To cite this article: Sébastien Incerti 2014 Phys. Med. Biol. 59 7565

View the article online for updates and enhancements.
Monte Carlo simulations are widely used for the simulation of particle-matter interactions. Among all software available today, the Geant4 Monte Carlo simulation toolkit (Agostinelli et al 2003, Allison et al 2006) is the fourth version of the GEANT series of simulation software (GEANT stands for GEometry ANd Tracking), which was initiated at the European Organization for Nuclear Research (CERN, Switzerland) in 1974, 40 years ago. Unlike its predecessors, Geant4 adopted object-oriented programming technology (C++) and was initially designed for High Energy Physics applications, in particular for the simulation of the Large Hadron Collider (LHC) ATLAS and CMS experiments, which recently observed the Higgs boson (ATLAS Collaboration 2012, CMS Collaboration 2012). Thanks to this object-oriented technology, the application domain of Geant4 progressively and naturally broadened toward other fields requiring particle-matter simulations, such as space science (Ivanchenko 2004) and medical physics (Carrier et al 2004). Today, the Geant4 toolkit is developed by an international collaboration and the Geant4 team closely interacts with experts in those application domains.

The ‘Geant4 2013 International User Conference at the Physics-Medicine-Biology frontier’ (http://geant4.in2p3.fr/2013) is the second conference organized in France aimed at gathering Geant4 users and Geant4 developers for applications in medical physics and radiobiology. The conference took place at the Mercure Château Chartrons conference hotel in Bordeaux, from 7–9 October. It was followed by a 2 d Geant4 tutorial for beginners focused on medical physics, consisting of a variety of lectures on recent developments (see for example (Ivanchenko et al 2014)) as well as practical hands-on experience on a dedicated Geant4 Virtual Machine (http://geant4.in2p3.fr), taught by Geant4 collaboration members (Incerti, Ivanchenko, Maire). A total of 105 participants were registered to the conference, attracting an impressive number of young researchers. The first Geant4 International User Conference at the Physics-Medicine-Biology frontier took place at the exact same location almost 10 years ago, on November 3–5, 2005 (http://geant4.in2p3.fr/2015). That was the first time that such a conference exclusively focused on Geant4 and its applications at the Physics-Medicine-Biology frontier proposed to conference participants the possibility of publishing their presented work in the Physics in Medicine & Biology journal. The conference was organized in seven sessions in order to cover all research activities presented by attendees, underlining the large variety of applications of the Geant4 toolkit in medical physics as well as its capabilities at different size and energy scales: medical imaging, classical and targeted radiotherapy, proton therapy, hadron therapy, instrumentation, radiobiology, and finally computing.
The medical imaging session first introduced the development of new Geant4 advanced electron ejection directionality models for low energy incoherent photon processes, undertaken by Brown et al in the global on-going effort of improving Geant4 physics accuracy. Then El Bitar et al described a successful evaluation of Geant4’s potential for the simulations of intrinsic point spread functions in pinhole Single Photon Emission Computed Tomography (SPECT) imaging, as an alternative to experimental measurements. They also presented a Geant4 based factorized system matrix—one of the key elements required for image reconstruction in pinhole SPECT (El Bitar et al 2014)—allowing them to reach acceptable computing times for clinical routine applications. Also in SPECT imaging, Garcia et al described an efficient method of generating images in reasonable computation times and with sufficient statistics, using 3D compartmental modelling of a patient’s anatomy and the GATE code. Cone-Beam Computed Tomography (CBCT) was later presented by Rit et al proposing a hybrid Geant4 based Monte Carlo/deterministic algorithm for scatter correction which shows better performance than pure Monte Carlo simulations. McNamara et al (2014) demonstrated using Geant4 the possibility of significantly improving image sensitivity and resolution in Positron Emission Tomography (PET), especially for high photon emission rates, by taking into account the polarization correlation of the photon pairs. Finally, Huet et al showed highly realistic simulations of patients with atherosclerotic lesions using GATE; these simulations are included in a database, which will be used to develop quantification methods for plaque imaging.

