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THE CLOUD-BASED IMPLEMENTATION AND STANDARDISATION OF ANTHROPOMORPHIC PHANTOMS AND THEIR APPLICATIONS

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ABSTRACT

Many radiation protection applications require the production of a large number of accurate simulations of radiation-human body interaction. This research focuses on the development of a new Geant4 application that generates voxelized anthropomorphic phantom models, enabling the reproducible and standardized production of numerous Geant4 simulations in cloud-based environments. This development integrates existing and publicly available models within Meiga, a framework for integrating Geant4-based applications. To standardize the simulations, ensure their reproducibility and uphold the FAIR paradigm, we generated an extended vocabulary schema using metadata and ontologies based on current standards. By utilizing virtualization containers, we leverage the scalability and flexibility of public and federated clouds, such as the European Open Science Cloud (EOSC). In this work we describe our implementation, provide some example results and outline the application's use for evaluating effective doses expected onboard commercial flights or assessing the effectiveness of radiation shielding materials in rapid neutron production facilities.

1 INTRODUCTION

In order to accurately predict the effects of ionizing radiation on living organisms, a comprehensive model of particle transport and radiation interactions in bio-materials must be developed, accounting for various combinations of factors such as different tissues, types of radiation, and incident radiation energies/spectra. Additionally, incident radiation geometries and molecular reaction effects produced by different species should be taken into account. Monte Carlo (MC) simulation is widely available and can accurately simulate radioactive transport problems in complex geometries and in a variety of different types of materials. MC tracking codes are essential tools for investigating radiation effects at various spatial scales and energy scales (Sempau 2002).

Among the various codes available, the Geant4 Monte Carlo simulation toolkit (Agostinelli, Allison, Amako, Apostolakis, Araujo, Arce, Asai, Axen, Banerjee, Barrand, et al. 2003) offers a general platform for radiation-matter interactions simulation and an approach for the development of accurate dose calculation applications (Sarrut, Arbor, Baudier, Borys, Etxebeste, Fuchs, Gajewski, Grevillot, Jan, Kagadis, Kang, Kirov, Kochebina, Krzemień, Lomax, Papadimitroulas, Pommranz, Roncali, Rucinski, Winterhalter, and Maigne 2022). Its hierarchical structure includes a set of components for geometric description, particle definition, navigation and tracking, electromagnetic fields, physical models for interactions (electromagnetic, hadronic, optical, photo-nuclear, and electro-nuclear), event scoring, visualization, and component management software (Allison, Amako, Apostolakis, Arce, Asai, Aso, Bagli, Bagulya, Banerjee, Barrand, et al. 2016). This software is widely used for its continuous improvements, its simulation performance, refinement of physical models, enhancement of its capabilities, and its open-source strategy. Thanks to the use of object-oriented languages (C++), the development of Geant4 physical models ranges from the simulation of high-energy physics experiments to new physics models and the development of other software relevant to various medical- and space-oriented applications(Caon 2004).

In the field of Geant4-based applications, our group is developing Meiga, a package of tools that allow for the integration of simulations in Geant4, sophisticated description of geometry, advanced 3D visualization tools, and validated physical models, with its own classes that simplify the development of different applications by integrating intermediate software layers between Geant4 libraries and non-specialized users. Meiga includes its own semantic analyzer of JSON text files that allows for the definition of inputs, such as detector geometries and materials, and simulation outputs, such as spectra, doses, or other observables. Meiga was originally designed and developed to facilitate the calculation of particle transport over hundreds or thousands of meters of rock with varying densities and compositions (Taboada, Sarmiento-Cano, Sedoski, and Asorey 2022), as well as for the design and characterization of particle detectors for muography (Taboada, Sarmiento-Cano, Sedoski, and Asorey 2022; Calderón-Ardila, Asorey, Almela, Sedoski, Varela, Leal, and Gómez-Berisso 2022), a novel technique that allows for the estimation of the spatial distribution of the density of large objects, such as an active volcano, by taking advantage of the high penetration capacity of high-energy atmospheric prompt muons (Tanaka 2022; Rubio-Montero, Pagán-Muñoz, Mayo-García, Pardo-Diaz, Sidelnik, and Asorey 2021a).

