more faithful to reality.

## Shielding Design for the Kansas State University Materials Interrogation Test Facility

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### Introduction

Large radionuclide sources pose a potential threat if accidentally or intentionally released into the environment. Kansas State University is part of a consortium that is investigating ways to replace dangerous radionuclides with machine sources, such as those commonly used in the oil well logging industry.

### Methods

As part of this research, the Kansas State University Materials Interrogation (KSUMI) facility, which mimics a borehole environment, has been designed and constructed. The facility includes a chamber that is 6.5 ft. wide by 6.5 ft. tall and 8 ft. deep with a horizontal 8 in. inner diameter aluminum pipe that extends the depth of the chamber. The chamber can be filled with a variety of materials, both liquid and solid. Various sources and detectors can be inserted into the horizontal pipe for both active and passive testing.

### Results

The MCNP6 code was used both to design an oil well logging benchmarking tool and to conduct shielding studies of the facility. Point detectors were simulated at key points inside and outside of the laboratory space to estimate the dose rate with a deuterium-tritium (DT) neutron generator capable of producing  $10^8$  neutrons per second in the benchmarking tool.

### Conclusions

As a result of the simulation studies, appropriate shielding was introduced to the KSUMI facility to keep dose rates at acceptable levels. Results of these shielding studies and lessons learned are presented.

## An Atomic Physics perspective on targeted therapy with Auger emitting radionuclides

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**Introduction:** Most of the radionuclides used in Nuclear Medicine for diagnostic and therapy purposes take advantage of the ionization properties of the gamma and X-rays emitted in the decay process of these isotopes. The X-ray emission competes with the Auger process by which an electron from an outer level fills a vacancy in an internal level and an external electron is emitted. As this process propagates from the inner level vacancy to the outer level, a cascade of X-ray and Auger emissions is formed. These Auger electrons have a very low energy but a very high linear energy transfer (LET). Due to their ability to cluster a large number of ionizations in a very short range, it has been studied the use of biomolecules bound with Auger emitters radionuclides to induced radiation damage in the vicinity of the DNA structures [1-3].

**Methods:** Current Auger spectra data [4] from radionuclides relevant for target therapy is based on the EADL [5] values of atomic transition amplitudes. These amplitudes were calculated in the framework of the independent particle model (IPM) underlying the Dirac-Hartree-Slater approach. This approach is known to give incorrect values for the outer shell transitions from where the very low energy Auger electrons are produced. In this work we used the multi-configuration Dirac-Fock method [6] to compute the Auger transition amplitudes for selected radionuclides. This approach accounts for electronic correlation. The dose at the DNA scale was simulated using the Monte Carlo code PENELOPE [7] to simulate the energy deposited in simplified cell model.

**Results and conclusions:** The MCDL to EADL ratio of transition amplitudes show differences up to 20% for the low energy transitions (high-LET). The simulations performed with this new data seem to indicate that these differences might have some impact inside the cell nucleus in the range of 0-1  $\mu\text{m}$ .

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## Diagnostic Reference Level for Computed Tomography Examinations In Sudan: A Multicentre Study

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### Introduction

Computed tomography (CT) imaging represents one of the largest sources of medical diagnostic ionizing radiation exposures to patients. As with other such clinical procedures, it is recommended to adopt diagnostic reference levels (DRL) in pursuit of optimized patient doses, eliminating unnecessary exposure. Present study has made evaluation of patient exposures received during CT procedures, seeking to establish a national DRL in Sudan for the particular technique.

### Methods

A total of 677 patients were examined in this study, involving 17 radiology departments equipped with different calibrated CT modalities. The patients were examined for head, chest, abdomen and pelvis issues. Patient weight and age ranges were 65- to 75 kg and 18- to 70 years respectively.

### Results

The radiation dose ranges for head, chest, abdomen and abdomen-pelvis were 831 mGy.cm to 1687 mGy.cm, 126 mGy.cm to 1104 mGy.cm, 1331 mGy.cm to 3172 mGy.cm and 370 mGy.cm to 1686.91 mGy.cm in that order. The mean and range of CTDIvol for head, chest, abdomen and abdomen- pelvis were 66.8 (31.0-225.0), 477.2 (3.0-20.0), 28.2(3.0-13.0) and 26.0 (4.0-80.0) correspondingly.

### Conclusions

Patient doses during CT procedures are seen to vary both between departments and within the same department, wide variation in technical settings suggesting need for staff training in CT dose optimization techniques. The patient doses observed herein are greater than that typically seen in other studies worldwide. DRLs are proposed for all of the investigated CT procedures.

## Assessment of imaging protocol and patient radiation exposure in pediatric computed tomography angiography

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### Introduction

Computed Tomography Angiography (CTA), which is noninvasive imaging procedure, frequently used for the diagnosis of blood vessels diseases. Due to advancement in CT equipment, shorter exposure time enabled accurate imaging of cardiovascular system. Pediatric patients are more sensitive to radiation than adults due to their rapidly dividing cell and long life expectancy. Thus, evaluation of pediatric exposure is crucial to ensure that the procedure is justified and the practice is optimized. The objective of this study were to evaluate pediatric patient's exposure and imaging protocols for different CTA procedures and to estimate the organ dose and cancer risk.

### Methods

A total of 147 pediatric CTA procedures were performed at king Fahd Medical City using 3 CT modalities (Philips Brilliance CT- 64 slice scanner, Siemens Somatom Definition Flash – 128 slice scanner- dual source and GE 750HD DISCOVERY-64slices-Dual energy. The image protocols and patient safety measures were evaluated according to the American college of radiologist (ACR) criteria. Ethics and Research committee approved the study and informed consent was obtained for child parents.

### Results

The mean patient dose for Circle of Willis (COW), carotid arteries, thoracic and abdominal aorta (TAA) and heart and vessels were  $992 \pm 798$  (204-2829),  $285 \pm 157$  (56.7-652),  $500 \pm 457$ , (112-1387) and  $229 \pm 197$ , (46-761), respectively. Pediatric average radiation risk is  $92 \times 10^{-5}$ .

### Conclusions

Patients' doses showed wide variation among the three CT modalities and even at the same machine and the same clinical investigation. The dose per procedure is higher compared to the previous studies suggesting that the dose is not optimized yet. Protection of radiosensitive organ is highly recommended for pediatric patients. A written protocol for pediatric patients is recommended to ensure that unnecessary exposure is eliminated.

## Dose Evaluation of a <sup>137</sup>-cesium source exposition using a solid water phantom

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### Introduction

Dose values in radiotherapy patients are important so that the treatment is efficient according to the protocols defined for each patient. Dose fractionation is often used in radiotherapy treatments and doses lower than those defined as therapeutics may be inefficient, as higher doses can cause injury and burns. Dosimetric films are often used for dose recording in radiotherapeutic processes and the calibration of these films must be performed so that they can be used as dosimeters.

### Methods

A phantom made of two solid water plates was used in exposures from a cesium-137 source. This phantom was placed 1,0 m from the source and a cone collimator with a diameter of 2.48 cm was used to limit the gamma beam. Radiochromic film sheets were used to record isodose curves at the frontal surface and 1 cm deep when the phantom was irradiated frontally. To obtain the dose variation in depth a second irradiation was done in lateral beam incidence in the phantom. The experiments were carried out at the Calibration and Dosimetry Laboratory (LACD) of the Nuclear Technology Development Center (CDTN) where Grafchromic EBT QD+ films were exposed to Entrance Kerma value of 2 Gy.

### Results

The images obtained from the film sheets allow obtain three curves to observe the absorbed dose variation: in the central longitudinal axis, to observe dose variations deep; dose variations in axial axis in at the entrance (around 2 Gy) and 1 cm deep where the dose recorded reached around 2.5 Gy.

### Conclusions

The obtained absorbed dose curves allow to observe dose variations at the entrance and 1 cm depth where the dose was higher than in the entrance, The increase of the absorbed dose initially happens in the depth and then reduces considerably with the beam penetration into the solid water phantom.

## Feasibility study on quality assurance of THOR-BNCT performed with TEPC

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### Introduction

In Taiwan, the use of Tsing Hua Open-pool Reactor (THOR) for boron neutron capture therapy (BNCT) has entered the second phase of clinical trials, patients need to check the neutron beam intensity and quality before treatment. Because the dual ion chamber and neutron activation analysis adopted by the quality assurance are time-consuming and complicated. The tissue equivalent proportional counter (TEPC) is usually used to measure the beam quality of different LET radiation, and also to measure the energy deposition characteristics. TEPC can simultaneously measure the dose contribution of different LET radiations in the mixed radiation field. This study evaluated the feasibility of TEPC for BNCT beam quality assurance to improve and simplify BNCT operations.

### Methods

This study used a self-made TEPC, which consists of a 2.5 cm diameter Rossi-type microdosimeter. TEPC filled with 32 torr propane-based tissue equivalent gas to simulate a 2  $\mu\text{m}$ -size cell. A built-in americium-241 ( $^{241}\text{Am}$ ) source used for energy calibration. Equivalent dose estimated by the TEPC is based on simultaneous measurement of absorbed dose and the average quality factor. TEPC with and without boron cover were considered to exclude and include thermal neutrons from the BNCT beam. In order to verify the doses of photon and neutron, TEPC was calibrated by the X-ray and californium-252 ( $^{252}\text{Cf}$ ) fields. The TEPC was placed in the same measurement position as the ion chamber and the activation detectors to measure the doses contributed from the photon, thermal neutron and fast neutron.

### Results

The neutron and photon doses measured by the TEPC were both within 15% difference compared with given X-ray and  $^{252}\text{Cf}$  irradiated doses. TEPC can provide good agreement with irradiated doses, because it can effectively measure low or high LET radiation and can measure the neutron radiation almost in the all-energy domain. The factors of dose-to-fluence corresponding to ion chamber and activation detectors were derived and indicated in this work.

### Conclusions

This study used TEPC to perform the dose analysis and verification in the X-ray and  $^{252}\text{Cf}$  field, the results showed good agreement with irradiated doses. By means of the derived factors of dose-to-fluence, TEPC measurement can instead of current beam quality assurance methods to improve and simplify BNCT operations.



## Monte Carlo study of the potential reduction in out-of-field dose using a flexible neutron absorber in single-ring wobbling proton therapy

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Proton radiotherapy represents a potentially significant advance in cancer therapy which allows the patient to live for a longer time. In the broad-beam methods such as the beam-wobbling and double-scatterer methods, resulting in an extra whole-body high-energy neutron dose, primarily from proton interactions with the final collimator. These exposures provide no known benefit and may increase a patient's risk of developing a radiogenic second cancer. It is essential to reduce the undesired secondary neutron exposure without influencing the clinical beam. This study aimed to explore strategies to reduce stray neutron radiation by simple modifications of the nozzle assembly. A Monte Carlo study with the PTSim and TOPAS was performed by assuming the beamline at the proton therapy center of Chang Gung Memorial Hospital. At first, we investigated the change of the neutron spectral fluence with various neutron absorber. Next, we investigated the reduction in the equivalent dose with an additional shield. The results of the additional shield are beneficial to reduce the neutron dose at positions farther than 20 cm from the field edge and without influencing the primary beam used in wobbling proton therapy. This study provides essential information for re-optimizing the arrangement of beamline devices.

Analysis of *Hp*(0,07) readings measured above the lead apron

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Introduction

The 2013/59/EURATOM establishes a new limit for the equivalent eye lens dose of 100 mSv in 5 years. IAEA accepts the use of a dosimeter above the lead apron as an estimator of the eye lens. The Spanish National Dosimetry Centre (CND) has been providing lead apron dosimeters since 1985. Currently there are 384 dosimeters distributed to 22 hospitals in different locations in Spain (>4500 annual readings).  
In order to evaluate the implications of the reduction of equivalent eye lens dose limit for exposed workers in sanitary environments, the monthly measurements of these dosimeters, mostly used by interventional, hemodynamics and vascular personnel, are analysed to provide an overview of the superficial doses received above the lead apron and its possible implications.

Methods

We extracted the *Hp*(0,07) values for all lead apron dosimeters with doses >0.1 mSv (the detection limit in CND) used by the wearer for only 1 month since 2013. We analysed 6776 values separately for three categories: physicians, nurses and technicians. To estimate the doses near the eye lens, all readings were multiplied by a geometrical factor of 0.75 (Clerinx et al. 2008).  
To prevent workers from exceeding the new dose limit, a monthly dose fraction of 1,7 mSv was considered.

Results

The table shows the percentage of health workers that wear lead apron dosimeters analysed and the percentage of dose readings that exceed 1,7 mSv. Approximately 1/3 of the physicians and 1/10 of the nurses analysed receive considerable doses.

	Total	>1,7 mSv
Physician	55.0%	15.64%
Nurse	37.4%	2.73%
Technician	7.6%	0.03%
	100%	18.40%

Table 1 Percentage of *Hp*(0,07) readings that exceed the monthly dose fraction

Conclusions

A significant amount of lead apron dosimeters receives monthly doses in excess of the monthly fraction of the dose limit. Workers and radiation protection experts need to be aware of the risks and the safety measures that can be implemented, such as leaded glasses and screens.

## Evaluation of the mean glandular dose and irradiation parameters in digital mammograms of patients with breasts with sparse fibroglandular densities

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### Introduction

This study aims to evaluate the mean glandular doses and to correlate them with the irradiation parameters during the digital field mammograms performed in patients with breasts of mammary parenchyma b, according to the BI-RADS® 5th edition.

### Methods

This study was conducted with 103 digital mammography images performed at a radiological clinic Curitiba, Paraná, Brazil. The mammographic exams were performed in a digital mammograph. Data such as age, BMI and the parameters used to perform the radiographs (kVp, mA, filter, breast thickness, compression force and mean glandular dose indicated in the equipment) were collected. Two radiologists performed the image analysis and performed the classification of mammary densities, in correlation with the ACR BI-RADS® 5th Edition. In this study, only breast images classified as category b were considered.

### Results

The age range of the patients varied from 34 to 81 years (mean of 57.5 years), BMI in the range of 19.8 to 36.4 kg/m<sup>2</sup> (mean of 28.15 kg/m<sup>2</sup>). The results showed that the radiographs were performed with voltage (kVp) ranging from 26 to 34 kVp (mean of 30 kVp), current between 100 to 190 mA (mean of 145 mA). The compressed thickness of the breast ranged from 2.2 to 9.4 cm (mean of 5.8 cm). For breast thicknesses below 7.0 cm a Rh filter was used and above 7.0 cm a Ag filter was used; the compression force ranged from 3.3 to 16.0N (mean of 9.65N) between 0.079 to 3.3mGy (mean of 1.69mGy).

### Conclusions

The study found BMI corresponding to overweight patients, wide variation of breast thickness, lower values of the compression force compared to the recommended parameters of the ACR, European guidelines and variation in the mean glandular dose. The characterization of the technical parameters in total field digital mammography in correlation with the categories of mammary composition, may contribute to the management, optimization of the exposure doses and image quality.

## Nuclear medicine in the Russian Federation at last decade: structure and doses

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**Introduction.** Over the past decade the nuclear medicine (NM) in Russia has been changing very quickly: the obsolete diagnostic equipment was replaced by modern gamma cameras, almost every NM department was equipped with SPECT and SPECT/CT scanners, about 30 new PET centers and satellite PET diagnostic departments were commissioned. The present research is aimed to examine the current state and trends in the NM development in the RF and observe the patient doses.

**Methods.** The statistical data of the Ministry of Health (form 30) on annual medical procedures, and data of the Sanitary-Epidemiological Service on doses of medical exposure (form 3-DOS) in RF were analyzed for the period from 2008 till 2017. Furthermore, detailed data on the number of examinations, used radiopharmaceuticals, input activities were collected in 42 NM departments and 14 PET diagnostic departments from 17 regions of the RF.

**Results.** The number of NM units and examinations decreased within the first decade of the XXith century in Russia, and it stabilized at the level of  $500 \pm 30$  thousand examinations annually between the years 2010-2017. Collective dose (CD) for Russian population from NM diagnostics decreased from  $2000 \pm 100$  Man·Sv in 2006 to  $1100 \pm 50$  Man·Sv in 2011-2013, then the CD began to increase, and in 2017 it was estimated as 2000 Man Sv. The mean dose per NM examination increased within four years from 2.5 to 3.9 mSv, 3.5 NM procedures per 1000 people were performed in 2017. Patients' effective doses for most examinations lie in the range from 1 to 4 mSv. The structure of radionuclide examinations changed in the past decade: the proportion of radiometric studies of kidney and thyroid decreased in 5-6 times from 30% to 5-6%; the number of image examinations of bones, whole body increased to 50-55 %, lungs, liver, and heart studies remained at 4-5% each. The structure of the NM examinations reflects the technical renovation of the NM units. The proportion of high-dose PET/CT examinations has increased to 10% of all NM procedures; more than 90% of them were whole body studies with  $^{18}\text{F}$ -FDG with average patient dose about 17 mSv. 60-70% of the received dose was due to X-ray CT. In multiphase CT scanning with contrast, dose increases dup to 25-30 mSv and contribution of CT increases to 80%.

**Conclusions.** The collected data demonstrate the increase of patient doses in the NM diagnostics that can be explained by the rapid introduction of high dose PET/CT methods into medical practice. Standardization of protocols, development and introduction of DRL, especially in CT part are the reliable way to optimize PET/CT examinations in Russia.

## An extrapolation chamber for the establishment of a primary radiation standard in $^{85}\text{Kr}$ and $^{147}\text{Pm}$ beta radiation beams

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### Introduction

At the Calibration Laboratory (LCI) of the IPEN/CNEN, studies are in development on the establishment of the Böhm extrapolation chamber model 23392 as a primary standard system for the dosimetry and calibration of beta-radiation sources and detectors. This chamber was already characterized at the LCI in  $^{90}\text{Sr}/^{90}\text{Y}$  beams using two different entrance windows: one of aluminized Mylar and another of Hostaphan. This extrapolation chamber was characterized in  $^{85}\text{Kr}$  and  $^{147}\text{Pm}$  beams. All tests were carried out with the reference  $^{90}\text{Sr}/^{90}\text{Y}$  source, for comparative purposes.

### Methods

A Keithley model 6517B electrometer was used for the measurements. The utilized radiation sources are part of the Beta Secondary Standard BSS2. Moreover, the Monte Carlo code MCNP5 was used to determine the absorbed dose rates and to compare them with the experimentally determined dose rates and with those from the PTB calibration certificate.

### Results

Saturation curves, ion collection efficiency, ion recombination, polarity effect, response stability, real null depth, linearity of response, variation of response as a function of source-detector distance, extrapolation curves, correction factors and absorbed dose rates were obtained. The ion collection efficiency was greater than 99%; the ionic recombination was less than 1%, and the polarity effect was greater than 1%. The stability of the response was lower than 0.15% for the repeatability test, and it was less than 0.36% for the reproducibility test. The difference between the experimental absorbed dose rates and those from the Monte Carlo model, compared to those from the calibration certificate, was less than 1.9% for all sources.

### Conclusions

All results of the performed tests are within the limits of the international recommendations. The results for the  $^{90}\text{Sr}/^{90}\text{Y}$  source were in the good agreement with previous works performed at LCI. These results are suitable for the establishment of a primary standard for beta radiation.

## Evaluation of various head flexion angles in hippocampal-avoidance whole-brain radiotherapy using volumetric modulated arc therapy

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### Introduction

Whole-brain radiotherapy (WBRT) with hippocampal avoidance improves neurocognitive function deterioration. To improve both planning and treatment efficiency, we investigated the feasibility of using the coplanar volumetric-modulated arc therapy (VMAT) technique with various head flexion angles for hippocampal avoidance during WBRT.

### Methods

Six patients with brain metastases were selected for study. We rotated patient CT images by 90° and changed the couch angle to simulate different head flexion angles. The VMAT treatment plans of each patient were computed under various head flexion angles using the Eclipse Treatment Planning System.

### Results

The plan with a head angle of 0° had the lowest PTV coverage and the highest normal organ dose. When the angle was equal to or greater than 15°, the maximum dose of the hippocampus and the PTV  $V_{30}$  met all dose constraints. The results obtained with head angles equal to or greater than 25° were better than those obtained at angles below 25° with the obviously decreased dose of the bilateral lenses.

### Conclusions

The study demonstrated that 15° is the minimum head flexion angle that should be adopted in clinical practice. For better dose coverage and uniformity for whole-brain PTV and dose reduction of critical organs, the study results suggested utilizing a head angle equal to or greater than 25°, while ensuring that patient comfort is maintained with larger head flexion angles. Compared with non-coplanar linac-based techniques or helical tomotherapy, a tilted head angle with the coplanar VMAT technique not only reduces plan complexity, but also improves treatment efficiency.

## DOSEtrace Research capabilities for radiation protection dosimeters: Training actions

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### Introduction

The overall objective of this EMPIR Capacity Building project, 17RPT01 DOSEtrace, is to improve SI traceable measurements of operational radiation protection quantities in the participating NMIs from emerging countries. For legal measurements according to EU COUNCIL DIRECTIVE 2013/59/EURATOM traceable measurements are required. The first work package in this project is a training action comprising a theoretical training course and a hands-on training in the laboratory. The Training Course covered the needs identified by a questionnaire and the experience from EURADOS WG2.

### Methods

In the one-week Training Course in Lisbon at IST the following topics were covered by nine lecturers: Radiation quantities & ISO 4037, dosimetric quantities, uncertainty evaluation, calibration and type-testing, types of comparisons, planning a comparisons to support CMCs, evaluation of comparisons, quality assurance, quality control, eye lens dosimetry, accreditation, QA audits. Three invited speakers from outside the consortium gave talks about the MRA CMC (Steven Judge, BIPM), evaluation of comparisons data (Maurice Cox, NPL) and the general organization of comparisons according EURAMET Guide No. 4 (Elsa Batista, IPQ).

In a two-day hands-on training in the laboratory at PTB the practical issues will be addressed.

### Results & Conclusions

The impact of the training actions are monitored by questionnaires after each action and by a validation at the end of the project. The TC-feedback showed that all participants were highly satisfied with the content and the structure of the course.

EURADOS WG2 organizes: regularly Training Courses for individual monitoring services, a learning network at the annual meeting and a discussion online-forum. Further and sustainable education concepts are needed. A network, e.g. a European Metrology Network (EMN), for the field of radiation protection dosimetry for coordination of such training actions would be very valuable.

## Comparative evaluation of image quality and dose between 2D full field digital mammography and digital breast tomosynthesis

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**Introduction:** The aim of the study was to compare the digital breast tomosynthesis (DBT) mode with 2D mode for full field digital mammography (FFDM) in respect of image quality and average glandular dose (AGD).

**Methods:** Twenty-eight mammographic units from seven different models with both 2D mode and DBT mode were included in this survey. Image quality evaluations were performed by the CIRS BR3D phantom and the Gammex modular DBT phantom for the phantom scores of fibers, speck groups, as well as masses, and for MTF, respectively. In addition, the ACR mammographic accreditation phantom was used to simulate averaged breast for AGD estimations. The image were acquired by clinical exposure parameters both in 2D mode and DBT mode. The incident air kerma and half value layer (HVL) were measured at the specific beam quality corresponded to the ACR phantom for further AGD calculations using the conversion factors provided by Dance.

**Results:** The mean values of fibers, speck groups and masses averaged from all mammographic units were  $2.6 \pm 0.6$ ,  $4.9 \pm 0.7$ , and  $2.9 \pm 1.0$  for 2D mode and  $4.5 \pm 0.6$ ,  $4.9 \pm 0.7$ , and  $5 \pm 0.6$  for DBT mode. Phantom scores of fibers and masses were significantly higher for DBT mode than that for 2D mode. The  $MTF_{0.5}$  ranged from 1.18 to 2.01 cycles/mm and 1.61 to 2.94 cycles/mm in tube-travel and in chest-wall nipple directions, respectively. The mean AGD for DBT mode were  $1.37 \pm 0.17$  mGy (range 0.98~1.64 mGy) and  $1.53 \pm 0.30$  mGy (range 0.99~2.18 mGy) for 2D mode and DBT mode, respectively.

**Conclusions:** The detectability of the fiber and mass in DBT mode was better than that in 2D mode. The AGD of DBT mode was higher for most of the systems as compared to 2D mode but remained below the acceptable dose values.



## Effect of Air Cavity Shape and Size on Interface Dose Evaluated by Using CVD Diamond Films

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### Introduction

Dose change occurred at interface (e.g., nasal cavity) of different tissues is difficult to estimate in treatment plans for radiotherapy. Dose re-distribution happens in cavity interfaces when high energy photons penetrate from soft tissue (e.g., brain) to a cavity (e.g., tumor located at the nasal sinus) due to electron nonequilibrium (ENE). In this study, the ENE was discussed by investigating the dose at interface of cavities in different shapes under irradiation by a photon beam

### Methods

Chemical vapor deposition (CVD) diamond membrane TLDs and a linear accelerator (ELEKTA Co.) were used in this study. The balloon added water was used fill different shapes of tissue-equivalent phantoms to probe the dose change at the cavity interface. The photon energy was 6 MeV, SSD was 100 cm, the field size was  $5 \times 5 \text{ cm}^2$ , and the exposure was 2 Gy. Different shapes (in cube, cylinder and triangular prism) of tissue-equivalent phantoms were used to investigate the effect of cavity size and shape.

### Results

Reducing cavity size with water balloon is effective to increase interface dose (84.9%) in cubic cavity similar to that in a non-cavity equivalent tissue (83.2%). For the cylinder phantom, the interface dose was 90% attenuated after the cavity size was reduced. As to that in triangular prism, the interface dose was 92% increased when the cavity was filled.

### Conclusions

The study concluded that reducing cavity size by using water balloon could decrease the interface dose in a cavity tissue, which can be applied to solve the problem of insufficient dose at the cavity interface.

## Comparative study of dose deposition by particle beams for pediatric oncologies, retinoblastoma and brain tumors using MCNPX.

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### Introduction

The study of new radiotherapy treatments brought improvements for patients affected by cancer. However, the difficulty for some specific cases, like retinoblastoma, proving to be a challenge in terms of healing. Pediatric, ocular and of the neuroaxis tumours are very delicate in relation to radiation therapy using beams of photons. Today, there is a growing use of Proton beams that can yield better results for such diseases. And in fact, due to the interaction with tissues, these beams cause less damage to healthy tissue adjacent to the damaged region. Pediatric Oncology also makes use of Proton beams due to this trait. In this work was made a comparison of deposition of dose of conventional beams of protons in ocular region and central nervous system in pediatric patients by means of computer simulation using Monte Carlo N-Particle eXtended (MCNPX).

### Methods

The radiation transport was simulated using MCNPX, initially was used a phantom box-shaped composed of water to determine the range of each beams according to its energies. Furthermore, the comparison of the dose distributions in the studied regions was made using some mathematical and voxel phantom. Was analyzed the behavior of each beam and its isodose curves.

### Results

A dose profile was built for each applied beam according to its energy, radiation distribution and isodoses curves on the phantom. Moreover, was evaluated the deposited dose on healthy tissue and tumor volume. Some differences were observed, not only for different beams, but for phantom as well.

### Conclusions

The dose was focused by modulating the beams, leading to a great decreased of scattered radiation. Proton beam presented the best results in comparison to the others, and the MCNPX did play a key role in these measures.

## Development of double dosimetry algorithm for assessment of effective dose to staff in interventional radiology

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**Introduction:** Medical staff involving interventional radiology (IR) procedures are significantly exposed to the scatter radiation because they stand in close proximity to the patient. In general, the personal dose equivalent at 10mm depth,  $H_p(10)$ , read from one dosimeter worn on the trunk of staff is assumed to be a good estimate of the effective dose and compared to the dose limits for regulatory compliance. This assumption is based on the exposure conditions that the radiation field is broad and rather homogeneous. However, staff in IR usually wear protective clothing like lead apron and thyroid shield which allow part of the body being exposed to much higher doses. The purpose of this study is to develop double dosimetry algorithm that can assess the effective dose of staff in IR.

**Methods:** To adequately estimate the effective doses of staff in IR, it is recommended that one under the apron and one over the apron where unshielded part of the body exposed. There are some changes in the process of calculating the effective dose in the 2007 recommendations of the ICRP; changes in the radiation weighting factors, tissue weighting factors and the computational reference phantoms. Therefore, this study attempts to set a new algorithm for interpreting two dosimeter readings to provide a proper estimate of the effective dose for staff, incorporating those changes in definition of effective dose. The effective doses were estimated using Monte Carlo simulations for various practical conditions based on the voxel reference phantom and the new tissue weighting factors.

**Results:** A new set of dosimetric weights was derived for the conditions such as lead apron (0.3mm, 0.5mm), beam direction or thyroid shield use, through the correlation evaluation between the calculated effective doses and individual dose equivalent. For the most common cases of under-couch beam projection, the proposed algorithm is given by,  $E=0.80(0.80) H_u + 0.04(0.05) H_o$  where  $E$  is the effective dose,  $H_u$  is the personal dose equivalent under the apron and  $H_o$  over the apron(on collar). The weighting factors in parenthesis are for the case of no thyroid shield.

**Conclusions:** The effective dose of staff in IR can be assessed by applying a personal dose equivalent to the proposed algorithm. The double dosimetry algorithms proposed in this study including the projection conditions, showed that the effective dose could be satisfied in the range of 0.97-1.97 times.

## Effect on calibration phantom composition for stoichiometric calibration in Monte Carlo simulation

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### Introduction

For Monte Carlo (MC) dose simulation, mass density and elemental weights are needed for pre-calculation of physical interaction cross sections. In a previous study, Schneider (Phys. Med. Biol. 45:459–78) applied stoichiometric calibration and interpolation techniques to generate mass density calibration curve (DCC) and to perform tissue segmentation. In this work, three phantom models were used to repeat Schneider's procedure and to study the effect of high Z element on the DCC and tissue segmentation results.

### Methods

Three phantom models, CIRS (Model 062M, =56), normalized CIRS (Model 062M, excluding Ba, =20) and Gammex RMI 467 phantom (=20) were used in this investigation. The first and third models use the original density and composition information provided by the vendors. The high Z element of Ba in the original CIRS phantom was intentionally excluded from processing to form the second phantom model. 13 CIRS 062M and 16 Gammex RMI 467 rods were measured to obtain the corresponding HU values in our RT590 (GE) CT machine with 120 kVp x-ray energy. In-house MATLAB codes were created for repeating calibration procedures described in the Schneider's paper. Results of the in-house codes were validated by comparing to values reported by Schneider.

### Results

For all 3 different calibration curves, when HU < 100 there isn't significant difference for calibration curves generated by different phantom. When HU > 100, for human tissue (Cortical bone) with same mass density 1.92 g/cm<sup>3</sup> the calibration curve calibrated by CIRS (Model 062M, =56) has the smallest HU (HU=1245) compared to normalized CIRS (Model 062M, =20, HU=1378) and Gammex RMI 467 phantom (=20, HU=1327).

### Conclusions

Phantom containing high atomic number may affect the calculated HU of human tissues; it will affect the stoichiometric calibration result for DCC result. From curve fitting by tissue and observing phantom dots, we can know that Gammex RMI 467 is the most tissue-like material in these three phantoms in our research.

## A MATLAB-based Graphical User Interface to Simulation with GATE Monte Carlo in Medical Physics

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### Introduction

GATE (Geant4 Application for Tomographic Emission) has been widely used to perform simulations in Medical Physics, since it has some advantages over other Monte Carlo codes, mainly in SPECT (Single Photon Emission Computed Tomography) and PET (Positron Emission Tomography) trials, and also because the output can be a volumetric map of absorbed dose or deposited energy. For dosimetry, this volumetric map can be fused with the phantom in three dimensions and purchase the absorbed dose or energy deposited in each organ. The calculation of the total or average absorbed dose or energy deposited in each organ can be obtained using MATLAB® Software. The objective of this work is to create a Graphical User Interface principally (GUI) to evaluate the simulations performed with GATE Simulations for Dosimetry in Medical Physics.

### Methods

Using a GUI in MATLAB®, the toolbox has been developed to run in MATLAB®, with a set of functions to be used for the analysis in GATE simulations data in dosimetry applications.

### Results

A program was created in MATLAB® to determine the dose absorbed in Gy or the energy deposited in MeV. Besides this, the program has specific tools for images visualization, as well as, other functionalities useful for researchers using GATE for simulations in the field of Dosimetry in Medical Physics.

### Conclusions

We have presented a GATE Simulations Toolbox for MATLAB®. The GUI-based tool presented in this paper may provide a set of MATLAB functions to perform a simple analysis of GATE Simulations Data. This proposed tool is public availability.

## The Impact of CT-density conversion curve for VMAT plans in Monaco Monte Carlo TPS: case of head and neck cancers

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### Introduction

Inaccurate CT-to-density conversion curve (CDCC) information may introduce errors in dose calculation. The aim of this study is to investigate the sensitivity of volumetric modulated arc radiotherapy (VMAT) plans for head and neck cancer (HNC) with Monaco TPS to the CDCC. To obtain this goal, a comparison between dosimetric parameters obtained by VMAT plans using 3 different CDCCs was established.

### Methods

A CIRS phantom was scanned on 3 different CT-Scan. data of 10 previously treated patients were selected randomly from the list of patients with head and neck cancer that have received VMAT with Monaco planning system at our institution. Plans were evaluated using DVH for PTVs and OARs, the planning DVH objectives used to assess plan quality for all plans included: minimum dose, D5%, D95%, V<95%, V>107% target, homogeneity index HI95% and conformity index CI95%.