The radiotherapy session started with presentations dedicated to the modelling of specific classical radiotherapy setups and equipment. First, Rached et al showed depth-dose simulations based on Geant4 for MV photons. Brochu et al (2014) presented the Geant4 simulation of the Elekta™ XVI Cone Beam Computed Tomography machine and its experimental validation, as well as 3D dosimetry, in the context of Image Guided Radiotherapy (IGRT). Using GATE, a complete and detailed description of a Siemens ONCOR™ 160 MLC Linac with its Mega Voltage—CBCT flat panel imaging detector has been modelled by Benhalouche et al for imaging, dose calculation and reconstruction. Casarino et al introduced the integration of DICOM images into the recent Geant4 ‘iort_therapy’ advanced example dedicated to the simulation of Intra-Operative Electron Radio-Therapy and discussed its deployment on a computing grid. On a similar topic, Bouzid-Jnah et al proposed a simulation of the Intrabeam™ system based on GATE, showing good agreement between patient dosimetry data and simulations. Pipek et al (2014) presented a flexible modular Geant4 model of the Leksell GammaKnife Perfexion™ that showed good agreement with other calculations and experimental data. A Geant4-based Helical Tomotherapy unit model developed by Esposito and colleagues showed nice agreement between simulated doses and experimental data. On the experimental side, Gobet et al measured the absolute energy distribution of the direct electron beam produced by a Varian 21Ex™ accelerator using a magnetic spectrometer and comparison with Geant4 simulations allowed the characterization of the beam source for Monte Carlo simulations of particle fluences in treated patients. Going on to internal dosimetry, Marcatili et al (2014) presented a hybrid multi-resolution model for Geant4 allowing a better characterization of energy deposition in small structures, maintaining reasonable computation times and using different voxel granularity, in the context of radiopharmaceutical dosimetry in clinical and preclinical settings. The same team, Villoing et al, also described the intercomparison of GATE and the Monte Carlo code MCNPX on the ICRP/ICRU female reference computational model for internal dosimetry aspects; they showed a very good agreement between both codes, underlining the relevance of GATE for radiopharmaceutical dosimetry. In brachytherapy, Landry et al successfully presented the combination of the layered mass geometry technique and the use of tetrahedral meshes for Geant4 brachytherapy.
applications where conventional techniques were found to be limiting. Also in brachytherapy, Lemaréchal et al presented a full Graphical Processing Units (GPU) Monte Carlo simulation based on Geant4, using a hybrid navigator dedicated to brachytherapy applications, going beyond the TG43 formalism and demonstrating a great potential for clinical practice. Finally, the session ended with a presentation by Oliveira et al who introduced the Quimera treatment planning system for radiotherapy, based on Geant4 and on parallel computing for fast phase space generation and dose calculation.

The third session was dedicated exclusively to proton therapy. Perl et al presented the status of the promising TOPAS Monte Carlo system; TOPAS simulations have matched experimentally measured spread out Bragg peaks and dose profiles well within clinical accuracy and this system is now used by almost 100 users in the world. Then, the same team, Fadeegon and colleagues, showed precise measurements performed on a proton beam with well known energy and accurate knowledge of the beam line components which can be used for benchmarking Monte Carlo systems. On the patient side, Giacometti et al demonstrated the implementation of a high resolution and detailed digital head phantom in Geant4 for Intensity Modulated proton Radiation Therapy and Computed Tomography. Janssen et al used TOPAS to investigate the correlation between prompt gamma emission from nuclear interactions and the range of protons inside the patient’s body, underlining the necessity of carefully taking into account tissue properties. Mueller and colleagues presented Geant4 simulations and corresponding experimental validation of prompt gamma emission during proton irradiation for in-beam SPECT based in vivo dosimetry as an alternative to PET. Hälg et al presented neutron dose characterization from measurements and Geant4 simulations in the context of pediatric proton therapy, studying in particular the influence of the phantom material. Regarding specific irradiation setups, the National Cancer Center team in the Republic of Korea (Jeong et al) presented Geant4 simulations of a beam nozzle model for proton therapy and found good agreement with Gafchromic™ film measurements. Regarding laser generated beams, Cirrone et al showed the simulation of an Energy Selection System obtained with Geant4 for laser accelerated proton beam lines at the Laboratory Nazionali del Sud (LNS) in Catania, Italy; these simulations can be used for the design of transport elements as well as detectors for dosimetry, in the context of the ELIMED project (MEDical and multidisciplinary applications at Extreme Light Infrastructure beam lines). Finally, more on the computing side, Garrido et al presented the implementation on a GPU of Geant4 processes for proton therapy simulations showing very significant acceleration factors of computing time for proton processes.

