Module MPE03: Monte Carlo simulations of X-ray imaging and patient dose

ABSTRACT

Title: Monte Carlo simulations of X-ray imaging and patient dose

Module Code: MPE03
Module Level: EQF level 8

Aims:
This course aims at providing the theoretical and practical abilities needed to apply the Monte Carlo simulation of radiation transport to x-ray imaging problems and to effectively use a general-purpose Monte Carlo code in simple situations. The coupling between ionising radiation and visible light, or electron-hole pairs, in conventional x-ray digital detectors will also be addressed.

Learning Outcomes:
At the end of the module the participants will be able to

MPE03.01. Assess the suitability of Monte Carlo algorithms for radiation transport applied to a given practical problem in x-ray imaging.
MPE03.02. Research and assess different Monte Carlo codes to decide the best suited for a particular problem.
MPE03.03. Construct a simplified model of an x-ray transport problem so that it can be efficiently simulated in a computer.
MPE03.04. Evaluate the adequacy of a set of transport parameters of a general-purpose Monte Carlo computer code to obtain simulation results in a reasonable amount of time.
MPE03.05. Design variance-reduction strategies to increment simulation efficiency in practical cases.
MPE03.06. Assess Monte Carlo simulation results and their accuracy to describe x-ray imaging problems.
MPE03.07. Research and critique models for photon, light and charge carrier transport in x-ray detection devices.
MPE03.08. Apply Monte Carlo techniques for patient dose optimisation in imaging techniques.
MPE03.09. Discuss the development of new medical imaging devices based on simulation results.
MPE03.10. Manage a Monte Carlo simulation project from beginning (conceptual modelling) to end (analysis of results).

Date and Location of Face-to-Face Component:
Dates: 15 - 19 june, 2015
Location:
School of Industrial Engineering of Barcelona (ETSEIB), Polytechnical University of Catalonia (UPC)
Av. Diagonal 647, 08028 Barcelona, Spain

Module Leader:
Dr Josep Sempau
Institute of Energy Technologies, Polytechnical University of Catalonia
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J Sempau is senior researcher. His main research topic is the development of Monte Carlo algorithms for the simulation of radiation transport and their application to medical physics. He is co-author of the Monte Carlo codes PENELOPE (https://www.oecd-nea.org/tools/abstract/detail/nea-1525), penEasy (http://www.upc.es/inte/downloads/penEasy.htm), MANTIS (ftp://150.148.3.24/mantis) and DPM (http://www.upc.es/inte/downloads/dpm.htm). His full list of publications can be found here: http://www.researcherid.com/rid/J-7834-2013 . His h-index is 18.

Faculty: Josep Sempau, José M. Fernández-Varea and Aldo Badano. Two invited lecturers are also being considered, although not confirmed yet.

Delivery of the module:
The module will use a combination of online material and face-to-face (f2f) sessions. The f2f part will be over a period of one week (40h), including an exam to assess the learning process. The online phase will be split in two parts, one (20 h) previous to the f2f phase and another one (20 h) after it. The online pre-f2f phase will be mostly asynchronous and based on reading material. The online post-f2f phase will be based on forums intended to discuss advanced exercises and further questions on the use of the simulation codes.

Total participant effort time:
80 hours

Assessment Mode:
Based on an exam with three sections. The first section will be a written exercise. The second and third sections will be practical exercises (with increasing level of difficulty) on the use of the simulation codes presented in the course.