The purpose of this work is to expand the capabilities of Meiga for studying the effects of radiation on human anatomy *in-silico*. This will enable the evaluation of radiotherapy and proton therapy doses, as well as the determination of the effective dose received by a person exposed to high radiation environments, such as those encountered onboard a commercial flight or inside a rapid-neutron production facility. In this regard, computational human phantoms are widely used in medical physics applications to estimate the dose within human tissues and organs resulting from specific radiation environments. The computational human phantoms were initially developed as a series of analytic phantom models. The first models were produced by the Oak Ridge National Laboratory (ORNL), which constructed the internal organs and boundaries of the phantom using simple geometries such as planes, cylinders, spheres, cones, elliptical cylinders, and ellipsoids (Large, Malaroda, Petasecca, Rosenfeld, and Guatelli 2020a). Subsequently, the Medical Committee on Internal Radiation Dose (MIRD) produced a similar series of analytical phantoms, whose dimensions and internal organ masses were designed in accordance with standards defined by the International Commission on Radiological Protection (ICRP) and the International Commission on Radiation Units (ICRU) (on Radiological Protection., on Radiation Units, and Measurements. 2009). Despite their lack of anatomical realism, these reference models have been used to provide consistent and reproducible radiation protection guidance for different types of exposures. In recent years, medical imaging technologies such as computed tomography (CT) and nuclear magnetic resonance imaging (MRI) have been improved, providing high-resolution cross-sectional digital images that allow for enhanced anatomical structure representation. These images are segmented, dividing images into smaller sections. All pixels belonging to a tissue or organ are assigned an identification number that replaces their original grey-scale value in the CT image. Currently, human voxelized models are designed based on these techniques, where a numeric index, material, and placement inside the phantom are associated with each generated voxel. One main issue of voxelization is, e.g., the overestimation of the mass and size of small structures when they are smaller than the voxel dimensions. In addition, organs with spherical approximations can also have overestimated surface areas, and the organ positions and shapes can vary depending on the position of the person, being standing, sitting or lying as the most common ones. Ongoing refinement of voxel phantoms aims to provide increasingly accurate human anatomy representation, allowing for more realistic estimations of organ doses. Some radiation transport codes have integrated different voxel phantom models in the past (Sato, Noguchi, Emoto, Koga, and Saito 2007; Martins, Cordeiro, Silva, Souza-Santos, Queiroz-Filho, and Hunt 2014; Franck, Laval, Borissov, Guillierme, and Bordy 2001; Costa, Sa, and Bonifacio 2015). However, previous voxel phantom implementations are generally unavailable to the public. The ICRP's Publication 110 has introduced voxelized anthropomorphic phantoms for adult males and females, which are now becoming the official computational models representing the adult Reference Male and Reference Female (Clement 2009).

To tackle the challenge of enhancing the spatial resolution of simulations by reducing voxel size, whilst mitigating the consequent computational demands resulting from an increased number of voxels, the utilization of virtualized containers is paramount. By encapsulating the application and its dependencies in virtualized containers, it becomes feasible to harness the vast computational resources offered by public and federated clouds, such as the European Open Science Cloud (ESOC). Standardized computational mechanisms are crucial for maximizing the benefits of the simulation framework, particularly for coordinating, sharing and curating results. To ensure the long-term sustainability of research, the European Commission is promoting several initiatives that adopt the Open-Science paradigm. These initiatives are based on the FAIR (findable, accessible, interoperable and reusable data) principles and the federation of virtual resources, including cloud services and virtual organizations.

In this study, we present a new application of the Meiga (Taboada, Sarmiento-Cano, Sedoski, and Asorey 2022) Geant4 framework based on the cloud-based implementation and standardization of the Geant4-based ICRP110 Adult Reference Male and Female anthropomorphic phantoms (Large, Malaroda, Petasecca, Rosenfeld, and Guatelli 2020b), providing some example calculations and delineate some of its possible applications in the field.