This session was followed by a session dedicated to hadron therapy. Regarding Geant4’s models accuracy, Agodi et al (De Napoli et al 2014) presented the first validation of Geant4 nuclear reaction models (Binary Intra-nuclear Cascade—BIC—and Quantum Molecular Dynamics—QMD—) against fragmentation data on thin and thick tissue equivalent targets obtained at the LNS, for their use in hadron therapy simulations. In the same spirit, Dudouet and colleagues showed 95 MeV/u Carbon fragmentation data measured for several target materials at the Grand Accélérateur National d’Ions Lourds (GANIL) in Caen, France, and compared them to Geant4 models: BIC, QMD and Liège Intra-Nuclear Cascade (INCL) for entrance channels, coupled to either the Generalized Evaporation Model (GEM) or Fermi Break-Up (FBU) models for the exit channel. Then, two groups presented the modelling of hadron therapy beam lines. Rimoldi et al presented a Geant4 simulation of the beam line active/passive components for treatment of ocular tumours at the CNAO, the National Center for Oncological Treatment (Pavia, Italy). Sefl et al simulated with Geant4 the carbon beam line at the Heavy Ion Medical Accelerator in Chiba, Japan; simulations were compared to track-etched detectors measurements (LET, depth dose). Regarding quality assurance in
hadron therapy, Martinez-Rovira and colleagues discussed the influence of the biological washout process for dose quantification in carbon therapy treatments by means of PET, using the GATE platform, and concluded accurate models and further measurements are necessary. Based on benchmarked Geant4 simulations, Pinto et al (2014) presented the design optimization of a time-of-flight based collimated camera prototype for online hadron therapy monitoring; they were able to reach a 1 mm ion-range position resolution. Regarding the development of new therapy approaches, a Geant4 simulation of the use of gold nanoparticles in hadron therapy was presented by Belamri and colleagues, a hot topic in medical physics. Fois et al introduced the concept of dose spatial fractionation in hadron therapy, based on GATE simulations, a promising approach for sparing healthy tissues. In addition, let us note the interesting talk (but for protons) by Cortes-Giraldo et al; they performed a critical comparison of dose-averaged LET calculation methods for clinical proton beams and made a recommendation for the unrestricted LET calculation in comparison to dose-mean lineal energy in microdosimetry.

The following session was dedicated to instrumentation. Gueye introduced the low energy electron accelerator facility (LELIA), which will be capable of delivering beams up to 20 MeV and is currently in construction at Hampton University, VA, USA. In particular, polarized electron beams will be available. Further investigation of fundamental processes as well as extension/validation of Geant4 models is foreseen. Then, Blake and colleagues presented the characterization of optical photon transport using Geant4 in novel electronic portal imaging devices incorporating water-equivalent plastic scintillators fibres for dosimetry in MV photon beams. Also, about the simulation of optical photon transport in plastic scintillation detectors, Nilsson et al identified the two most influencing parameters (the surface finish and the reflectivity) using the GATE platform. Two new specific Geant4-based codes were then presented. Dietz-Laursonn and colleagues created the GODDeSS (Geant4 Objects for Detailed Detectors with Scintillators and Silicon photomultipliers) Geant4-based simulation tool, which provides many functionalities for an easier modelling of scintillator tiles with silicon photomultipliers readout; this tool is suitable for multi-scale detector design and optimization in astroparticle physics, accelerator-based high energy particle physics as well as medical physics. Finally, Martin et al introduced a new field of application for Geant4 simulations, paleo-dosimetric datation, allowing a more accurate calculation of dose rate required for the dating of archaeological objects, such as sedimentary grains of quartz, heated flints, or teeth. The simulation requirements for this field are similar to medical physics’.