MODULE DATA		
Module Homepage	www.eutempe-rx.eu	
Module Code	MPE03	
Module Leader/s Please limit CV to a max of 250 words and to what is relevant to this module.	Dr. Josep Sempau Institute of Energy Technologies, Polytechnical University of Catalonia (UPC) Av. Diagonal 647, 08028 Barcelona, Spain email: josep.sempau@upc.es J Sempau is senior researcher at the UPC. His main research interests are the development of Monte Carlo algorithms for the simulation of radiation transport and their application to medical physics. He is co-author of several Monte Carlo codes: PENELOPE (https://www.oecd-nea.org/tools/abstract/detail/nea-1525), a general-purpose simulation system for the transport of electron-gamma showers; penEasy (http://www.upc.es/inte/downloads/penEasy.htm), a general-purpose main program for PENELOPE with emphasis on medical physics; MANTIS (ftp://150.148.3.24/mantis), a code that couples PENELOPE/penEasy with a light photon transport code in scintillating structures; and DPM (http://www.upc.es/inte/downloads/dpm.htm), a fast code for the simulation of external beam radiotherapy treatments. His full list of publications can be found here: http://www.researcherid.com/rid/J-7834-2013 . His h-index is 18.	
Teaching Staff Teaching staff should be either recognised MPEs or in possession of a PhD. If not please contact the Secretary of the QAC.	Dr. Josep Sempau (UPC) Dr. José M. Fernández-Varea (Ass. Prof., University of Barcelona) Dr. Aldo Badano (Senior scientist, U.S. Food and Drug Administration) Two invited lecturers are also being considered, although not confirmed yet.	
Candidate Assessment (all assessments open book)	**Written Assessment (open book):**	A 1-hour multiple choice exam.
	Practical Assessment (open book):	A 4-hours session with several practical simulation exercises
Module Duration The TOTAL number of hours of participant effort	**Online phase** Asynchronous methods should be used whenever possible so that	The online component will be split in two parts. The first part will be delivered before the f2f phase with an estimated 20 h reading effort by the participants. This part will be fully asynchronous and will spread, approximately, over a period of 3 weeks. The second part will be held after the f2f phase and will contain an estimated effort of 20 h. This part will be structured as a set of forums to discuss advanced exercises that will have been proposed during the f2f phase.

<table>
<tr><td rowspan="2">should be about 80. (including lectures, reading of assigned compulsory texts, participation in online fora etc)</td><td>participants would not need to take time off their clinical duties and there will not be a problem with time zones. However synchronous methods (evenings or weekends only) should be used when crucial.</td><td></td></tr>
<tr><td>Face-to-face phase

Must include 1 day for revision and 1 day for the assessment proper.</td><td>5 days, including 1 day for assessment and preparation of the online post-f2f phase.

All modules: All learning materials including presentations will be sent to the participants 2 weeks before the first day of the face-to-face phase.</td></tr>
<tr><td>Date and location of Face-to-Face</td><td colspan="2">Barcelona, 15 - 19 june, 2015</td></tr>
<tr><td>Date of Assessment
Normally last day of face-to-face phase.</td><td colspan="2">Last day of the face-to-face phase.</td></tr>
<tr><td rowspan="9">Breakdown of participant effort time</td><td>Module Component</td><td>Estimated Time</td></tr>
<tr><td>Online lectures, seminars, tutorials, fora</td><td>20 hours</td></tr>
<tr><td>Online compulsory reading</td><td>20 hours</td></tr>
<tr><td>Face-to-face lectures, seminars, tutorials, fora</td><td>15 hours</td></tr>
<tr><td>Face-to-face exercises/ practical sessions</td><td>25 hours</td></tr>
<tr><td>Face-to-face laboratory/clinical exercises</td><td>0 hours</td></tr>
<tr><td>Total participant effort time</td><td>80 hours</td></tr>
<tr><td>Free day for exam preparation day (same for all modules)</td><td></td></tr>
<tr><td>1 day for assessment (same for all modules)</td><td>1 day</td></tr>
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PRE-REQUISITES FOR THE MODULE	
Minimum entry qualifications, training and years of experience for *all* modules Same for all modules	EQF Level 6 in Physics (BSc Physics or equivalent) EQF Level 7 in Medical Physics (MSc Medical Physics or equivalent) 2 year equivalent clinical training in D&IR for clinical Medical Physicists 2 year equivalent Industry/Radiation Authority experience for Industry/Radiation Authority personnel.
Assumed previous KSC for *all* modules from the 'Inventory of Learning Outcomes for the MPE in Europe' (Annex I of the 'European Guidelines on the MPE') Same for all modules	GENERIC SKILLS : Generic Skills Required at EQF level 7 KSC FOR THE MPE AS PHYSICAL SCIENTIST: All Knowledge learning outcomes to EQF level 7 KSC FOR THE MPE AS A HEALTHCARE PROFESSIONAL: All Knowledge learning outcomes to EQF level 7 KSC FOR THE MPE AS EXPERT IN CLINICAL MEDICAL RADIOLOGICAL DEVICES & RADIATION PROTECTION: All Knowledge learning outcomes to EQF level 7 KSC SPECIFIC FOR THE MPE IN DIAGNOSTIC & INTERVENTIONAL RADIOLOGY: All Knowledge learning outcomes to EQF level 7 The Skills and Competences included in the IAEA document 'Clinical Training of Medical Physicists Specializing in Diagnostic Radiology' (IAEA Training Course Series, 47, 2010) to EQF level 7.
Pre-requisite EUTEMPE-RX online summary modules for *all* modules	MPE01 Development of the profession and the challenges for the MPE (D&IR) in Europe (online summary version accessible to all participants in all courses)
Additional pre-requisite EUTEMPE-RX online summary modules for *this* module Different for each module.	None required