Paired t-test analysis was used to analyze the results. The number of UM of each arc, the total number of UM, the conformity and the heterogeneity indexes, were compared.

### Results

A serious variation in the DVHs of the PTVs and the OARs were observed, a variation up to 12% for the OARs, and up to 6% for the PTVs were found. The number of UM of each arc and the total number of UM were found invariable. The conformity index (CI) and homogeneity index (HI) were acceptable.

### Conclusions

It is important to consider the use of a specific (CDCC) for planning each VMAT treatment, A wrong (CDCC) will lead to a serious difference in delivering the wanted dose. The need to use the appropriate CT-to-density conversion curve through the treatment planning system is very clear.

## GEANT4 simulation in proton medical imaging

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### Introduction

Imaging techniques using protons are currently being actively developed for proton therapy. Presently, many researchers use the GEANT4 toolkit to simulate proton imaging devices, without detailed analysis of its precision for the case of thick absorbers. In this paper we present a systematic comparison of the quantities important for proton imaging as simulated by different physics lists of GEANT4 (version 9.6.p03) in the conditions close to those of proton medical imaging.

### Methods

We evaluated the physics lists FTF\_BIC\_EMY, FTFP\_BERT\_EMY, QGSP\_BERT\_95\_EMY, QGSP\_BERT\_EMY, QGSP\_BIC\_EMY, and QGSP\_BIC\_EMY. Comparison was performed for initial energies between a few and a few hundred MeV with the statistic of  $10^7$  protons. The kinetic energies, angles, and coordinates of protons exiting the absorber were analysed.

### Results

The influence of models BERT and BIC on exit energy does not exceed 0.05% and the difference between the EMY and EMV models reaches a few percentage points. At the energies where nuclear processes dominate, the BERT model provides more protons. For energies of hundreds of MeV, a clear difference between the BERT and BIC models was observed 5 to 15 MeV below the maximum. Nuclear processes begin to affect the electromagnetic peak at 5–5.5 MeV below the maximum. The difference between the BERT and BIC models in exit angle and displacement does not exceed 0.5%. For the EMY and EMV models, it reaches 20%. In the region where inelastic processes dominate, significant difference between the BERT and BIC models was observed for energies of hundreds of MeV. The region at which inelastic processes begin to affect the elastic peak is  $\sim 2$  standard deviations for displacement and is  $\sim 3.5$  standard deviations for angle.

### Conclusions

Thanks to high statistics, the obtained results may be used not only in proton imaging but also as a test for nuclear models in future experiments with thick absorbers.





## Production and study of thermoluminescent materials for low dose dosimetry applications

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### Introduction

Thermoluminescent dosimeters (TLDs) are widely used for the quantification of radiation doses in different applications. Calcium sulfate doped with dysprosium ( $\text{CaSO}_4:\text{Dy}$ ) is widely used for these purposes and is the only TLD commercially produced in Brazil.

The goal of this work was to produce TLD pellets with  $\text{CaSO}_4$  doped with different rare earths and to study its response parameters, such as the emission curve, sensitivity, energetic and dose dependence and fading.

### Methods

TLDs were produced using the Yamashita method, in that the crystals are formed with  $\text{CaCO}_3$  solution of  $\text{H}_2\text{SO}_4$ . The produced pellets were of  $\text{CaSO}_4$  doped with Dy:Tm, Tm, Dy:Tb, Tb, Eu and Dy:Eu. Pellets of  $\text{CaSO}_4:\text{Dy}$ , produced and marketed by MRA Indústria Ltda, Brazil, were used for comparison.

Beams ranging from 30 to 120 kVp from an X-ray unit (model ISOVOL TITAN 160-EG) were used for the energy dependence study. All the other tests were performed using  $\text{Cs}^{137}$ . The calibration dose was 2.02 mGy. The pre-irradiation thermal treatment was at 300°C for 20 min, and the pre-reading thermal treatment was at 100°C for 30 min. The readings were performed with a Thermo Scientific TL reader (model Harshaw TLD 3500).

### Results

The produced pellets of  $\text{CaSO}_4:\text{Tm}$  presented the largest response ( $153 \pm 14$  nC/mGy), 17% higher than the commercial pellets in average. The pellets of  $\text{CaSO}_4:\text{Tb}$  and  $\text{CaSO}_4:\text{Eu}$  presented the smallest responses (88% and 42% of the commercial pellets). After 21 days, there was 5% fading for the  $\text{CaSO}_4:\text{Tm}$  pellets, 9% for  $\text{CaSO}_4:\text{Dy,Tm}$  and 13% for  $\text{CaSO}_4:\text{Dy}$ . Moreover, the pellets of  $\text{CaSO}_4:\text{Tm}$  presented the higher homogeneity coefficient (36%). All the pellets presented energy dependence in agreement with the literature, being maximum for beam N40 (ISO 4037-1).

### Conclusions

The TL materials produced, especially  $\text{CaSO}_4:\text{Tm}$ , presented dosimetric characteristics suitable for diverse applications, with enough sensitivity for applications in individual dosimetry.

## Individual Dose Monitoring of Medical Staff in Ukraine

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### Introduction

The individual dose monitoring of occupational exposure for medical staff in Ukraine is carried out from 1979 by Central Personal Dosimetry Laboratory of Medical Staff. At present Laboratory assures the dose monitoring on a quarterly basis for 6,200 personnel from 710 medical hospitals.

### Methods

TLD-method is used: detectors LiF (Mg, Ti) and dosimeters type DTU-1, which can measure the equivalent dose  $H_p(10)$ . The dose range is 0.10 to 1.0 Sv, photon energy range 0.015 - 3.0 MeV. For photon energy more 100 keV the uncertainty is about  $\pm 10$ -15%, if  $H_p(10) > 1.0$  mSv and it is not more  $\pm 30\%$ , if  $H_p(10) < 0.5$  mSv. For low photon energy (25-60 keV) the uncertainty can reach + (40-60) %. Laboratory developed dose calculation algorithm for improvement of accuracy.

### Results

The annual analysis of the personal dosimetry results for 35 different groups of medical staff are carried out using the software IDAIS which allows collecting in database the individual doses of each person for all monitoring periods and provides the creation of reports with data about annual and cumulated doses of each worker. The total annual reports with collective and average annual doses of medical staff are sent to each hospitals and summary report – to Regulatory Authorities. All cases of exceeding the dose limit for category A and annual reference level are analyzed. For most of medical staff (up to 95-98 %) the annual doses are less than 2 mSv (average doses -0.5-0.7 mSv). The professional groups with highest doses in medicine are radio-manipulation nurses, who make manual brachytherapy, and nurses in Nuclear Medicine (radionuclide therapy and diagnostics) and personnel in Interventional Radiology. The average annual doses of these groups are up to 2.0-5.0 mSv, 2.0-3.0 mSv and 1.5-2.5 mSv respectively.

### Conclusions

Further optimization of radiation protection personnel in medical radiology should be aimed at the decrease of doses of personnel in these professional groups.

## MEASUREMENT OF PHOTOELECTRON GENERATION IN A GOLD COATED GLASS SLIDE THERMOLUMINESCENCE DOSIMETER

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### Introduction

The radiotherapy of tumour cells focuses on maximising the radiation dose while at the same time seeking to not exceed normal tissue tolerance. In order to further enhance dose to a tumour, methods for radiosensitisation of the tumour are sought by increasing the radiation interaction cross-section of the tissue using high atomic number (Z) materials. In principle, since the product photoelectrons and Auger electrons have relatively high linear energy transfer (up to ~12 keV) and short range, infusion of the treated tissue with high-Z media during photon irradiation would result in a greater fraction of the incident photon energy being imparted, thus localizing enhancement of dose. An approach in nanotechnology is to create potential for improving the outcome in cancer treatment using metallic nanomaterials; gold nanoparticles appear promising as a radiosensitising agent and dose enhancer due to both the chemical properties of gold and the tumour specificity of appropriately sized nanoparticles. Also, gold is chemically inert, biologically nonreactive, and molecularly stable. In this study, via use of analogue nanometer-scale gold-coated glass-slide thermoluminescence (TL) dosimeters, we examine development of an accurate measurement system in quantifying the energy deposition due to secondary electrons, also measuring photoelectron-enhanced dose close to a tissue interface. The proposed dosimeters have been irradiated using an X-ray set operated at 150 kVp. To verify the delivered dose, Monte Carlo simulation of the experimental setup will be performed. Further to this, the thermoluminescence of uncoated glass slides dosimeters of two different thicknesses, 0.13 and 1.00 mm, have also been characterized, including dose response, energy response, glow curve reproducibility, sensitivity and fading.

### Methods

**Sample collection and preparation** The commercial glass slide samples used herein, the manufacture of two companies, are made from amorphous silica glass. With areal dimensions 25 mm × 75 mm, they are of thickness ranging from 0.13 to 1.00 mm. The commercial borosilicate microscope glass slides have been cut into regular pieces of approximately 0.5 × 0.5 cm using a diamond cutter. The mass of each individual glass slide TLDs has been determined using an electronic balance, allowing TL yield to be normalized to unit mass of the irradiated samples.

**Uncoated-glass slide thermoluminescence dosimeters (TLDs) characterization** Thermoluminescence (TL) characterization of the uncoated commercial glass slide has also been undertaken, examining dose response, energy response, glow curve characteristics, fading, sensitivity and reproducibility. Irradiation of the samples has been made through use of a <sup>60</sup>Co gamma irradiator, covering the dose range from a 5 to 25 Gy.

**Gold-coated glass slide thermoluminescence dosimeters (TLDs)** Investigation has been undertaken of the dose enhancement due to photoelectron generation through irradiation with x-rays generated at kilovoltage potentials for different thicknesses (20 - 100 nm) of gold, Z = 79, built up as thin layers coated onto the glass slides. For the latter, use has been made of a sputter coating unit (Emitech K575X) provided by the Photonic Research Centre, UM. The samples have been irradiated at the University Malaya Medical Centre (UMMC), use being made of an orthovoltage X-ray unit (GULMAY); the TL media was exposed to 150 kVp x-ray beams to give a dose of 2 Gy. The source to sample surface distance (SSD) is set at 100 cm, with a field size of 20 × 20 cm<sup>2</sup>. The samples were placed on top of a 30 × 30 cm<sup>2</sup> water equivalent phantom

(solid water<sup>TM</sup>) of thickness 6 cm to simulate scattering of human tissue. The glass slides were placed at the centre of the phantom (i.e. 3 cm depth) with the coated side face upwards, the X-ray tube aligned via the applicator of the X-ray unit with 3 cm stand off from the phantom to the applicator. Using a HARSHAW 350 TLD reader, the samples have been readout 12 hours post irradiation, allowing uniform control of thermal fading. The readout was carried out in a nitrogen gas rich atmosphere to suppress oxidation and triboluminescence effects.

Results

It is desirable in radiotherapy dosimetry for the measurement system to produce a linear response to absorbed dose. In terms of linearity, Fig. 1 (a) shows that both the 0.13 and 1.00 mm thickness of glass slides have a highly linear response (linear fitting curve  $R^2 > 92.1\%$ ) over the investigated dose range, 5 to 25 Gy. Meanwhile, 1.00 mm glass slides produce significant TL intensity of a factor of 25 times that of 0.13 mm glass slides. Fig. 1(b) shows the glow curves of 0.13 and 1.00 mm thickness glass slides due to <sup>60</sup>Co irradiation, delivering doses of 20 and 25 Gy. In all such cases, it is apparent that as expected the glow curve generated at the 25 Gy dose are proportionally greater in terms of the TL intensity peak compared to the 20 Gy dose, the area under the curve representing the radiation energy deposited. The glow curve area is given in terms of TL yield per unit mass of fibre per unit dose for a particular source of radiation (i.e. TL yield.mg<sup>-1</sup>.Gy<sup>-1</sup>).

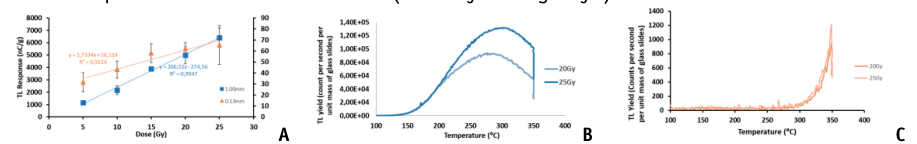


Figure 1 The (A) dose response and (B) (C) glow curves for uncoated glass slides of thickness 0.13 (orange data points) and 1.00 mm (blue data points) irradiated by the <sup>60</sup>Co source, with entrance dose ranging from 5-25 Gy, together with standard error of the mean. The dotted lines are least square fits to the data.

It is important in use of the glass slides that any energy dependence be characterized. It is apparent at greater photon energy (i.e. that associated with a potential of 140 kVp) (Figure 2), that the TL yields responds linearly with increase in x-ray energy. The energy dependence of the glass slides in the lower energy range can be explained by the non-soft tissue equivalence of glass, in accordance with the associated energy absorption coefficients, dominated by the photoelectric effect at lower photon energies, thus, pointing to a potential for energy discrimination of the incident photons if these glass slides are used in conjunction with another TLD type such as TLD 100.

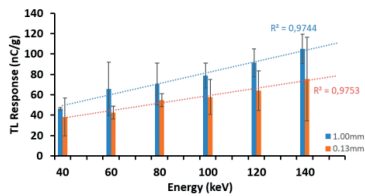


Figure 2 Energy response of uncoated glass slides of 1 0.13 and 1.00 mm thickness irradiated to a dose of 2 Gy with X-rays of 40, 60, 80, 100, 120 and 140 kVp. Uncertainties are quoted in terms of standard error of the mean.

Conclusions

In the present study, the dosimetry of uncoated glass slides have been shown to possess a number of desirable characteristics, demonstrated using gamma irradiations. Given their ease of handling and low cost, these various features make the glass slide a promising TL material for use as a dosimetric system in a number of clinical applications. Extending beyond present study, it is the intention to characterize the high atomic number coatings (gold in this case), providing the highest TL yield for both therapeutic and diagnostic applications.

## Optically and thermally stimulated luminescence in $\text{LaAlO}_3:\text{Dy}^{3+}$ beta irradiated

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**Introduction.** Stimulated luminescence (OSL) is one of the many known stimulated phenomena in condensed matter that can be used for luminescent material characterization. Both thermally and optically processes became a successful practical tool in radiation dosimetry. Special attention is dedicated to bioceramic as a material of choice for many dosimetric applications.

**Methods.** This paper reports experimental results of dysprosium trivalent ion doped lanthanum aluminate ( $\text{LaAlO}_3:\text{Dy}^{3+}$ ) using thermally stimulated luminescence (TSL) and optically stimulated luminescence (OSL) techniques. Samples of  $\text{LaAlO}_3:\text{Dy}^{3+}$  were irradiated to beta doses, in air, from 500 mGy up to 50 Gy and then were analyzed using both TL and OSL techniques to determine their luminescent properties.

**Results.** Nanostructured powders were confirmed by X-ray diffraction technique. Luminescent phosphors show a thermoluminescent glow curve obtained being exposed beta radiation which of two peaks: one located at around 180°C and the second one at 280°C. Meanwhile, OSL decay is exponential form. TL and OSL response as a function beta radiation dose was linear in the studied dose interval (from 500 mGy up to 50 Gy).

**Conclusions.** The very good sensitivity and moderate fading will make this phosphor suitable for beta radiation dosimetry, using both TL and OSL techniques.

## Design and implementation of a gamma spectrometry mobile unit using LaBr<sub>3</sub> detectors

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### Introduction

This study describes the equipment implementation and calibration of a mobile gamma spectrometry unit using LaBr<sub>3</sub> detectors. The objective of the mobile unit is to obtain a radiological map of Catalonia (Spain). The mobile unit is equipped with a software that stabilises and calibrates the collected spectra and calculates the ambient dose equivalent in real-time. In addition, another software permits to visualise and locate the calculated ambient dose equivalent and other parameters on the map of Catalonia.

### Methods

The mobile unit consists of two 2"x2" LaBr<sub>3</sub> scintillation detectors mounted on the top of a 4x4 car. The car is equipped with a portable computer to control spectra acquisition and a GPS system that associates a position to each spectrum. Each spectrum is stabilised and calibrated. Then, the ambient dose equivalent is calculated with a self-development method. Finally, an algorithm using a spectral windows method obtains the activity concentration of certain isotopes of interest, such as <sup>137</sup>Cs.

The extension of Catalonia was divided in 1425 cells of 5x5 km<sup>2</sup>. Before starting the measurements, we planned the route to ensure a proper distribution and a minimum quantity of spectra within each cell. During the acquisition, the computer placed inside the car shows in real-time the value of the ambient dose equivalent and the exact location. Therefore, when the software obtains an unexpectedly high value, the driver of the car is able to modify the route to acquire more spectra.

### Results

We tested the equipment and the software taking a first set of data that included 70000 spectra. The calculated ambient dose equivalent obtained corresponded to one another for both LaBr<sub>3</sub> detectors. The activity concentration of <sup>137</sup>Cs was null in all measurements except in one occasion.

### Conclusions

A mobile unit with LaBr<sub>3</sub> scintillation detectors was designed to obtain a radiological map of Catalonia. The equipment and the software implemented performed satisfactorily in all measurements, therefore the mobile unit is ready to continue acquiring data.

## APPLICABILITY OF AIR VEHICLES ON RADIOLOGICAL AND NUCLEAR MONITORING – A LITERATURE AND HISTORICAL REVIEW

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### Introduction

In radiological and nuclear events, it's not usually known *a priori* the distribution of the contamination as well as its intensity in the affected areas, making it hard to establish a safe line of action. One of the main troubles of the response teams to this type of occurrence is the confirmation of the radiological plume's spread direction and the contamination level verification in ways to avoid the accidental exposure of the team, aircraft or the community to dose levels beyond the accepted ones for the situation, as well as monitoring the on-site contamination after the occurrence. The problem becomes even more pressing when it involves the use of manned air vehicles since its speed makes an evasive situation difficult to be taken in a short period or too risky to be done in certain cases.

### Methods

The article intends to analyze the applicability and limitations of air vehicles in radiological agents monitoring at radiological and nuclear situations, by means of searching in the literature the possibilities of integration of radiological and nuclear sensors in aircrafts and its suitability for use in contaminated environment or source tracking and their use in accident scenarios, like Fukushima.

### Results

The use of UAVs in radiation monitoring has become a crucial tool in supporting efficient responses to nuclear accidents and disasters as it can provide high resolution information without endangering workers or incurring great expense. After the Fukushima incident in 2011, there was a notable increase in UAV radiation monitoring researches, each one assessing different aircraft types and detection methods, presenting several solutions for radiation monitoring.

### Conclusions

The systems can be combined to perform different missions and surveys rating their benefits and limitations. Future studies should look to further identify the advantages/disadvantages of each of the respective systems and compare the practical uses of a range of systems and algorithms that are available to use.

## Use of ceramic $\alpha\text{-Al}_2\text{O}_3$ detectors for discriminate beta and photon fields

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### Introduction

Anion defective single crystal detectors  $\alpha\text{-Al}_2\text{O}_3$  grown by the Czochralski method are widely used for personal and area monitoring. A methodology for the production of polycrystalline  $\alpha\text{-Al}_2\text{O}_3$  ceramics based on the sol-gel method was developed in our research group. These ceramics were studied by both thermally and optically stimulated luminescence, and they are successfully used for area monitoring in our institute. Unlike single crystal detectors, the ceramic detector used has low translucency, which facilitates discrimination between beta radiation fields and photon fields namely gamma and X-ray. A comparative simulation study was done by the MCNPX code.

### Methods

A group of 10 detectors was previously annealed and irradiated with a beta source -  $^{90}\text{Sr}/^{90}\text{Y}$ , available in a RISØ TL/OSL DA-20 reader. The detectors were irradiated by one second, corresponding to 14 mGy. The TL readings used a heating rate of 5 °C/s from room temperature up to 250 °C. The OSL readings used blue light stimulation and a Hoya U-340 filter. In the first essay, the irradiation and reading were done on the same detector face. In the second essay, the irradiation and reading were done on different faces. The essays were repeated using a  $^{137}\text{Cs}$  gamma source with the same group of detectors. These experiments were modeled in MCNPX.

### Results

The mean evaluated dose on direct reading was 35% higher than the inverse reading for beta irradiation with an uncertainty of about 5%. For gamma radiation, the result was quite different. The mean evaluated dose on direct reading was 2% higher than the inverse reading with an uncertainty about 5%. The simulations presented consistent results compared to the experiments.

### Conclusion

In principle, it is possible to discriminate between beta and gamma radiation fields using the ceramic detectors without radiation filters or algorithms. Additional experiments and simulations are in progress in order to study the response on other radiation energy ranges.



## Dosimetric characterization of thin diodes in an electron beam facility for radiation processing

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**Introduction:** Silicon diodes have been employed as relative dosimeters in clinical photon and electron beams. However, they are prone to radiation damage that produces a drop of their current sensitivities with increasing accumulated doses. This effect is attributed to the decrease of the minority carrier diffusion lengths which diminishes the sensitive volume of the diode. Theoretically, it is possible to mitigate the decay of the current sensitivity by choosing diodes with thicknesses smaller than the lowest minority carrier diffusion lengths anticipated for the foreseen accumulated dose. This surmise has been followed up in this work by evaluating the response of thin diodes (SFH00206K) for the dosimetry of electron beams used in radiation processing.

**Methods:** The diode with 10  $\mu\text{m}$  of depletion layer at 0V was produced on n type Si wafers of 220  $\mu\text{m}$  thickness. As a dosimeter, the device was housed in a probe and connected to an electrometer to be operated in short-circuit current mode without bias voltage. To carry out the irradiation, the probe was placed on a conveyor belt that crosses the radiation field of a 1.5 MeV electron beam.

**Results:** The currents were registered as a function of the exposure time for dose-rates within 2-8 kGy/s and accumulated doses up to 350 kGy. The dosimeter was characterized with respect to the linearity between current and dose-rate, repeatability and reproducibility of the current signals. Its lifespan was investigated, particularly addressing the stability of the current sensitivity factor with increasing absorbed doses. The measurements were benchmarked against calculations of the current taking into account the fraction of the electron energy deposited in the active volume of the diode, the dose-rate, and the values of diffusion lengths.

**Conclusion:** All experimental data so far obtained prove that this diode can be used in electron beam dosimetry. Furthermore, a fair agreement was found between theoretical and experimental results.

## Anomaly Detection of TLD Glow Curves Using Support Vector Machines

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### Introduction

Computerized Glow Curve Analysis (CGCA) has been intensively investigated for the past few decades. CGCA has used different methods from glow curve deconvolution into isolated peaks, through semi-automatic SW tools for the detection of outliers, to SW that discovers anomalous curves by using predefined rules.

### Methods

The method presented here tackles the subject using an automatic algorithm for accurately detecting anomalies in TLD glow curves. A Support Vector Machines (SVM) classifier, which is a machine learning classification algorithm, is used for classifying the glow curves into two categories: an acceptable i.e. 'regular' curve, or a curve that shows any kind of anomaly i.e. an 'anomalous' curve. The SVM treats the glow curves data as a large ensemble of statistical data, and identifies anomalous glow curve shapes by statistical means. This classification method consists of three steps. The first one is the manual classification of a library of glow curves by a human user into the above two classes. The second one is applying an iterative training algorithm onto these glow curves. Finally, a comparison between an unidentified glow curve and these two pre-classified sets is done, and the SVM evaluates a classification probability to each of the two classes.

### Results

Results show about 97% accuracy of the correct classification to either one of the classes.

### Conclusions

This work describes an automatic algorithm that improves both the accuracy of the anomalous GCs detection and its quality control process.

The accuracy of the SVM algorithm was calculated to be 97%. The automatic nature of the algorithm ensures repeatability and is a major advantage over manual inspection.

## Evaluation of transparent and black commercial soda-lime glass irradiated with gamma radiation

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### Introduction

The linearity characteristic in radiation dosimetry presents a growing interest. Glasses have been applied to radiation high doses. The goal of this work was to expose transparent and dark commercial soda-lime glasses samples to high doses and to use the UV-Vis spectrophotometry technique for their evaluation.

### Methods

Transparent and dark commercial soda-lime glasses with dimensions of 1 x 10 x 40 mm<sup>3</sup> were irradiated with doses from 1 kGy to 10 kGy using a <sup>60</sup>Co Gamma-Cell system 220, and then were evaluated with the UV-Vis technique. The sensitivity and linearity characteristics were evaluated with the absorbed profiles of the multivariate calibration Partial Least Square Regression (PLSR) and Principle Component Regression (PCR) techniques.

### Results

The PLSR and PCR techniques showed, on the range of 1-10 kGy, for the calibration curves, of transparent and black commercial soda-lime glass, linearity values of 0.9432 and 0.9422 respectively using just three components on both methods. The spectra present a baseline variation (and maximum absorbance values) proportional to the absorbed dose received by the samples. These results show that it is possible to use the technique of UV-Vis to determine if the glass samples were irradiated or not. The color changes for transparent glass irradiated with absorbed doses from 1 kGy up to 10 kGy. This color variation in relation to absorbed dose indicates that the glasses may be used as YES/NO dosimeters.

### Conclusions

The UV-Vis measurements may be useful in gamma radiation dosimetry, using the spectra of irradiated glasses; the highest linearity was shown in order respectively for transparent and black commercial soda-lime glass; the glass samples changed their coloration proportional to the absorbed doses, and they may be used as Yes/No detectors and as high-dose dosimeters. The results indicate a good linear response and the radiation detectors present potential use for radiation dosimetry in high doses.



## Investigation of semiconductor polymer-Tl<sub>2</sub>O<sub>3</sub> nanocomposites for x-ray detection

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### Introduction

The functionality of organic polymers can be modified by doping them with ionic liquids and addition of application-designed nanoparticles. In this study, we report on the synthesis and characterization of composite semiconducting polymer – nanoparticle membranes for x-ray detection.

### Methods

The membranes are made of poly(vinyl alcohol) (PVA) organic polymer that is doped with ionic liquid (IL) to control its electrical conductivity. Tl<sub>2</sub>O<sub>3</sub> nanoparticles with different weight concentrations synthesized using a microwave assisted technique with size of are added to the polymer. Homogeneous polymer-nanoparticle membranes are produced using solution casting method and tested.

### Results

The electrical impedance testes showed that the dc electrical resistance of the membranes decrease with increasing both nanoparticle concentration and temperature, and therefore the activation energy was found to increase with increasing nanoparticle concentration. It was found that these fabricated composite membranes are conductometric x-ray sensor, and their response increase with increasing x-ray generator voltage.

### Conclusions

They exhibit semiconducting properties, easy to fabricate, low cost, and cab be utilization in the x-ray detection.

## From DNA damage simulation to cell death simulation by the Biophysics Monte Carlo Simulation Code -- NASIC

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### Introduction

As the more and more widely used particle therapy, it's necessary to evaluate the radiation biology effects of high LET, such as proton and carbon ion. In order to study the track structure in nanometer scale and the radiation biological effect induced by radiation of different types and LETs, we developed a biophysics nanodosimetry Monte Carlo simulation code (NASIC).

### Methods

NASIC is developed with the guidance of the biological theory, referring to the similar biophysics simulation codes over the world. It consists of physical module, pre-chemical module, chemical module, geometric module and biological module. Using a step by step method, it can simulate the physical track structure of particles and generate the chemical species. These chemical species will diffuse and react with each other, with time going on. Besides, an atom-by-atom model of interphase nucleus with 46 chromatins and 2 nucleoli was developed. The DNA damage can be simulated, including the yields of DNA strand breaks and the frequency distribution of different length DNA fragments. With the simulation of NHEJ repair process, NASIC can provide the different types of chromosome aberration, such as dicentrics, acentrics, centric ring and chromosome deletion. Furthermore, three cell death models were constructed, from the DSB yield to cell death, from the frequency distribution of DNA fragments to cell death and from chromosome aberration to cell death.

### Results

All the simulation results are close to the published experimental data, including the DNA damage, the chromosome aberration and the cell survival fraction. And the cell death models can be applied to all kinds of radiation types and energies.

### Conclusions

NASIC can simulate the different biological endpoints accurately. It's a very useful tool to study the track structure and radiation biological effects of different types and LETs radiation. It can also be used to evaluate the radiation biological effects in particle therapy.

Thursday May, 30





## Recent Work of ICRP Committee 1 on Radiation Effects – From Low-Dose and Low-Dose-Rate Effects to Individual Radiation Response

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Committee 1 of the International Commission on Radiological Protection (ICRP) focusses on the risk of induction of cancer and heritable disease (stochastic effects), and the underlying mechanisms of radiation action. The Committee also discusses the risks, severity, and mechanisms of induction of tissue/organ damage and developmental defects (tissue effects). Endpoints considered manifest on various organisation levels from sub-cellular systems (e.g., DNA), to cells, tissues, animals and humans. As of 2019, the Committee includes 15 members from 11 countries with expertise in various fields such as biology, genetics, human and veterinary medicine, mathematics and statistics, physics and dosimetry, radioecology, and epidemiology. This variety in scientific background reflects the interdisciplinary nature of work done by C1 members to quantify radiation risk to humans and non-human biota.

Currently, C1 is running five active task groups: TG64 on “Cancer Risk from Alpha Emitters”, TG91 on “Radiation Risk Inference at Low-dose and Low-dose Rate Exposure for Radiological Protection Purposes”, TG99 on “Reference Animals and Plants (RAPs) Monographs”, TG102 on “Detriment Calculation Methodology”, and more recently TG111 on “Factors Governing the Individual Response of Humans to Ionising Radiation”. In addition, a number of Working Parties deal with further topics that are relevant for low-dose radiation effects and radiation protection.

This presentation gives an overview on the most recent activities of this Committee.

## **Interdisciplinary dosimetry research supporting medical (and wider) uses of ionising radiation**

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Medical exposures form the largest manmade contributor to total ionising radiation exposure of the UK population and, in recent years, a number of new technologies have been developed to improve treatment and prognosis of individuals treated with radiation for diseases such as cancer. However, there is evidence of public, patient and medical professional concern that radiation protection regulations and practices, as well as understanding of potential long term adverse health effects (in the context of other health risks), have not always 'kept pace' with technological developments in this field.

The 'Radiation Theme' of the PHE and Newcastle University Health Protection Research Unit project 'Chemical and Radiation Threats and Hazards' is focused on addressing this need, through a genuinely interdisciplinary approach bringing together world leading epidemiologists, radiation biologists, clinicians, statisticians and event artists - through a strong focus on public and patient involvement.

Recent outputs from the consortium include publications on new conclusions regarding risk following CT exposure and cardiac catheterisation, data of relevance to the reduced eye dose limits in the recently revised UK Ionising Radiation Regulations, and further development towards use of biological endpoints that can be used as markers of radiation risk to support personalised use of radiation in medicine and in wider fields.

## Low doses of ionizing radiation: where do we stand now?

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The use of ionizing radiation in medicine plays an important role in the modern world since it is an effective tool in diagnosing and treating patients. Radiotherapy uses high doses of ionizing radiation to shrink tumors and kill cancer cells while lower doses of ionizing radiation are used in benign diseases particularly in inflammation-related diseases as several studies show that low doses of ionizing radiation (LDIR) have anti-inflammatory properties. It is also important to note that target organs receive during diagnostic X-ray examinations and interventional procedures that are increasingly used in clinical practice. Moreover, healthy peritumoral tissues are also exposed to low doses of ionizing radiation during radiotherapy.

Although the molecular mechanisms by which high doses act are well studied, it is still a challenge to reveal the cellular and molecular effects of LDIR.

Strikingly, we previously demonstrated that moderate to low doses of ionizing radiation (doses lower or equal to 0.8 Gy) activate endothelial cells and promote neovascularization in different experimental models. *In vitro*, LDIR induce a rapid phosphorylation of several endothelial cell proteins, including VEGF and consequently activate the endothelium and modulate the expression of pro-angiogenic factors. Using different animal models, we showed that LDIR promote angiogenesis during zebrafish development or adult fin regeneration and, in a murine matrixes assay. In a mouse model of hindlimb ischemia, LDIR stimulated neovascularization (0.3 Gy administered during 4 consecutive days). Interestingly, using murine tumor models whole body LDIR (0.3 Gy) promoted tumor growth and metastasis formation by enhancing angiogenesis. Since whole body exposure was applied, the data suggested that LDIR do not change the metastatic organotropism. Noteworthy, using human biopsies we validated the experimental data showing an activation of endothelial cells and increase of the microvascular density in peritumoral tissues exposed to LDIR. This effect should be taken into account in the treatment plan report for patient follow-up and in future studies to correlate these doses with potential tumor dissemination.

Interestingly, using a mouse model of hindlimb ischemia we also found an innovative, non-invasive strategy to induce therapeutic neovascularization, emerging as a novel approach in the treatment of critical limb ischemia patients.

Further research is warranted to unravel the effects of LDIR and their challenges in the future will be addressed during this presentation.

## **A Roadmap to a Roadmap: Perspectives on Recent Low Dose Initiatives in the United States**

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A series of initiatives in the United States have been undertaken by various stakeholders towards advancing the dialogue of the future prospects for low dose regulation and research. Recently, the National Academies of Sciences, Engineering, and Medicine hosted the Gilbert W. Beebe Symposium in Washington, D.C., to discuss the need for a long-term strategy to guide low-dose radiation research. Notably, the symposium discussed the status of low dose research in the U.S. and internationally, priority scientific goals for low dose research; potential value of a long-term strategy to guide U.S. low dose research; criteria to judge success; and evaluating options for organizing such a research initiative. The outcomes of this event and other synergistic activities, such as those of professional societies, will be discussed.