2 MATERIAL AND METHODS

2.1 Structure of the Meiga Framework

Meiga is a software framework that allows for the calculation of particle propagation through different materials and the simulation of detector responses. The framework comprises a range of C++ classes, each serving a specific function. It achieves this through the integration of Geant4 simulations, which perform the particle transport and calculates the detector response. Geant4 is utilized as an external toolkit, and Meiga provides the necessary interfaces for users to access detector descriptions and run managers. Meiga includes a variety of customisable applications that enable non-experts to run and access simulated data by using configuration files written using the JSON standard. The customisable applications allow users to tailor the framework to their specific needs (Taboada, Sarmiento-Cano, Sedoski, and Asorey 2022).

Meiga was originally designed for muography studies, and the simulation workflow is based on three consecutive steps. The first step consists of the injection of the high-energy flux of secondary particles at ground level. These particles are produced during the interaction of energetic cosmic rays with the atmosphere, producing the atmospheric background radiation, mainly composed of electromagnetic particles ($e^{\pm}$ and γ), muons ($\mu^{\pm}$), and hadrons (mainly p, n, $\pi^{\pm}$). From those, only a small fraction of muons possess enough energy to traverse across hundreds or even thousands of meters of rock. Depending on the geometry and the density profile of the studied object, the minimum muon energy could even be up to hundreds of GeV (Rubio-Montero, Pagán-Muñoz, Mayo-García, Pardo-Diaz, Sidelnik, and Asorey 2021b; Bertolli, Sarmiento-Cano, and Asorey 2022). Meiga includes the EcoMug library (Pagano, Bonomi, Donzella, Zenoni, Zumerle, and Zurlo 2021) for a fast generation of samples of atmospheric muons. However, for obtaining a more accurate distribution of the expected atmospheric flux at the site, Meiga includes a module for handling the secondary particles file produced by ARTI, a publicly available framework (Asorey, Sarmiento-Cano, Suárez-Durán, and Rubio-Montero 2022), developed for the precise calculation of the atmospheric background in any place of the World and under realistic and real-time atmospheric and geomagnetic conditions (Sarmiento-Cano, Suárez-Durán, Calderón-Ardila, Vásquez-Ramírez, Jaimes-Motta, Núñez, Dasso, Sidelnik, and Asorey 2022), and including the high-energy components of the muon flux (Rubio-Montero, Pagán-Muñoz, Mayo-García, Pardo-Diaz, Sidelnik, and Asorey 2021b). Once the flux is injected, the propagation through the ground takes place. The rock can be modeled, as any other material in Geant4, from its average density and atomic composition. Even more, it is also possible to configure layers of different types of rocks with different geometries if the internal structure is known, or if different configurations need to be assayed. All the possible interactions of the incoming radiation with the medium are taken into account, producing the final flux of muons that traversed across the volcano (Tanaka 2022), or reach the subterranean ground for mining prospecting applications (Taboada, Sarmiento-Cano, Sedoski, and Asorey 2022). The final step is to simulate the response of the detector. For this matter, Meiga includes different types of detectors typically used in astroparticle physics, such as water Cherenkov detectors (WCD) with large photomultiplier tubes (PMT) (Peña-Rodríguez, Pisco-Guabave, Sierra-Porta, Suárez-Durán, Arenas-Flórez, Pérez-Archila, Sanabria-Gómez, Asorey, and Núñez 2020), or arrays of plastic-based organic scintillator strips with wavelength shifters multi-clade fibre optics connected to multi-anode PMTs (Calderón-Ardila, Asorey, Almela, Sedoski, Varela, Leal, and Gómez-Berisso 2022), or small silicon photomultipliers (SiPM) (Peña-Rodríguez, Sánchez-Villafrades, Asorey, and Núñez 2023).

The top level of Meiga's hierarchical structure is the `Event`, which sets the workflow during execution. This structure defines variables that describe the detector and the simulation data, and a connection is established between them. The `Detector` class provides an interface to the `Event`, from which the detector's description can be read. Once the simulation is executed, the input file containing the data is read and stored in the `Event`. They share the detector implementation, physics conditions, and secondary generation or input. The process starts by invoking the set mandatory user initialisation classes, which set the simulation options from the `Event`. The detector geometry, materials used in its construction, selection of all physics processes to be simulated, and the definition of primary particles are configured. This setup can be done manually, or automatically using predefined detector models and physics lists that are contained in the G4Models class. Simulation data is stored in two ways: using user hooks, where the information extracted from simulations is stored in the `SimDatas` class, and using the built-in scoring commands available in Geant4. Data can be accessed at the event and detector levels through the `SimData` class. Similarly, the command-based scoring functionality allows for the collection of data from simulations.