MODULE CONTENT: AIM and SUMMARY LEARNING OUTCOMES	
Aim	The Monte Carlo (MC) method is widely regarded as the state of the art in radiation transport calculations. It is desirable to provide medical physics experts with the abilities required to understand the fundamentals of the method and the details of its application in clinical cases. This course aims at fulfilling this need. More precisely, this course aims at providing the theoretical and practical abilities needed to apply MC simulation to x-ray imaging problems and to effectively use a general-purpose Monte Carlo code in simple situations. The coupling between ionising radiation and visible light, or electron-hole pairs, in conventional x-ray digital detectors will also be addressed.
Learning Outcomes (10 – 15 learning outcomes which provide an overview of the KSC addressed in the module)	MPE03.01. Assess the suitability of Monte Carlo algorithms for radiation transport applied to a given practical problem in x-ray imaging. MPE03.02. Research and assess different Monte Carlo codes to decide the best suited for a particular problem. MPE03.03. Construct a simplified model of an x-ray transport problem so that it can be efficiently simulated in a computer. MPE03.04. Evaluate the adequacy of a set of transport parameters of a general-purpose Monte Carlo computer code to obtain simulation results in an reasonable amount of time. MPE03.05. Design variance-reduction strategies to increment simulation efficiency in practical cases MPE03.06. Assess Monte Carlo simulation results and their accuracy to describe x-ray imaging problems. MPE03.07. Research and critique models for x-ray, light and charge carrier transport in imaging devices. MPE03.08. Apply Monte Carlo techniques for patient dose optimisation in imaging techniques MPE03.09. Discuss the development of new medical imaging devices based on simulation results MPE03.10. Manage a Monte Carlo simulation project from beginning (conceptual modelling) to end (analysis of results)