## Radon Exposure Assessment and Dosimetry for Risk Estimation in Hydrotherapy Centers

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### Introduction

In countries with long historical tradition in thermal water therapy and with several mineral-medicinal thermal sources, workplaces within thermal centers may be a source of radon exposure which may be intensified if these are located in regions of high level of natural radiation.

According to the EU Directive 2013/59/EURATOM, each Member State shall identify, by means of survey or any other adequate mean, the work activities where a significant increase in the exposure from natural radiation sources may occur, including thermal centers where the exposure to thoron/radon daughters or gamma radiation may occur.

### Methods

The purpose of this work was to perform a radiological characterization of selected thermal centers based on indoor dosimetry. The effective doses received by workers due to radon inhalation were estimated and gamma dose rates were measured through continuous periods. The radon risk for indoor exposure was assessed on a probabilistic basis considering probabilistic distributions for the different parameters involved.

### Results

Radon levels within the thermal centers ranged from 73 to 4335 Bq/m<sup>3</sup> and the values within the workers dwellings are of the same order of magnitude, 68-4051 Bq/m<sup>3</sup>. Approximately 66 % of indoor radon concentration values are above the maximum EU reference (300 Bq/m<sup>3</sup>) and 94 % of the effective dose is higher than 1 mSv/year. In some situations, radon levels at residential environments are much higher than at workplaces and effective doses are higher than 6 mSv/year, both at residential and work environments.

### Conclusions

The results from this study showed that several reference level (indoor radon levels, effective dose) were exceed both at occupational and residential environments. In addition there are several cases where the reference level of “an existing exposure situations”, 6 mSv/y is also exceed, and in these cases, according to the EU Directive 2013/59/EURATOM, the exposure should be classified as “a planned exposure situation” and actions should be taken. The results at worker’s dwellings are also worrisome being sometimes higher than in the occupational environments.

## Indoor radon concentration in dwellings of the workers of the old uranium mine of Urgeiriça (Central Portugal)

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The Urgeiriça mine was the main site of exploration of radioactive ores in Portugal. The operations began in 1913 and were concluded in the year 2000. During this period, a vein was explored through underground mining. Most of the ores explored in ca. 60 other mining sites were processed in the Urgeiriça facilities. This resulted in a high production of waste which was accumulated in several tailings of this mining area.

Since 2001, the Portuguese government has been responsible for the environmental remediation works in the Urgeiriça area through the company EDM (*Empresa de Desenvolvimento Mineiro*). So far, around 30M€ have been invested only in the Urgeiriça area.

In the early 1950s, two residential districts were built near the mining area by the English company who was, at the time, responsible for the mine (CPR), to provide support to the workers. During the environmental rehabilitation programme, research revealed the presence of radioisotope-enriched material in this dwellings, similar to those which were deposited in the old tailings. This prompted the creation of a rehabilitation programme for such dwellings, which is currently being implemented.

To assess radiological risk and ionising radiation exposure doses, radon gas concentration was measured in 124 homes using 493 passive CR-39 detectors. The project was carried out in two phases (P1 and P2), but the results were similar in both cases. Radon gas concentration in indoor air fell within the range of 46 to 6 094 Bq.m<sup>-3</sup>. The arithmetic mean was 936 Bq.m<sup>-3</sup> (P1) and 742 Bq.m<sup>-3</sup> (P2), exhibiting high variability in both cases with coefficients of variation between 50 to 60%. Radon concentration is lower than 400 Bq.m<sup>-3</sup> in 30-40% of the measurements, and higher than 1 000 Bq.m<sup>-3</sup> in 20-30% of the detectors that were analysed. The integration of this data with information obtained for other radiological variables made it possible to identify which dwellings required remediation, as well as the degree of intervention necessary for each one.

## Preliminary analysis of the radon concentration in waters of the Municipality of Bibala, Angola: Implications on public consumption

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### Introduction

Radon,  $^{222}\text{Rn}$ , is a noble, odourless, tasteless, colourless gas that results from the radioactive decay of uranium and radium present in soil and rocks. Being an inert gas does not react chemically and therefore is not perceptible by the human senses. Radon is the largest contributor to radioactive pollution in groundwater. When ingested can cause serious damage even considering low radiation doses. One of the long-term effects of exposure to radon is the occurrence of oncological diseases in the population. The objective of this work is essentially to evaluate the concentration of radon in samples of water used for public consumption in the region of Bibala, Angola.

### Methods

The determination of the radon concentration in water samples was performed with the RAD7 equipment, manufactured by the American company DurrIDGE, using the RAD7 H<sub>2</sub>O technique. This technique uses specific protocols that provide a direct reading of the radon concentration in the water sample.

### Results

The determination of radon concentration in the Bibala municipality was performed in 26 locations. The water was collected in water catchment holes at different depths. Of the analyzed samples, five presented values above 100 Bq/L, being 207 Bq/L the maximum value found and 39 Bq/L the lowest measured value.

### Conclusions

According to the measured values we can conclude that the existing radon in the analysed water samples contributes to an effective annual dose of 0.62 mSv for adults and 1.22 mSv for children. These values are above the Reference Dose Level (RDL) of the World Health Organization which sets an effective dose of 0.1 mSv/year. However, there is no legislation in Angola establishing parametric values for radon concentration in water.

## Radon and its implications in the daily life of the population

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### Introduction

Human exposure to radon and radon decay products in homes, workplaces and other buildings is one of the main risks of ionizing radiation, causing thousands of deaths from lung cancer. The average annual effective dose was estimated to be 2.4 mSv from the natural sources, out of which, approximately 1.0 mSv is because of the exposure of radon (UNSCEAR, 2000). Radon is considered a radiotoxic and carcinogenic gas and results from the natural radioactive decay of uranium (<sup>238</sup>U) present in the soil and rocks as well as the drinking water and building materials.

Over the last years, the building industry has developed new building materials that may contain significant quantities of naturally or technologically enhanced levels of radioactivity. For that reason, it is important to evaluate the amount of natural radioactivity present in the building materials, which are used in the construction of dwellings in order to minimize and reduce the human radon exposure.

### Methods

The radium (<sup>226</sup>Ra) activity concentration in ornamental rocks and composites commonly used as building materials was determined by gamma-ray spectrometry, using HpGe detectors, whereas radon (<sup>222</sup>Rn) exhalation rates were measured using a continuous radon monitor (active technique) and solid state nuclear track detectors (passive technique). The emanation fraction and alpha index were also calculated.

### Results

On average, the measured <sup>226</sup>Ra values range from 5 to 123.4 Bq Kg<sup>-1</sup> and, as expected, the results show that the radon exhalation rate is higher in granites samples relative to others building materials. The radon exhalation rate in terms of mass varies from  $0.9 \pm 0.2$  to  $16.9 \pm 1.8$  mBq kg<sup>-1</sup> h<sup>-1</sup> for the passive technique, and between  $10.6 \pm 2.6$  and  $70.3 \pm 9.8$  mBq kg<sup>-1</sup> h<sup>-1</sup> for the active technique.

### Conclusions

The use of the analysed building materials was considered safe for inhabitants and not representing a public health hazard if used for the construction of dwellings or workplaces.



## Evaluation of the Radon Exposure Potential in Buildings in the Municipality of Lubango

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### Introduction

Radon is a noble gas, and being inert, can move freely through the porosities of the soil and the rocks. It is abundant in some granite soils and because it doesn't react with other elements it doesn't become bonded to other atoms, easily mixing with the atmospheric air. Outdoor radon gas gets diluted and isn't a concern to public health. However, confined inside buildings can build up to high levels and become a health risk, especially when ventilation is poor or none at all. The main objective of this work is the determination of radon concentration in family dwellings and public buildings in the city of Lubango, Angola.

### Methods

The release of radon gas from the soil varies daily and seasonally so that within the dwelling, its level fluctuates throughout the day. For this reason the use of active detectors allow us to understand potential individual hazards. On the other hand the use of passive detectors can provide results of the annual average concentration. In this work, passive CR-39 detectors were deployed in selected buildings for a period of 90 days. After appropriate physico-chemical treatment, the Radosys equipment was used to read the nuclear tracks left by alpha particles on the detectors.

### Results

The determination of the radon concentration in the city of Lubango was carried out in 59 single-family dwellings and 9 public buildings. The results obtained show that in 64% of the selected dwellings the concentration of radon was greater than 100 Bq/m<sup>3</sup>.

### Conclusions

Taking into account the obtained results we can conclude that the values found are above the reference value of 100 Bq/m<sup>3</sup>, recommended by the World Health Organization, although no legislation in Angola establishes reference levels for radon exposure.

## A low-cost radon monitor

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### Introduction

Radon gas and its polonium progeny decay through alpha emission. Windowless Si-PIN photodiodes are sensitive to alpha particles and can be used as radon detectors. Many devices have been built for radon detection using this principle. A favorite choice are Si-PIN photodiodes from Hamamatsu S3590 series. This photodiode features good energy resolution, but its price, in the hundred euros range is a drawback if the goal is to build a simple radon monitor. Silonex produces a low-cost planar Si-PIN detector (SLCD-61N5) with a thin window, making it usable for radon detection. The energy resolution is limited by the thin window, but the photodiode can be used as a counter.

### Methods

The signal of the photodiode is read by a transimpedance amplifier. The amplified signal is then discriminated, shaped and fed to an Arduino microcontroller. The Arduino counts the number of hits on the photodiode due to alpha particle interactions. The Arduino is connected to a computer where data is recorded. The setup is enclosed in box where radon gas enters through a set of holes drilled on the box wall. The photodiode sits behind a maze that stops light from hitting it.

### Results

The monitor was tested in a box that can be filled with radon exhaled by rocks containing uranium ore. The box filling and emptying was simultaneously recorded by the monitor and a Geiger counter. Both detectors present similar counting curves.

### Conclusions

A low-cost radon monitor can be build using a low-cost photodiode from Silonex and using an Arduino as acquisition system.

## NUMERICAL ANALYSIS OF THE IRRADIATION AND HEATING PROCESSES OF THERMOLUMINESCENT MATERIALS

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### Introduction

In this work, three numerical simulations have been carried out to show the compatibility between the analysis methods based on the mathematical functions associated with First Order Kinetic approximation and the traps filling process during irradiation. The main idea used in the followed simulations, is that **the trapping probability coefficients  $A_i$  [ $\text{cm}^3 \cdot \text{Seg}^{-1}$ ] are not negligible**, so there is no restriction for the free electrons generated, during both process (irradiation and heating), to be trapped into the traps. Therefore the simulations (irradiation and heating processes) have been carried out integrating the sum of all trapping probability coefficient plus the recombination probability into the differential equations system.

### Methods

The physic model is based on the well-known theory of bands of energy in solids for TL materials, developed by Randalls and Wilkins in 1945, which is implemented into a software tools for executing numerical analysis/simulations, it has been developed in the CIEMAT into the Radiation Dosimetry Unit and it is divided in two modules. The first module is an application based on the algorithms developed for the TL glow curve deconvolution analysis, assuming first order kinetics peaks; include automatic detection of peak position and first estimation for the kinetic parameters. The second module defines and solves the differential equations system to simulate the temporal evolution of electron concentration into the traps and levels into a TL material.

### Results

A systematic deviation appears when the first order kinetic mathematical functions for fitting TL glow curve are used, but these deviations can be reduced if all the traps are far away of saturation situation and there is a relationship between the TL glow curve shape and the absorbed dose.

### Conclusions

The results shows as the new ideas are useful to achieve a correct integration between the trap probability coefficient, that cannot be negligible, and the FOK approximations.

## Correcting the dose enhancement near gold nanoparticles from simulation results biased by lack of secondary particle equilibrium

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### Introduction

Gold nanoparticles (GNP) are known to enhance the biological effect of photon irradiation, mainly due to dose enhancement in their vicinity, as shown by Monte Carlo (MC) simulations. In the absence of charged particle equilibrium (CPE) in the simulation setup, however, the simulations predict a biased dose enhancement. In this work, a method for correcting biased results is presented.

### Methods

The irradiation of a spherical GNP surrounded by water was simulated for a parallel photon beam of dimensions comparable to that of the NP. The absorbed dose to water was calculated with and without the GNP for two different GNP diameters and three different x-ray spectra. Using known photon interaction data, the absorbed dose was determined analytically in a setup ensuring CPE by assuming i) a comparable lack of charged particles with and without GNP and ii) a negligible influence of the changes in the biased radiation energy spectrum on the emission of secondary electrons by the GNP.

### Results

The simple analytical method used in this work showed that, for all six combinations of GNP dimensions and photon spectra, the dose enhancement factors obtained in conditions of CPE resulted to be about an order of magnitude smaller than in narrow-beam MC simulations. Furthermore, if CPE is ensured, significant dose enhancement is only found within the first 100 nm to 200 nm around the GNP rather than extending to several micrometers. Both results are in agreement with deterministic calculations for broad beams found in the literature. Scattered photons interacting with the GNP do not significantly change these observations.

### Conclusions

To compensate for a lack of CPE, a more realistic estimate of absorbed dose to water in the absence of the GNP can be obtained by analytical calculations using known photon interaction data. This method allows for a correction of biased, narrow-beam MC simulations with reduced computing time with respect to accurate broad-beam simulations.

Dosimetric assessment in different tumor sub-volumes with Auger electron-emitting radionuclides:  $^{99m}\text{Tc}$ ,  $^{125}\text{I}$ ,  $^{161}\text{Tb}$ , and  $^{177}\text{Lu}$

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Internal radiotherapy using Auger-emitting radionuclides is a relatively new technique that presents interesting advantages with respect to external radiotherapy, such as localized tumor efficacy. The aim of this study was to assess the dosimetric effectiveness in irradiating a tumor partitioned in different sub-volumes, with different radionuclides directed at each tumor phenotype:  $^{99m}\text{Tc}$ ,  $^{125}\text{I}$ ,  $^{161}\text{Tb}$ , and  $^{177}\text{Lu}$ .

State of the art Monte Carlo PENELOPE code and ICRP reference voxel phantom were used in order to mimic a lung tumor volume composed by four different phenotypes. For each radionuclide above mentioned, the decay mode (accessed through ICRP-107 data files) was considered, namely Auger electrons and  $\beta$ , X and  $\gamma$  radiation. Two main radiation therapy scenarios were simulated: i) the entire tumor was irradiated homogeneously with each of the radionuclides; ii) each tumor sub-volume was filled with a different radionuclide. The optimal dosimetric configuration was studied in terms of Dose Efficiency (DE), defined as the maximum tumor-to-healthy dose ratio.

The Monte Carlo model was validated by comparing Specific Absorbed Fractions of the ICRP reference voxel phantom present in bibliography. In the first scenario, calculations showed that the highest DE is reached by  $^{177}\text{Lu}$ . Namely, with  $^{177}\text{Lu}$  a gain dose factor (GDF) of about 1.7, 2.5 and 45.4 could be achieved, with respect to  $^{161}\text{Tb}$ ,  $^{125}\text{I}$  and  $^{99m}\text{Tc}$ , respectively. In the second scenario, the combination of three  $^{177}\text{Lu}$  sources in three tumor sub-volumes and one  $^{125}\text{I}$  source in the fourth sub-volume resulted in a higher GDF (of about 1.24) with respect to the use of  $^{177}\text{Lu}$  homogeneously in all tumor sub-volumes.

According to this study, the hypothetical use of different electron beam qualities directed to different tumor phenotypes of the same tumor could act as a radio-sensitizer and, at the same time, minimize dose to the surrounding healthy tissues.

**CT conversion method for retrospective analysis of carbon-ion radiotherapy treatment plan using Monte Carlo simulation.**

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**Introduction**

Most treatment planning system (TPS) used in carbon-ion radiotherapy (CIRT) facilities are implemented with pencil beam algorithm which cannot compute dose by secondary particles  $D_{\text{sec}}$  and scattering particle accurately  $D_{\text{sca}}$  whereas these dose are the main source to surrounding normal tissues. Therefore, it may help the treatment outcome if we can do retrospective analysis using Monte Carlo (MC) simulation which is able to calculate  $D_{\text{sec}}$  and  $D_{\text{sca}}$ . To facilitate re-calculation of treatment plan in MC code, we proposed one is used to convert CT number to mass density and elemental composition of a specific material.

**Methods**

In this work, we used the CT number to stopping power ratio table in TPS and the standard tissues of reference adult phantoms in ICRP-110 to converse CT number to density and material composition. To verify the conversion method corresponding to the TPS, we calculated the depth dose distribution in the homogeneous phantom with ten different material by TPS (XiO-N, ELEKTA, and Mitsubishi Electric) and MC code (PHITS) and compared the range. To evaluate if the proposed method can represent the TPS in a certain degree and in the meanwhile calculate  $D_{\text{sec}}$  and  $D_{\text{sca}}$ , we make a treatment plan with a simple geometry in XiO-N, re-calculated it in MC and measured it using advanced Markus chamber and pin-point chamber were used for depth dose distribution and lateral dose distribution, respectively.

**Results**

In the homogeneous phantom made of different materials, range difference between TPS and MC are within 1 mm. The measured range agreed well with the range calculated by TPS and MC. On the other hand, the measured dose distribution in the penumbra region and fragment region agreed well with that calculated by MC code whereas significant difference between TPS and measured data were observed.

**Conclusions**

In this work, we proposed a method to convert CT number to mass density and elemental composition of a material.

## Investigation of a correction method to improve the accuracy of clinical dosimetry calculations for radiopharmaceutical therapy

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### Introduction

Molecular radiotherapy delivers radiation to malignant cells whilst minimising the damage to healthy tissue via the interaction of radiopharmaceuticals with molecular sites and receptors. Clinical tumour dosimetry is often performed using so-called S-values calculated under the assumption of a unit density spherical representations of a tumour with uniform uptake. The aim of this study is to quantify the impact of tumour shape on absorbed dose estimates to investigate the potential for parametrised correction factor dependant on tumour shape parameters.

### Methods

The EGSnrc/EGS++ Monte Carlo (MC) code [1] was used to generate S-values for <sup>32</sup>P, <sup>89</sup>Sr, <sup>90</sup>Y, <sup>131</sup>I, <sup>153</sup>Sm, <sup>166</sup>Ho, <sup>177</sup>Lu, <sup>186</sup>Re and <sup>188</sup>Re, using the decay data from the RADTABS/MIRD software [2]. To study the impact of tumour shape on the self-irradiation absorbed dose S-values, a set of constant volume cylinders was used: 1, 5, 10, 20, 50 and 100 ml with radii ranging of 0.3-5 cm. Cylinder S-values were compared to the sphere values.

### Results

A dependency between the cylinder surface-area-to-volume ratio and the S-values was found for cylinders of the same volume, where the cylinder S-value peaked at the smallest surface area. The dependency with surface area decreased for larger tumour volumes. The smallest and largest differences were observed for low and high energy radionuclides, respectively. For a 10 ml tumour, the differences ranged between 0.03% and 4.1% for <sup>177</sup>Lu, and between 1.9% and 36% for <sup>90</sup>Y, corresponding to cylinder radii of 1.25 and 3.5 cm.

### Conclusions

Sphere S-values routinely used in clinical dosimetry can significantly overestimate the absorbed dose delivered to tumours, in particular for high energy radionuclides such as <sup>90</sup>Y. For a given tumour volume, the error introduced in the tumour absorbed dose increased with the surface area. Further tumour shapes and a parametrised correction method will be investigated.





## Design of a compact shielding envelope and elements of radiological protection at the TRIUMF-ARIEL facility

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### Introduction

The Advanced Rare Isotope Laboratory (ARIEL) is currently under construction at TRIUMF. ARIEL's mission is to supply existing experiments with more diverse and more intense radioactive ion beams produced via the Isotope Separation On-Line (ISOL) method. The drivers inducing the nuclear reactions at ARIEL include a 500 MeV proton beam from the main cyclotron as well as a 35 MeV electron beam with the intent of simultaneous operation using two separate additional target stations. The generated radioactive ion beams will be made available to experiments in condensed matter and subatomic physics as well as practical applications such as medical isotopes for life sciences research.

### Methods

This work details the various simulations performed using the Monte Carlo particle transport and interaction code FLUKA. The code was systematically employed to predict prompt and residual radiation levels to characterize the radiation fields generated via the irradiation of various types of targets. An iterative combined development process between CAD-based engineering of the shielding envelop, nuclear physics optimization of the target system and particle tracing simulations was established.

### Results

Preliminary simulation studies resulted in the selection of shielding materials and respective thicknesses with the goal of maximizing attenuation while mitigating residual activation. The results provide clarity regarding operational constraints and aid in determination of expected dose rates outside of shielding in high occupancy areas. A series of optimization steps followed the preliminary work, testing various parameters including beam power, target material and shielding configurations. These results were evaluated considering technical feasibility, safety, and economic impacts on ARIEL construction and eventual operation.

### Conclusions

Although the project in its infancy is expected to proceed through stages of increasing complexity, the shielding and radiation transport modeling completed to date helps to define and validate nominal operation and failure scenario procedures for all future project stages.

## TRIUMF's ARIEL facility radioactive waste storage and disposal studies

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### Introduction

TRIUMF is currently constructing the Advanced Rare Isotope Laboratory (ARIEL). When completed, the facility will increase significantly the availability, variety and intensity of exotic radioactive ion beams available for physics experiments. The benefit of increased science output however brings the associated detriment that the amount of high-level irradiated waste material produced increases proportionally with the number of targets irradiated. This added burden poses additional challenges in remote handling, waste retrieval, containment, and disposal processes and inputs to the design of these systems in terms of shielding, capacity, etc. need to be generated.

### Methods

This work used the Monte Carlo particle transport and interaction code FLUKA to model different potential targets to determine approximate radionuclide inventories of the waste generated. The study considered both different target materials and assembly components. An internally developed MATLAB script was used to verify FLUKA predicted dose rates and shielding effectiveness.

### Results

The results of the simulations were catalogued within a database, benchmarked with measurements of similar existing TRIUMF waste. The data were finally processed via independent MATLAB scripts in an effort to categorize predicted ARIEL waste and assess options for storage and disposal. This work additionally informs the expected remote handling of irradiated vessels by providing residual dose rate estimates to be used in the planning of target retrieval procedures. The results provide estimates for both shielding and decay time required for the different targets at the various stages and locations of storage and containment.

### Conclusions

In summary, this work is an essential component towards determination of the required storage capacity, including plans for processing and shipment of radioactive waste produced during ARIEL operation.

## Dose Rate Evaluation of Two Modified Options for the Dry Cask Storage at Chin Shan Nuclear Power Plant Using a Hybrid Deterministic/Monte Carlo Method

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### Introduction

An independent spent-fuel storage installation (ISFSI) at the Chin Shan nuclear power plant (NPP1) in Taiwan was built in order to remove spent nuclear fuels before the start of decommissioning. According to its safety analysis report, the standard storage cask is essentially the design of the NAC-UMS system, which includes a canister, steel liner, concrete shielding, air inlets/outlets, and other supporting structures. In addition, an add-on concrete shield (AOS) was designed to surround the cask top and side surfaces in order to enhance the original cask shielding because of a short distance to the nearest site boundary and a stringent dose limit. The Atomic Energy Council has approved the first-phase of the facility with a total of 30 storage casks, allowing the removal of 1680 spent fuels from the crowded spent fuel pool for interim dry storage. However, due to strong opposition from nearby residents and anti-nuclear groups, the facility cannot get approval from the local authority to start its operation. After several years' delay, the government recently announced that spent nuclear fuels in Taiwan will be kept in indoor facilities in a bid to gain public support for solving political deadlock. Compared to the original plan in outdoor environment, two modified options for the existing dry cask storage at NPP1 were considered and evaluated in terms of dose rate distribution.

### Materials and Methods

Monte Carlo transport calculations for a large-sized and heavily-shield ISFSI facility essentially involves many calculational difficulties and, therefore, effective variance reduction techniques are indispensable. In this study, the modeling of the storage cask loaded with the design-basis fuel was carefully implemented to ensure consistency with those specified in the safety analysis report. A full-scale calculation model of the original ISFSI layout including 30 casks with detailed geometry was established first. Two modified options of the facility are as follows: the first one is housing the 30 standard storage casks (without their AOS) in a concrete building and the second option is simply housing the 30 casks with their AOS in a steel structure building covered with thin metal sheet. This study performed dose assessment for the three configurations.

### Results and Conclusions

Based on advanced variance reduction techniques and powerful geometry modeling capabilities, the hybrid deterministic/Monte Carlo code MAVRIC can solve this challenging shielding problem by directly simulating the radiation transport in a full-scale model, tracking radiation from the neutron and gamma-ray sources in canisters up to site boundaries. Detailed dose rate distributions around these ISFSI configurations were obtained and compared.

## Measurement of small field output factors for a linear accelerator with several detectors and EBT3 radiochromic film

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### Introduction

Small field output factors (OF) determination is particularly important in the commissioning of SRS and SBRT techniques with considerable impact in the accuracy of patient treatments. Small field OF measurements are challenging due to beam and detector characteristics such as loss of lateral charged particle equilibrium, partial occlusion of the source and size of the detector.

Recently IAEA published TRS 483 a code of practice for dosimetry of small fields.

In this context, the aim of this work was to determine small field OF for a linear accelerator and provide a comparison of the measurements for several detectors and for EBT3 radiochromic film.

### Methods

OF for an Elekta Synergy S Beam Modulator at 6 MV photon beam were measured, for field sizes ranging from 0.8 cm to 10.4 cm (side of the square field), with the following detectors: PTW 60003 diamond, PTW 60017 Diode E, PTW 31016 PinPoint ion chamber and PTW 31010 (0.125 cm<sup>3</sup>) ion chamber.

The TRS 483 code of practice and formalism were followed for the determination of the OF. OF were also determined with a reference passive dosimeter, the Gafchromic EBT3 film. A multichannel film dosimetry protocol with nonuniformity correction was used for the film calibration and processing.

### Results

Obtained OF show excellent agreement (< 1%) of the diamond detector, including TRS 483 correction factors, with EBT3 film in all measured field sizes. PinPoint and 0.125 cm<sup>3</sup> chambers, including the correction factors, also show excellent agreement with EBT3 film for field sizes  $\geq 1.6$  cm. Diode E showed an increased over response only in the smallest field size where, including the correction factors, the difference to EBT3 film was 4%.

### Conclusions

Small field OF for the linear accelerator of this study were determined.

The results support that the diamond detector with TRS 483 correction factors and EBT3 film dosimetry are suitable for the determination of small field OF.

Further investigation is needed regarding the response of the diode E in the smallest field.

## Irradiation Aging of the CMS DT Muon Detector

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### Introduction

During High Luminosity Large Hadron Collider (HL-LHC), the Compact Muon Solenoid (CMS) needs to sustain an integrated dose ten times higher than expected in LHC. Irradiation campaigns have been performed to assess the capability of operating under such conditions and the radiation aging. Here we present results for the Drift Tube (DT) chambers, which are wire gaseous detectors used to identify, reconstruct and trigger on muons.

### Methods

The DT chamber installed at the Gamma Irradiation Facility (GIF++) at CERN is being irradiated with a high activity Cesium 137 source over several months. The characterization of the dose deposited on the chamber has been made using different devices to cross-check the measurement. A RADMON sensor with a radiation sensing field effect transistor, a RAMSES detector based on an ionization chamber and a commercial portable Geiger-Müller dosimeter. The HV currents of the chambers at CMS during collisions are measured as a function of instantaneous luminosity to extrapolate to HL-LHC conditions. Proportional tubes has been used both at CMS and GIF++ both to correct for pressure variations and to compare aging caused by the different radiation spectra.

### Results

The measured dose on the chamber and the extrapolation to HL-LHC is presented. Also, several corrections have to be made due to the large dimension of the DT chamber and the non-uniform irradiation. The currents provided by the DT wires as a function of the integrated dose are shown and the curve of the loss of gain expected versus the dose is obtained and extrapolated to the expected HL-LHC values.

### Conclusions

The results obtained allow predicting a degradation in the DT chambers in the order of a factor 3 in gain for the most exposed chambers. The effect on muon reconstruction is very mild. Different mitigation techniques are being tested such as operating at lower voltages and shielding the outer part of the detector to avoid the irradiation from backscattering.



## Pulse-by-pulse dosimetry of intensity modulated radiotherapy with a CVD diamond detector

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### Introduction

CVD diamond detectors have been shown to have excellent spatial resolution and a high degree of tissue-equivalence, in a form-factor that is suitable for radiotherapy dosimetry. Recently accurate, pulse-by-pulse dosimetry of a therapeutic LINAC has been demonstrated for dose-per-pulse in the range 0.05-0.5 mGy.

### Methods

In this work diamond detectors have been used to measure the time-varying dose associated with the dramatic changes in pulse-rate and intensity of a volumetric modulated arc therapy (VMAT). Methods for comparing data from the diamond detector to the intended treatment have been developed, where use is made of LINAC log files to quantify the position of the gantry angle of the LINAC as a function of time. A gamma-like index that compares cumulative and instantaneous dose with gantry angle against treatment tables has been developed.

### Results

Measurement of the pulses was performed at a variety of pulse-rates and source-distances including at points under the primary collimator. The diamond detector was shown to be able to detect radiation pulses as low as 0.002 mGy/pulse. A small amount of leakage was detected and shown to depend on the average dose-rate, with a time-constant of approximately 200 ms. The leakage current was monitored continuously between pulses and the dose per pulse corrected accordingly. All pulses in the VMAT delivery were shown to be detected which reached a minimum dose of 0.016 mGy/pulse. Gamma analysis with a distance criterion of within 8° in gantry angle and 5% of the cumulative dose gave a pass-rates in excess of 95%, suggesting that with more relaxed criterion it was possible to detect errors with low false-positive rates.

### Conclusions

With such excellent sensitivity the diamond detector proves to be extremely versatile, measuring a time varying dose at the level of the patient or below shielding apparatus and therefore without perturbing the beam. The development of the gamma analysis to indicate a time-resolved failure in a treatment is novel. The measure could be used to detect an incorrectly delivered treatment before the full unintended dose is delivered.

## One Year of Distributed Optical Fiber Radiation Dosimetry at CERN

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### Introduction

CERN's accelerator complex is characterized by very complex mixed field radiation environments, which can cause failures of important electronic components and systems. To avoid these detrimental events, it is crucial to monitor the radiation dose levels and to qualify all installed electronic equipment. Because of the sheer size of the involved facilities (several kilometers in length), in the last years we have developed and deployed a distributed and online radiation dose monitoring system, which is based on optical fiber sensing. In the presentation, we will briefly illustrate the working principle of such system. We will report on the monitoring data acquired in the operational year 2018, during which the Distributed Optical Fiber Radiation Sensor (DOFRS) was already deployed in the Proton Synchrotron Booster (PSB, ~160 m in length) and the Proton Synchrotron (PS, ~628 m).

### Methods

The DOFRS system is composed by two essential parts, a radiation sensitive Optical Fiber (OF) and an Optical Time Domain Reflectometer (OTDR). The radiation sensitive OF is selected, qualified and calibrated in order to be employed not only as a distributed radiation detector, but also as a distributed dosimeter. After briefly discussing these aspects, we will illustrate how we implemented the DOFRS system at CERN.

### Results

During the operational year 2018 at CERN, the DOFRS systems installed in the PSB (2017) and PS (2018) have been acquiring distributed radiation dose maps of these two accelerators for 270 days without interruption, measuring doses in the range of 1 Gy to 1 kGy over a useful total length of roughly 800 m. We will report on these results.

### Conclusions

In our contribution, we will briefly review the key features of the DOFRS system, from working principle to achieved performance. We will report on the use of this system at CERN in 2018, showing the results obtained in a real case scenario: a full year of distributed radiation dose monitoring at CERN accelerators.



## ***Intercomparison of active and passive dosimeters and methods in extremely high dose rate environments produced by very short and intense photon pulses***

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### **Introduction**

Recent advances in laser driven accelerators boosted the development of high dose-rate fast pulsed systems all over the world, *e.g.* the new European Extreme Light Infrastructures. The stray radiation comprises primarily high-energy photons, resulting in extremely high dose rates within a pulse duration of the order of pico-/femto-seconds. Dose measurements in such conditions have to be evaluated to validate methods. To tackle this challenge EURADOS started a program of dosimeters intercomparison. As no reference exists for ultrashort pulsed fields, a progressive approach is proposed, starting by a first evaluation in fields with  $\mu\text{s}$  pulse duration. With  $\mu\text{s}$  pulses, a dosimetric reference can be established; the instruments capable of working correctly in this field will be candidates for further tests in laser driven accelerator facilities.

### **Methods**

The first comparison took place at the Centre Hospitalier Universitaire Vaudois with an electron LINAC in Sept. 2017 involving 7 European institutes. The 6 MeV electron bunches, 2.2  $\mu\text{s}$  pulse width, impinged on a 1.8 cm thick iron target, obtaining a photon field whose time structure approached that of the stray radiation of a laser-accelerated beam, with a tunable air kerma rate per pulse of the order of 1E6 Gy/h. The tested dosimeters were both active (ion chambers) and passive (TLD, RPL, OSL, alanine, DIS, PADC, electrets, film badges).

### **Results**

Each measurement was compared to both the reference air kerma rate set on the machine and Monte Carlo simulations. All instruments, except electrets, responded linearly to air kerma rate variations, without showing any recombination dependence, thus being selected as possible candidates for further studies.

### **Conclusions**

The intercomparison was extremely useful to test instruments, models and measurement procedures. The results will be a starting point for further experimental and methodological radiation protection research at laser-accelerator facilities.