The Meiga framework contains a set of utilities, including a parser of configuration files, physics constants, and geometry and mathematical calculations. Configuration files allow users to handle the simulation settings better. Physics constants set the units and particle definitions of a common system between the external packages used (such as ARTI) and Geant4.

One of the benefits of using the modular and extensible design of Meiga, is that it provides a set of predefined detector models and physics lists, which can be easily extended or modified to suit the user's needs. These models and lists can be used as a starting point to develop custom detectors and physics processes, saving the user significant development time and effort. For doing that, the new classes developed inherit properties and methods from the classes provided in the framework. For instance, new detector classes can be created by inheriting from the `Detector` class or new materials can be defined in the `Materials` class. Also, new action classes can be created to perform additional tasks during the simulation.

Additionally, Meiga's hierarchical structure allows for easy management of simulation data using *setters* and *getters* methods provided by the framework, making it easy to extract and analyse the data. Furthermore, the use of scoring meshes makes it easy to collect and visualize simulation data.

Meiga also includes a set of utilities for handling configuration files, physics constants, and mathematical calculations. These utilities can be used to configure simulation settings and perform common mathematical operations. The use of standardized configuration files formats such as JSON and XML makes it easy to exchange simulation settings and data with other applications, and even for standardisation the production of digital twins.

2.2 The Meiga implementation of anthropomorphic phantoms

A new application called `G4ICRPHumanPhantomSimulator` has been developed in our computational framework by harnessing the extension capabilities of MEIGA. modeling the interaction between radiation and a computational model of the human body is enabled by this application. Following the recommendations of the ICRP110 publication (Clement 2009), two models of an anthropomorphic voxelized phantom were generated in two ways: (a) by voxelizing the geometry from DICOM images and (b) by creating a mesh based on the Adult Male and Female reference computer models defined in ICRP110 publication (Large, Malaroda, Petasecca, Rosenfeld, and Guatelli 2020b). The main sources from the ICRP110 adult reference voxel phantoms, which are included as two advanced examples in the Geant4 application, `DicomG4` and `human-phantom`, were adapted to build this application,(Large, Malaroda, Petasecca, Rosenfeld, and Guatelli 2020b). Two CT scans were respectively acquired from a male and a female subject in a supine position with the arms parallel to the body, as shown in Figure 1. The main characteristics of the ICRP110 Adult Reference Computational Phantom can be found in Table 1 of (Large, Malaroda, Petasecca, Rosenfeld, and Guatelli 2020b) for reference. In the first trials, the original slices of 512x512 pixels were reduced to 64x64 voxels to reduce the computational cost.

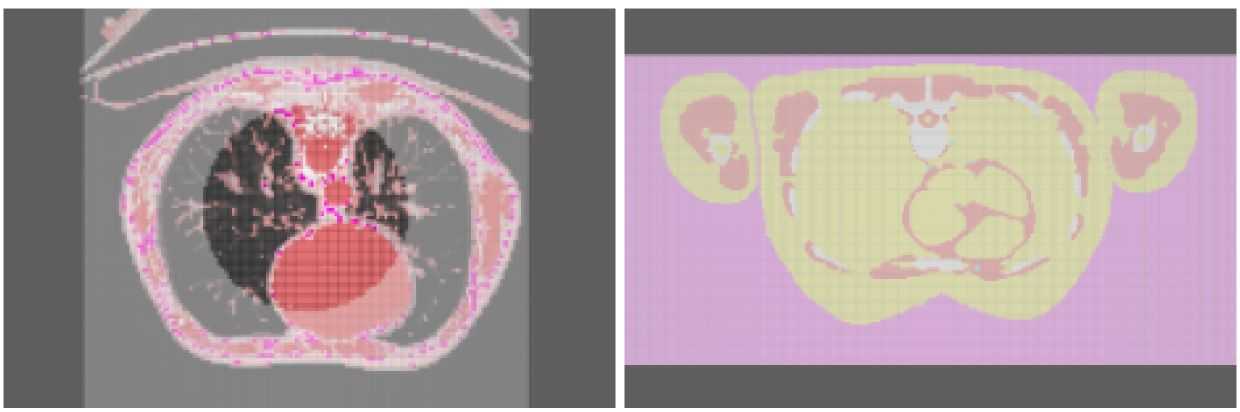

Figure 1: A section of the anthropomorphic phantoms adapted for MEIGA: the `DicomG4` reference model (left), and visualization the voxelised female phantom from the `human-phantom` examples in the slice number 265 (right).

