Modelling ICRP110 Adult Reference Voxel Phantoms for dosimetric applications: Development of a new Geant4 Advanced Example

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Abstract. The reference adult male and female voxel phantoms described in the International Commission on Radiological Protection (ICRP) publication 110 have been successfully implemented in a Geant4 application named ICRP110Phantoms. The application allows users to simulate either the whole or a partial phantom, including as little as a single cross-sectional slice. The Geant4 application allows users to estimate the absorbed dose in individual voxels and in entire organs. As example of application, the ICRP110Phantoms was used to estimate the dose deposited by a mono-energetic 125 MeV proton pencil beam, incident on the left breast and passing through the lungs and heart, modelled in partial chest phantoms of both male and female ICRP110 phantoms. The ICRP110Phantoms will be released in Geant4 as an Advanced Example to allow its use in the wider scientific community. This Geant4 Advanced Example application can be utilised for dosimetric studies in radiotherapy, nuclear medicine and radiation protection.

1. Introduction

Primarily coupled with radiation transport codes, computational human phantoms provide an excellent means of investigating in-silico the effects of radiation on the human anatomy. They are widely used in medical physics applications including radiotherapy, nuclear medicine and radiation protection [1, 2], to estimate the dose within human tissues and organs produced by a specific radiation environment [3].

The earliest computational human phantoms were a series of analytical phantom models produced by the Oak Ridge National Laboratory (ORNL), constructed using simple geometries such as planes, spheres, cylinders, cones, ellipsoids and elliptical cylinders to represent internal organs and the phantom boundaries [4]. Following the ORNL phantoms, a similar series of analytical phantoms were adopted by the Medical Internal Radiation Dose Committee (MIRD), hence referred to as MIRD phantoms [5], with internal organ dimensions and masses designed to be in close agreement to the standards defined by the International Commission on Radiological Protection (ICRP) [6, 7] and the International Commission on Radiation Units (ICRU) [8]. A major disadvantage of analytical phantoms arise in the use of simple geometrical volumes to model organs, translating in an approximate description of the human anatomy [9].

As the use of medical imaging technologies such as Computed Tomography (CT) and Medical Resonance Imagining (MRI) increased, the ability to view the human anatomy via high-resolution cross-sectional digital images gave rise to the development of voxelised human phantoms [4]. Medical images
are used to create voxels, to which a material and a numerical index to identify the voxels position within the phantom are associated [10]. As voxelised phantoms are constructed using medical images of real human anatomy, they are a significant improvement over analytical phantoms in terms of anatomical accuracy. However, the short comings of voxel models include their over-approximation in size and mass of some phantom structures whose dimensions are smaller than the voxel dimensions (such as skin or bone surfaces), as well as the step-like nature of organ surfaces (rather than a smooth surface).

The continued development of voxel phantoms aims to represent the human anatomy with ever-increasing realism to allow for more realistic organ dose estimations [4]. Various voxel phantom models have been implemented in multiple radiation transport codes primarily for radioprotection studies in the past [9-12]. However, almost all previous voxel phantom implementations are not publicly available. The ICRPs Publication 110 (ICRP110) presents adult male and female voxel phantoms that are “the official computational models representing the adult Reference Male and Reference Female” [13].

In this work we describe the implementation of the ICRP110 adult Reference Male and Reference Female voxel phantoms in a dedicated Geant4 [14] user application called ICRP110Phantoms. This application is due for release in the forthcoming December 2020 version of Geant4. This will be the first time that ICRP110 voxelised phantoms will be modelled in a Geant4 Advanced Example, allowing the scientific community to utilise this application for specific medical physics studies.

2. Geant4 ICRP110 Voxelised Phantom

2.1. The ICRP110 phantom

The adult male and female reference computational phantoms detailed in ICRP 110 [13] were created based on the CT image data sets of a male and a female individual whose characteristics were adapted to closely approximate those of the ICRP adult Reference Male and Reference Female, defined in previous ICRP publications [6, 7]. The CT scans were acquired with both individuals laying supine and with arms resting parallel alongside the body.