## Measurements of low energy X-rays radiated from Crookes tubes in education field by using radiophotoluminescence dosimeter

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### Introduction

Crookes tube is widely used for not only electricity but also radiological educations. It is said some Crookes tubes radiate large dose of X-rays from several tens years ago, but the energy is very low and conventional survey meter (even NaI scintillator) is useless, then the dosimetry is quite difficult for teachers in education field. In this study, we use CZT detector to estimate energy spectrum and ionizing chamber to obtain dose in our laboratory. Furthermore, we use radiophotoluminescence (RPL) dosimeter to measure the dose and also energy of X-ray in education field in Japan.

### Methods

Measurement service using RPL dosimeter is provided by Chiyoda Technol Co. using Ag<sup>+</sup> doped phosphate glass and 5 filters in one 'Glass badge'. In this study, type-FX is selected for the measurement which is used to measure low energy X-ray (10keV – 80keV), and furthermore, effective energy is obtained using filters of different thickness and material (it is required that there is no b-rays or high energy g-rays).

Measurements at education field have been achieved based on the same measurement protocol. Put a glass badge in front of a 2L PET bottle with curing tape to easy setting at correct height. To obtain a dose at 1m (standard distance from Crookes tube to students), measurements at 15cm, 30cm and 50cm were performed and these results were extrapolated to 1m using an inverse square function because a dose at 1m is rather small to measure directly using a glass badge. Measurement time was 10min for each that correspond the standard time of observation of Crookes tube. A voltage setting of induction coil which is used for high voltage supply for Crookes tube was depend on each teacher to investigate the actual condition of education field. In this first study, 37Crookes tubes were explored.

### Results

Even at 15cm, the dose ( $H_p(0.07)$ ) of 18/37 Crookes tubes were smaller than the identification limit (50mSv), and at 1m, it was estimated that the dose of 25/37 Crookes tubes were smaller than 50mSv in 10min.

On the other hand, most strong tube showed  $H_p(0.07)$ : 32.6mSv at 15cm and 0.93mSv at 1m. The effective energy was 25keV. In this case, the teacher increased the voltage to the maximum to investigate the upper limit, so it not represents the realities. And in addition, this dose is  $H_p(0.07)$  and the energy of X-rays were estimated as 16 to 25keV. With 1cm water attenuate such low energy X-ray to 1/2 to 1/3 (then  $H_p(10)$  does not represent effective dose), and dose is not uniform like of expanded and aligned field. Accordingly, effective dose is approximated smaller than 1/10 of  $H_p(0.07)$  but proper estimation of effective dose with low energy X-ray is not established.

### Conclusions

Low energy X-rays radiated from Crookes tube used in education field were measured using glass badge. The maximum dose at 1m was 0.93mSv in 10min, but it was  $H_p(0.07)$  and the energy was 25keV. Effective dose is not estimated, and so further study is required to establish a guideline for safe examination in education field.

## Nanodosimetry: from radiation physics to radiation biology

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### Introduction

Radiation-induced damage to living cells is ruled, to the greater part, by the pattern of inelastic interactions of ionizing particles in sub-cellular targets (e.g. the DNA). In consequence, the radiation effectiveness should be defined more in terms of physical quantities that are directly related to the particle-track structure than in terms of macroscopic quantities like absorbed dose and linear energy transfer (LET). At the same time, these quantities should be measurable by physical means. To tackle this challenge, a track-structure based concept of radiation damage has been developed, assuming that the initial damage to nanometre sized volumes like the DNA is mainly ruled by the number of ionizing processes of single particles within the target volume.

### Methods

Three different types of nanodosimeters have been developed to date, which measure the frequency distribution of ionization cluster size, i.e. the number of ionizations produced in a specified target volume by single ion tracks. The measured ionization-cluster size distributions are used to calculate, as potential descriptors of damage complexity, the probabilities  $F_k$  of cluster-size formation for cluster sizes greater than or equal to a fixed number  $k = 1, 2, 3, \dots$ , as a function of radiation quality (particle type and velocity). Finally, these probabilities are compared with the radiobiological cross sections of V79 and HSG cells for protons, helium and carbon ions.

### Results

It was found that the quantities  $F_k$  are proportional to radiobiological inactivation cross sections at specific survival levels, which supports new concept of radiation quality based on the track structure characterization at the nanometre level. .

### Conclusions

Measurable characteristics of the particle track structure can be used to predict biological cell survival for several radiation qualities.

## DNA circuitry as a radiosensitive detector for the quantification of radiation damage

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### Introduction

The goal of this project is to investigate the usability of DNA as a radiosensitive detector material. Here, the magnitude of radiation-induced damages can be connected to a physical parameter, namely the conductivity of the DNA. An important application of this experiment is the validation of Monte Carlo simulations used for the assessment of radiation damage in biological targets. The development of DNA-based dosimeters is another possible application. Such a dosimeter would need no weighting factors accounting for the harmfulness of the radiation type. Consequently, the knowledge of the exact composition of the radiation field is not necessary.

### Methods

DNA molecules are immobilized between gold electrodes using dielectrophoretic trapping. These samples can be electrically characterized and used for irradiation experiments. The electrical resistance of the DNA samples is measured with impedance spectroscopy, which can be carried out in situ during irradiation. The DNA samples were irradiated with alpha particles. To differentiate from environmental and aging effects, the conductivity of a non-irradiated reference DNA sample was measured simultaneously.

### Results

In all cases a change in the AC-phase was observed during the irradiation, while no changes were observed before and after irradiation. The decrease in AC-phase signal is an evidence for an increase of the overall impedance. The electrical signal of the reference samples did either not, or only slightly differ from their original values.

### Conclusions

We have found that the conductivity of DNA samples does indeed change when being exposed to ionizing radiation. A relation between the radiation damages in DNA and the impedance as a physical parameter was established. The next step in this project will be the quantification of this connection.

## Nanometric track structure properties for particle beam treatment planning

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### Introduction

Nanodosimetry aims to develop a new concept of radiation quality based on measurable properties of particle track structure that correlate with late effects at cellular level. In particular, it has been shown for several radiation qualities (defined by ion type and energy) that the cumulative probabilities  $F_k$  of measuring more than  $k$  ionizations within a nanometric volume are proportional to inactivation cross sections for different biological end-points. The track structure characteristics  $F_k$  of specific radiation qualities can be integrated into treatment planning systems to optimize the treatment plans, based on a nanodosimetric description of the mixed radiation field along the treatment depth. We present a new approach towards this aim, based on an analytical parametrization of  $F_k$  as a function of particle type and energy.

### Methods

Starting from the theoretical analysis of the stochastics of radiation interactions in nanometric volumes, we derived new analytical fitting functions of  $F_1$ ,  $F_2$  and  $F_3$  as a function of particle energy. Best fit parameters were then derived for mono-energetic proton and carbon ion beams in the energy range from 1 to 200 MeV/u, focusing on targets less than 2 nm in size, which are relevant for the estimation of biological effects. Results of measurements and Monte Carlo simulations are presented.

### Results

The fitting of  $F_k$  as a function of energy shows excellent agreement for all particle types and target sizes, thus allowing the parametrization of  $F_k$  for individual particles, as a function of ion type and energy. Weighting the relevant track structure properties  $F_k$ , local descriptors of radiation quality can be obtained also for mixed fields.

### Conclusions

The presented procedure allows to calculate the mixed-field  $F_k$  value in a fast and accurate way, allowing an efficient implementation in treatment planning systems. The relevance of this quantity for the estimation of radiation damage at cellular level has still to be confirmed in direct experimental comparison.

## Nanodosimetric analysis of proton tracks in a spread-out Bragg peak

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### Introduction

In BioQuaRT project [1] a simple relation between nanodosimetric characteristics of particle track structure and cell inactivation was found [2]. For potential use in clinical situations, options have been studied for translating nanodosimetric results for single targets to the voxel level [3]. This work presents an attempt to addressing the issue of RBE variation in a spread-out Bragg peak (SOBP) of protons based on nanodosimetric track structure analysis.

### Methods

Ionization track structure has been simulated using Geant4-DNA for protons of 100 MeV initial energy propagating in water. The frequency distribution of ionization clusters formed in target volumes corresponding to a 10 base-pairs segment of DNA was obtained as a function of the radial distance between target and proton trajectory for a set of positions along the proton path. Radial dependence of nanodosimetric parameters was analyzed using a heuristic model function to obtain an 'effective track cross section'(ETCS) as a function of the proton's residual range. The results were convolved with range distributions suggested in literature for constructing a SOBP.

### Results

The radial dependence of ionization cluster formation in the penumbra region showed a transition from an inverse power law to exponential behavior at the track end. The ETCS shows an increase in the distal end region of the SOBP in qualitative agreement with radiobiological observations of enhanced cell damage in this region.

### Conclusions

The results demonstrate that nanodosimetric track characteristics may be used for qualitatively predicting the variation of the probability for induction of lethal lesions in cells. Further analysis will investigate whether using different target sizes and correlations between targets allows a quantitative prediction.

[1] H. Palmans et al., Br. J. Radiology 88: 20140392 (2015)

[2] V. Conte et al., Radiat. Meas. 106, 506-511 (2017)

[3] F. Alexander et al., Phys. Med. Biol. 60, 9145-9156 (2015)

## Development of a Track Imaging Nanodosimeter

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### Abstract

Micro- and nanodosimetry are tools to predict biological radiation effects in complex radiation environments. So far, 'classical' nanodosimetry accounts for the stochastic nature of energy deposition by radiation in single volumes of sizes related to the dimensions of the most relevant entity in biological matter, the DNA.

However, the higher level of organization of the DNA, which is coiled around nucleosomes and folded to larger structures, implies that the biological effect depends not only on the local damage but also on the proximity distribution of two or more DNA lesions. Both parameters can be obtained by track structure measurement or numerical simulation.

Here we present an experimental device under development, which shall be able to measure the ionisation track structure of a particle in a volume of about 100 nm simulated edge length with a spatial resolution of a few nm. To obtain the highest possible spatial resolution, a TPC detecting the ionisation ions, instead of the electrons, is important. This requires efficient conversion of slow ions to free electrons in the detection plane. Furthermore, stable multiplication of these electrons and a compact readout system, capable of measuring the spatial and temporal correlation of each event are required.

For these challenges new concepts and results will be presented. For ion conversion promising functionalized surfaces with low work functions were investigated, where free electrons are produced by potential ionisation.

Multiplication of single free electrons to a measureable signal follow the concept of dielectrically quenched avalanche formation. New structures based on multistep TGEM and results for amplification at low pressure are presented. The readout will be performed by a Timepix ASIC. This chip can be assembled in units of ca 9 cm<sup>2</sup> size and handles event throughputs of 80 MHz, sufficient to 3d-image all ionisation events of a single particle track crossing the volume of the TPC.

## Particle track structure measurements from 0.5 to 18 nm

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### Introduction

Nanodosimetry has been developed to explore new concepts of radiation quality that builds on measurable characteristics of the particle track structure (ionisation pattern) at the nanometre scale. Experimental nanodosimetry is aimed at direct measurement of the ionisation clusters created by a track of a single ionising particle in volumes equivalent to single DNA strands or its more complex structures.

At present, three fully functional nanodosemeters exist: the Jet Counter (JC) at NCBJ, Poland, the Ion Counter at PTB, Germany, and the Startrack Counter at INFN-LNL, Italy. Among them, the Jet Counter is characterized by the widest range of available target sizes. An overview of the measuring capabilities of JC device in the range from 0.5 to 18 nm will be presented, as well as a discussion about its limitations.

### Methods

The Jet Counter nanodosemeter is gas-based detector, i.e. the size of the simulated nanometric target volume is expressed in terms of equivalent mass thickness, and is created in cylindrical volume with low-density gas. Geometric size of the target is 10 mm in length and 10 mm in diameter. By varying gas density the equivalent size can be adjust in range from 0.5 to almost 20 nm. The target is obtained by gas expansion from a reservoir R by a pulse operating piezoelectric valve PZ. The size of the equivalent is monitored by the transmission of a 1 keV electron beam. Gas molecules ionized by single projectiles form ionisation clusters of different size. Each ion is extracted and counted by single-ion detector on event-by-event basis. The single-ion counting efficiency is estimated to be 70-80%. The estimation of probability distribution of creation of ionization cluster of given size is a raw result of single experiment for given target-size and given radiation quality. In the presented experiments, the source of alpha particles, <sup>241</sup>Am, was used to irradiate nitrogen gas targets of different sizes.

### Results

Selected results of 10 experiments will be presented in form of mean-cluster-size vs target-size dependence. The impact of secondary electrons and their role in observed non-linearity in presented dependency will be discussed. Phenomena limiting available target range and possible corrections will be explained.

### Conclusions

The Jet Counter device can be used for reliable measurements of ionisation cluster-size distributions for target sizes ranging from 1 to 16 nm. Extending this range further in both directions requires some additional corrections, which reliability has yet to be proven. Nevertheless, The results obtained using the device can play an important role in the validation of Monte Carlo codes and a better understanding of the structure of the ionizing particle track at nanoscale.



## A new secondary standard for ambient dose equivalent $H^*(10)$

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### Introduction

A secondary standard instrument for the ambient dose equivalent  $H^*(10)$  provides the opportunity of direct measurements instead of calculating  $H^*(10)$  from air kerma by applying conversion coefficients. As these conversion coefficients are strongly dependent on the photon energy, especially for dosimetry in unknown radiation fields it is mandatory to measure operational quantities directly to obtain reliable results with low uncertainties. A commercially available secondary standard for ambient dose equivalent  $H^*(10)$  currently does not exist.

### Methods

The design of the developed  $H^*(10)$  chamber is based on a well-established spherical ionization chamber for air kerma to ensure an easily feasible and cost-effective production of the final chamber. Monte Carlo simulations were performed with the EGSnrc cavity code. The simulation geometry of the air kerma chamber was modified in many different ways to find suitable materials and designs for a response according to  $H^*(10)$ . For the construction of the prototypes the two most promising designs were chosen.

### Results

Measurements of both prototypes in X-ray fields from N-10 to N-300 and in Cs-137 and Co-60 radionuclide fields show that the requirements regarding the energy-dependence of the response according to ISO 4037-2 are fulfilled. For using the secondary standard also at higher energies (R-C and R-F fields) further optimization of the chamber might be necessary. The two prototypes are compared regarding their response and the technical practicability of the construction process.

### Conclusions

The developed prototypes of a  $H^*(10)$  ionization chamber fulfill the ISO 4037-2 requirements for secondary standards within the energy range of 10 keV to 1.25 MeV. Besides a secondary standard the chambers are also suitable to be used as area dosimeter for  $H^*(10)$  in combination with an electrometer, as needed for reliable and traceable dosimetry in unknown radiation fields.

## Electronic Dosimeters in Pulsed Fields of Ionising Radiation: New Generalised IEC Technical Specification for Type Testing

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### Introduction

Active electronic dosimeters, personal as well as area dosimeters, are used in radiation fields for X-ray diagnostics in human and veterinary medicine and in accelerator-driven fields for therapy as well as for scientific studies and research. Nowadays, these radiation fields are increasingly pulsed. Nearly all recent active electronic dosimeters are based on counting techniques, which implies a limited maximum measurable dose rate due to dead-time effects. Besides the many advantages of such direct-reading dosimeters, e.g. dose (rate) alarms, this disadvantage becomes significant in pulsed radiation fields. In the case of a pulse dose rate above the limit of the dosimeter, the indicated value for the acquired dose may be significantly wrong.

### Methods

Since 2012, a technical specification for direct-reading dosimeters using counting techniques has been available as IEC/TS 62743 Ed. 1. It describes a set of relevant parameters of a dosimeter to decide whether the dosimeter is applicable in a given radiation field or not. Additionally, the IEC/TS describes methods to determine these relevant parameters.

Some of these parameters are limited to dosimeters using counting techniques, therefore a more generalised test procedure has been developed: IEC/TS 63050 specifies test methods to determine the relevant parameters of the dosimeter according the generalized procedure.

The new technical specification IEC/TS 63050 is, like the IEC/TS 62743, designed in such a way that the user of the dosimeter can decide – based on the parameters of the dosimeter and the known parameters of the radiation field – if the dosimeter is suitable for his specific workplace.

### Results & Conclusions

The basic procedure of IEC/TS 63050 will be explained on examples and will be validated by comparison with testing results according to IEC/TS 62743.

## Active personal dosimeters in pulsed reference and medical fields

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### Introduction

Within the EURADOS Working Group 12 the performance of active electronic personal dosimeters in pulsed radiation fields in medicine was investigated. This project was divided in several tasks. Task was to evaluate the performance of the dosimeters in pulsed reference fields according ISO/TS 18090-1 and in realistic workplace fields in hospitals. Both measurement scenarios have been compared.

### Methods

A survey by WG12 identifies the most widely used electronic personal dosimeters [1]. A selection of these active electronic personal dosimeters was irradiated in the pulsed reference fields at PTB and in realistic exposure scenarios at the Städtische Klinikum Braunschweig. As reference instrument, two different ionization chambers have been used:  $H_p(10)$  chamber (10 ccm) and a spherical HS01 (1000 ccm) for  $H^*(10)$ . The chambers were connected to a mobile measurement system of PTB which is capable to measure in pulsed radiation fields[2]. The chosen personal dosimeters, Thermo Fisher Scientific EPD Mk 2, Mirion Technologies DMC 3000 and Unfors Raysafe i2 were tested in typical medical scenarios.

### Results

In many expose situations, the response of the electronic dosimeters was within 20 % to the expected dose value. But depending on the type of dosimeter, the response can drop below 20 % already below a dose rate of 1 Sv/h, which can be reached already in the scattered radiation fields. Other types of dosimeter can be used till 10 Sv/h with a response of 80 %.

### Conclusions

Exposure conditions at different workplaces clearly set minimum requirements for personal dosimeters in use.

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[2] Hupe, O., Ankerhold, U.: *Determination of ambient and personal dose equivalent for personal and cargo security screening*. Rad. Prot. Dosim. Vol. 121 No. 4, 429-337 (2006)

Comparison of personnel effective doses calculated with different dosimetry models

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Introduction

The International Commission on Radiological Protection (ICRP), in its Publication 139, shows the different methodologies used to estimate the effective dose to exposed workers in interventional procedures. Different acceptable models are presented for this estimation, based on different combinations of the readings given by the dosimeters worn over and under the leaded apron. The objective of this study is to compare the effective doses calculated with the different models, using real dose measurements from exposed workers from Spanish institutions.

Methods

More than 3500 data corresponding to users who simultaneously used over and under apron dosimeters were analysed, of which 880 exceeded the registration dose of 0.1 mSv. The effective dose ( $E$ ) was estimated according to the equation:  $E = \alpha H_u + \beta H_o$ , where  $H_u$  and  $H_o$  correspond to personal dose equivalent  $H_p(10)$  measured under and over leaded apron, respectively, and  $\alpha$  and  $\beta$  coefficients depend on the estimation model used and are presented in Table 1.

Table 1 Methods used and  $\alpha$  and  $\beta$  values for effective dose estimation

Model	Description	$\alpha$	$\beta$
1	<i>Von Boetticher et al.</i> (2010) – with thyroid shielding	0.79	0.051
2	<i>Swiss Ordinance</i> (2008) – with thyroid shielding	1	0.05
3	<i>Martin and Magee</i> (2013) – only over apron dosimeter used	0	0.1
4	<i>Common practice</i> – only under apron dosimeter used	1	0

Results

The effective dose of model 1 ( $E_1$ ) was taken as reference. Figure 1 shows the relative difference between the effective doses of the different models ( $E_i$ ), compared to the reference  $E_1$ . In Figure 2, the distribution of the  $E_i / E_1$  ratios is represented.

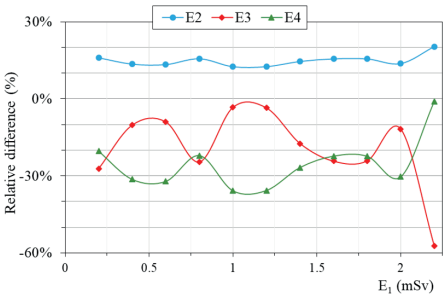


Figure 1 Relative difference of the estimated effective dose ( $E_i$ ) respect to the reference model ( $E_1$ )

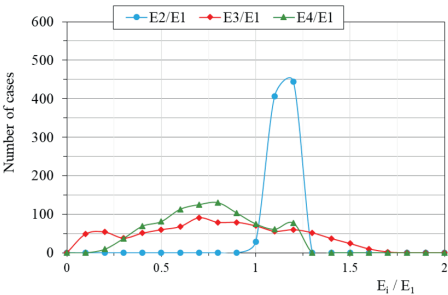


Figure 2 Distribution of the  $E_i / E_1$  ratios

Conclusions

This study shows the high dispersion existing in effective dose estimation when different models are used with data belonging to real users, which makes evident the need to reach a consensus. In most cases, the use of a single dosimeter would underestimate the effective dose when compared to the double dosimetry approach.

Relationships between eye lens doses and over apron doses in interventional procedures

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Introduction

The Directive 2013/59/EURATOM establishes a substantial reduction in the equivalent eye lens dose limit for exposed workers, which requires greater control and radiation protection of personnel. As a consequence, it has been necessary to design specific dosimeters to monitor the eye lens dose, such as the prototype by the Spanish National Dosimetry Centre (CND). It also remains an internationally accepted practice to estimate the eye lens dose from a dosimeter placed over the lead apron (at chest or neck level) and applying the appropriate correction factors to the measured  $H_p(0.07)$ . The aim of this study was to evaluate a relationship between the  $H_p(3)$  dose measured by an eye lens dosimeter and the  $H_p(0.07)$  dose measured by a whole body dosimeter placed at chest and at neck level, for different medical departments that perform interventional procedures.

Methods

The following set of three dosimeters was used: the CND's eye lens dosimeter prototype, calibrated in terms of  $H_p(3)$  and placed outside the leaded glasses next to the most exposed eye, and two CND's whole body dosimeters specifically calibrated to measure  $H_p(0.07)$  above a leaded shield. The three dosimeters were delivered to each participant in the study, which involved 61 users from 11 different institutions and from 5 different medical specialties.

Results

A linear least-squares regression was performed for each medical specialty, obtaining results presented in Table 1:

**Table 1** Results of the linear regression:  $H_p(3)_{lens} = m \times H_p(0.07)_{chest \text{ or } thyroid}$ . The number of results, the slope and the determination coefficient obtained for each specialty are shown.

Medical Specialty	CHEST			THYROID		
	number of results	m	R <sup>2</sup>	number of results	m	R <sup>2</sup>
Vascular Surgery	10	0.68	0.92	10	1.06	0.57
Hemodynamics	45	0.33	0.95	41	0.74	0.85
Neuroradiology	7	0.93	0.77	7	0.90	0.95
Interventional Radiology	21	0.33	0.59	22	0.55	0.66
Vascular Radiology	19	0.36	0.75	18	0.71	0.50

The slopes shown in the table correspond to the desired factors, which are different for each specialty studied due to geometric factors. Additionally, the attenuation factor of the leaded glasses, if used, must be added.

Conclusions

The evaluated factors enable an estimation of the eye lens equivalent dose from a chest or thyroid dosimeter worn above an apron or thyroid collar. The results show that dosimeters placed on the chest perform better than those placed on the thyroid when used as a proxy to estimate eye lens dose.

## Eye Lens Dosimetry at CANDU Power Plants

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### Introduction

In 2012, the ICRP recommended a lower dose limits to the lens of the eye<sup>1</sup>. The new proposed limit was lowered from 150 to 20 mSv per year. To address this issue in nuclear industry, Ontario Power Generation (OPG) and Bruce Power (BP) initiated a collaborative project with McMaster University. The goal of the project was to quantify gamma and beta fields in terms of fluence rate spectra, i.e. to measure the source term in CANDU power plants, and to convert this source term into dosimetric quantities of interest. These are: protection quantities (eye lens dose, effective dose and skin dose) and operational quantities ( $H_p(10)$ ,  $H_p(0.07)$  and  $H_p(3)$ ). Once measurements and data analysis are performed, eye lens dose can be compared with  $H_p(10)$  and  $H_p(0.07)$  to find out whether independent dosimetry is required for eye lens protection, or present dosimetry is adequate.

### Methods

We measured beta and gamma fluence rate spectra in three CANDU reactors in Ontario: Pickering and Darlington sites (of OPG), as well as BP sites. The instruments used were polyvinyl-toluene (PVT) plastic scintillator, EJ-204, from ELJEN Technology and  $\text{LaBr}_3(\text{Ce})$  scintillator, Brilliance 380, from Saint-Gobain. The plastic scintillator was used for measuring integrated beta/gamma spectra, while  $\text{LaBr}_3(\text{Ce})$  scintillator was used for gamma spectroscopy only. The measurements of the open systems were performed; in particular open boilers during the sites' outages. Data analysis has been performed using direct, as well as spectral unfolding methods.

### Results

It has been found that the gamma portions of  $H_p(10)$  and  $H_p(0.07)$  are conservative estimates of gamma portion of eye lens dose, while beta portion of  $H_p(0.07)$  is a very conservative estimate of beta portion of eye lens dose. This is in agreement with literature by Behrens, et al.<sup>2</sup> Hence OPG and BP whole body TLD system is an adequate protection for eye lens dose in CANDU power plants.

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1 ICRP Publication 118 (2012)

2 Behrens, Rad. Prot. Dosim., 174-3 (2016), 348-370

## The Characteristic Radiation of Copper K $\alpha$

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### Introduction

The spectrum given by the characteristic radiation of atoms is used in a number of fields of science ranging from astrophysics to nanopowders. The photoemission lines of copper provide a benchmark for both experimental and theoretical X-ray calibration in the transition metals worldwide. The K $\alpha_{1,2}$  line, caused by the 2p  $\rightarrow$  1s transition, is a doublet due to the fine structure splitting of the 2p subshell. The 2p satellite, K $\alpha_{3,4}$ , is due to a 2p spectator vacancy causing the transition: [1s2p]<sup>-1</sup>  $\rightarrow$  [2p]<sup>-2</sup>. The characterisation of the Cu spectrum is presented here, including the 2p satellite component for only the third time in the literature.

### Methods

The University of Melbourne backgammon detector was used to record the X-ray spectrum of Cu. Characteristic X-ray radiation was generated by a MACScience SRA M18XH1 water cooled rotating anode source. The X-rays produced were then directed through a monolithic Si channel-cut crystal and projected onto the beryllium window of the backgammon type detector.

### Results

The spectra have been fitted using five Voigt profiles. A Levenberg-Marquardt fitting procedure was used to fit the data with three different approaches, a residual analysis fit, a peak-by-peak fit and a simultaneous constrained fit. The simultaneous constrained fit was able to achieve modest  $\chi^2_r$ , while capturing the physical processes present in the data, therefore, we can tie the satellite lines integrated intensity to the probability of shake processes.

### Conclusions

We report a 3d shake probability of 18.39(22)%, in good agreement with the current best parameterizations. Our 2p satellite line indicates the probability of a 2p electron being excited due to the creation of a vacancy in the 1s subshell is 0.549(19)%. Typically, theoretical determination of shake probabilities have been lower than those found experimentally, indicating that more investigation, both experimentally and theoretically, is required in the field.



## Investigation of various concrete compositions with respect to gamma radiation transmission properties

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### Introduction

Reinforced concrete shielded buildings show a few cases where the measured observations are in contradiction to structural engineering predictions i.e. they were not consistent with the shielding properties expected from theoretical calculations. In addition, there is a lack of data concerning shielding properties of different concrete materials. Hence “ordinary” concrete is often used as reference material in shielding predictions.

Since concrete is a building material which is designable for specific requirements like for radiation protection in interim storage facilities for high-level waste and in surface facilities of deep geologic repositories, more detailed information about concrete radiation shielding properties is desirable.

Thus, in this work different concrete samples were investigated with respect to their gamma radiation transmission properties.

### Methods

Experiments and Monte Carlo simulations concerning gamma ray transmission properties of different concrete samples were realized. At iBMB sets of different concrete plates were prepared and their composition and densities were determined.

The following sample types were shipped to KIT-INE: ordinary, hematite, and barite concrete. At KIT-INE collimated gamma ray beams from standard sources were directed onto a set-up of different numbers of concrete plates by means of a lead collimator. The transmission of mono-energetic gamma radiation was determined from spectra recorded by a high-purity Germanium detector.

### Results

The results of the gamma spectroscopic measurements, respective transmission data and corresponding half-value layers will be presented. The outcome will be compared to existing literature values.

### Conclusions

An accurate specification of the concrete composition is very important to achieve a good agreement between Monte Carlo simulations and measurements. Therefore, it is worth pointing out the effort at iBMB to provide well-defined samples as well as detailed composition and density values for the different concrete plates.

Since concrete for radiation shielding of buildings is a significant cost factor, construction planning based on “ordinary” concrete assumptions may lead to excessive costs. Thus, it is advisable to consider concrete properties more detailed in the construction plans.

## Reducing Uncertainty in Polyethylene Dosimetry Using Multiple Measurement Techniques

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Investigations of radiation effects often require measurement of ionizing doses beyond the range of other dosimetric techniques. One method proposed for such measurements is Fourier-transform infrared (FTIR) spectroscopy in high-density polyethylene (HDPE). The measurements are nondestructive and conceptually straightforward to perform, while the material is inexpensive and readily available. Historically, the use of FTIR spectroscopy in ionizing radiation dosimetry has focused on measurements of very thin samples, with strict preparation protocols that have limited its adoption as a practical routine dosimeter. Thin samples must be safeguarded from many environmental factors, and can suffer interference fringe effects complicating analysis. Investigation of alternative FTIR methods using attenuated total reflectance has demonstrated the technique to be unreliable in HPDE.

The current work evaluates a combination FTIR spectrometry and colorimetric response of relatively thick (1-3 mm) HDPE samples over the absorbed dose range from 10 kGy to 1.2 MGy. Machine-lathed HPDE discs were irradiated in a Co-60 facility across a wide range of dose rates and under both inert atmosphere and in air. Transmission-mode FTIR was used to measure the absorbed dose response of unsaturated transvinylene and carbonyl peaks. The results showed insensitivity to variations in the sample production. Samples were later exposed to elevated temperatures, nearing the melting point of the material itself, with no effect on the infrared transmission spectrum. This strongly suggests long term stability of the dosimeters. Following FTIR analysis, each sample was digitally scanned and the average grayscale color of each irradiated sample measured using the open source software ImageJ. The development process of the discoloration was explored as a function of ionizing dose. Overall, combining the colorimetric and the infrared measurements together reduces uncertainty and improves reproducibility.

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## Assessment of the radiological impact of NORM ceramic industry in Spain

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### Introduction

NORM (Naturally Occurring Radioactive Materials) are widely present in the ceramic industry due to the use of zircon sand, which contains natural  $^{238}\text{U}$  chain and  $^{232}\text{Th}$  chain. In particular, work activities in zircon sand milling plants in Spain must be controlled following national regulations (RD 783/2001 and IS-33) and the evaluation of the radiological impact of these industries must be performed following safety guides from the Spanish Nuclear Safety Council (CSN) (GS 11-03). To fulfill the regulation, a study of several zircon sand milling plants in Spain has been performed.

### Methods

The significant radionuclides and the areas or processes with radiological risk have been identified. Raw materials and end products were characterized as a source term and an estimation of the total effective doses (external and internal) received by workers and the public were calculated. In particular, the estimation of doses to workers was made by identifying homogeneous exposure groups (HEG). TLDs were used for external dose, and internal doses by inhalation were obtained from activities of ceramic materials and total dust content. Dust content was evaluated with static air samplers or personal air samplers (PAS). Doses to the public were estimated taking into account the atmospheric emissions and evaluated with PC-CREAM.

### Results

Zircon sand, flours and micronized presented a range of  $^{238}\text{U}$  activity from 1906 to 4064 Bq/kg and  $^{232}\text{Th}$  of 287 to 815 Bq/kg. The main HEG in these industries were milling operator, bagging operator and maintenance operator. Dust content in the milling area ranges from 0.10 to 8.11 mg/m<sup>3</sup> and in the bagging area, from 0.95 to 5.25 mg/m<sup>3</sup>; lower values were found in the storage area, from 0.09 to 1.09 mg/m<sup>3</sup>. External effective doses to workers were very low, but internal doses range from 0.04 to 0.64 mSv/year. Doses to the public range from 0.02 to 0.5 µSv/year.

### Conclusions

The study in the NORM ceramic industry in Spain reveals that the main doses to occupationally exposed workers are due to internal doses. However, the methodology of estimation is very conservative and it could be interesting to improve the characterization of the inhaled term source in order to obtain more realistic internal dose when the results are close to the limit values.



## Neutron and gamma-ray radiation fields characterisation in an $^{241}\text{Am}$ -Be irradiator in view of its use as research testing tool

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### Introduction

A neutron irradiation facility based on four  $^{241}\text{Am}$ -Be sources, each with activity  $1.11 \cdot 10^{11}$  Bq (yield  $\sim 7.0 \cdot 10^6$  n s<sup>-1</sup>), put in Plexiglas pipes inside a tank filled with water both as moderator and biological shielding, was realized at DEIM Department. The aim of this work is to evaluate neutron and gamma fluxes in several points inside the central irradiation channel, in view of its use as a testing tool in various research activities. For this goal, an experimental measurement campaign was started also to validate Monte Carlo (MCNP5 code) simulation results.

### Methods

Experimental measurements of neutron radiation fields (fast and thermal) were realized both by neutron activation with selected materials, bare and cadmium covered gold foils, TLD600 and TLD700 dosimeters. Results were compared with the values obtained by a MCNP5 simulation performed adopting a previously validated model.