The initialization and construction of the phantoms are performed in the constructor of the `Detector` class, as explained in the Meiga workflow. This class extracts the information from the new Event structure. A world volume of a 2 m^3 cube and filled with air. Depending on the user's input, the corresponding phantom model (DICOM or ICRP110 mode) is selected. Consequently, a set of methods adapted from each model imports information from the ASCII files `DICOMData.dat`, `FemaleData.dat` or `MaleData.dat`. These files contain information about the 142 organs and the corresponding 53 building materials associated with each voxel, including those filled with air. Additionally, a special method was programmed for varying the voxel size and the corresponding number of voxels intended for specific applications. As outlined in the publication by Large *et al.* (2020), voxel data and corresponding material IDs are saved to a dedicated array before constructing a parameterized volume using the Geant4 Nested Parameterization functionality. This approach involves a nested strategy, where the geometry has a three-dimensional regular reputation of the same size and shape of volumes, without any gaps between them. The material of each volume changes based on its position. Rather than using a direct three-dimensional parameterized volume, the first (sagittal) and second (coronal) axes can be sequentially replicated, followed by one-dimensional parameterization along the third axis (axial). This strategy is more efficient in terms of memory access and consumption for geometry optimization and provides faster navigation for a large number of voxels. The dose information observed at each voxel is recorded in a JSON file for further analysis by the subsequent analysis tools that are available in MEIGA. In addition to the input JSON file, this file is also processed to generate the corresponding metadata, as will be elaborated in the next subsection.

2.3 Workflow of the Virtualized Meiga Application

In the field of medical applications, there is an ever-increasing demand for accurate simulations of radiation-matter interactions. Such simulations require significant computational resources, which are becoming more widely available as computing and storage capabilities continue to grow. However, there remains a pressing need to standardize the production, analysis, curation, and access of synthetic, and eventually measured, data. Recent efforts have therefore focused on integrating and standardizing our astroparticle and muography simulation and data analysis codes within the European Open Science Cloud (EOSC) ecosystem (Rubio-Montero, Pagán-Muñoz, Mayo-García, Pardo-Diaz, Sidelnik, and Asorey 2021b).

The integration of application codes aims to define, generate, and store data and metadata using tools that can be deployed in virtualized and containerized environments based on Docker images (Rubio-Montero, Pagán-Muñoz, Mayo-García, Pardo-Diaz, Sidelnik, and Asorey 2021a). Such efforts are expected to facilitate the sharing of data and promote collaboration by adopting the Open Science paradigm with the FAIR (Findable, Accessible, Interoperable, Re-usable data) principles, and the federation of virtual resources and organizations. The use of Docker images enables the sharing of tools and workflows, making it easier to reproduce results.

We have deployed a cloud-based production system for simulating radiation-matter interactions in an anthropomorphic phantom that is fully integrated within the Meiga framework, which was described in the previous section. This was achieved by deploying the new `G4ICRP110HumaPhantomSimulator` docker container in a constrained set of cloud resources that were provisioned by EOSC. The docker includes all the Meiga framework dependencies, including ROOT, a data analysis framework (Brun and Rademakers 1997), Geant4, and the corresponding parsers for XML and JSON files.

For building this production computing virtual facility, we followed the same schema explained in (Rubio-Montero, Pagán-Muñoz, Mayo-García, Pardo-Diaz, Sidelnik, and Asorey 2021a), including the utilization of several EOSC- and EGI-based services: **Geant EduTeams** and **EGI Check-in** as the primary identity providers for accessing the resources, **EGI DataHub** as the cloud storage service based on OneData - a globally distributed cloud file system that enables various ways of accessing and sharing data and metadata, and the Infrastructure Manager (IM) from the **EGI Check-in** service. For this work, we established a virtual cluster based on a Slurm Workload Manager job scheduler with one virtual master (*v-master*) and 8 *v-nodes*, each equipped with 8 Intel Xeon Core E7 processors, and 250 GB of shared memory and disk each. We configured Docker to use both unified and equally as needed. Additionally, we included a local version of the MEGA command line for possible users who do not have access to the EOSC services. This provides a secure, cloud-based exchange repository for the configuration input files and storage of the resulting outputs.