The session dedicated to radiobiology presented the largest number of talks, in particular for applications related to the Geant4-DNA project (Incerti et al 2010a 2010b). During the session, Geant4-DNA radiolysis simulation capabilities were presented (Karamitros et al 2014), a key requirement for the simulation of non-direct DNA damage, as well as a short review of existing models for the simulation of chemical kinetics. Then, Stepan and colleagues presented the coupling of Geant4-DNA simulated track structures with the RADAMOL code in order to describe radiation action on short DNA plasmids in liquid water, taking into account both scanvengerable and non-scanvengerable DNA damage pathways. Regarding geometries of biological targets, Villagrassa et al showed the implementation of a high granularity DNA geometrical target combined with Geant4-DNA physics for direct clustered damage quantification; they also introduced the BioQuaRT project aimed at developing a multi-scale simulation platform for biological damage evaluation. Using Geant4-DNA, Francis et al (2014) presented the nanometric transport of 400 MeV amu$^{-1}$ Carbon beam fragmentation products in liquid water, generated using Geant4 fragmentation (QMD) and analyzed the biological effects of fragments using the DBSCAN clustering algorithm. Also on geometries, Poole and colleagues proposed a technique for deriving morphologically
3D geometries of cells obtained from 2D confocal microscopy images, allowing an evaluation of the morphology influence on doses to cells in radiotherapy, still poorly investigated. The Hampton U group first presented (Gills et al) a study of the correlation between physical processes in liquid water simulated with Geant4-DNA and DNA damage for monoenergetic electrons. They (Black et al) also simulated with Geant4 the energy deposition in liquid water from polarized and un-polarized electron and photon beams, suggesting further studies for a possible use of polarized beams. Arnaud et al presented dosimetric calculations at the cell scale for Auger radionuclide emitters using Geant4-DNA physics processes, combined with a realistic cell geometry and source distribution, obtained from immunofluorescence imaging with a confocal microscope. Shin et al presented a simplified geometrical model of DNA including Adenine, Thymine, Guanine and Cytosine materials, which could be coupled with Geant4-DNA physics processes for DNA breakage simulation in proton therapy. Scarpetelli and colleagues (Lin et al 2014) at the Massachusetts General Hospital in Boston, USA, presented the quantification of proton dose enhancement resulting from the use of gold nanoparticles (GNPs), combining Geant4 and Geant4-DNA simulations, and they suggested possible biological effects in very close proximity to the GNPs. Regarding coupling to other codes or models, Romano and colleagues presented an extension of the Geant4 ‘hadrontherapy’ advanced example capable of predicting Relative Biological Effect as a function of depth for specific cell lines and incident ions; coupling Geant4 with the Local Effect Model, it becomes possible to calculate cell survival fraction as well as biological dose. Burigo and colleagues on their side coupled their Geant4-based Monte Carlo model for Heavy-Ion Therapy (MCHIT) code with a modified version of the Microdosimetric Kinetic (MK) model allowing the calculation of microdosimetry spectra and RBE estimation as a function of depth in water; in addition, they suggested interestingly that helium and lithium beams could be promising options for ion-cancer therapy. Casiraghi et al presented simulations of experimental nanodosimetric quantities such as ion cluster size distributions in water (with Geant4-DNA) and low-pressure propane gas (with the PTra code) for applications in Mixed-Field Radiation Therapy (MFRT). These results are expected to be relevant for radiation therapy with protons and ions, where mixed radiation fields are present. Regarding non-targeted effects, Kuncic and colleagues presented Geant4 simulations of targeted microbeam irradiation of a realistic cell cytoplasm; their results corroborated the emerging view that ionizations inflicted on key organelles such as mitochondria, are critical to bystander responses. Finally, Pham et al showed the integration of Geant4-DNA physics into the GATE platform; this was illustrated by the presentation of simulated direct DNA damage in biological targets, including a di-nucleosome implemented from the Protein Data Bank, in a global attempt to extend the GATE platform for multi-scale simulation of ionizing radiation effects.