As regards gamma-ray fluxes, contributions at 60 keV energy, associated with decay of  $^{241}\text{Am}$ , and at 2.2 MeV, due to the radiative capture of neutrons in the water biological shield were determined with use of bare and lead shielded TLD700 dosimeters.

### Results

Both gamma and neutron fields behaviours along irradiation channel axis were determined, besides thermal and fast contributions of neutron flux were evaluated. For gamma-ray fluxes, from the lying plane of the sources up to about 8 cm, the main contribution in the gamma field comes from 60 keV of  $^{241}\text{Am}$ , while, above 8 cm, the contribution of 2.2 MeV prevails. Experimental values confirmed with a good correspondence (within 5%) MCNP5 evaluation for each examined position inside irradiation channel.

### Conclusions

The comparison between the experimental data and the ones obtained performing MCNP5 simulation allowed the determination of both neutron (fast and thermal) and gamma fields in several points inside the irradiation channel. So, the main parameters for any irradiation plans can be easily established.

## Recombination methods in dosimetry of the mixed radiation fields – the New Deal

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### Introduction

Boron Neutron Capture Therapy, hadron radiotherapy, cosmic radiation, aircrew radiation protection - how to deal with Quality Factor Q and dose equivalent in unknown mixed radiation fields?

### Methods

Measurements of the exposure to primary or secondary neutron radiation is still not described enough, there are many types of the detectors (TEPCs, REM-counters, TLD etc.) but none of them is “the number one”.

For more than 50 years, in the National Centre for Nuclear Research, Poland Recombination Chambers and recombination methods are being developed. This specified devices are the detectors whose response depends on the incident particles Linear Energy Transfer LET, and the main consequence of this feature is possibility to the Recombination index of Radiation Quality RIQ (estimator of Q) determination. Otherwise recombination detectors are useful in characterization the mixed radiation fields due to  $\gamma/n$  components for wide dose rate range.

### Results

In the past some of recombination chambers (e.g. REM-2, F1) were used around the world e.g. CERN, JINR or Fermilab. They are very successful constructions described in many papers and are still unsurpassed in many applications. The aim of this study is to present new types of recombination chambers being currently developed:

- ring-shape chamber KP-1 for hadron radiotherapy,
- high-sensitive, large volume chamber REM-3 - three types - summative, differential and double,
- beam chamber F5 and F6,
- multi-signal chamber KW-1 for neutron spectrometry.

### Conclusions

Newly designed detectors and developing of the recombination methods will be useful for characterization of the mixed radiation fields in medicine, radiation protection, research and many others. Current work on detectors gives hope for a fabrication a new-type fully functional detectors based on recombination methods. On-going work is also to introduce our technology to serial production and commercialization.

## Characterization of the new heavy-water moderated $^{252}\text{Cf}$ neutron source at Spanish Neutron Standards Laboratory (CIEMAT).

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### Introduction

Neutron Standards Laboratory at CIEMAT (CIEMAT-LPN), Spanish national reference for calibration of neutron detectors, counts with two calibration sources,  $^{252}\text{Cf}$  and  $^{241}\text{Am-Be}$  stored in water which are remotely manipulated. The Standard ISO 8529-1 recommends having a heavy-water moderated  $^{252}\text{Cf}$  neutron source and its development and characterization is shown in this work.

### Methods

This new neutron standard consists of a stainless steel sphere with 30 cm of internal diameter filled with  $\text{D}_2\text{O}$  designed to place a  $^{252}\text{Cf}$  neutron source in its center. It has been developed at CIEMAT-LPN and characterized through MC simulations and spectral measurements. To complete it and make use of shadow cone method a new “shadow cylinder” of stainless steel and polyethylene has been developed too.

A detailed MCNP simulation of  $^{252}\text{Cf}$  neutron source inside the heavy water sphere, has been performed to study the effect of different elements, like capsule holder and capsule cover inside the sphere or the influence of stainless-steel and Cd thickness and heavy water composition. The model has been validated with experimental measurements with a BSS spectrometer and these results have been compared with recommended ISO spectrum for  $^{252}\text{Cf-D}_2\text{O}$ .

### Results

The obtained values for neutron fluence, ambient equivalent dose, conversion and transmission coefficients for simulated model, and spectral measurements agree reasonably with ISO standard.

The analysis of the different elements that constitutes the system show that capsule holder, adapters and sheath are clearly negligible for reasonable thickness. But, on the contrary, heavy water percentage is very important in the results.

### Conclusions

CIEMAT-LPN has developed a new neutron standard following ISO 8529-1 recommendations based on  $^{252}\text{Cf}$  moderated in a heavy water sphere and the whole system has been characterized with MC simulations and compared with ISO standard and validate through spectral measurements.





## Characterisation of borosilicate glass slides as a potential thermoluminescent dosimeter

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Thermoluminescence dosimetry is widely used for both personal radiation monitoring and high-dose dosimetry in radiotherapy. In this work the thermoluminescent dosimetric properties of commercial low-cost Borosilicate Glass slides were characterized in a 250kV clinical therapy x-beam. The reproducibility and linearity were determined from analysis of the glow curves obtained for radiation doses of 0.5, 1, 2, 4, 6, 8, and 10 Gy. Reproducibility was such that an accuracy of  $\pm 5\%$  was obtained following an appropriate screening process. The response was also linear to dose thus demonstrating that borosilicate glass slides have a potential use in radiotherapy dosimetry. Further work is in progress to characterize the borosilicate glass slides other kilovoltage x-ray energies, megavoltage photons and electrons as well as neutron beams. Glass microfiber filters were also examined, however the results for this material showed less promise as a viable radiotherapy dosimetry system compared to Borosilicate Glass.

## Dosimetric Measurement of Scattered Radiation for Simulated Head and Neck Radiotherapy with a Hand-Made Oral Prosthesis

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### Introduction

During the radiotherapy for head and neck tumors, the oral cavity and cheek area would be inevitably exposed to high-energy radiation, thus the material surface of the teeth, dental restorations with high atomic number, or alloy prosthodontics would generate backscatter electrons that cause the buccal mucosa adjacent to these materials to receive a localized high dose enhancement, which primarily leads to side effects or oral mucositis in patients. In this study, the dosimeters were used to measure the oral cavity dose by oral prosthesis in radiotherapy.

### Methods

Based on the size of the adult oral cavity, this study use acrylic resin to make an oral prosthesis with two grooves on the left and right sides for placing three molars. The distance between the inner cheek and the side surface of the teeth could be accurately adjusted every 1 mm from 0 mm to 5 mm. This study employed the film type thermoluminescent dosimeter with a thickness of 0.1 mm and optically stimulated luminescent dosimeters with a thickness of 0.2 mm to measure the absorbed dose inside the buccal mucosa in order to reduce the dose interference from the X-ray treatment. The fixed three real molars in a row located at the left side of the prosthesis, and employed 6 MV photons and intensity modulated radiation therapy to treat and simulate oral cancer, as well as measure the attenuation of the molar's backscatter dose from 0 mm to 5 mm in an up-beam direction.

### Results

The dose results showed 5% variation between OSLD and TLD. This study results showed that every 3 mm, the prosthesis had attenuated the enhancement of backscatter dose under 3%. The irradiation dose enhancement in a single direction was twice higher than through IMRT 7-field treatment.

### Conclusions

The OSLD is a new option that could be simple and feasible to measure the dose enhancements in the buccal mucosa which result from backscatter electrons of the teeth and alloy dentures during head and neck radiotherapy.

## Dosimetric characterization of 3D printed phantoms at different infill percentage for diagnostic x-ray energy range

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### Introduction

The use of 3D printing and filaments commonly found commercially for development of phantoms has been investigated in recent years due to the cost of materials and improvements in the quality of printers. The application of this technique for radiation protection and dosimetry requires a complex study of the quality control and the interaction of printed materials with different radiation beams. The aim of this paper is to characterize 3D printed phantoms and printing set-ups for different infill percentages for diagnostic energy beams.

### Methods

3D printing performance was studied using the RAISE 3D PRO2 printer from IPEN for printing with PLA (Polylactic Acid) and ABS (Acrylonitrile Butadiene Styrene) filaments. Printing characteristics such as repeatability, reproducibility, effective density by displaced water mass and porosity at 100% infill were studied. Plate samples of 8x8x1cm<sup>3</sup> were printed and, using the Pantak Seifert irradiator with different x-ray qualities in the diagnostic energy range, the attenuation coefficients were obtained experimentally for different percentages of plates infill.

### Results

By printing three identical samples for each print mode, the 3D printing system had a repeatability better than 1.0% for masses and average of 0.7% for the dimensions of the printed objects, obtaining the highest variations in small printed parts. Little to no porosity has been found on the printed pieces with 100% infill, giving to the printed objects the same density of the chosen filament. The attenuation coefficients were determined for the different beam qualities and it was verified that the variation in the values decreases as the infill quality increases.

### Conclusions

The results show that the printing system have excellent repeatability and print quality. The different printing modes characterized together with their attenuation coefficients for the x-ray beams will be studied and used in the development of new 3D printed phantoms in our institute.

## Radiation dose assessment to caregivers of the out-patients treated with iodine-131 for thyroid

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### Introduction

The release of out-patients after treatment with iodine-131(I-131) for thyroid may cause the risk of radiation to family members. And there is no national regulation in Taiwan to limit the dose for the release of out-patients.

### Methods

This study assesses the radiation exposure to caregivers of the patients treated with I-131 for thyroid carcinoma. The study population comprised the family caregivers and the patients were treated with I-131 for thyroid carcinoma from four hospitals which the protocol and procedures were approved by the appropriate institutional review board (IRB). The dose rates at 1 meter from the patients were measured by survey meter when they left hospitals. Dosimetry data to caregivers were obtained by two thermoluminescent dosimetry badges in front of the chest for at least 1 week and were adjusted to give an estimate of values which might have been expected if the dosimeters had been worn indefinitely.

### Results

When the patients treated with I-131 left the hospitals, the dose rates at 1 meter away from the patients ranged from 15 to 50  $\mu\text{Sv/h}$ . And the exposure to all the caregivers were well less than 1 mSv that is the limit recommendation from ICRP for public.

### Conclusions

At present there are no national regulation in Taiwan to the release of out-patients after treatment with I-131. This study has provided useful information on radiation safety and exposure to caregivers of patients treated with I-131. On the condition that the radiation dose rates at 1 meter for the patients are below 50  $\mu\text{Sv/h}$ , the release of out-patients has no distinct radiation risk.

## Treatment of mixtures of lead and barite powders in ceramic materials for the shielding of ionizing radiation by the thermal spray process

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**Introduction:** This work shows a treatment of recycled lead (Pb) powder and barite powder (BaSO<sub>4</sub>) coating ceramic material by thermal sprayin (TF), oxyacetylene flame (FS), in order to produce tiles to coat walls, to be used as radiation protection material (wall shielding) subject to ionizing radiation in clinics, hospitals and industrial environments. It is expected that it will be easy to carry out projects and renovations in hospital or industrial environments that have, as working material, ionizing radiation in order to protect the individuals involved.

**Methods:** The sintering of Pb (50%) and BaSO<sub>4</sub> (50%) powders, continued by deposition by TF FS process and characterizing the coating (microstructure, thickness, adhesion, porosity, phases formed ), and verifying their behavior when exposed to ionizing radiation, using as an attenuation component in the shielding of this radiation.

**Results:** The coatings were characterized and evaluated for their X-ray attenuation properties, experimentally, to trace the attenuation curves as a function of the thickness of the coating, proving itself capable of acting as a protective barrier.

**Discussion:** It was found that the coatings of the Pb and BaSO<sub>4</sub> mixture, which has low porosity, good adhesion, microstructure with formation of PbBaSO<sub>4</sub>, with excellent distribution of the Pb and BaSO<sub>4</sub> lamellae, and the results of the attenuation assay show that the coating improves the attenuation of Ceramic materials are therefore recommended as protective barriers and shielding against ionizing radiation (X-rays) in hospital, dental and industrial environments.

## Dosimetric characterization of high-linearity bone radiation detector exposed to gamma-rays

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### Introduction

In radiation physics, the study of new alternative dosimeters is of interest on the growing branch of dosimetric characterization of solid-state dosimeters for radiotherapy applications in the Medical Physics fields. There are innumerable emerging techniques for reading and processing multivariate data to assess the possible linear behavior of dosimeters; such methods are the multivariate calibration Partial Least Square Regression (PLSR) and Principle Component Regression (PCR) techniques. The goal of this work was to expose bone samples to high doses and to use the FTIR spectrophotometry technique to evaluate the sensitivity and linearity of the absorbed profiles using PLSR and PCR analyses.

### Methods

Small cubes with size approximately of 0.5 cm<sup>3</sup> composed the bone samples, used in this work. The samples were irradiated in triplicates, with absorbed doses of 10, 100, 250, 400 and 500 Gy using a <sup>60</sup>Co Gamma Cell-220 system (dose rate of 1.089 kGy/h); afterwards, the absorbance spectrum of each sample was acquired on a Fourier Transform Infrared (FTIR) Spectrometer (Frontier/Perkin Elmer) with an optical step of 1 nm from 400 nm to 4000 nm.

### Results

The absorbance for high sensitivity peaks was observed for each bone sample, at the 552 nm, 991 nm and 1650 nm wavelengths in decreasing magnitude. The PLSR and PCR techniques showed, on the range from 10 Gy to 500 Gy, for the calibration curves of the system, a linearity of 0.9432 and 0.9422 respectively, using just three components on both methods.

### Conclusions

The results indicate an acceptable linear response, and therefore this material may be an interesting radiation detector.

## Concrete analysis for radiological protection

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### Introduction

In radiological protection, providing barriers to ionizing radiation is essential because they protect as human beings as the environment against the undesirable radiation effects. For the construction of barriers against radiation, we usually use elements with high atomic number, e.g. lead and their derivatives. The procedures necessary to obtain the best proportion between the constituent materials of the concrete, also known as binders and aggregates, are the main assemblies to be understood and studied [2]. The study aims to elaborate on 4 different compositions of concrete traces, intercalating small and large aggregates (sand and brittle) with two types of binders, (standard and structural cement), to subject each composition to compression tests, as well as to the analyses of x-ray diffraction (XRD), x-ray fluorescence (XRF), to evaluate the attenuation of X-rays.

### Materials and Methods

The materials used in this study come from civil construction. For the characteristics of this study, the composition is binder, better known as cement, which brings two compositions of resistances, the first one is classified as “all work” presenting maximum resistance of 10Mpa (megapascal), and the second is classified as “structural works” with maximum resistance of 30Mpa. In this study, we took as a basis the composition of the traces as 1: 3: 3, which means that for each part of the cement were added three parts of large aggregate and three parts of small aggregates. Six specimens of evidence were performed for the tests, according to Brazilian technical standards [3]. After the development of the concrete traces, the traditional molds were executed and a special mold of each trait in a “ladder” format, the traditional traits were submitted to tests of resistance to compression, the special traits were subjected to tests to determine the attenuation of the materials, and the difference between the traces involved. With the remaining content of the mechanical strength tests samples were drawn for characterization analyzes, which presented the present compositions of each component in each trace.

### Results

After the development of the concrete traces, the traditional molds were executed and a special mold of each trait in a “ladder” format, the traditional traits were submitted to tests of resistance to compression, which presented the results: trace 01- mean: 15.79Mpa; trace 02- mean: 10.88Mpa; trace 03- mean: 25.63Mpa, and trace 04- mean: 27,64Mpa. The special traits will be submitted to tests with X-ray techniques to determine the attenuation of the materials and the difference between the traces involved. Each characteristic was analyzed after 28 days of confection because this is the curing period of the concrete. The analyzes are still ongoing concerning X-ray attenuation.

**Conclusion**

Although some tests are still in progress, it was found out that concrete presents different attenuations according to its thickness and composition, results that may be directly related to the mechanical strength of each trait. With this study, we will try to understand the differences of each thickness mitigation response present in each material, and its relation to the composition of each material.

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## Dose conversion coefficients for medical diagnostic imaging with the Chinese reference phantoms

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### Introduction

In China, the current standard for estimation of the examinee's organ doses in X-ray diagnosis was developed based on ICRP Publication 34, in which the dose conversion coefficients were calculated based on the stylized phantom. A project is carried out to update this standard with the development of the more precise phantoms and the latest dose estimation method. In this paper, the organ and effective dose conversion coefficients of the examinee for the CT scanning, X-ray radiology and mammography are calculated based on the Chinese reference voxel phantoms.

### Methods

The Chinese reference adult male (CRAM) and female (CRAF) voxel phantoms and a series of pediatric phantoms at ages of 3 month, 1, 5, 10, and 15 year were developed in our research group. All the phantoms consist of more than 90 organs and tissues, including all the radiosensitive organs and tissues for effective dose calculation. The height, weight, organ and tissue masses of all the phantoms matched the Chinese reference value. In addition, a 3D detailed breast model was constructed for mammography simulation. All the simulations in this work were performed with Geant4. In the simulation for CT scanning, the CT scanner model was based on a third-generation MDCT from GE Corporation (GE LightSpeed 16). In order to provide a fast dose estimation for CT scans with different scan lengths, a series of simulations for axial scans was performed for each phantom and CT scanning parameter to construct a database of organ dose for each single axial scan. The organ and effective dose conversion coefficients of chest, abdomen, lumbar spine and pelvis X-ray radiography with different field sizes were simulated. In the simulation for mammography, the calculations use compressed breast models to obtain absorbed dose of glandular tissue and the dose conversion coefficients.

### Results

Dose conversion coefficients for examinee undergoing CT scanning, X-ray radiology and mammography are calculated based on the CRAM, CRAF voxel phantoms, a series of pediatric phantoms of different ages and a series of compressed breast models of different glandularity and thickness.

### Conclusions

The data calculated in this paper will provide references for the revision of the national standard for the estimation of the examinee's organ doses generated by X-ray diagnosis.

## Establishment of diagnostic X-ray air kerma standard in Taiwan

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### Introduction

Diagnostic X-ray air kerma standards were established at the Institute of Nuclear Energy Research (INER, Taiwan) in accordance with the recommendations of IEC 61267. The radiation qualities established by INER include IEC 61267 RQR, RQA and RQT. Among them, RQR is used to simulate the energy spectrum generated from the X-ray machine, RQA is used to simulate the energy spectrum after passing through the human body, and RQT is used to simulate the energy spectrum of computed tomography (CT).

### Methods

A tungsten target X-ray machine, 99.9% pure aluminum and copper filters were used to build the IEC 61267 radiation qualities. A cylindrical free-air chamber (FAC) is used as the X-ray air kerma primary standard. The FAC correction factors, including air attenuation, window attenuation, ion recombination, photon-scattering, electron-loss and shadow-effect, were evaluated by experiments or Monte Carlo methods.

### Results

The half value layers (HVL) of these radiation qualities were measured by FAC, and the HVL differences between INER and IEC 61267 are less than 3%. The uncertainty of measurement was evaluated according to ISO GUM, and the relative standard uncertainty of primary standard is 0.52% ( $k=1$ ). An ionization chamber (Exradin A5) was sent to PTB and calibrated with IEC 61267 RQR and RQA qualities. When comparing the calibration factors between PTB and INER, the differences are less than 1.25%.

### Conclusions

The air kerma standard of diagnostic X-ray has been established at INER, and it will provide dose calibration services in Taiwan to improve medical quality.

## A Novel Method to Improve Learning Efficiency of Artificial Neural Network Algorithm to Estimate Dose Distribution for Radiation Treatment

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### Introduction

Both the accuracy and the speed of dose calculation are crucial a clinical field of radiation treatment. This study intended to apply an artificial neural network (ANN) to develop a real-time computing algorithm for dose calculation for radiation treatment. In order to assess the feasibility of using neural network, a neural network algorithm was constructed and compared with the results obtained with Monte Carlo calculations.

### Methods

First of all, a step known as learning process is necessary. We considered the data set with the pairs of a point-wise dose and its position for training an ANN. The ANN was modeled using the Neural Network tool of MATLAB 7.0 (Mathworks, USA). It was constructed with the three layers including one hidden layer. From the investigation of basic characteristic of learning algorithm of neural network, it is noted that the steep dose gradient in the penumbra region causes the inefficient learning performance and propagate the error in to the whole region of radiation field. A novel method was contrived introducing the intermediate tuning stage in which the weight of hidden layer unit is firstly optimized considering an analytic function with less steep gradient as a dummy target/output and transferred to the original target dose distribution.

### Results

It provided the successful escapement from the local minima. Except for the penumbra region, the error was less than 5%. By using the dose data measured by 1.5cm interval, the dose distribution was successfully calculated by 0.5cm mesh size. It is indicated that the feasibility of using neural network was verified.

### Conclusions

It is expected to a neural network could be developed successfully to achieve a real-time calculation of dose distribution in the human body by using the novel method.



## Preclinical Dosimetry in the Development of New Radiopharmaceuticals through Monte Carlo Simulation

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### Introduction

Estimated internal absorbed dose distribution in the preclinical phase is an essential requirement in the research and development of new radiopharmaceuticals in Nuclear Medicine. Monte Carlo (MC) simulation combined with computational small animal models provides new tools to estimate the absorbed doses in organs or tissues of interest, predicting possible effects of the radiation use in diagnosis and treatment of diseases. The aim of this study was the development of a dosimetric tool by MC simulation to be applied in preclinical research in the development of new radiopharmaceutical.

### Methods

A voxelized mouse phantom (C57BL/6 lineage) was developed from Computed Tomography (CT) images for input to the GATE (MC) code, version 7.1. Ten organs were identified and segmented by SLICER 3D software. MC simulations were made for each source organ separately to calculate *S-factors* for two radiopharmaceuticals: <sup>18</sup>F-FDG and <sup>99m</sup>Tc-Ixolaris. The output data are volumetric maps of deposited energy. MatLab software was used to extract the deposited energy in each organ.

### Results

The results showed that the mass values of the simulator developed in this study agreed with the model proposed by literature. The simulation procedure was validated comparing the obtained *S-factors* for <sup>18</sup>F –FDG with the reported in the literature. The results were very close to the literature, with discrepancies ranging from 2 to 47%, attributed to modeling different organ masses. The *S-factors* and absorbed dose were calculated for each organ for the new radiopharmaceutical <sup>99m</sup>Tc-Ixolaris.

### Conclusions

The simulator developed in this work was adequate and could be used in other applications. With the methodology developed in this work it is possible to evaluate biodistributions without the sacrifice of a large number of animals. The methodology developed in this work will help preclinical studies of biodistribution and dosimetry, fundamental to the development of new radiopharmaceuticals.

## Comparison of the Response Between Different Dosimeters in Clinical Beams: A Monte Carlo Study

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### Introduction

In order to guarantee the dosimetric characteristics of new dosimeter materials, experimental tests must be performed, however these procedures require time and high cost. Thus, computational simulations can be performed as an alternative to experimental procedures for obtaining information. With prediction of computational results, experimental tests can be performed under very specific conditions. Thus, the union of the laboratory tests with the computer simulation is beneficial, because while the laboratory practice can obtain accurate results with a lot of technique and instrumentation, the simulations can indicate the expected results with a methodology of low cost and with less time. This present work has the objective of compare the relative absorbed dose, for radiotherapy directed energies, between two internationally widespread Monte Carlo simulation codes: MCNPX and PENELOPE-2008.

### Methods

Cylindrical detectors were arranged inside a phantom with dimensions 14 x 14 x 21 cm<sup>3</sup>, filled with 4 different dosimetric material: TLD-100, MAGIC, MAGAT and GD-301. The source surface distance 100 cm for the 6 MV beam and 40 cm for the 250 kV beam, 10 x 10 cm<sup>2</sup> field size and the sensitive volume of the detectors 8,65 mm<sup>3</sup> which represents the dimensions of detectors of the TLD-100 types and GD-301. The results were validated in water with relative deviation less than 2%.

### Results

The analysis of the behavior from MAGAT, MAGIC and TLD-100 reached the values for water equivalence and percentage deep dose curve expected by the literature. When dealing specifically with lower energies, there was an imprecision between the codes when simulated the GD-301 dosimeter, the main hypothesis to justify this behavior is that in the low energy range for this type of material, the electrons reach very quickly the cutoff energy and the simulation loses accuracy within the first 2 cm. We should also consider that divergences between codes are also expected because PENELOPE and MCNPX use a different nuclear and cross section database.

### Conclusions

For both Monte Carlo codes this data demonstrates that the simulation developed for this research faithfully reproduce the actual irradiation conditions as well as the spectra for 6 MV and 250 kV and therefore should be used in future work for the study of new dosimetric materials and radiotherapy research.

## Activation study of a 15 MeV LINAC via Monte Carlo simulation

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### Introduction

Medical linear accelerators are increasingly used in radiotherapy. During the operational life of the accelerator, the different components of the LINAC head become radioactive due to photonuclear reactions. Activation Induced has to be evaluated to assess not only the dose due to residual activation but also the amount of radioactive waste that has to be managed in the dismantling phase of the facility. The aim of this work is to define a Monte Carlo approach for the preliminary assessment of activation levels of a LINAC head.

### Methods

In this work the MC code FLUKA was used to simulate an Elekta Precise Treatment System 15 MeV LINAC installed in 2004 at the Bellaria Hospital (Bologna, IT) and routinely used in radiotherapeutic treatments. The model of the LINAC head implemented includes the tungsten target, the primary collimator, the flattening filter, the monitor chamber, the wedge and secondary collimators. A pencil electron beam with energies of 12.3 MeV was simulated to reproduce typical irradiation conditions. The activation of the LINAC head was assessed in each component after 14 years of operation reproducing the typical workload of the accelerator.

### Results

The main long-lived radionuclides found in head components are W-185, W-181 and Re-184 in the target; W-185, W-181, Ni-63, Co-57, Fe-55, Mn-54 in collimators; Ni-63, Co-57, Fe-55 and Mn-54 in filters, while in other simulated components no significant activation was assessed. As expected the most active component is the target.

### Conclusions

Monte Carlo simulations allow to assess preliminarily the residual activation of a LINAC head reproducing more accurately, compared to analytical methods, complex geometry conditions. Moreover a preliminary evaluation of the radioactive waste generated allows to identify critical issues and possible countermeasures to be taken to decrease future dismantling costs.





## New approaches in dosimetry surveillance using electronic devices.

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### Introduction

The equipment and processes used in dosimetry could be improved in functionality incorporating new technologies already used in other fields with successful results.

*GDES-Innovation* has developed an electronic dosimetry system that allows the direct measurement and the dose record obtained automatized in real time, to perform the monitoring of the workers dosimetry exposed to ionizing radiation, in a reliable and simplified manner.

### Methods

The developed dosimeter incorporates bluetooth communication, through which the data is sent to a centralized server in the web. These radiological measures are assigned to the exposed workers of each facility, who require dosimetry control. *GDES-Innovation* has adapted the developed dosimeters to two modes of use: •Area dosimeter in continuous measurement mode. •Personal dosimeter assigned in personal mode. A web application has been developed for the management and query of the automated dosimetric information with the documentation, being accessible to the user, the installation and the Dosimetry Service.

### Results

During its development, several essays have been carried out in order to guarantee the compliance with the specifications according to technical and regulatory requirements. Validation tests of dosimetry magnitudes have also been carried out in reference facilities such as the *Institute of Energy Technologies (INTE)* and the *National Center for Dosimetry (CND)* in Spain. It is currently used as pilot system in several medical and industrial radioactive facilities.

### Conclusions

The monitoring system for dosimetry surveillance of exposed workers developed by GDES-Innovation, offers the possibility to access to the dosimetric data in easy and efficient way, incorporating an automated control and recording system of the radiation doses to which the personnel is exposed in real time. It provides an innovative approach that facilitates the date use and management of both the user and the External Personal Dosimetry Service.

## Energy dependence of an individual dosimeter: Experimental and PENELOPE-Monte Carlo simulation results.

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### Introduction

Thermoluminescent dosimetry is widely used for individual monitoring. In Brazil,  $\text{CaSO}_4:\text{Dy}$  is the most used phosphor for that purpose. The energy dependence coefficients obtained for these dosimeters are used to determine the operational quantities in individual monitoring. The goal of this work was to assess the energy dependence curves of the multi-filter thermoluminescent dosimeter used at Brazilian laboratory CIDRA.

### Methods

Experimental data was obtained in selected energies and Monte Carlo simulation with PENELOPE was used to interpolate experimental data. CIDRA's dosimeter employs three  $\text{CaSO}_4:\text{Dy}$  detectors in an acrylic badge. The three  $\text{CaSO}_4:\text{Dy}$  pellets are filtered by plastic, copper and copper+lead, respectively. The dosimeters were irradiated with beams ranging from 15 to 250 keV, as described in ISO 4037-1. Monte Carlo simulations with PENELOPE were performed in the same geometry and irradiation conditions. The energy dependence curves were used to determine  $\text{Hp}(10)$  in a blind test for 63 dosimeters irradiated in beams ranging from 15 keV up to Cs-137. Trumpet curves were used to evaluate the  $\text{Hp}(10)$  assessments.

### Results

Experimental and simulated curves show similar behavior, presenting high energy dependence of the  $\text{CaSO}_4:\text{Dy}$  for energies lower than 250 keV, as shown in the literature. The largest energy dependence was found for the pellet positioned between the copper+lead filters (0.01 relative response to 15 keV relative to Cs-137). The maximum differences between experimental and simulated data was observed also for the copper+lead filter in the energy range of 30 to 70 keV (up to 4.5%). All the  $\text{Hp}(10)$  values determined for the 63 dosimeters were inside the trumpet acceptance limits.

### Conclusions

The comparisons of obtained experimental and simulated results show that simulation has become an essential tool, making it possible to interpolate and extrapolate energy dependence coefficients used in individual monitoring dose determinations.

## A Snapshot of Occupational Radiation Dose in Veterinary Radiology

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### Introduction

Radiology is one of the most important diagnostic tool in veterinary medicine. Occupational exposure to ionizing radiation have a potential risk to veterinarians as the radiation dose might be increased due to practices such as restraining animals and holding image receptors. The objective of this study was to evaluate the annual effective dose received by veterinarians and assistants during radiographic examinations performed in Equine Hospital.

### Methods

Retrospective analysis of radiation dose record for year 2015 and 2016. All workers dealing with the ionizing radiation (physicians, radiological technologists and grooms) in the hospital were involved in the study. All workers who potentially exposed to radiation during their routine work are equipped with TLD and occupational doses are calculated on quarterly bases. Hp (10) was considered when calculating the monitored annual effective dose.

### Results

Total of 112 TLD readings were analyzed. The average annual collective dose for all workers was 0.84 mSv. The highest annual effective dose was recorded by radiological technologist (2.23 mSv) in 2016. Annual effective dose was 1.09 mSv ( $\pm 0.92$  SD) , 0.92 mSv ( $\pm 0.8$  SD) and 0.56 mSv ( $\pm 0.51$ SD) for radiological technologists, grooms and physicians respectively.

### Conclusions

Individual doses were below the recommended limit by the ICRP. However, the study highlights the doctors received lower dose than radiologic technologists and grooms. There is a need to raise the awareness of workers in the veterinary radiology. The study also recommends utilization of ALARA principle and other guidelines for radiation protection in veterinary hospitals to ensure safe practice.

## Development and verification of a new OSL-eye-lens dosimeter and algorithm

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### Introduction

For some special radiation practices, such as radiation workers operating radioisotopes in nuclear medicine department, eye lens exposure is inevitable and is usually obtained higher radiation doses. ICRP-118 report recommended a new limitation of averaged 20 mSv per year on eye lens for workers. The issue of lens dose has been focused during these years.

### Methods

This study developed a new optically stimulated luminescent, OSL, eye-lens (OSL eye-lens) dosimeter. Each OSL eye-lens dosimeter consists of two OSL dosimetry chips. The dimension of the OSL eye-lens dosimeter is 1cm in diameter and 0.3 cm in thickness. The dose algorithm was also designed to calculate the dose considering the correction of energy dependence.

### Results

The new OSL eye-lens dosimeter and algorithm were verified by means of the blind tests irradiated by X ray, gamma ray and beta sources in the National Radiation Standard Laboratory of Institute of Nuclear Energy Research (INER) in Taiwan. And the comparison tests with other commercial lens dosimeters were also made and discussed.

### Conclusions

Most current commercial eye-lens dosimeters are typically in TLD type and consist of single dosimetry chip, and do not have the ability to distinguish the energies of irradiated radiation. A new OSL eye-lens dosimeter was developed and verified in this study.

## Occupational exposure doses in a Nuclear Medicine Department

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### Introduction

Controlling doses received from workers occupationally exposed to radiation is a fundamental part of any radiation protection program, and also contributes to ensure radiological safety conditions. This study aimed to evaluate exposure doses of professionals involved in a Nuclear Medicine Department (NMD) that performs an average of 4426 diagnostic and therapeutic procedures per year. Dose values were compared with dose limits established in national law.

### Methods

NMD professionals are controlled by thermoluminescent body dosimeters placed under the precordial region. Physicians, NM technicians, nurses, radiopharmaceuticals, hospital physicists and operational assistants are monitored in a monthly frequency. Technicians and nurses also use an extremity dosimeter. Cardiologists and cardiopneumology technicians, who collaborate with the NMD, technical assistants and the cleaning staff are controlled by a trimestral body dosimetry. The dosimeters are read by an independent laboratory and the results, upon reception, are verified by the hospital physicists. This study evaluated equivalent personal dose Hp(10) and Hp(0.07) reported during 3 years.