Standardized schemes based on linked data have become increasingly prevalent in the trend towards Open Data. To follow this direction, we decided to utilize standardized schemes for the metadata of this application due to their simplicity and compatibility. Specifically, we defined the metadata using JSON-LD 1.1 (W3C), a language syntax now promoted by the big players of the sector, such as Google, that is becoming the standard replacement for heavier syntaxes like RDF/XML or Turtle. The main vocabulary used in this application is DCAT-AP2, which is a specific profile of DCAT2 (W3C) recommended for repositories, content aggregators, or data consumers related to the public sector. Furthermore, we utilized the `RadiationTherapy` class in schema.org (Brickley, Corlosquet, Douglas, et al. 2022) to describe the synthetic data generated in each irradiation simulation. This includes information such as the treatment modality, radiation type, and target anatomy.

In addition to utilizing the standardized schemes for metadata, we used the *MedicalEntity* class to describe the anatomical structure or system involved in the therapy simulated. To link the simulated data with datasets containing information about absorbed, equivalent, or effective doses calculated in gray or sievert, we made use of the *includedInDataCatalog* property of the *MedicalIntangible* schema. To provide a more comprehensive and interoperable description, we are developing a new MEIGA vocabulary (`meiga::`), which leverages the Radiation Oncology Ontology (Deckker, van Soest, Marshall, et al. 2022) to extend the current schema with additional properties required for these computations. With this extension, we will be able to produce a richer and more standardized description, facilitating the interoperability and reusability of the data generated by our simulations.

3 DISCUSSION OF RESULTS AND CONCLUSIONS

For testing the functionality of the ICRP110 human phantoms implementation in Meiga, different sets of trials were executed. As an example, Figure 2 presents the absorbed dose as a function of the depth for four different tests performed using the newly developed Meiga application, `G4ICRPHumanPhantomSimulator`. These tests were performed using four different types of radiation: 10^6 photons of energy $E_e = 10\,\mathrm{MeV}$, 10^6 electrons of energy $E_e = 10\,\mathrm{MeV}$, 10^6 protons of energy $E_e = 20\,\mathrm{MeV}$ and 10^6 neutrons of energy $E_e = 10\,\mathrm{MeV}$. The results show the variation of absorbed dose as a function of depth in the human body for each type of radiation, corresponding to the expected profile of the deposited energy as a function of the distance. The previously described virtual cluster completed these tests in only 8 CPU·hours, which should be highlighted as the processors executing the tasks are not by far from an ultimate generation actually. This demonstrates not only the accuracy of the results from the physics point of view but also the potential of the Meiga application as a practical and efficient tool for radiation protection and medical imaging applications.

With the introduction of `G4ICRPHumanPhantomSimulator`, this newly developed Geant4 application using Meiga for simulating the interaction between radiation and a computational model of the human body, a wider set of new studies will be achievable. Thus, the application can generate a voxelized phantom model by voxelizing the geometry from DICOM images or by creating a mesh based on the Adult Male and Female reference computer models by adapting the existing models in a more modular fashion and benefiting from Meiga capabilities to facilitate the production of a large number of Geant4 simulations in cloud-based environments.

To ensure the reproducibility and standardization of the simulations, we developed an extended vocabulary schema based on current standards. In addition to using DICOM images and reference computational phantoms, our approach utilizes metadata, ontologies, and persistent identifiers to guarantee that the data generated by our simulations will be easily discoverable, accessible, and reusable, thereby upholding the FAIR paradigm. By employing virtualized containers, we can exploit the scalability and flexibility of public and federated clouds, such as the European Open Science Cloud, and make our simulations available to a broader scientific community.