MODULE CONTENT: TARGET KSC TO BE DEVELOPED TO EQF LEVEL 8 From the 'Inventory of Learning Outcomes for the MPE in Europe' (Annex I of the 'European Guidelines on the MPE')	
KSC targeted in *all* modules These learning outcomes are common to and permeate *all* modules, although to a varying degree according to the topic of the module.	GENERIC SKILLS : All 'Generic Skills Required at EQF level 8' KSC FOR THE MPE AS PHYSICAL SCIENTIST: All Skills and Competences to EQF level 8 KSC FOR THE MPE AS A HEALTHCARE PROFESSIONAL: All Skills and Competences to EQF level 8 KSC FOR THE MPE AS EXPERT IN CLINICAL MEDICAL RADIOLOGICAL DEVICES & RADIATION PROTECTION (AND OTHER PHYSICAL AGENTS AS APPROPRIATE): All KSC for Scientific Problem Solving Service to EQF level 8 KSC SPECIFIC FOR THE MPE IN DIAGNOSTIC & INTERVENTIONAL RADIOLOGY: All KSC for Scientific Problem Solving Service to EQF level 8
***PRIMARY KSC* targeted in *this* module** These are the KSC which would be developed to Level 8 during this module. These should be mostly Skills and Competences. However, Knowledge learning outcomes should also be included when the knowledge normally acquired during Level 7 programmes is insufficient for the development of the skills and competences to level 8. The KSC codes from the 'European Guidelines on the MPE' should be inserted for easy reference.	**KSC FOR THE MPE AS A PHYSICAL SCIENTIST** K22. Explain quantitatively the following characteristics of ionizing radiation sensors / detectors: pulse height spectrum and energy resolution, counting curves and plateau, detection efficiency and energy response, dead time, detection threshold and temporal resolution. K35. Explain quantitatively and in detail the interactions of ionising and non-ionising electromagnetic radiations, particulate radiation, ultrasound, static electric and magnetic fields with inanimate and animate matter (including energy absorption/deposition), K41. Explain the statistics of nuclear decay, photon / particle interactions with matter and ionizing radiation measurement. K42. Explain the principles of modelling and simulation including statistical modelling based on Monte-Carlo techniques. **KSC FOR THE MPE AS EXPERT IN CLINICAL MEDICAL RADIOLOGICAL DEVICES & RADIATION PROTECTION (AND OTHER PHYSICAL AGENTS AS APPROPRIATE)** K33. Explain the fundamental characteristics and limitations of the various models / algorithms used in the quantification of patient doses from external sources of ionising radiation. S1. Apply the general concepts, principles, theories and practices of physics to the solution of clinical problems concerning the optimised clinical use of medical devices and safety / risk management with respect to associated ionizing radiations and other physical agents.

	S10. Interpret the results of dosimetry measurements. S29. Use appropriate physical / software test objects / phantoms, data acquisition protocols, data recording forms, national / European / international protocols to measure the performance indicators of medical devices in own area of medical physics, assess deviations from acceptable values (as indicated by manufacturer and international / European / national standard setting bodies), evaluate the relevance of deviations for clinical practice and suggest actions for restoring default performance. S34. Analyze the medical devices used in own area of medical physics practice and investigate their design, functioning, associated signal / image processing, safety features, typical specifications and performance indicators. C3. Take responsibility for applying the general concepts, principles, theories and practices of physics to the solution of clinical problems concerning the optimal use of medical devices and management of risk from associated ionizing radiations and other physical agents in own area of medical physics practice. C11. Take responsibility for dosimetric investigations and the supervision of dosimetry measurements. **KSC SPECIFIC FOR THE MPE IN DIAGNOSTIC & INTERVENTIONAL RADIOLOGY** K13. For each imaging modality, define and explain device performance indicators relevant to image quality outcomes (e.g., limiting spatial and contrast resolutions, SNR, geometric accuracy) including discussion of accuracy, precision and stability. K14. For each imaging modality, explain the relationship between target image quality outcomes and imaging device performance indicators. K22. For each imaging modality, explain device design variables which impact device performance indicators (e.g., focal spot size in the case of x-ray imaging). K23. For each imaging modality, explain user controlled variables/settings and their impact on image quality/diagnostic efficacy and patient risk. K26. For each imaging modality, explain differences in device design and their effects on image quality and patient safety for dedicated devices (e.g., mammography, dental systems for projection x-ray imaging). K27. Explain in detail x-ray projection and CT imaging devices for general projection x-ray imaging (DDR, CR and film-screen where this is