### Results

Nurses received the highest total body dose values (maximum annual values of 2.14 mSv (Hp(10)) and 2.01 mSv (Hp(0.07))), while physicists and physicians represent the lowest dose values. For ring dosimeters, the technicians are those with higher dose values (maximum annual Hp(0.07) of 24.88 mSv). Considering trimestral dosimeters, cardiology physicians and cardiopneumology technicians record the highest doses, while technical assistants and cleaning service generally have values below registration level.

### Conclusions

During the audited period, there was a monthly equivalent dose higher than 10 mSv recorded by the ring dosimeter for one technician due to an insufficient turnover of the usual shifts. The monthly whole body dose limits for occupationally exposed professionals were not exceeded in any of the audited months for any of the professionals.

## Type testing of $^7\text{Li}_2^{11}\text{B}_4\text{O}_7\text{:Cu}$ finger thermoluminescent dosimeters for the assessment of $H_p(0.07)$

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### Introduction

The personal equivalent dose  $H_p(0.07)$  in hands is estimated by the Ciemat External Dosimetry Service (EDS) using ring dosimeters. This paper deals with the tests carried out to complete the extremity dosimetry system type-testing, according to the "Spanish Protocol for characterization and calibration of extremity dosimeters", developed by the Spanish regulatory body, and based on the former ISO 12794:2000 standard.

### Methods

The Ciemat EDS extremity dosimeter, consist of one  $^7\text{Li}_2^{11}\text{B}_4\text{O}_7\text{:Cu}$  detector (model UD-807 from Panasonic) inside two different types of ring-holders that provide appropriate filtration depending on the presence or not of low energy beta radiation in the user facility.

Irradiations were mostly carried out by the Ciemat Ionizing Radiations Metrology Laboratory, in reference conditions.

The readouts were performed using the Panasonic readers, models UD-710 and UD-716, calibrated in terms of the operational quantity  $H_p(0.07)$ .

The following performance requirements were tested: homogeneity, reproducibility, linearity, energy and angular response to photon and beta radiations, stability under different environmental conditions, detection threshold, residue, self-irradiation and effect of light exposure on the dosimeter.

### Results

The results show that most performance requirements comply with the Spanish protocol acceptance criteria. Only small deviations were detected, mainly related to environmental conditions, dosimeter residue and optical fading.

### Conclusions

The paper shows that the extremity dosimetry system of the Ciemat EDS is suitable for the dosimetric surveillance of exposed workers, according to the Spanish regulations.

**Assessment of patient's and occupational exposure from PET/CT with Fluoro-D-Glucose (18F-FDG)**

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**Introduction**

Positron Emission Tomography/Computed Tomography (PET/CT) is a reasonable diagnostic modality for detection of primary and metastatic malignancy. The first trade PET/CT scanner performed in early 2001, and presently over 2,000 PET/CT scanners are working worldwide. Fluoro-D-Glucose (18F-FDG, T<sub>1/2</sub> = 109.7 minutes). Patients and staff may receive significant doses during the procedure. Therefore, radiation protection and safety assessment is required to ensure that the practice comply with the international guidelines. The objectives of this study is to evaluate patients and occupational exposure (Positron ( $\beta^+$ ) energy = 249.8 KeV & Gamma energy = 511 KeV) during diagnostic Fluoro-D-Glucose, measure the ambient doses and estimate the radiation risk.

**Methods**

A total 636 patients (Lymphoma = 178, Nasopharyngeal Carcinoma = 82, Thyroid = 30 and others = 337) were undergone Fluoro-D-Glucose diagnostic during 6 months at King Faisal Specialist Hospital and Research Center, Riyadh, Saudi Arabia. Patient's exposure was estimated based in measured on administrated radioactivity and the dose from combined CT in Positron Emission Tomography/Computed Tomography (GE PET/CT VCT) device. Occupational and ambient doses were measured using calibrated thermos-luminescent dosimeters (TLDs) with automatic TLD reader (Harshaw 6600).

**Results**

The mean and range of administered activity (AA, MBq) and effective dose (mSv) for Lymphoma were  $433.9 \pm 70.6$  (297.5-735.9) and  $8.2 \pm 1.3$  (5.7-13.9), respectively. The mean and range of AA (MBq) and effective dose (mSv) for Nasopharyngeal carcinoma were  $417.7 \pm 55.9$  (325.6-547.6) and  $7.9 \pm 1.1$  (6.2-10.4). The mean and range of AA (MBq) and effective dose (mSv) for thyroid were  $450.1 \pm 55.9$  (344.1-566.1) and  $8.6 \pm 1.4$  (6.5-10.8). The mean and range of AA (MBq) and effective dose (mSv) for others procedures were  $421.6 \pm 58.3$  (283.4-606.8) and  $8.0 \pm 1.1$  (5.4-11.5) at the same order. The mean and range of tube current-time product (mAs) for CT procedure were  $15.5 \pm 2.7$  (10.5-17.0). Constant tube voltage (kVp, 120)) was used for all patients.

**Conclusions**

Patients received significant dose during PET/CT procedures depending in the clinical indication of the procedures and imaging protocol. CT dose compose 60% of patients doses, Therefore, optimisation of CT aquisition parameter is vital to reduce the dose to its minimal value. Patients doses slightly higher compared to previous studies. Protection of patients from unnecessary radiation and shielding of radiosensitive organs is recommended regardless of the clinical indication of the procedure. Staff doses within the recommended anual dose limit.



## Proficiency Testing and Criteria Comparison for External Personnel Dosimeters Evaluation in Taiwan

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### Introduction

The personnel dosimetry proficiency testing in Taiwan are always performed by the National Radiation Standard Laboratory (NRSL) of the Institute of Nuclear Energy Research (INER) for radiation measurement of laboratory accreditation. Nowadays, the 10<sup>th</sup> external personnel dosimetry performances have been conducted according to the Taiwan Accreditation Foundation (TAF) criteria, TAF-CNLA-T08(3) technical criterion, and the conformity assessment concept was based on the U.S. test criteria — the ANSI/HPS N13.11-2001 standard. In response to the latest release of ANSI/HPS N13.11-2009(R2015), the purpose of this paper is to reanalyze the personnel dose equivalent data of the three recent proficiency tests and study the criterion feasibility of the ANSI/HPS N13.11 -2009(R2015) edition for improvement of measurement quality and traceability of individual dosimetry evaluation laboratories in Taiwan.

### Methods

The domestic radiation dose data were reevaluated with the ANSI/HPS N13.11-2009(R2015) criterion which defines different testing items, numbers of dosimeters, radiation source types and stricter limitations than the 2001 version. One of the individual dosimetry data was obtained from the tenth proficiency testing and completed under cooperation among NRSL and the 8 tested laboratories using 5 different types of detectors from 2016 to 2017. The used dosimeters were of the 4 thermoluminescent dosimeter (TLD) types HARSHAW, Panasonic, RADOS and Thermo, and 1 optically stimulated luminescence dosimetry (OSLD) type LANDAUER.

### Results

The results showed all the 8 tested laboratories passed all the six-category tests of the latest technical specifications. The performance quotients of 4 laboratories were below 20% and the others were below 30% which showed that the technical competence of each laboratory was pretty good.

### Conclusions

With the ANSI/HPS N13.11 standard evolving from the 2001 version to the 2009 version, related criteria applicability was also performed for different testing items and stricter limitations of performance criteria. In Taiwan, all the participants were able to pass the proficiency testing based on ANSI/HPS N13.11-2009(R2015).



## Trace elements and Radon in Groundwater across the State of Qatar

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### Introduction

Groundwater represents an important strategic resource to achieve water security for Qatar. In addition to being the only natural water reservoir, most rural areas in Qatar depend on groundwater for their irrigation and farming needs. Comprehensive and dynamic characterization of groundwater parameters and quality are critically needed to develop effective management strategies. It is also important to highlight the potential health risk associated with contaminated and polluted ground water and the impact on the human health.

### Methods

In this work, recent research activities have been undertaken by QEERI in collaboration with national stakeholders to address this important topic. In particular, the characterization of Naturally Occurring Radioactive Materials (NORM) in groundwater together with the chemistry characterization since recent studies have shown an increased level of radioactivity in the soil in the state of Qatar. Around 50 field visits have been conducted to measure the radon level in groundwater and to collect water samples from different wells across the state of Qatar. Several physical parameters such as TDS, EC, pH, and temperatures were also measured in addition to the field radon measurements which were measured using Rad-7.

### Results and Conclusions

The measured radon concentration varied from 2.71 Bq/l to 60.7 Bq/L. This range is within the average level. The estimated values of average annual effective dose from ingestion of water and inhalation of water-borne radon were also normal and below the WHO recommended reference dose level (RDL) in 2004. Details on the measured levels of radioactivity and some other heavy metals and their indications will be presented.

## Evaluation of the maximum emitting layer of Rn-222 in cementitious building materials

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**Introduction** – Radionuclides present in construction materials are of interest in the view of environmental radioactivity. The limitations established have focused on the concentration of Ra-226 and the consequent exhalation of Rn-222. A physical/mathematical model developed at the Laboratory of Applied Nuclear Physics (LFNA/UTFPR) correlates the exhaled Rn-222 with the Ra-226 inherent to the material. The model considers the exhalation of Rn-222 by a plane surface that simulates exhalation in floors, walls and ceilings. Determination of the maximum emitting layer of Rn-222 that effectively exhales is important to support the model. The objective of this research is to determine the maximum emissive layer of Rn-222 that provides internal diffusion and exhalation of radon-222 in cementitious materials.

**Methods** - Cylindrical samples were made of common cement paste and cement paste with sand of high Ra-226 concentration. The samples (thicknesses 1 to 5 cm) were sealed in order to ensure the exhalation of Rn-222 through one surface. Samples and diffusion chambers containing CR-39 solid-state detectors were inserted into a glass vessel. The samples/detectors were stored for 30 days. Subsequently, the detectors were chemically etched and the nuclear tracks in the CR-39 detectors were counted.

**Results** – For each type of sample a curve was fitted whose threshold indicated the maximum emitting layer. The results obtained on the samples of common cement paste indicated a maximum emitting layer of 2cm. For samples of cement paste with sand with high Ra-226 concentration, no threshold was observed, indicating that the maximum emitting layer is greater than 5cm.

**Conclusions** - The maximum emitting layer thickness of Rn-222 of common materials determined by curve fitting was 2cm. For materials with high concentration of Ra-226 there is an indication that the emitter layer is larger than 5cm. The obtained results subsidize the physical/mathematical model developed in the LFNA/UTFPR.

## Environmental impact assessment relevant to accidental events during nuclear reactor plants decommissioning activities

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Environmental Impact Assessment (EIA) is an analysis procedure of effects on the environment of important projects provided with Directive No. 85/337/EEC, thereafter amended by Directives No. 97/11/EC and No. 2003/35/EC. In this framework, the "Environmental Impact Assessment for Decommissioning Regulations" (EIADR) [1], requires a detailed analysis of the environmental impact due also to radiation exposure or radioactive contamination

The planning of the various operations must be based on a systematic approach capable of integrating the analysis of environmental impacts with risk analysis, especially if possible incidental situations or undesirable dangerous conditions might occur. The non-routine aspects of decommissioning activities make sometimes risk of radioactive leaks due to human errors higher than in operational phase [2].

Decommissioning plans must ensure environmental sustainability and interventions designed, implemented and monitored must minimize both conventional and radiological environmental impact. However, there is no standard technique but rather a variety of strategies that often depend on the national legislation.

In this work, a new methodology called "Environmental Impact Mode and Criticality Analysis" (EIMCA) is proposed to integrate into EIA studies of possible scenarios that may induce negative effects on environmental components and, therefore, dangerous exposure situations for the health of operators and population. This procedure was set up with the aim of enabling the analyst to produce a more exhaustive forecasting framework compared to that defined by the application of the procedures already adopted for the assessment of environmental impacts.

[1] Nuclear Reactors (Environmental Impact Assessment for Decommissioning) Regulations 1999, SI 1999 No. 2892; HMSO 1999, ISBN 0-11-085395-4

[2] Bussell et al (2002) Environmental Impact for the Decommissioning of Nuclear Installations-Final Report EC Contract B4-3040/99/136035/MAR/C2



## Transmission properties of X-ray radiated from Crookes tube used in teaching of science

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Since the radiological education was added to school's curricula by MEXT in Japan, Crookes tube has been used as a fundamental equipment in science education at junior-high schools in Japan<sup>1)</sup>. Crookes tube is a discharge tube with vacuum usually using induction coil as a power supply. An induction coil supplies the variable high voltage to a Crookes tube that the voltage is controlled by a discharge distance of electrodes and a voltage of the primary coil.

During demonstrations, X-ray from Crookes tube is possible exposure to a teacher and participated student. It was reported in Japan that the X-ray radiated from the Crookes tube had very low energy (about 20 keV) but the dose was very high ( $H_p(0.07)$  up to several hundred mSv/h)<sup>2)</sup>. It is necessary to accomplish the radiation protection and safety guideline for the education using Crookes tubes that have not been evaluated sufficiently yet.

The radiation shielding protection should assure to attenuate radiation intensity significantly. Transparent materials are useful for radiation shielding materials because student have to observe the behavior of electron beam in a Crookes tube. In this study, the shielding materials such as transparent acrylic, transparent lead-acrylic, glass, and aluminum were used to estimate the attenuation properties of low X-ray energy with the variable applied voltage. The transmission was measured by an ambient dose using ionization chamber, and the effective energy of X-ray was interpolated from Al linear attenuation coefficient and the CZT detector. The increase of output power dial on the induction coil changed the distribution of applied voltage, and that resulted in the X-ray energy shift to higher energy region in the spectrum. The dose is attenuated following the Lambert-Beer law through shielding materials. The attenuated dose has been investigated both calculation and measurement with the various X-ray energy in a range of about 14 keV – 20 keV (peak energy). By using the transparent acrylic, it showed that there was different between theoretical and experimental attenuation results. The respective theoretical and experimental values were 31.2  $\mu$ Sv/h, 35.4  $\mu$ Sv/h (14.4 keV), and 1.19 mSv/h, 1.44 mSv/h (15.8 keV), respectively. The difference between the theoretical and experimental results may reflect the broad distribution of X-ray energy.

1) Ministry of Education, Culture, Sports, Science and Technology (MEXT), [http://www.mext.go.jp/b\\_menu/shuppan/sonota/detail/1311072.htm](http://www.mext.go.jp/b_menu/shuppan/sonota/detail/1311072.htm)

2) Ohmori Giroh (1995), X-ray exposure in the teaching of science at junior and senior high schools (NIRS-M—105), Japan, 107-112 [in Japanese].

## Induced activity measurements in Cu target for Ne and C ions

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### Introduction

The decommissioning of old accelerator facilities requires activation cross section data to estimate the residual activities induced in the accelerator components. But experimental data of induced activities are very scarce for low energy (lower than several tens MeV) heavy ions which were required for decommissioning of accelerator facilities such as tandem accelerator and cyclotron. We therefore irradiated 148, 217 MeV carbon ions and 126, 189 MeV neon ions onto a Cu target to obtain experimental data of residual radioactivities for low energy heavy ions.

### Methods

Irradiation experiments were performed at cyclotron facility (NIRS-930), National Institutes for Quantum and Radiological Science and Technology. The Cu targets were composed of a stack of natural Cu foils. The beam current on the Cu target was recorded with a current integrator, connected to a multichannel scaler to monitor the fluctuations of the carbon and neon beam. The Cu targets were irradiated with beam intensity from 30 to 180 nA, for irradiation time from 1 to 4 hours. After irradiation, we measured the gamma-ray spectra from Cu samples with a HPGe detector.

### Results

The spatial distribution of residual activities in Cu target were obtained by gamma-ray spectroscopy. The residual activities increase with the Cu target thickness for heavier mass products than Cu. On the other hand, residual activities decrease with the Cu target thickness for lighter mass products than Cu.

### Conclusions

The experimental data of induced activities in Cu target for Ne and C ions. The present results will be useful as benchmark data to evaluate nuclear data and investigate the accuracy of calculation codes.



## Radiation monitoring network at ALBA Synchrotron

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### Introduction

ALBA is a Spanish synchrotron facility generating bright beams of synchrotron radiation from a 3 GeV electron accelerator. The radiation fields produced by synchrotron accelerators like ALBA are complex fields composed of electrons, gamma and neutrons of a wide energy range, with an important pulsed behaviour and very important spatial variations. The radiation detectors commonly used for radiation protection purposes at these facilities usually include an ensemble of active and passive detectors with different responses, when compared one to each other, from their energy response to their behaviour in presence of pulsed fields.

### Methods

In order to control the radiation levels around the shielding structures in use at ALBA an active network of radiation detectors has been installed and linked to the Personnel Safety System (PSS), managing the operation permits and the accesses of the different accelerators and beamlines, from day 1 of operation. In parallel, a complete dosimetry program based on passive dosimeters, TLD and neutron, has been deployed for personnel and area dosimetry.

### Results

The radiation levels and patterns observed by the radiation monitoring ALBA network during almost 7 years of operations are summarised in this poster. A comparison between active and passive detectors is also presented, as well as an analysis of the correlations seen between different types of electron losses and the radiation pattern produced when they occur.

### Conclusions

The good performance of the radiation monitoring program of ALBA and the radiation levels present in our facility are presented and analysed in this poster.

## Comparing Measurement Methods and Monte-Carlo Simulations to assess dose levels in the irradiation rooms during treatment in the MedAustron hadron therapy center

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### Introduction

MedAustron is a synchrotron based accelerator center for cancer therapy using hadrons for therapy as well as for research. The center is located in the Eastern part of Austria.

Patients are treated with protons, up to 250 MeV, and in the near future, carbon ions of up to 400 MeV will also be available for the treatment of patients.

A “patrol-control-system” has been installed, to detect and counteract the possibility that individuals, other than the patient are in the irradiation room when the particle beam is introduced into the treatment room. Still, it cannot be completely ruled out that a person is present in the irradiation room during treatment. For this highly unlikely, but possible scenario it is crucial to have a relatively simple tool to assess the dose applied to that person as accurate as possible in the shortest amount of time, thus enabling us to report to the authorities. For this purpose, Monte Carlo simulations we feel are suitable, if some simplifications would be implemented.

### Methods

Wide range REM counters as well as gamma detectors were used to assess the accumulated dose during the proton-treatment of a patients. The dose values from different positions in the room as well as in the entrance maze were then compared to the results of a simplified Monte Carlo Simulation.

### Results

The measurement results and the simulation results are in agreement. Furthermore, it was shown that dose rates during proton-treatment, especially in the areas within in the entrance were very low and in the unlikely case of staff members being present in the rooms, the dose received was negligible without any noticeable health effect.

### Conclusions

A method using Monte Carlo simulations was found to assess doses applied to persons (besides the patient) in accident scenarios during treatment. This method is reasonably efficient due to simplifications in the simulations in order to report to the authorities on a timely manner. This method should be tested in the same way for carbon ions as soon as ion beams are used for patient treatment at the MedAustron facility. Higher dose rates can be expected for these cases.

## Comparison of response of passive and active dosimetry systems at laser-based facility

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### Introduction

ELI Beamlines is the Czech Republic based pillar of the Extreme Light Infrastructure ERIC, which aims at the development of a new class of international laser laboratories devoted inter alia to the research in the field of laser-driven particle acceleration.

The radiation protection in this type of environments is challenging because of the ultra-short (10 fs) length of the generated pulse.

In such pulsed fields, the response of active dosimeter seems to be unreliable, while the response of passive systems is still being investigated.

### Methods

Therefore, to understand the behavior of the dosimeters and establishing adequate radiation protection protocols for laser-based facilities, it is fundamental to compare data from active and passive dosimetry systems with Monte Carlo simulations and experimental data obtained by laser diagnostics.

### Results

The TERESA beamline (TEst-bed for high-REpetition-rate Source of Accelerated particles), prepared as proof of concept of the acceleration mechanisms for protons and electrons (reaching energies of several tens of MeVs), started its commissioning in 2018.

### Conclusions

In this contribution, the results from the first experimental campaigns will be presented. Responses of passive (OSL, films) and active systems will be compared with the expectations from Monte Carlo simulations, performed by FLUKA. The reliability of different detection systems and of our approach in the specific environment of radiation fields generated by high power lasers will be discussed.



## Neutron spectrum determination of accelerator-driven d(10)+Be neutron source using the multi-foil activation technique

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### Introduction

The accelerator-driven neutron generators with beryllium target represent the useful devices for production of neutron beams of high intensities. At the Nuclear Physics Institute (NPI) of the CAS, the cyclotron-based fast neutron sources of the white- and quasi-monoenergetic spectra are operated employing Be/Li-targets and variable proton (up to 36 MeV) and deuteron beams (up to 20 MeV) delivered by the U-120M cyclotron. Recently, the d+Be source reaction for 10 MeV deuteron beam was studied at the NPI.

### Methods

Neutron spectrum of the d(10)+Be source reaction studied in close source-to-sample distance was investigated utilizing the multi-foil activation technique. Sets of eight activation materials (Au, Co, Ti, In, Al, Fe, Ni, Nb) were irradiated by neutrons from the d(10)+Be source, and irradiated activation foils were analysed using the gamma-ray spectroscopy technique (HPGe detector).

### Results

From measured reaction rates and corresponding activation cross-sections from EAF-2010 nuclear data library, the broad neutron energy spectrum of d+Be source reaction for 10 MeV deuterons was reconstructed employing the modified version of SAND-II unfolding code. Initial guess neutron spectrum, necessary for unfolding procedure, was obtained from Monte Carlo MCNPX calculation. Fast neutron flux of determined d(10)+Be neutron field has reached the value of  $10^{10} \text{ cm}^{-2}\text{s}^{-1}$ .

### Conclusions

At the NPI CAS, the d(10)+Be neutron source reaction for thick Be-target was recently studied, new d(10)+Be neutron field was successfully developed, and the broad neutron spectrum was determined for the first time. The novel d(10)+Be neutron spectrum is convenient for neutron cross-section data validation within the ITER and IFMIF-DONES research programs, experimental simulation of the fast neutron spectrum of nuclear reactors, applications of neutron activation analysis, and hardness tests of materials against fast neutrons.

## RADIATION DOSE TO MALAYSIAN POPULACE VIA THE CONSUMPTION OF COFFEE

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Following the emergence of increasingly busy lifestyles, the consumption of coffee is becoming one of the most popular stimulating drink to Malaysians. To meet the increasing local demand, coffee beans are cultivating in several locations such as in Kelantan, Kedah, Selangor, Terengganu and as well as Sabah. Together with the nutrients, natural radionuclides in soil are taken up by plants, subsequently appear to the human body through their consumption. This study deals with the assessment of natural radionuclides ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ ) in coffee produced and consumed in Malaysia. A total of 12 brands of coffee samples were collected from some local supermarkets in Kuala Lumpur. The samples were analyzed by HPGe gamma-ray spectrometry, and the obtained range of activities (Bq/kg) of  $6.41 \pm 1.30 - 21.39 \pm 2.44$ ,  $6.63 \pm 1.81 - 47.96 \pm 10.55$ , and  $220.01 \pm 11.99 - 1509.76 \pm 72.28$  for  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ , respectively. Mean activity concentrations of  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  showed below the world average values of 67Bq/kg and 82Bq/kg, respectively while the mean activity of  $^{40}\text{K}$  exceeds the global average of 310Bq/kg. Several radiological hazard indices were estimated, and most of them showed the values within the limiting range recommended by the UNSCEAR. Although, the studied coffee samples do not contribute to any significant radiological risk to Malaysian populace but cumulative exposures via daily dietary intake may pose an unavoidable risk to public health. Thus, periodic monitoring of radiation level in coffee may help to control the quality of coffee to avoid any radiological risk to human.

## TLD-600/TLD-700 thermoluminescent dosimetric pair for monitoring aerospace neutron fields.

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### Introduction

The cosmic radiation that strike the top of the earth's atmosphere produces showers of secondary ionizing particles, where neutrons represent the largest portion of this radiation in the altitudes of commercial flights. In addition to the doses in the crews, neutrons can cause undesirable effects in the onboard instrumentation. The methodology and the calibration of the TLD-600/TLD-700 thermoluminescent dosimeter pair as thermal neutron fluence sensor and its application in the dosimetry of mixed fields of wide-spectrum neutrons (from thermal to GeV) are presented in this work. Such fields are of aerospace interest because they represent the neutron fields generated by cosmic radiation in the atmosphere near the ground and in flight altitudes.

### Methods

The pair of thermoluminescent dosimeters was applied as a thermal neutron sensor in a fast neutron dosimeter developed at the Laboratory of Aerospace Dosimetry of the Institute of Advanced Studies (IEAv).

### Results

Verification tests of the performance of this dosimeter in reference neutron fields of isotopic sources ( $^{241}\text{Am}$ -Be,  $^{252}\text{Cf}$  and  $^{252}\text{Cf}$  in  $\text{D}_2\text{O}$ ) and high energy of the CERN-EU arrangement (Cosmic Energy Reference Field, Europe), which approximately reproduces the neutron energy spectrum at aircraft flight altitudes are reported. The calibration factor of the thermoluminescent response to thermal neutrons determined in the present study ( $5.65 \pm 0.19 \text{ pC}^{-1} \cdot \text{cm}^{-2}$ ) was also verified in a reference unidirectional thermal field. The IEAv's dosimeter was used to measure the 14 MeV neutron flux produced by a Deuterium-Tritium type neutron generator and also to monitoring the neutron flux in soil at the IEAv's Cosmic Radiation Monitoring Station at 1840 m altitude.

### Conclusions

This is a passive dosimeter that does not interfere with on-board instrumentation, so that it can be used in dosimetry on board aircraft and manned orbital stations, where neutrons contribute significantly in doses.





Friday May, 31



## Dosimetry issues in Radiological and Nuclear Emergency Preparedness and Response

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In the case of a nuclear or radiological accident involving significant releases of radioactivity, the basis for decisions on the implementation of protective actions for the population and the emergency responders should be a good radiological characterization of the situation. In the early phase of the accident, the main concern is to decide under uncertainty whether an evacuation, sheltering or iodine thyroid blocking are required. It is necessary to have a good dose prognosis using state-of-the art models for atmospheric dispersion and dose assessment, complemented with real time data supplied by fixed radiation monitoring networks and mobile units, both terrestrial and airborne. In complex scenarios with persons potentially irradiated, decisions on their treatment would require an initial screening followed by a more detailed dose evaluation using biological dosimetry, whole body counting, in vitro measurements of biological samples and other methods. Particular attention is necessary to thyroid dose monitoring, especially for children and pregnant women. In the intermediate phase, radioactivity controls in air, food and water, and detailed characterization of the contamination levels of large areas would be necessary to decide on the termination of the urgent protective actions adopted during the early phase or on new countermeasures like food bans, decontamination of areas or relocation of people from the hottest zones. Reference dose levels for the existing exposure situation in the long-term are set in terms of residual dose, and realistic dose projection models should be employed together with monitoring data to produce a good assessment in which to base such transcendental decisions. Besides the official experts, other actors like affected citizens or local institutions may collect radiological data. Protocols should be prepared to assist in such data collection by stakeholders and to integrate them. Qualified personnel and suitable individual dosimetry systems for the public should be made available to allow people knowing their radiation exposure, including where, when and how they are exposed. Measurements of ambient exposure levels, of individual external exposures, of concentrations of radionuclides in foodstuffs and in the environment, as well as the individual internal exposure should be maintained in the long-term together with support to understand the relevance of such data, so that people can make their own protection decisions. All together, these are great challenges related to dosimetry issues which need to be duly addressed.

## **RADON DOSIMETRY- Biological, internal dosimetry and radiometric issues**

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The effects of radon in lung cancer risk have first been reported from epidemiological studies of underground miners. Increased incidence of respiratory-tract tumours in animals exposed to radon and its decay products has also been observed experimentally. More recent epidemiological studies have shown that the risk is also significant for residential exposure to radon at concentrations above approximately 200 Bq.m<sup>-3</sup>. Radon was classified as a human carcinogen in 1988 by IARC, the World Health Organization, and is now widely regarded as the second cause of human lung cancer after tobacco smoking. Calculations of absorbed doses to different regions of the lung and other tissues, e.g. the bone marrow, and the effective dose may be carried using morphometric models and input parameters including the activity concentration of radon gas in air, the breathing rate, the activity size distribution of the aerosol, the unattached fraction. A number of approximations and hypotheses have to be made for these dose calculations. In its Publication 137 the International Commission on Radiological Protection (ICRP) recommended new dose coefficients for radon and its progeny which are based on the dosimetric approach and applicable to various representative occupational situations. There are specific methods for measuring the radon activity concentration and the potential alpha energy concentration of its short-lived decay products, for area measurements or individual monitoring. The choice of measurement method will depend on the expected level of concentration and on the intended use of the data.

## **Dosimetry at Accelerators - State-of-the-art and challenging issues**

**Marco Silari**

CERN, Esplanade des Particules 1, 1217 Meyrin, Switzerland

The talk will first give a brief overview of RAMSES, the current CERN radiological surveillance system: an advanced, integrated and multi-functionality monitoring system which includes a broad range of detectors to monitor prompt radiation produced by beam losses during operation, induced radioactivity in accelerator components in the surrounding equipment and in air, and water/air releases. The specific challenge of detecting strongly pulsed radiation at particle accelerators will be addressed. Ongoing and future developments at CERN will then be discussed: CROME, the new generation of monitoring system for Radiation Protection, and W-MON, a distributed network of small and interconnected radiation sensors for continuous monitoring of radioactivity in waste containers (a full description of which is given in a contributed oral presentation).

## Application of dosimetry to estimate activity in irradiated samples

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Dosimetry is the science to evaluate radiation doses. That is, to evaluate the effects of the radiation on the man. It is very important to know these effects on operators and other people working around a radioactive installation or handling radioactive sources. Even more, the effect on the public must be known and shielding and other protection measures should be adopted. On the other hand, the measurement of doses is easier than that of activity. Especially for high values of activity, it may be difficult its measurement, while absorbed dose can be measured with less difficulties. Then, dosimetry can be used to estimate the activity generated in metals undergoing irradiation in a nuclear reactor.

For instance, the irradiation of gains or other metallic components in the core of the reactor can generate high activities, mainly after a long irradiation period. To measure these activities the irradiated materials should be placed under some meters of water. This situation is quite complicated to put under water a germanium detector with its accessories to obtain a good spectrum that permits to estimate the activity of the irradiated piece. Furthermore, the Ge detector should be calibrated in energy and efficiency for the same geometry and situation. On the other hand, using the appropriate equations activity can be estimated from the measured dose. Measurements can be done some time after the irradiation, taking into account the corresponding decay.

This procedure was very useful to indirectly validate a Monte Carlo (MC) model to analyse activation of metals in nuclear reactors. For this propose, a second MC model was developed to calculate the dose produced by the activated metal. It has been applied to estimate the activation of control rods in a BWR and also the activation of a stainless steel sample in both a research and a training reactor. It can be also applied to other situations where a neutron activation is produced such as an Am-Be source or a Troxler device.

## A Novel, Population-based Approach to Astronaut Radiation Risk

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### Introduction

NASA limits the career radiation risk for astronauts to 3% risk of exposure-induced death (REID) at the upper 95% confidence interval. Limiting radiation risk instead of effective dose leads to shorter allowable mission durations for younger, female astronauts than for older, male astronauts due to differences in radiosensitivity based on epidemiological models. We hypothesize that evaluating radiation risk on the basis of the astronaut population will increase opportunity for mission participation.

### Methods

A population model is defined using age and gender characteristics of the current NASA astronaut corps. REID distributions associated with several missions of interest, including a one-year mission on the International Space Station and a Mars mission, are evaluated as a function of astronaut age and gender using NASA radiation transport and risk calculation tools. The REID distribution for the astronaut population model is constructed via Monte Carlo sampling and compared with distributions for specific combinations of age and gender.

### Results

The REID at the upper 95% confidence interval for the astronaut population is generally greater than that of male astronauts only and less than that of female astronauts only. The largest differences occur for younger females and older males. For certain missions, this approach increases the number of potential participants to include younger female astronauts who would currently not be eligible for flight or be subjected to an additional waiver process.

### Conclusions

Evaluating radiation risk associated with a space mission for the astronaut population instead of at specific ages for males and females separately expands the pool of potential spaceflight participants for certain missions. This approach leads to better compliance with the ethical principle of fairness and the ethical responsibility for equality of opportunity.

## Validation of Geant4 model based predictions of radiation hazards in manned missions to Mars with the RAD/MSL data

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### Introduction

Manned missions to Mars are the next step in human exploration of the solar system. NASA plans to send a manned mission to Mars in the decade of 2030. One of the most limiting factors to this kind of missions is the radiation hazard. To provide a better protection of the crew it is necessary to fully understand the radiation environment in space and its effects of human organs and tissues. The main radiation sources of concern are the trapped particles in the Van Allen (VA) belts, the galactic cosmic radiation (GCR), and the solar energetic particles (SEP) events. [1,2]

### Methods

In the present work, the different radiation environment scenarios to be met by a future mission to Mars, including Mars surface stays, are discussed and the Geant4 simulation toolkit is used to simulate the interactions between radiation and matter. For the case of Mars surface stays, the detailed Martian Energetic Environment Model (dMEREM) is used [3,4] to predict the radiation environment on the Martian surface. dMEREM is a Geant4 based model developed by LIP for the European Space Agency. We have implemented a simplified computational version of the RAD/MSL detector [5] to simulate the RAD response to the radiation environment during the mission scenarios and to compare it with the RAD measurements.