The potential applications of our work are numerous. For instance, our approach can improve the evaluation of the effective dose expected onboard commercial flights and will be integrated into the next version of the ACORDE code (Asorey, Suárez-Durán, and Mayo-García 2023). The adaptation of this model for sitting and standing people on board commercial airplane Geant-4 models, such as the Airbus A330 and the Airbus A350 vessels, is underway. It can also be employed for the evaluation of the effectiveness of various radiation shielding materials in rapid neutron production facilities, and to evaluate the effective dose a trapped person could experience in case of a severe accident within these facilities.

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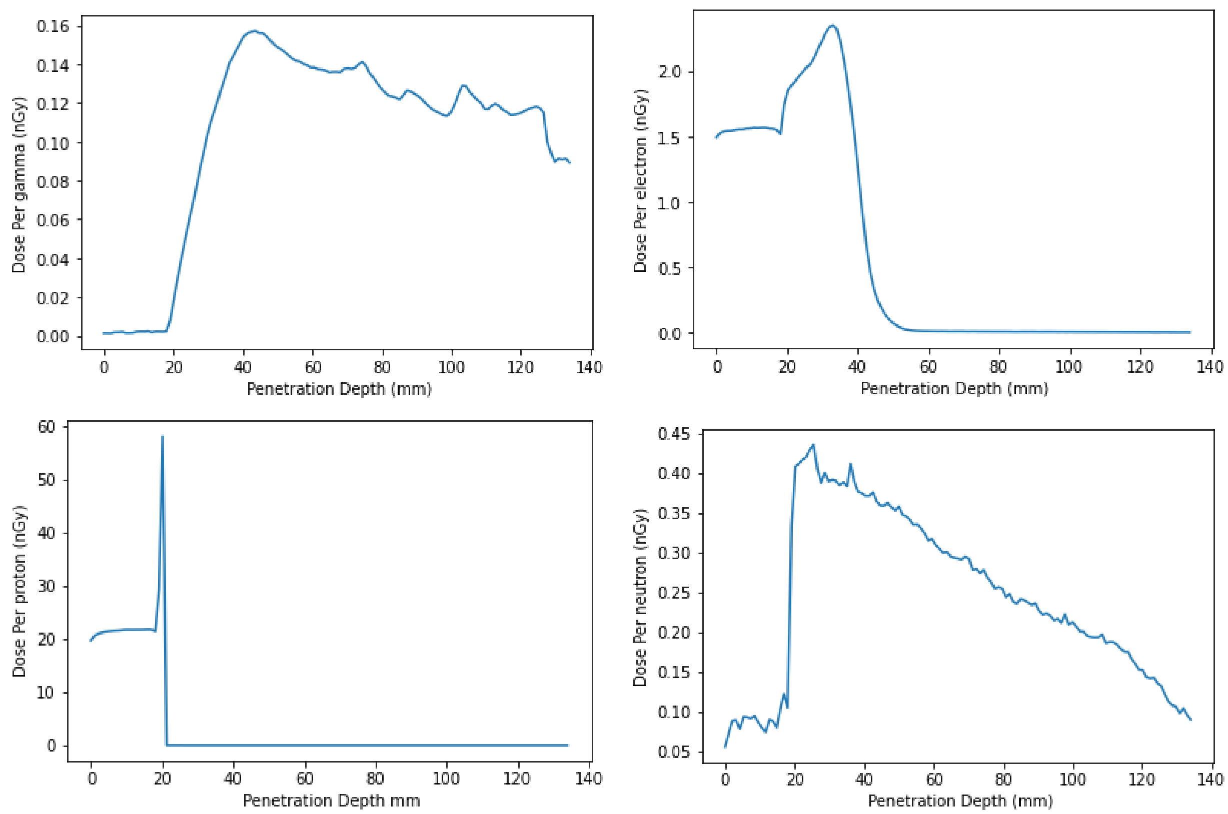

Figure 2: The absorbed dose as a function of depth is shown for four tests performed using the new `G4ICRPHumanPhantomSimulator` application in MEIGA: 1) 10^6 photons of energy $E_e = 10$,MeV (top-left), 2) 10^6 electrons of energy $E_e = 10$,MeV (top-right), 3) 10^6 protons of energy $E_e = 20$,MeV, and 4) 10^6 neutrons of energy $E_e = 10$,MeV.

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