	still valid), chest systems, mammography (including tomosynthesis), dental systems (intra-oral, OPG, cephalometric systems), mobile, dual energy projection x-ray imaging, flat panel/image intensifier/mobile/over/under table fluoroscopes and C-arms, interventional systems, paediatric systems, radiostereometric (RSA) systems, stereotactic / biopsy systems (e.g., mammography), dual energy X-ray absorptiometry (DXA), sequential/axial and helical mode CT, multidetector CT, dual source/energy CT, volumetric CT scanners, CT scanners for radiotherapy planning, CT fluoroscopy and cone-beam CT, K28. Define and explain the effect of variation of the following performance indicators on image quality in projection x-ray imaging (spatial resolution, contrast resolution, contrast to noise ratio, point spread function, modulation transfer function, noise power spectrum, detective quantum efficiency, noise equivalent quanta). K52. For each imaging modality define patient safety /dosimetry related indicators/quantities S1. For each modality, operate imaging devices at the level necessary for give advice on optimization of imaging protocols, quality control, image quality manipulation, and carry out research when the available evidence for advice is not sufficient. S2. For each modality predict the effect on image quality and diagnostic accuracy when changing scanning and reconstruction parameters. S3. Manipulate acquisition parameters for all forms of projection x-ray imaging devices (e.g., kV, filtration, mAs, sensitivity ('speed'), collimation, magnification, SID, SSD, frame rate, screening time, manual/AED modes, compression), explain the effect on image quality and relevant patient dose quantities (and occupational dose particularly when this is correlated with patient dose) and relevance to specific clinical studies. S4. Manipulate acquisition parameters for all forms of CT imaging (e.g., kV, bowtie filter, mA, rotation time, tube current modulation, noise index, pitch, collimation, scanned field of view, slice thickness, beam collimation, over beaming, over scanning), explain the effect on image quality and relevant patient dose quantities (and occupational dose particularly when this is correlated with patient dose) and relevance to specific clinical studies. S11. Use modelling and simulation software (e.g. Matlab, SimuLink) to solve problems in the processing of imaging data. S12. For each imaging modality, identify and carry out appropriate patient / occupational / public safety related dosimetric measurements and calculations. S14. For each imaging modality, select appropriate phantoms/phantom materials for dosimetry. S15. Use specialized dosimetry software / conversion coefficients to calculate effective doses and organ absorbed doses from dosimetry

	measurements. S25. Evaluate imaging device performance for each imaging modality, from the measurement of suitable performance indicators using suitable test objects / phantoms. S35. For each imaging modality, manipulate acquisition parameters (e.g., tube voltage, filtration, contour filters, tube current, exposure time, field size, magnification in projection x-ray imaging) to optimize image quality and patient dose. S36. For each imaging modality, explain the effect of operator selectable parameters on image quality and hence clinical utility. S41. For each imaging modality identify and correct causes of below target image quality and safety criteria. S43. For each modality recognize, explain and give advice regarding image artefacts. C4. For each imaging modality, take responsibility for the measurement of appropriate patient / occupational / public safety related dosimetric monitoring quantities. C19. For each imaging modality, give advice regarding the adjustment of protocols to the needs of particular clients in studies which are complex, unusual, beyond-protocol and non-predictable.
***SECONDARY KSC* targeted in *this* module** (EQF Level 8) These are the KSC that are included in the module but would be given less attention owing to time constraints. Please insert the KSC code from the 'European Guidelines on the MPE' project KSC Inventory.	**<u>KSC FOR THE MPE AS A PHYSICAL SCIENTIST</u>** K8. Explain nuclear and electron energy levels, ionization, nuclear isomers and the auger effect. K33. Explain quantitatively and in detail the properties and means of production and control of ionising and non-ionising electromagnetic radiations, particulate radiation beams and ultrasound including the characteristics of the radiation fields in both air and tissue. K34. Distinguish between ionising radiations with a direct or indirect mechanism for energy transfer and deposition. K37. Discuss the characteristics of the common statistical distributions: normal, log-normal, t, Poisson. S1. Manage the acquisition, editing, analysis, interpretation, presentation, and reporting of measurement data.