### Results:

Comparisons between the doses measured with RAD/MSL and those obtained using a RAD/MSL computational model will be presented for both cruise phase and stay on Mars surface.

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## Total Ionizing Dose estimation and response of ASIC VATA466 to be flown in RADEM aboard the JUICE mission

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### Introduction

Radiation degradation of semiconductor devices is a known issue for instruments flown in space. EEE components used in space applications must comply with strict standards in order to prevent partial or total mission failure. For Earth orbit, Radiation Hardness Assurance (RHA) methodology has already been, in most part, standardized, while for missions outside the Earth's magnetosphere, a more customized approach is needed. For the Jupiter Icy moons Explorer (JUICE), ESA's next class-L mission to the Jovian system, a large effort is required in order to ensure component reliability for the full mission duration, considering the high flux high energy electron environment around the gas giant. In this work we present Total Ionizing Dose (TID) calculation methodology and corresponding testing of the ASIC VATA466, specifically designed for the Radiation Hard Electron Monitor (RADEM) aboard the JUICE mission, which will perform spectral measurement and dose calculations of the environment.

### Methods

To qualify the ASIC VATA466 two activities were executed: computation of (TID) and dose rate at ASIC level; and Co60 testing. Since there is no way to measure TID levels before the mission, detailed Geant4 simulations were performed in order to obtain TID values with as low as possible uncertainty. Co60 testing of the ASIC at High Dose Rate up to 3kGy(Si) was performed in Santiago de Compostela to assess component parametric and functional response to the computed TID levels.

### Results

TID values computed for the whole mission with the full geometry of RADEM 's flight model imported to Geant4 are discussed. ASIC TID is below 2kGy(Si) given a Radiation Design Margin (RDM) of two. TID tests performed show parametric degradation but no functional failure.

### Conclusions

TID for the ASIC VATA466 was estimated with low uncertainty for the whole JUICE mission resorting to Geant4 simulations. Co60 testing was also performed in order to assess component reliability for the mission. It was concluded that in the foreseen conditions, the ASIC is expected to survive the harsh radiation environment of the mission.

## An In-Depth Analysis of Aviation Route Doses for the Longest Distance Flight from Taiwan

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### Introduction

Airline crew members and frequent flyers are exposed to elevated radiation levels because of reduced protection of the atmosphere against galactic cosmic ray induced secondary radiation. Determining flight doses depends on numerous factors, including flying distance between two airports, actual flight route and solar activity. At present, the longest distance flight from Taiwan flies from Taipei to Houston, operated by EVA Airways with a flying distance of more than 13,000 km that takes approximately 13 hours outbound and approximately 16 hours inbound. Focusing on the flight, this study performed an in-depth analysis of aviation route doses by considering the effects of flight route variation and great-circle approximation.

### Materials and Methods

A total of 680 flights between Taipei and Houston were operated in 2017, 340 outbound and 340 inbound flights. Actual flying routes of these flights were purchased from the flight tracking website FlightAware. The self-developed NTHU Flight Dose Calculator was used in this study. Based on a database generated using a series of high-fidelity FLUKA simulations of galactic cosmic ray propagation in the atmosphere, the dose calculator is a user-friendly tool for assessing radiation exposure of air travel over real flight routes or default great-circle paths between airports. The dose calculator has been benchmarked by comparing its predictions with the results of 11 codes summarized in the EURADOS-2012-03 report and the overall agreement between various codes was satisfactory, approximately within 20% from the median values. In addition, the program comes with auxiliary Python scripts that were developed to automate repeated analyses of a large number of flights.

### Results and Conclusions

The average dose of 340 outbound flights from Taipei to Houston was estimated to be  $54.6 \pm 7.8$   $\mu\text{Sv}$  and that of 340 inbound flights from Houston to Taipei was estimated to be  $64.4 \pm 7.9$   $\mu\text{Sv}$ , leading to an estimate of  $119.0 \pm 11.0$   $\mu\text{Sv}$  for a round-trip flight. The standard deviation associated with the mean value was approximately 10%, which offered a quantification of the effect caused by flight route variation. Instead of actual flight routes, the great-circle path is usually a good approximation in predicting aviation route doses for long-haul flights. Under the same conditions of average flying altitude and speed, the round-trip dose was estimated to be  $133.6 \pm 9.6$   $\mu\text{Sv}$ , approximately 12% higher than that derived from actual flight routes. More detailed results and explanations will be presented at the conference.

## Assessment of patients and occupational exposure from thyroid treatment with Radioiodine -131

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### Introduction

Thyroid cancer incidence is 10% of total cancer in human worldwide, with slightly higher ( $\approx 2.0$  -3.0 times) incidence in female. Radioiodine-131 ( $T_{1/2}=8.02$  days) is widely accepted for treatment of thyroid cancer adjunct to surgery or to treat inoperable cancer and hyperthyroidism (overactive thyroid). Staff may receive significant doses during the procedure. Therefore, radiation protection and safety assessment is required to ensure that the practice comply with the international guidelines. The objectives of this study is to evaluate patients and occupational exposure (energy = 606 keV) during therapeutic radioiodine, measure the ambient doses and estimate the radiation risk.

### Methods

A total 207 patients were undergone radioiodine therapy during 6 months at King Faisal Specialist Hospital and Research Center, Riyadh, Saudi Arabia. Patient's exposure was estimated based in measured on radioactivity at 30 cm, 100 cm and 300 cm during hospitalization using calibrated survey meters (Victoreen 451P, Fluke Biomedical). Occupational and ambient doses were measured using calibrated thermos-luminescent dosimeters (TLDs) with automatic TLD reader (Harshaw 6600).

### Results

The mean and range of administered activity (AA, MBq) and effective dose (mSv) were  $4243.7 \pm 2021.4$  (1668.9-8066.0) and  $24.2 \pm 11.6$  (9.5-45.9), respectively. The mean and range of AA (MBq) and effective dose (mSv) were  $1507.9 \pm 324.1$  (977.9-1836.9) and  $8.6 \pm 1.8$  (5.6-10.5) at the same order. The annual occupational doses were 1.0 mSv. The ambient doses at isolation rooms corridors is 1.2 mSv while ambient doses at nursing station was below the detection limit.

### Conclusions

Hyperthyroidism Patient expose staff to less radiation compared to cancer patients due to rapid clearance of the iodine and lower AA. Occupational exposure is the least compared to previous published studies due to well defined protocol and that department protocol comply within the international safety requirement.

## Occupational Radiation Dose and Adherence to Radiation Safety Practices in Two Hospitals of UAE: Retrospective Cross-sectional Cohort Study

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### Introduction

Analysis of occupational radiation exposure helps in optimizing imaging protocols, determining adequacy of radiation protection measures, and providing a base to assess lifetime cancer risks for medical workers and initiate long-term follow-up studies. The aim of the study was to analyze the occupational radiation exposure history from 2002 to 2016) at two hospitals (A and B) in the United Arab Emirates and to investigate their practice of radiation protection measures.

### Methods

A cross-sectional retrospective cohort design was used. The study were divided into two phases: 1) retrospective assessment of occupational radiation dose for medical workers in hospital "A" and "B" assessed and 2) a questionnaire was used to investigate their adherence to radiation protection safety measure.

### Results

Total of 952 TLD readings obtained during the study period and classified per hospital, occupation and department. The average collective dose was 0.601 mSv, and the highest dose was measured in the year 2005 (0.829 mSv) and 2014 (0.825 mSv). Statistical significant difference between hospital (A) and (B) was noticed only in year 2002. Cardiologists and nurses had statistically high mean of occupational radiation dose. The evaluation of radiation protection practice revealed that majority of medical workers have good practice while 42% demonstrated average level of radiation protection practice. Nevertheless, there was no significance different ( $p > 0.05$ ) observed between practice and job position, or practice and department.

### Conclusions

Overall, the mean occupational radiation dose data for the two hospitals was significantly lower than the standard of 20 mSv per year, according to the international and national recommendations. Radiation protection practice was considered to be good among medical workers. However, continuous evaluation of occupational radiation dose and radiation protection practise is important to ensure practice to safety measures.

## Use of a real-time device to discriminate low and high dose-rates received by medical staff in Interventional Radiology procedures

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### Introduction

The issue of radioprotection of medical staff during Interventional Radiology procedures has grown in importance in parallel with the increase of number, type and complexity of procedures, and also in light of the more restrictive exposure limits defined recently. The decrease of lens limit from 150 mSv/y to 20 mSv/y and the possibility that lens damage would depend on the dose rate demands to precisely measure the dose absorbed as a function of dose-rate. A Real-time Active Pixel Dosimeter developed in the framework of the INFN RAPID project, could indeed perform such task, measuring the dose-rate with a few Hz frequency. In this work, we will describe the results obtained equipping medical staff with RAPID devices during a measurement campaign at S. Giovanni Battista Hospital (Foligno, Italy).

### Methods

Wireless RAPID devices have been worn over the forearms and/or over the chest protective vest by the medical staff. For each procedure, each device had a TLD dosimeter placed nearby. The real-time dose-rate readings were acquired at 5Hz rate and in continuous reading mode. After each procedure the DAQ was stopped, the TLDs removed and replaced by new ones. Data have been analyzed using a custom algorithm to suppress background and differentiate among high and low dose-rate signals.

### Results

For each procedure where the dose was over the sensitivity of the TLDs the correlation with RAPID dose readings has been within 5% precision. Device sensitivity has been found to be about 10 nGy/200 ms, while fluoroscopy signal ranges typically on the  $\mu\text{Gy}/200\text{ ms}$  and fluorography 50 times more. Hence the discrimination capability of the RAPID device among the three cases is always better than 50:1.

### Conclusions

The RAPID device is well suited to measure real-time exposure of medical staff performing Interventional Radiology procedures. Hence it can differentiate between high and low dose-rate exposure and then contribute to a better determination of effective lens damaging.

## Organ dose measurements using an adult anthropomorphic phantom and risk estimation of cancer incidence from CBCT exposures

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**Introduction** Cone-beam CT (CBCT) has become an essential tool for pre-treatment verification of the patient's position and for targeting the tumor volume localization in Image Guided Radiotherapy (IGRT). CBCT imaging is employed on a daily-basis, for each treatment fraction, and several times per patient, to ensure that the patient's position is correct. This leads to cumulative imaging doses to the tissues surrounding the exposed target-organs. The objective of this work is to determine the patient organ doses from a thorax CBCT scan in order to estimate risk of cancer incidence due to CBCT exposures.

**Methods** A thorax CBCT scan was performed in an anthropomorphic phantom of an adult male (CIRS ATOM) and the organ doses were assessed from point measurements using thermoluminescent detectors (TLDs). The measurements were performed using a CBCT imaging system mounted on a LINAC (Edge™, Varian Medical Systems). The lifetime attributable risk (LAR) of cancer incidence was determined using the BEIR risk models.

**Results** Considering a single thorax CBCT scan, the highest organ doses were calculated for heart and left lung which registered values of  $5,84 \pm 0,93$  mGy and  $4,90 \pm 0,78$  mGy, respectively. In contrast, the lowest organ dose was determined for right lung, with an absorbed dose of  $3,07 \pm 0,49$  mGy. Regarding risk estimation, after a complete course of IGRT treatment for lung cancer (24 fractions) and assuming that, at least, one CBCT scan is performed per fraction, the LAR of cancer incidence varies between 27 to 309 cases per 100.000 exposed persons, depending on the organ evaluated.

**Conclusions** This work highlights the need to determine radiation induced cancer risks arising from CBCT repeated exposures in order to optimize the selected scanning protocols and consequently the radiological protection of patient. Furthermore, accurate organ dose calculation is fundamental to reduce the uncertainties associated with radiological risk estimation in imaging procedures.

## A guideline proposal for employment of aircrafts on radiological and nuclear scenarios

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### Introduction

Since Chernobyl accident, it is known that aircrafts are employed on radiological and nuclear scenarios for rescue, monitoring and transport missions. There are historical records that show cases of crew exposure and aerial vehicles contamination on this kind of events. Nevertheless, there are no international documents to guide the procedures and cautions to be taken by authorities and decision makers, so that the present work evaluates comprehensively this employment, considering the radioprotection and dosimetry precautions on the various steps of the mission.

### Methods

The accidents' records studied included the use of both manned and unmanned aircraft. The radioprotection and dosimetry cautions for both crew and aircraft have been evaluated for the steps of planning, execution, reception after mission and decontamination, when needed. Environmental and occupational factors were considered as well as the specificities of air missions, such as the use of active equipment on aircrafts, the establishment of reference levels compatible with air missions, risk assessment on plume's spread and air routes, situation awareness for decision-making, etc.

### Results

The analysis identifies the risks, factors and cautions in each step of the mission, proposing and laying the foundation for the formulation of a technical document that can guide the safe employment of air vehicles on these scenarios.

### Conclusions

The establishment of criteria, limits, procedures and specific cautions enables an adequate planning and preparation before the use of aerial vehicles, avoiding failures and mistaken procedures during an occurrence, which have been reported in the existing literature. Although some countries keep internal manuals on some of these subjects, a general guideline considering international experience would certainly help to protect the people, environment and equipment.

## Development of a rapid procedure for gross alpha and gross beta evaluation in water samples in emergency situations

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### Introduction

The Laboratorio de Radiactividad Ambiental of the Universitat Politècnica de València (LRA-UPV) participates as a support laboratory in case of radiological emergency within the emergency preparedness plan of the Valencian Community (Spain). Gross alpha and gross beta determination in water samples is an important indicative of the radiological quality of the water and a screening method in an emergency situation to reduce internal exposure by ingestion.

### Methods

The LRA-UPV developed a rapid test and operating procedure for the determination of gross alpha and gross beta activity in water samples based on the direct counting of the sample by liquid scintillation in Quantulus 1220 to reduce time, avoid cross-contamination of samples and reduce the exposure due to handling active samples. The procedure is applicable to water with different salt content (from 5 g/L of continental and drinking water, to 35 g/L of sea water) and pH.

### Results

Samples were prepared by mixing 8 mL of the sample and 12 mL of Ultima Gold LLT in a 20 mL polyethylene vials. The Pulse Shape Discriminator parameter (PSA) was optimized to minimize the total interference ( $\alpha + \beta$ ) and allow the simultaneous measurement of alpha and beta emitters for different quenching values (SQP(E)). Standard solutions of  $^{241}\text{Am}$  and  $^{90}\text{Sr}/^{90}\text{Y}$  were prepared at the LRA-UPV in order to establish the optimum PSA and the alpha and beta efficiencies for different SQP(E). Finally, the method was tested for different alpha-beta ratios (1:1, 1:10, 10:1) and validated with spiked samples prepared by the laboratory and intercomparison samples. Moreover, the measurement procedure is based on a screening measurement of 10 minutes to determine the quenching parameter and identify the active samples. A second measurement of 60 minutes is performed to calculate the activity of the sample with low uncertainty and get better limits of detection.

### Conclusions

The proposed procedure allows the evaluation of gross alpha and gross beta activity in a large number of water samples in the first hours of the emergency, offering reliable results with appropriate uncertainties according to the time of measurement and the requirements of the regulatory authority.



## CIEMAT WBC capabilities for responding in case of nuclear and radiological emergencies

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### Introduction

In a nuclear or radiological emergency, it is necessary to develop fast and effective methods in order to assess the internal exposure for workers and exposed population. CIEMAT Whole Body Counter has implemented techniques to determine gamma emitters in thyroid, and total body for different age groups (1, 5, 10, 15 years and adults) according to ICRP 89. Furthermore, WBC laboratory has developed a new method for calibration and in vivo measurement with germanium detectors (LEGe) of radioactive contamination in wounds produced at different depths by the deposit of  $\alpha/\gamma$  emitters.

### Methods

Fastscan counter and Low Energy Germanium (LEGe) detection system inside a shielded room were calibrated for in vivo measurement of gamma emitters in total body and radioiodine in thyroid. For total body calibration purpose, different configurations of an active BOMAB phantom were utilized in order to simulate reference children and male and female according to ANSI 13.35 standard. In case of thyroid measurement, a set of thyroid neck phantoms for children and adults a thyroid neck phantom following specifications of the ANSI n13.44 standard were utilized for calibration purposes. Thyroid glands were simulated using cylindrical vials filled with a homogeneously distributed liquid solution of  $^{131}\text{I}$ . In case of wound measurement, to perform calibration of the LEGe detector for the measurement of the contamination of X and  $\gamma$  emitters in wounds, circular radioactive sources of PMMA equivalent to tissue were utilized adding inactive PMMA plates to simulate different depths of skin.

### Results

In total body calibrations, efficiencies vary with energy for each phantom. Detection limit (DL) of Cs-137 (300s) in Fastscan counter varies among 105-155 Bq and in LEGe (1800s) between 18.7-57 Bq depending on the phantom size.

It is similar in thyroid calibration; DL in Fastscan (300s) varies among 26-42 Bq and in LEGe detector (1200s) between 4.6-6.2 Bq.

Wounds calibration varies with contamination depth. DL (600s) for Cs-137 is around 1 Bq.

### Conclusions

Calibration methodologies have been developed for in vivo measurement of  $^{131}\text{I}$  in thyroid, in total body, and wounds of exposed population in emergencies. To use different calibration phantoms for adults and children allows measuring realistic activities improving the response in emergencies. Efficiency depends on source size, in all calibrations and in wounds calibrations depends on the contamination depth.

## Use of gamma cameras for internal monitoring of high-energy photon emitting radionuclides based on urine samples in emergency situations

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### Introduction:

Nuclear and radiologic accidents may lead to intakes of radionuclides by public individuals and workers. In such situations, internal monitoring is essential to provide the necessary information to first responders for taking correct remediation actions. Bioassay data allow classifying and evaluating the severity of the accident as well as preventing the increase of contaminated areas and people and assessing the efficacy of decontamination actions and decorporation treatments.

This study describes the calibration of gamma cameras for use on internal monitoring of high energy photon emitting radionuclides in humans based on urine samples. The proposed technique should be applied in prompt response during emergencies.

**Methods:** Gamma cameras available in four public hospitals located in the city of Rio the Janeiro were calibrated using a set of 1-liter standard liquid sources of Co-57, Na-22, Cs-137 and Mn-57 supplied by the Metrology Laboratory of the IRD. "Efficiency vs Energy" curves at 5, 10, 15 and 20 cm were obtained. Calibration factors, Minimum Detectable Activities, Minimum Detectable Intakes and Minimum Detectable Effective Doses were calculated for Ru-103, Cs-134, Cs-137 and Co-60.

**Results:** The equipment evaluated in this work present enough sensitivity to detect activities of the selected radionuclides of interest in urine samples that would result in internal doses below 1 mSv, taking into consideration the exposure scenario adopted in the accident simulation.

**Conclusions:** The gamma-camera is a medical device readily available in most public hospitals. It is suitable to evaluate incorporation of radionuclides by humans in emergency situations.

## Organ Dose and Radiogenic Risk in Cone-Beam Computed Tomography Examinations

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### Introduction

During last decade development, Cone beam computed tomography(CBCT) offers large range of imaging method. CBCT gives advantages compare to other extraoral radiographic imaging ,but the contributes of radiation dose to patients is a point of concern. The aim of this study is to provide a full understanding and determination of absorbed dose and estimation of effective dose to eye lens and thyroid for patient during CBCT examinations and to estimate the radiogenic risk resulted from radiation exposure.

### Methods

A total of 420 pediatric and adults patients were investigated in this study for different clinical indications at Dental clinic, College of Dentistry, Prince Sattam bin Abdulaziz University. All procedures were performed using caresteam dental CBCT(Carestream Health, Inc, NY, USA). Surface organ doses (eye lens and thyroid) was estimated using 148 thermoluminescent dosimeters (TLDs). Deep organ doses was estimated using PCXMC software

### Results

The mean tube voltage (kVp)  $80 \pm 10$  (70-110) and the mean tube current (mA) is 4.0 (3.1-8.0) and the mean exposure time (s) was  $12 \pm 4$  (10.0-22.0). The overall mean and range of patients' effective dose values ( $\mu$  Sv) of 5.8.  $\pm 3.50$  (3.8-12.1).

### Conclusions

Thyroid doses is the the highest among other organs because no protection shield is used for all patients. Patients doses is slightly higher compared to previous studies. Poor patient protection condition were noticed. Staff training of prime priority regardless of low dose value compared to other imaging modalities.

## Alanine Pellets Comparison using EPR Spectrometer suitable to be use in Quality Assurance of Gamma Knife System in Romania

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### Introduction

In the last decade, the use of alanine/ESR system was extended to radiotherapy doses. In stereotactic radiosurgery, doses up to 70 Gy are delivered to the brain tumor preserving healthy tissues. This type of treatment is delivered using dedicated equipment, like Cyberknife or Gamma Knife. Alanine dosimeters are characterized by their small size (5 mm diameter) and by similarity with human tissue. They are well adapted for this wide dose range for which the dosimeter response is linear, independent of dose rate and energy for the range around few MeV. Therefore Alanine/ESR system is a suitable method for accurate and stable dose measurements as passive dosimeters for reference dosimetry for narrow treatment beams, which makes it an excellent candidate for end to end testing of radiosurgery treatments using Gamma Knife. The present work describes the development of the alanine/ESR method at IFIN-HH in Romania including the optimization of ESR spectrometer parameters for the radiosurgery dose range in the frame of an IFIN-HH and LNE-LNHB collaboration. IFIN-HH alanine dose measurements capability is presented regarding an inter comparison between LNE-LNHB and IFIN-HH of calibration curves using two different types of alanine pellets.

### Methods

Two sets of two types of alanine pellets (pellets provided by Bruker and Synergy health) were irradiated at the DOSEO platform of LNE-LNHB using a Varian Truebeam® medical accelerator. The dose range of the 4 sets of alanine pellets lies from 4 Gy up to 88 Gy. EPR measurements were performed using A Bruker ELEXSYS E500 EPR spectrometer at LNE-LNHB and a MicroEMX EPR spectrometer at IFIN-HH at regulated room temperature ( $20 \pm 2^\circ\text{C}$ ) and humidity ( $40 \pm 10\%\text{HR}$ ). Readouts were made 7 days after irradiation of the dosimeters for the two types of alanine pellets in each laboratory. Tubes in Suprasil quartz with 5mm internal diameter were used for maintaining the pellet in an ER 4119 HS resonator readout cavity for both laboratories.

### Results

Calibration curves are established for the two types of alanine pellets using EPR spectrometers of each laboratory. In order to compare the two types of alanine pellets, each pellet's EPR response was normalised to the alanine mass. The results show that both dosimetry systems have linear dose/response relationship in the radiosurgery dose range.

### Conclusions

Calibration curve slopes of the two types of alanine pellets agree within their uncertainties at LNE-LNHB and at IFIN-HH laboratories, which confirms the equivalence of using alanine pellets provided by Bruker and by Synergy Health for absorbed dose measurements. The results obtained validates the alanine/ESR system used at IFIN-HH and data obtained, corroborates that alanine/ESR system could be suitable as a transfer standard dosimetry system for a Gamma Knife Unit.

## Evaluation of the dose distribution of tomotherapy using polymer gel dosimeters and optical computed tomography with ring artifact correction

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### Introduction

Tomotherapy can provide highly conformal dose distribution through multiple beam irradiation. It has been proved the availability and reliability of polymer gel dosimeters (PGDs) on evaluating such dose distribution with high dose gradient. In several dose readout tools, optical computed tomography (OCT) has the benefits of rapid readout, high spatial and dose resolution and no additional dose delivered to PGD samples compared with magnetic resonance imaging and computed tomography. However, the OCT images reconstructed using filtered-back projection usually contaminated by ring artifacts. These artifacts deviate the light attenuation coefficients in the OCT images and bias following converted dose results. In this study, we verified the dose distribution of the tomotherapy using the NIPAM PGD and a DeskCAT OCT scanner. In addition, a ring artifact correction method was applied to improve the accuracy of measured dose distribution.

### Methods

The dose distribution of the tomotherapy of a real clinical case of brain tumor was evaluated using a *N*-Isopropylacrylamide (NIPAM) PGD. The irradiated PGD was scanned using a DeskCAT OCT scanner 24-hr after dose delivery. The ring artifact correction was performed by median filtering of the OCT in polar coordinate. The acquired OCT images with and without ring artifact correction were compared, and the converted dose distributions were compared with that generated from a treatment planning system.

### Results

The applied method with proper filter length can effectively reduce the artifacts and improve the uniformity of the measured dose distribution. The ring artifact correction improved the pass rate of the measured dose distribution calculated using a three-dimensional gamma evaluation with 3%/3mm criteria from 86.3% to 96.9%.

### Conclusions

We concluded that the PGD and OCT with ring artifact correction could be useful for pre-treatment verification of the tomotherapy.

## Absorbed and Effective Doses evaluation in a pediatric PET/CT scan

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### Introduction

Positron Emission Tomography (PET) associated with Computed Tomography (CT) are becoming increasingly important imaging tools in the noninvasive evaluation and monitoring of children with known or suspected malignant diseases. These compound tomographic devices allow the overlapping of functional images obtained from the administration of radiopharmaceuticals and anatomical images generated by X-ray beam attenuation. Although the immediate benefit to the individual patient can be substantial, the relatively high radiation doses associated with PET/CT compared with conventional exams have raised health care. This is especially concerning for children, who are more sensitive to radiation-induced carcinogenesis and have many remaining years of life for cancer to develop.

### Methods

In this study, the absorbed and effective doses generated by the CT scan and incorporated by the administration of the radionuclide <sup>18</sup>F-FDG were evaluate in the most radiosensitive organs. To evaluate the CT dose, radiochromic film strips were positioned into the pediatric body phantom built by PMMA volumes. The CT protocol performed was the standard pediatric whole-body scanning used in the service where the study was done. The calculation of the effective dose from the injected activity in the patient was performed using the ICRP 106 Biokinetic model.

### Results

Analyzing the results, the organ that presented the highest absorbed dose was the bladder. When the effective dose is analyzed, the values found were higher for the lung, followed by the bladder and the stomach. This is explained by the radiosensitivity of the tissues.

### Conclusions

The CT scan is responsible for almost 60% of the effective dose in the PET/CT examination, hence the importance of the tomographic protocol optimization, reducing doses to the minimum necessary. It is important to emphasize the importance of patient-specific size use in exposure dose estimation for <sup>18</sup>F-FDG PET/CT.

## Dose estimation per Occupationally Exposed Individual for the burden of eighty patients per week considering doses of preparing room, radioisotope injection, hall circulation, and command room according to AAPM 108

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### Introduction:

Radioprotection of PET/CT facilities presents special challenges due to the 511-keV annihilation photons. Specially, the shielding for such positron-related photons is of utmost relevance. Since the patients become a radioactive source, one should consider the entire time they spend in the clinic. Thus, we present a careful planning considering the total doses generated according to the AAPM 108.

### Methods:

We used the AAPM 108 regulation for the dose estimation according to the following parameters: a) sum of doses in the PET/CT room due to the preparing room; b) sum of doses in the circulation hall due to the PET/CT rooms; c) sum of doses in the PET/CT command room due to the preparing room; d) contribution of the radiopharmacy laboratory in the weekly dose; e) dose estimation due to the contribution of injection and patient placement. We hypothesized  $n=80$  for patient burden.

### Results:

a) six preparing room showed a weekly sum of doses  $D=229.89 \mu\text{Sv/week}$ ; b) the weekly effective dose in the circulation hall was  $D=103.75 \mu\text{Sv/week}$ ; c) no estimation needed in the command room due to the preparing room, shielded with 15 cm concrete-equivalent; d) the weekly effective dose of radiopharmacy laboratory was  $D=0.28 \mu\text{Sv/week}$  considering a daily activity of 7,400 MBq on each supply; e) Dose due to a 3 seconds injection procedure was  $D=802 \mu\text{Sv/week}$ ; dose due to the patient placement was  $D=145 \mu\text{Sv/week}$ , leading to an overall contribution  $D = 947 \mu\text{Sv/week}$ . Finally, taking into account the occupation factor of  $1/8$  for preparing room and acquisition room, we found  $D=42 \mu\text{Sv/week}$ .

### Conclusions:

With six preparing rooms and 4 workers in the facility, even with the maximum patient burden presented, we would not achieve the over-dose. Therefore, every worker would have monthly dose lower than the threshold of 1 mSv/month, specifically 0.6 mSv/month/OEI.

## Measurement and Reconstruction of High Energy Photon Beam Spectra using Compton Spectrometry

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### Introduction

The Compton spectrometry method is presented how one efficient technique for measurement of high energy photon beams spectra that are produced in linear accelerators and Cobalt radiotherapy machine, used in treatment cancer patients. In this work was made the measuring of the pulse height spectra PHS for one Co-60 machine of clinical uses, from this spectra and using the previous response matrix constructed for the spectrometry system with a deconvolution method was recovery the photon fluence spectra of the clinical machine; the main objective is applied this method in the measuring and reconstruction of the bremsstrahlung spectra for one clinical linear accelerator of photons.

### Methods

Previously was made the characterization of one NaI(Tl) detector, obtaining the energy response functions for the Compton spectrometer with the objective of construct the response matrix of the system, in next was checked the functionality of the spectrometry system making mechanical test and radiation test by a measurement of the pulse height spectra in Compton configuration for X-rays of 70-100 KV with Compton angle of  $90^\circ$ , in order to obtaining the response of the spectrometer at this energies. Finally was made the measuring of the pulse height spectra for one Co-60 machine at different Compton angles with the purpose of recovery the fluence spectra of the clinical machine.

### Results

Were obtained the pulse height spectra for one Co-60 Theratron-780 machine and subsequently was recovery the photon fluence spectra of the clinical machine using the response matrix constructed, watching good relationship with the spectra obtained for Monte Carlo Simulation, and also with the recovered spectra for one calibration standard source of Co-60.

### Conclusions

The Compton spectrometry method used for recovery the fluence spectra of the clinical machine show a good definition of the two peaks corresponding at the radiotherapy Co-60 source and one relationship with the spectra obtained for the standard calibration source, in consequences this method would be used in the measuring and reconstruction of the bremsstrahlung spectra of one linear accelerator of clinical uses.



## Comparative dosimetric study between the Acuros XB and AAA algorithm for treatment of lung tumor with RapidArc technique

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### Introduction

The aim of this study is to assess the dosimetric impact of the Acuros XB algorithm (AXB), in comparison with Anisotropic Analytical Algorithm (AAA) calculation, for lung cancer treatment plans created with RapidArc technique.

### Methods

A CT dataset of 59 patients with lung cancer and treated with linear accelerator Truebeam (Varian) with 6MV were selected to this study. The differences between doses obtained by the planning performed with the algorithm Acuros (AXB) and the AAA were evaluated. The planning were calculated for boths with the same number of monitor units and for AXB it was used the option "dose to medium" and 2.5mm grid size. The physical parameters of dose volume histogram (DVH) for PTV: minimum dose (Dmin), near-minimal dose (D98%), mean dose (Dmed), near-maximum dose (D2%) and maximum dose (Dmax) were used to compare the results with both algorithms.

### Results

The results showed that the AAA overestimates the dose values for the : Dmin (5.4%), D98% (2.1%), Dmed (0.6%) and D2% (0.1%). For Dmax value was underestimated by -0.6% with  $p < 0.05$  and for D2% there was no significant difference. The calculation time was higher for AAA than for AXB with  $p < 0.05$ , confirming that in radiotherapy techniques using high number of arcs, like VMAT, the algorithm AXB presents calculation time faster than AAA.

### Conclusions

The AXB algorithm should be used in preference to AAA for cases in which PTVs are involved with tissues of highly different densities, such as lung, for avoid overestimation of the minimum target doses compared to actual delivered dose. In addition, the calculation time was significantly shorter for AXB with RapidArc.

## Quality control in “Intensity Modulated Radiation Therapy-IMRT” using thermoluminescent dosimeters

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### Introduction

Quality assurance in radiation therapy included all actions to ensure the maximum dose for the target volume (tumour) and minimum dose for the healthy tissues. The use of thermoluminescent detectors for evaluation of the absorbed doses in treatments that involve the use of ionizing radiation is widespread and well established in clinical routine. The quality measures are employed to validate system performance, such as IMRT quality assurance (QA). An example for IMRT QA is the decision not to treat the patient if the comparison between a point-dose measurement and the planned value exceeds a predefined acceptance criterion ( $\pm 5\%$ ). This work aimed the evaluation of absorbed doses with the use of thermoluminescent detectors (TLDs) of lithium fluoride doped with magnesium and titanium (LiF:Mg,Ti) and a polymethylmethacrylate (PMMA) phantom in Intensity Modulated Radiation Therapy – IMRT planning.

### Methods

In this study the PMMA phantom simulated a patient in treatment. The central cavity (rectangular format) was considered like target volume (tumour) and the others four cavities were considered like organs at risk. The TLDs were positioned inside the cavities; each cavity has an EVA mold for the positioning of TLDs.

Results

Table 1: Absorbed doses calculated by TLDs and treatment planning system (TPS).