The last session was dedicated to computing aspects. Borys et al presented a graphical user interface (‘what you see is what you get’) for Geant4 based on an extension of the Blender software, allowing Geometry Description Markup Language export. Poole and colleagues presented a cached parameterisation technique for navigating in Geant4 replicated geometries that are larger than memory. This is particularly useful when working with geometrical models of biological tissues made of many cells. The last three presentations were focused on the GATE platform. First, Smekens et al proposed two variance reduction techniques based on the kerma approximation: the track length estimation method and a hybrid simulation for voxelized geometries combining Monte Carlo splitting and an exponential track length estimation method, both showing significant gain in computing time. Then Bert et al presented the development of a hybrid GPU/CPU approach for the main medical physics applications currently supported by the GATE software. Considering photon transport in voxelized phantoms, they reported significant acceleration factors for PET, CT, optical and radiotherapy simulations.
Finally, Gaens et al further extended the GPU framework of GATE in order to perform scatter correction for the Siemens™ MR-BrainPET, including detector response description; they also reported computing time acceleration compatible with clinical use.

The talks presented at the conference and the papers presented in this selection give a recent overview of Geant4 and associated tools capabilities in medical physics. We expect they will be useful to the community and will encourage the organization of regular future events around Geant4 and its on-going developments at the Physics-Medicine-Biology frontier.

We would like to express our deep gratitude to colleagues at the Centre d’Études Nucléaires de Bordeaux-Gradignan, who have very kindly contributed to the preparation of this conference: Philippe Barberet, Guillaume Dévès, Nathalie Favret, Isabelle Moreau, Philippe Moretto, Sylvie Perrève, Gladys Saez, Catherine Seznec and Hervé Seznec. We also thank the conference International Scientific Committee members for their suggestions, in particular the kind support of Frank Verhaegen, and also John Allison from the Geant4 collaboration. We are indebted to the IOP Publishing staff and to the reviewers of all submitted papers for their time, dedication and kindness. We also would like to thank our funding institutions and partners: the Centre d’Études Nucléaires de Bordeaux-Gradignan (CENBG), the Centre National de la Recherche Scientifique (CNRS) and the Institut National de Physique des Particules et de Physique Nucléaire (IN2P3), the University of Bordeaux and its Initiative d’Excellence (IdEx), the Conseil Régional d’Aquitaine, the Institut Bergonié and the Fonds Européen de Recherche et Développement Régional (FEDER), the Groupement de Recherche « Modélisation et Instrumentation pour l’Imagerie Biomédicale » and the Geant4 Collaboration. Finally, and above all, we would like to thank all authors and conference participants for sharing their exciting results with the community in a friendly spirit.

References

Brochu F et al 2014 Geant4 simulation of the elekta XVI kV CBCT unit for accurate description of potential late toxicity effects of image-guided radiotherapy Geant4 2013 Int. User Conf. at the Physics-Medicine-Biology Frontier
Carrier J F, Archambault L, Beaulieu L and Roy R 2004 Validation of GEANT4, an object-oriented Monte Carlo toolkit, for simulations in medical physics Med. Phys. 31 484–92
De Napoli M et al 2014 Nuclear reaction measurements on tissue-equivalent materials and GEANT4 Monte Carlo simulations for hadrontherapy Geant4 2013 Int. User Conf. at the Physics-Medicine-Biology Frontier
Francis Z et al 2014 Carbon ion fragmentation effects on the nanometric level behind the Bragg peak depth Geant4 2013 Int. User Conf. at the Physics-Medicine-Biology Frontier
Incerti S et al 2010b Comparison of GEANT4 very low energy cross section models with experimental data in water Med. Phys. 37 4692–708


McNamara A et al 2014 Towards optimal imaging with PET: an in silico feasibility study Geant4 2013 Int. User Conf. at the Physics-Medicine-Biology Frontier

Marcatili S et al 2014 Multi-scale hybrid models for radiopharmaceutical dosimetry with Geant4 Geant4 2013 Int. User Conf. at the Physics-Medicine-Biology Frontier

Pinto M et al 2014 Design optimisation of a TOF-based collimated camera prototype for online hadrontherapy monitoring Geant4 2013 Int. User Conf. at the Physics-Medicine-Biology Frontier

Pipek J et al 2014 A modular geant4 model of leksell gamma knife perfexion™ Pipek Geant4 2013 Int. User Conf. at the Physics-Medicine-Biology Frontier

Guest Editor

Sébastien Incerti

Centre National de la Recherche Scientifique, Institut National de Physique Nucléaire et de Physique des Particules, Université de Bordeaux, Centre d’Etudes Nucléaires de Bordeaux-Gradignan, Gradignan, France