	<u>KSC FOR THE MPE AS EXPERT IN CLINICAL MEDICAL RADIOLOGICAL DEVICES & RADIATION PROTECTION (AND OTHER PHYSICAL AGENTS AS APPROPRIATE)</u> K9. Define patient dosimetric quantities for each clinical procedure in own area of medical physics practice and explain the method used for their measurement / calculation. K10. Explain the relationship between the various dosimetric quantities used (e.g., between energy fluence, kerma and absorbed dose for photon beams including the concept of charged particle equilibrium). K31. Define the radiation dosimetry quantities used in patient risk assessment and their use in the radiation protection of patients. K44. Define and measure or calculate the operational quantities (including units and inter-relationships) used in personal dosimetry in own area of medical physics practice (e.g., ambient, directional and personal dose equivalents at recommended depth, annual limit on intake, derived air concentration). S9. Develop rigorous dosimetry protocols in own area of medical physics practice. S13. Convert dosimetry quantities measured in air or other medium to relevant dosimetric quantities in tissue. **<u>KSC SPECIFIC FOR THE MPE IN DIAGNOSTIC & INTERVENTIONAL RADIOLOGY</u>** K4. Explain in detail the principles of image quality measurement: linear systems theory, types of contrast (subject, image and display), unsharpness (LSR, PSF, LSF, MTF), lag, noise (including sources, noise power spectra, effect of lag on noise, noise propagation in image subtraction), SNR (including Rose model, Wagner's taxonomy, CNR, relation to dose, NEQ, DQE, NPS etc).
***NEW KSC* which are NOT** INCLUDED in the 'Inventory of Learning Outcomes for the MPE in Europe'.	Snn. Operate a general-purpose Monte Carlo code efficiently for simple simulation problems. Snn. Describe in detail how Monte Carlo simulations of x-ray detectors can be used to extract information on the performance of imaging devices. Snn. Relate data obtained from Monte Carlo simulations with image performance indicators.

OUTLINE TEACHING PLAN	
Online phase	We propose to split the online phase in two parts. The first part, held before the face2face phase, will basically consist in a series of readings on the topics below. A preliminary list of topics is the following: 1. General aspects on the Monte Carlo method applied to radiation transport 2. Physics and physics models used to describe the interactions of photons and electrons with matter 3. Selected topics on the use of the PENELOPE code (a widely known general purpose Monte Carlo for radiation transport) 4. Modelling of kV x-ray units During the online part held after the face2face, participants will be invited to solve more advanced exercises. Several forums will be organised to discuss the solution to these exercises and to answer questions related with all the material distributed during the course.
Face-to- Face Phase	The preliminary syllabus of the face2face phase is included below. ---------- DAY 1 0. Welcome 1. Monte Carlo simulation of radiation transport 1.1 The Monte Carlo method 1.2 Radiation transport Break & revision 1.3 Variance-reduction techniques 2. Photon and electron EM physics 2.1 Photon interactions 2.2 Electron interactions 2.3 Condensed simulation 2.4 General-purpose simulation codes 3. The PENELOPE/penEasy system 3.1 Distribution, structure and operation 3.2 Material data files

	---------- DAY 2 3.3 Quadric geometries Break & revision 3.4 Voxelised geometries 3.5 Triangle mesh geometries 4. penEasy exercises 4.1 Computation of absorbed dose distributions 4.2 Spectrometry ---------- DAY 3 4.3 X-ray tube & image formation Break & revision 4.4 Dose distribution in voxels 5. Physics of imaging detectors 5.1 Scintillators 5.2 Semiconductors 5.3 Imaging metrics: Swank, MTF, NPS, DQE 5.4 Photon counters 5.5 Imaging simulation codes Discussion & revision ---------- DAY 4 6. The MANTIS family of codes 6.1 Distribution, structure and operation 6.2 Material data files 6.3 Geometry definition Break & revision 6.4 Outputs 6.5 Demos and applications 7. Other applications 7.1 Invited lecture 1

	7.2 Invited lecture 2 Candidates (not contacted yet): Kristina Bliznakova David Dance (Guildford group, breast dosimetry) Michael Ljungberg (Lund, SIMIND code) Discussion & revision ---------- DAY 5 Exam part I (Theory) Exam part II (Exercises) Prepare online post phase