Cavity	Position	Absorbed doses by TPS (Gy)	Absorbed doses calculated by LiF:Mg,Ti			Mean ± SD (Gy)
			1 <sup>st</sup> measure (Gy)	2 <sup>nd</sup> measure (Gy)	3 <sup>rd</sup> measure (Gy)	
Rectangular (Tumour)	7	1.94	2.01	2.02	2.06	2.03 ± 0.03
	8	1.95	2.01	2.10	2.00	2.04 ± 0.05
	9	1.95	2.02	1.79	1.94	1.91 ± 0.12
	10	2.01	2.24	2.12	2.12	2.16 ± 0.07
	11	1.99	2.10	2.20	2.13	2.15 ± 0.05
	12	1.99	2.18	2.12	2.07	2.12 ± 0.05
Triangle	1	0.28	0.27	0.28	0.27	0.27 ± 0.01
	2	0.31	0.33	0.29	0.31	0.31 ± 0.02
	3	0.71	0.82	0.73	0.77	0.77 ± 0.05
Small square	1	0.79	0.75	0.74	0.82	0.77 ± 0.04
	2	0.43	0.35	0.38	0.32	0.35 ± 0.03
	3	0.23	0.24	0.22	0.22	0.23 ± 0.02
Circle	1	1.17	1.03	1.09	1.19	1.11 ± 0.08
	2	0.5	0.48	0.43	0.44	0.45 ± 0.03
	3	0.22	0.22	0.19	0.23	0.21 ± 0.02
Big square	1	0.3	0.30	0.27	0.35	0.31 ± 0.04
	2	0.37	0.36	0.37	0.35	0.36 ± 0.01
	3	0.95	0.85	1.23	0.89	0.99 ± 0.21

Conclusions

The results demonstrated the good agreement for the absorbed doses calculated by TLDs of LiF:Mg,Ti and the doses provided by the treatment planning system. The successful of the radiotherapy treatment is based on the quality control of radiation doses distributed by linear accelerators.

## EVALUATION OF DOSE AND DIAGNOSTIC IMAGE QUALITY USING BRAZILIAN BREAST PHANTOM

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### Introduction

The main goal of the mammography technique is to have a diagnostic image with many details about the mammary structure and administering the possible smallest dose to the patient. Since that the mammary tissues have a similar attenuation to X-rays, it could disguise some injuries.

The average glandular dose is a parameter that could be used as an estimate of the average dose received by the patient and, together with the evaluation of the quality of the image, allows the optimization of this technique.

### Methods

The breast phantom of the Brazilian College of Radiology was used with compressed standard breast of 50 mm and 50% glandular tissue. All the exposures were made on a mammography equipment using CR plates.

For the estimation of the average glandular dose, the method described in TRS 457 was followed, for which the half-value layer was initially estimated.

To evaluate the diagnostic image quality Brazilian recommendations (ANVISA) were used to indicate the minimum detection parameters of that a diagnostic image should present.

### Results

The half-value layer (HVL) was estimated to be 0.323 mm Al using the Mo/Mo combination; with this value it was possible to estimate the average glandular dose in 1.87 mGy.

In the breast phantom image obtained it was possible to visualize all the minimal structures necessary for the image to be considered as acceptable to make the diagnosis.

### Conclusions

The value of the HVL is within the recommended value for the target/filter combination used and the average glandular dose is below the recommended limit of 3 mGy.

The diagnostic image can be considered acceptable because it allowed to visualize the structures required by Brazilian regulations.

## Personal dose equivalent of $^{18}\text{F}$ -FDG PET assessed using a semiconductor personnel dosimeter to protect workers from radiation.

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### Introduction

In Positron emission tomography with  $^{18}\text{F}$ -FDG PET, patients receive internal exposure to radioisotopes. In contrast, the personal dose equivalent of the radiation workers has changed with improvements in the system performance and new acquisition method. Although personal monitoring has previously been reported, reevaluation in the newer environment is necessary. The personal dose equivalent is measured by using personal monitoring equipment according to recommendations by the ICRP. In this study, the personal dose equivalent of different radiation workers related to  $^{18}\text{F}$ -FDG PET was measured minutely or hourly and analyzed.

### Methods

For the measurements, a semiconductor dosimeter using a Si solid state detector, sized 68 mm × 32 mm × 14 mm, which is capable of measuring gamma rays of 80 keV~1.2 MeV with an accuracy of  $\pm 10\%$ , was used. The software in the instrument could easily display the minutely dose, the hourly dose, the monthly cumulative dose, and the daily cumulative dose, as well as trend graphs.

### Results

Radiation workers with duties involving high external exposure doses (Measured value) included doctors doing diagnosis ( $4.8 \mu\text{Sv}$ ), nurses removing injection needles ( $3.1 \mu\text{Sv}$ ), pharmacists doing quality control tests ( $2.9 \mu\text{Sv}$ ), nuclear medicine technologists operating PET-CT ( $6.5 \mu\text{Sv}$ ), and cyclotron engineers operating the system ( $^{18}\text{F}$ ) and performing checks ( $13.4 \mu\text{Sv}$ ).

### Conclusions

This study clarified factors related to the external exposure dose through the analysis of daily work duties. These results will be helpful for reducing the external exposure dose of radiation workers and for planning time distribution.



## Simulation of radiographic images from computational models rendering for use in dosimetry

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### Introduction

The use of computational models simulating regions of human anatomy has been employed in the health field, which are applied for different purposes, for example, in education, in Dosimetry, among others. In this context, the objective of this work is to develop computational models of the knee and elbow joints that allow to be the basis for the simulation of radiographic images.

### Methods

To accomplish the work, we used the free software Blender 3d, which has virtual environments that enabled the construction of computational models, consisting of mesh surfaces, of the bones that compose the joints of the knee and elbow. Each bone was modeled individually in a virtual environment of its own and was subsequently inserted into the same environment so that it was possible to reproduce the various radiological positioning specific to these regions. To obtain the simulated radiographic image, the computational models were rendered in the virtual environment.

### Results

The simulated radiographic images presented characteristics similar to the radiographs of real human structures.

### Conclusions

Thus, the developed models presented potential to be employed in the development of phantoms that allow the simulation of images and doses received by patients in radiographic examinations. They also present potential to add value in the formation of radiology professionals, as well as contributing as an auxiliary tool for professionals who want to optimize the doses used to perform radiological examinations.

## Determination of interaction quantities of radiation with dosimeters through PENELOPE code

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### Introduction

The dosimetric response of the dosimeters can be evaluated through the quantities of interaction of radiation with matter. These interaction quantities can be determined by simulation PENELOPE code. The aim of this work was to use this code to simulate the materials of the Thermoluminescent dosimeter (TLD), Gafchromic film and MAGIC-f gel dosimeters and evaluate its response to radiation through the quantities of interaction of radiation: attenuation coefficients ( $\mu$ ) and stopping power (S) for each dosimeter.

### Methods

The PENELOPE-Monte Carlo code simulation version 2008 were used to “construct” materials of dosimeter through the chemical compound: TLD (LiF), Gafchromic film EBT2 and MAGIC-f gel. The material constructed were used for simulation reference conditions radiation following the recommendation of TRS 398 AIEA. The two quantities mass stopping power and mass coefficient attenuation were obtained in depth relative to the measurements of parameter for quantifying the beam quality; for this work we used 6MV photons and 9MeV electrons beams.

### Results

For the photon beam the maximum perceptual difference of 2.4% was found when comparing the values of the attenuation coefficients of the TLD dosimeter with others in 20cm depth. For electrons the maximum perceptual difference up to 9.5% were found, when compared the EBT2 film relative to the other dosimeters.

### Conclusions

In this context, previously shown the ability of the PENELOPE code to preview the response of the dosimeters currently used and propose to develop new material dosimeter. Moreover, the material constructed can be useful for studies of response and comparison with reference dosimeters.



## A comparison of age-dependent organ depth distributions: stylized versus voxel phantom series

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### **Introduction**

The main parameter influencing organ dosimetry from external irradiation is the organ's position below the surface of the body. Initially, models of the human body were defined through surface equations (stylized phantoms) and have now been advanced by more anatomically realistic models based on medical patient images (voxel phantoms). The impact of this shift in modelling has been studied rigorously through comparisons of external dosimetry simulation results. For photon irradiation, differences in organ dose between the series are often interpreted as differences in organ depth and positioning. This work, however, represents the first effort to quantify the differences in organ depths between a stylized and voxel phantom series.

### **Methods**

For this work, the revised ORNL stylized phantom series and the voxel UF/NCI phantom series were used. Both series include whole-body models of the newborn; the 1-, 5-, 10-, and 15-year-old; and the adult human. Organ depths from six different directions applicable to external dosimetry were found: the caudal, cranial, left and right lateral, front, and back. Organ depths in the stylized phantom were found through a ray tracing technique used in the Monte Carlo code MCNP6. Organ depths in the voxel phantom were found through phantom matrix manipulation.

### **Results**

Resultant organ depth comparison plots have been created for twenty-four organs, for all ages, in each of the six directions. These plots are used to explain the results within a literature review of relevant photon external dosimetry papers which use these phantoms.

### **Conclusions**

Organ depths for the ORNL and UF/NCI phantom series can be used to explain the dependency of multiple organ doses on the exposed body type, and therefore the amount of shielding, as well as to provide knowledge of the shift in organ position and shape between the series. Future work applicable to internal dosimetry may be explored through chord length comparisons of source to target organs.



## 3D dosimetry based on SPECT/CT: Evaluation for Lutetium Therapy using Monte Carlo simulation and the NEMA phantom

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### Introduction

When external radiotherapy is not applicable, radionuclide therapy can be an alternative for treating some kind of tumors. In this therapy, radionuclides are administered to the patient, often in a form where the radionuclide is labelled to a molecule that plays the active part in the localization of the tumor. Since the aim is to impart lethal damage to tumor cells while maintaining possible side-effects to normal tissues at tolerable levels, a proper and accurate personalized dosimetry should be a pre-requisite. In radionuclide therapy, there is a need to measure the distribution of the radiopharmaceutical in vivo, as well as its re-distribution over time, in order to estimate the absorbed dose to different organs and tumors. Measurements are usually performed by molecular imaging, more specifically planar and SPECT (Single-Photon Emission Computed Tomography) imaging, combined with CT.

### Methods

The most accurate, but also the most time-consuming method for absorbed dose rate calculation is to use a full Monte Carlo-based transport program. In this work, the MCNP Monte Carlo code has been used to transport the emitted particles (photons and electrons) of Lutetium-177 distribution inside the NEMA phantom. To that, the CT-derived density images have been used to generate the 3D model of the phantom in MCNP using CAD and mesh tools. The version of MCNP (v.6.1.1) presents as a novelty the use of meshed geometries to create models.

### Results

After MCNP6.1.1 simulation, the three-dimensional dose distribution can be shown using visualization software ParaView. The results of this study have been validated with data offered by the *Hospital Universitari La Fe de Valencia*, reflecting the high accuracy of Monte Carlo results obtained.

### Conclusions

This paper presents the innovation of using unstructured mesh geometries in Monte Carlo calculations to analyze 3D doses in organs of patients under a Lutetium-177 treatment. This means a direct impact on patients because it provides an optimization of received dose.

## Mammographic density assessment with the LIBRA software

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### Introduction

High breast density is one of the major risk-factor for breast cancer. It reduces effectiveness of mammographic examination because of the masking effect of the dense tissue. Besides, a number of studies have shown that the amount of fibroglandular tissue correlates with risk of developing breast cancer. Mammographic density is usually measured by qualitative assessment of the parenchyma or quantitatively by percent density. In the present study, we estimate the precision of the Laboratory for Breast Radiodensity Assessment (LIBRA) software tool, apparently the only publicly available fully automated software for mammographic density measurement.

### Methods

Results of examination of 316 women without symptoms of breast cancer were selected from a mammography database (June 2016, through February 2017). Mammographic exams of patients with breast implants, surgeries, biopsies, marker clips and activated charcoal were excluded from the evaluation. All digital mammograms were obtained on a Selenia Dimensions mammography system (Hologic).

### Results

The densities of the mammographic craniocaudal and mediolateral oblique images of the same breast were compared for two types of images: "FOR PROCESSING" and "FOR PRESENTATION".

### Conclusions

The achievable accuracy of the density measurement with the LIBRA software decreases linearly from 1% to 7% in the density range up to 60%.

## PLASMA REACTOR TO VIABILIZE THE VOLUMETRIC REDUCTION OF RADIOACTIVE WASTES

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### Introduction

According to the International Atomic Energy Agency – IAEA, nuclear waste, also known as, radioactive waste, is any material containing a higher concentration of radionuclides than those considered safe by the national authorities. In Brazil, there is a National Nuclear Energy Commission to regulate. These wastes can be generated in nuclear power plants, industries, hospitals and research institutes.

To permanently dispose of these radioactive wastes of low and medium level of radioactivity safely and cost effectively, these should be transformed into the physical and chemical compounds suitable for radionuclides immobilization with maximum volume and exhaust gaseous reduction.

Incineration is used as a treatment for a very wide range of wastes. Incineration itself is commonly only one part of a complex waste treatment system that altogether, provides for the overall management of the broad range of wastes that arise in society. The objective of waste incineration, in common with most waste treatments, is to treat waste so as to reduce its volume and hazard, whilst capturing (and thus concentrating) or destroying potentially harmful substances.

The incineration of waste is one of the most widespread and effective technologies allowing considerably to reduce waste volume. In this scope, among the promising technologies for the radioactive waste treatment is the plasma technology that allows reducing substantially the waste volume after exposing them to temperatures above 2500°C. In the planning and management of radioactive waste, the challenges related to plasma technology are presented as a motivation factor for the possible implantation of plasma reactors in nuclear plants and research centers with the objective of improving the process of radioactive waste treatment. In this way, this work aims to evaluate the use of plasma technology for the incineration of radioactive waste for volumetric reduction and immobilization of this waste.

### Methods

In this work, a plasma reactor was used for waste incineration, and all reactor parameters (electric energy ranges, maximum arc current, maximum working voltage, air flow, maximum energy conversion efficiency, average temperature of heated gas, heated enthalpy) was controlled based on literature. The experiment was carried out in the plasma reactor (laboratory scale) of LPP in the ITA, using plasma torch transferred arc and with gaseous argon oxidizing agent. The electrical and thermal characteristics of the auxiliary systems of the plasma reactor

were obtained using transducers and thermocouples. The composition of the gases in the process was analyzed using mass spectrometer and spectrophotometer.

**Results**

The accuracy of the data was important to ensure good results in the process, which allowed the extraction of relevant information from the experiments performed. The volumetric reduction reached 92% in relation to the sample before being processed, with a peak temperature of 1800°C. Although a larger amount of argon flow intensify the cooling of the inner wall of the reactor, and further promote the dilution of the plasma, the arc voltage increases, resulting in higher power operation.

**Conclusions**

In the present work a high efficiency thermal transfer torch was characterized , able to validate the use of the plasma jet for the treatment of radioactive waste.

## Optically stimulated luminescence dosimetric characteristics $\text{TiO}_2\text{:Ce}$

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**Introduction.** Optically stimulated luminescence (OSL) is one of the many known stimulated phenomena in condensed matter that can be induced by ionizing radiation and that became a successful practical tool in radiation dosimetry. Special attention is dedicated to bioceramic as a material of choice for many dosimetric applications.

**Methods.** In this work, experimental results of OSL properties in  $\text{TiO}_2\text{:Ce}$  nanomaterials prepared by microemulsion (ME) assisted sol-gel technique were reported. Titania-ceria nanoparticles in anatase phase were synthesized. The nanostructures samples were irradiated with beta particles of  $^{90}\text{Sr}/^{90}\text{Y}$  in a wide doses range.

**Results.** Nanostructured powders were confirmed by X-ray diffraction technique. OSL signal of Ce doped  $\text{TiO}_2$  showed an exponential OSL signal decay. The nanostructures samples were irradiated with beta particles of  $^{90}\text{Sr}/^{90}\text{Y}$  showing a linear behavior in the doses range studied. OSL response of powders showed good reproducibility with 5% standard deviation.

**Conclusions.** The OSL response has a good reproducibility, with deviations of around 5%, making these  $\text{TiO}_2\text{:Ce}$  nanomaterials suitable for beta radiation dosimetry applications.

## Radioactive waste management in a Nuclear Medicine Department

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### Introduction

As a result of manipulating radionuclides, a Nuclear Medicine Department (NMD) produces radioactive waste which should be appropriately managed and disposed. Waste management has to follow Regulatory Guidance, which aims to harmonize the procedures for managing authorized discharges. In this work, we present the waste management system implemented to comply with the requirements of the referred guidance.

### Methods

Solid waste includes materials used in preparation and administration of radiopharmaceuticals (bioboxes, ventilation systems and vials), patient's excreta (diapers and urine collectors) and others. They are identified with a radioactive symbol date of elimination, and placed to decay in a waste store room. Before the waste is eliminated from the NMD it is monitored. A labelling system was also implemented to identify released residues. Radioactive effluents from the NMD are routed alternately to two tanks for decay. Liquid wastes are only allowed to be discharged into the hospital sewage after a sample has been evaluated by spectrophotometry by an external entity. All monitoring and discharges are recorded in a database.

### Results

In the audited period there were 733 procedures (720 with Tc-99m, 12 with I-123 and 1 with I-131). Each bag of solid waste is identified with a label containing a unique ID number, type of waste, description of contents, radiation dose rate at contact and production, monitoring and discharge date. 70% of the waste produced is related to manipulation of Tc-99m, most of which are waste from the nursing and exam rooms (84%). Each tank takes about two months to fill and is left one month decaying before monitoring. There was no trace of radionuclides in 71% of the samples.

### Conclusions

Radioactive waste is released only when the values are below discharge limits, not representing a significant radiological impact. Segregation, storage, monitoring, registration and labelling system implemented complies with the legal requirements for radioactive waste management.



## Fading and Retrospective Responses for Thermoluminescent Dosimetry of Silica Beads Irradiated with High-dose Electron-beam

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### Introduction

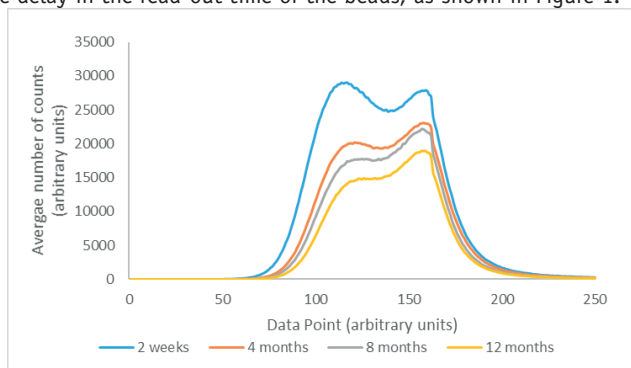
Our studies focus on the TL responses of 10 different coloured batch produced silica beads (manufacturer Toho, Japan) for doses up to 250 kGy, which includes the typically dose ranges applicable to industry and sterilisation. We have studied the fading effect for a year in delay at 4 month intervals and the residual TL response for 2<sup>nd</sup> readouts.

### Methods

Electron irradiation was completed using the Alurtron Electron Beam Facility, as part of Agensi Nuklear Malaysia for a variety of doses ranging from 1kGy to 250kGy. Glow-curves were obtained using the Risø TL/OSL reader with a detection range of 100nm to 625nm.

### Results

We present the evidence of fading TL response for 5 doses from 1kGy to 250kGy for 4 fading periods equally spaced over a year. Glow-curves for certain colours suggest two electron traps, activated at these high doses. The ratio of the TL contribution from these two electron traps varies with the delay in the read-out time of the beads, as shown in Figure 1.



*Figure 1 - Glowcurves of Red beads irradiated with 250kGy across the range of fading time intervals.*

Retrospective studies show that TL responses can still be obtained weeks after the 1<sup>st</sup> readout, with the delay for the 2<sup>nd</sup> readout delayed by a month for 18 doses across the range of 1kGy to 250kGy. Only Pink, Frosted and Rose beads show a response after using the same heat cycle and filters as used in the 1<sup>st</sup> readout, with an average response of 0.33% to 0.43% across all doses for both colours of the TL response of the 1<sup>st</sup> readout.

### Conclusions

Batch produced silica beads are a possible candidate as dosimeters at industrial or sterilization doses. Fading over different periods of time and at different doses has determined that they can retain a suitable TL response despite fading studies and/or delayed readouts with the possibility for retrospective dosimetry.

## Evaluation of the FTIR technique for the linearity assessment of commercial soda-lime glass irradiated with gamma radiation

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### Introduction

High dose dosimetry is one of the most important branches of everyday activities related to medical and industrial applications. Nevertheless, the use of materials that respond in a linear manner has advantages over nonlinear materials, since the dose calculation procedure in linear materials relies solely upon direct proportions to the delivered dose. The evaluation techniques are also important to identify the possible linear ranges, and the new Fourier-transform infrared spectroscopy (FTIR) technique has been used to this objective. This work aims to investigate the linearity response and its sensitivity, using mainly the FTIR technique.

### Methods

Cubic samples of a soda-lime glass type with composition of  $\text{Li}_2\text{O} \cdot 0.2\text{B}_2\text{O}_3 + 10 \text{ mol\% of } (0.25\text{Li}_2\text{O} + 0.25\text{La}_2\text{O}_3 + \text{TiO}_2)$  were irradiated with doses from 1 kGy to 12 kGy, using a  $^{60}\text{Co}$  Gamma-Cell system 220. The response was evaluated using the FTIR technique.

### Results

The sensitivity and linearity characteristics were evaluated with the absorbed profiles of the multivariate calibration Partial Least Square Regression (PLSR), with its loadings performing a linear regression; from the slope value, the sensitivity of the glass at the absorbed dose range was obtained. The PLSR technique showed, on the range of 1-12 kGy, that the soda-lime glass type presents linearity value of 0.8532 using just three components. The results of the linearity test were obtained for the FTIR technique.

### Conclusions

The FTIR technique was applied to assess the linear behavior based of the glass spectrum, showing its usefulness to identify possible linear dose regions and also the overall sensitivity of the glass samples to dose. Therefore, the results obtained indicate a good linear response, showing therefore a potential use of this glass-soda lime type for radiation dosimetry in high doses.

## Comparison of doses, secondary particle yields and LET spectra between semiconductor reliability testing using protons and neutrons

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### Introduction

In decades, sizes for the microelectronic device is becoming smaller and smaller, and is becoming more and more sensitive to ionization radiations like protons and neutrons from the cosmic ray. To test its reliability of a semiconductor unit, one can irradiate this sample under a high intensity fast neutron beam and measure the event counts. However, the facility which can provide neutron testing is quite limited and expensive. An alternative plan is using the high intensity proton beam produced by medical accelerators. In this study, we using Monte Carlo simulation to compare doses, secondary particle yields and LET spectra between semiconductor reliability testing using protons and neutrons with some simplified layer outs.

### Methods

GEANT4 10.04.p02 is used to simulate doses, secondary particle yields and LET spectra for both proton and neutron tests for three test scenarios including, 1) blanket silicon, 2) blanket silicon with back-end structure, and 3) blank silicon covered by a thin layer SiGe and back-end structure. The energy selection is based on the reliability testing protocol and the availability of proton facility in Chang Gung Memorial Hospital Proton Center. In each case, the incident particle number is normalized to flux equal to  $10^{10}$  particles/cm<sup>2</sup>. The scoring volume is 100 nm thickness silicon behind the blanket silicon.

### Results

The results from selected energy of neutron from 13.75 MeV to 750 MeV and proton from 63 to 230 MeV have been calculated. For the dose different, in same flux, the proton will give 50-100 times higher dose to the sample. This indicate that proton tests may be more efficient than neutron tests. In addition, the LET spectra in proton tests and neutron tests is similar when incident energy larger than 100 MeV for both particles. This shows the equivalence of testing using both particles. Also the secondary particle yields from proton and neutron tests are also similar.

### Conclusions

In this study, we found that when incident particle energy are higher than 100 MeV for both particles, the LET spectra and secondary particle yields are similar in both neutron and proton. Proton tests is equivalent and more efficient than neutron tests in semiconductor reliability tests.

## Influence of ionizing radiation on photo-thermo-stimulated exoelectron emission spectra of $Gd_2O_3$ nanoparticles and films

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### Introduction

The influence of ionizing radiation on photo-thermo-stimulated exoelectron emission (EE) spectra of gadolinium oxide ( $Gd_2O_3$ ) nanoparticles and films was studied. During the irradiation, electrons can be excited from valence band and trapped in the localized states. The trapped electrons can be released from the localized states by thermal or photo stimulation. The released exoelectrons have low energies, in the order of several eV, and are emitted from a surface layer with thickness less than 10 nm. This makes it promising to use EE to detect radiation doses absorbed in several nanometers thick layers.

### Methods

$Gd_2O_3$  films and nanoparticles (the average diameter 60 nm) were deposited on a dielectric substrate (glass,  $SiO_2$ ) by an extraction-pyrolytic method. The extract, a solution of gadolinium valerate in valeric acid, was deposited on the substrate and the samples were thermally treated (pyrolysis): heated from the room temperature up to 550 °C and annealed for 60 minutes in the atmospheric air. The fabricated samples were exposed to accelerated electrons (5 MeV) and alpha particles (Pu-239,  $\alpha$ -particle energy 5.1 MeV). Photo-thermo-stimulated EE spectra of  $Gd_2O_3$  were measured before and after the irradiation. Photo and thermal stimulation was delivered simultaneously. For the photostimulation, a wavelength close to the photoelectric work function of  $Gd_2O_3$  was used.

### Results

EE spectra of  $Gd_2O_3$  had emission maximum at a temperature around 460 °C after the irradiation with alpha particles. The maxima were absent after the irradiation with accelerated electrons.

### Conclusion

Photo-thermo-stimulated EE is a promising method to detect doses of short-range radiation such as alpha particles absorbed in nano thin layers of  $Gd_2O_3$ .

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## Microdosimetry modelling for evaluation of the therapeutic effect of different radionuclides in various cell and micrometastasis geometries

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### Introduction

To increase the efficiency of short range Auger electrons for cancer treatment, the associated targeting molecules need to be internalized into the cell to increase the biological effect of DNA bond breaking. We study the therapeutic potentials of  $^{177}\text{Lu}$  versus  $^{161}\text{Tb}$  in SkBr3 geometries at different internalization ratios.

### Methods

Image statistics from SkBr3 (breast cancer) 2D cell cultures (Figure 1) was used to calculate cellular self doses and cross doses. The radiation kernel functions were evaluated using Monte Carlo simulations with the EGSnrc/EDKNRC codes [1]. We used minimum and maximum values of internalization as limiting cases and calculated the accumulated dose to the cell nuclei.



Figure 1 Left to right: Section of raw image, cell membranes, whole cell, cytoplasm.

### Results

$^{161}\text{Tb}$  has a larger effect than  $^{177}\text{Lu}$  for any given time after application of radioactivity (Figure 2). The biological parameters used in the standard model for cell survival were  $a = 4$  and  $b = 9$  [2]. For  $^{161}\text{Tb}$  (left hand panel in Figure 3) the contribution to the dose from both the cytoplasm and the cell membrane are dominated by the Auger and conversion modes. Most of the dose from  $^{177}\text{Lu}$  is from the *beta*-modes which deposit energy at a larger distance, and more of the energy is therefore deposited outside the cell layer.

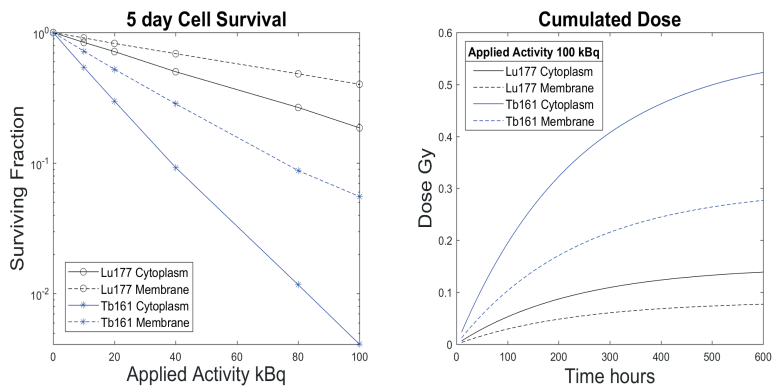


Figure 2 Curves labeled “Cytoplasm” are for 100% internalization, and “Membrane” 0%.

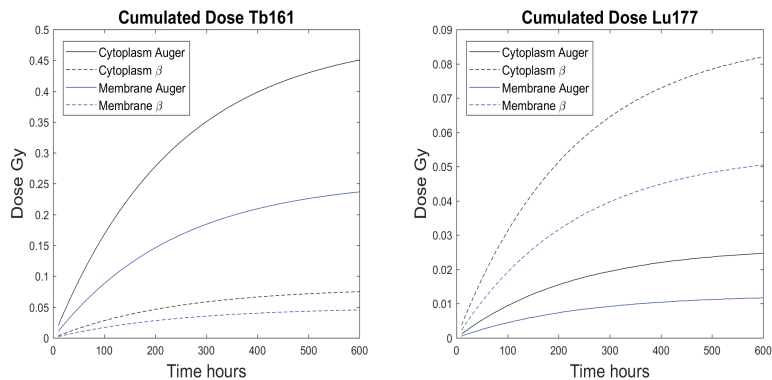


Figure 3 The dose from Auger and conversion electrons (full lines labeled “Auger”), and *beta*-electrons (dashed lines).

Conclusions

For 2D cell distributions,  $^{161}\text{Tb}$  produced a higher cell-nuclear dose than  $^{177}\text{Lu}$ , regardless of the internalization ratio between the cytoplasm and cell membrane.  $^{161}\text{Tb}$  has a higher number of Auger-electrons, and most of the dose from  $^{177}\text{Lu}$  is from the longer-range *beta*-electrons. Thus,  $^{177}\text{Lu}$  can have a larger effect in close packed 3D cell clusters.

[1] Kawrakow I, 2000 *Med. Phys.* 27:499-513  
[2] van Leeuwen CM, et al. 2018 *Radiat Oncol.* 13(1):96

## Silicon photonics for micron-scale dosimetry and calorimetry of industrial and radiotherapy beams

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### Introduction

The past few decades have witnessed exponential growth in the development and adoption of silicon photonics devices as sensors for various scientific applications. Because they can be fabricated at very small (micron) spatial scales and possess excellent sensitivity to changes in temperature and strain of the substrate or host material, they would confer numerous advantages for micron-scale detection of the effects of absorbed dose if the devices were suitably resistant to radiation damage. A recent study<sup>1</sup> demonstrated that such sensors undergo negligible degradation with MGy absorbed dose in ca. 1 MeV gamma- and electron-beam irradiations. We have since conducted preliminary calorimetry measurements with such devices and will report the results of that work here.

### Methods

Micron-scale Bragg waveguides and micro-loop resonators fabricated on silicon chips of ~1 mm thickness were irradiated with ~1 MeV electron beams provided by a Van de Graaff, at nominal dose rates of kGy/s. Interrogation of device response was done with a C-band laser swept over the resonance peak of the sensors, and resonance wavelength was logged as a function of time through multiple 30-s on/off cycles of the electron beam. Device response is compared with the output of finite-element modelling of heat transport and dose measurements obtained by co-irradiated alanine pellets (analyzed via EPR).

### Results

Dose-induced response of irradiated sensors, obtained by time- and frequency-domain techniques, shows good qualitative agreement with finite-element results and with expectations based on alanine measurements. More refined analysis is currently underway.

### Conclusions

Initial results bode well for these devices as a platform for micro-scale dosimetry.

<sup>1</sup>Z. Ahmed, L. T. Cumberland, N. N. Klimov, I. M. Pazos, R. E. Tosh & R. Fitzgerald. Assessing Radiation Hardness of Silicon Photonic Sensors. *Scientific Reports* volume 8, Article number: 13007 (2018) DOI: [10.1038/s41598-018-31286-9](https://doi.org/10.1038/s41598-018-31286-9)



## Measurement of correlations between two nanometric volumes in the track structure of $^{241}\text{Am}$ alpha particles

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Generally, it is assumed that multiple ionisations in a single nanometre-sized site are the most important quantity for the biological effects of radiation. For denser ionising particles, however, the spatial correlation of such ionisation clusters that lead to DNA double strand breaks (DSBs) becomes also important. Two spatially separated DSBs, each of several nanometres in size, can result in the loss of a whole DNA loop. This loop can be of substantial length depending on the geometrical position of the two target volumes and the degree of damage produced in the respective targets by a passing primary particle.

To investigate correlations of ionisations created by the same primary particle in two spatially separated nanometre-sized target volumes, the ion-counting nanodosimeter operated at PTB was upgraded with a 2-d position sensitive detector (PSD). Applying two time windows to the drift time distribution of the target gas ions allows to define two spatially separated target volumes, which are also imaged by the PSD.

The measured quantity is a two-dimensional probability distribution  $P_{n,m}(Q, V_1, V_2)$  that exactly  $n$  ions are created in target volume  $V_1$  and  $m$  ions are created in target volume  $V_2$  for a primary particle of radiation quality  $Q$ . Measurements of correlated ionisation cluster size distributions (ICSDs) were carried out with  $^{241}\text{Am}$  alpha particles in different target gases ( $\text{H}_2\text{O}$ ,  $\text{C}_3\text{H}_8$ ,  $\text{C}_4\text{H}_8\text{O}$ ) for different irradiation geometries. The measurements carried out in a target gas of 1.2 mbar  $\text{C}_3\text{H}_8$  were compared with Monte-Carlo simulations.

The Monte-Carlo simulations agree well with the measurements in 1.2 mbar  $\text{C}_3\text{H}_8$  for the different irradiation geometries. Generally, the product of the cumulative probabilities of the uncorrelated ICSDs  $F_k(V_1) \cdot F_k(V_2)$  is found to deviate from the cumulative probabilities of the correlated ICSDs  $F_{k,k}(V_1, V_2)$  ( $k = 2, 3$ ). However, for a special type of geometries the deviations are only small.