The resulting male voxel phantom was based on the CT scan of a 38-year-old individual 1.76 m tall and weighing just under 70 kg. The raw CT voxel data was scaled to closely match the ICRPs Reference Male (1.76 m tall and a mass of 73 kg) characteristics. Similarly, the resulting female phantom was based on the CT scan of a 43-year-old individual 1.67 m tall and a mass of 59 kg. Once again, voxel scaling was performed to produce a voxel phantom matching the specifications of the Reference Female (1.63 m tall and a mass of 60 kg). The properties of the obtained adult male and female reference voxel phantom are presented in table 1.

The ICRP notes that both phantoms have additional slices of skin added at the very top and bottom of the phantoms to ensure that all surface voxels are skin. The inclusion of these layers is optional as they are not accounted for in the reference phantom properties of table 1 [13]. For the purposes of this study, the top and bottom skin slices are included. In the ICRP110 phantoms, in addition to the top and bottom skin layers, 140 organ tissues are identified. Each organ tissue is comprised of one of 53 phantom materials, defined by the ICRP publication 110 in terms of chemical composition and density. The voxel data files detailing the ICRP110 adult reference computational phantoms are freely available on the ICRPs webpage for publication 1104.

2.1.1. Reformatting of ICRP110 Phantom Data.

The original data files of the ICRP110 phantoms detail the entire 3D phantom voxel descriptions in a single ASCII (plain text) file. The position of the ASCII entry within this primary data file corresponds to the position of a voxel within the human phantoms. The value of the ASCII entry in each position within the 1D array (an integer between 0 and 141) assigns each corresponding voxel to a specific organ/tissue of the phantom.

4 Accessed at https://www.icrp.org/publication.asp?id=ICRP%20Publication%20110
Table 1. Defining properties of the ICRP110 Adult Reference Computational Phantoms.
Source: ICRP Publication 110 [13].

| Property                          | Male     | Female    |
|-----------------------------------|----------|-----------|
| Height (m)                        | 1.76     | 1.63      |
| Mass (kg)                         | 73.0     | 60.0      |
| Number of Voxels                  | 1,946,375| 3,886,020 |
| Slice thickness (mm)              | 8.0      | 4.84      |
| Voxel in-plane Resolution (mm)    | 2.137    | 1.775     |
| Voxel Volume (mm$^3$)             | 36.54    | 15.25     |
| Number of voxels along X          | 254      | 299       |
| Number of voxels along Y          | 127      | 137       |
| Number of slices (Z)              | 220 (+2)$^a$ | 346 (+2)$^a$ |
| Number of Unique Organ Identifiers| 140$^b$  | 140$^b$   |
| Number of Unique Materials        | 53       | 53        |

$^a$ Additional slices of skin at top and bottom of both male and female phantoms
$^b$ 141 organ IDs including the top and bottom skin layers which have their own

To provide the option of easily selecting a specific section of the entire phantom to model, the two original ASCII data files were resampled into 222 and 348 individual files for the male and female phantoms respectively, each file representing an axial (z) “slice” of the human phantom. The created data files are labelled as AM_slice1.g4dat to AM_slice222.g4dat in the case of the male phantom and AF_slice1.g4dat to AF_slice348.g4dat for the female phantom, where the slice numbers start at the base (or feet) of the phantom and increase moving towards the phantom head. Voxels that don’t belong to the phantoms are set to air.

2.2. Geant4 application implementation details

In ICRP110Phantoms the modelling of the phantoms is performed in the Detector Construction class. An air-filled cube (World volume) of 2 m$^3$ is created. The method ReadPhantomData() imports information from the text file ‘Data.dat’ including the number of slices (transverse sections) to model, the number of voxels in each slice and the voxel sizes. The method ReadPhantomDataFiles() reads the phantom slice input files containing the information of each voxel (voxel number and organ ID) within each phantom slice. The organ IDs vary between 0 and 141, and are associated to one of the total 52 ICRP110 phantom materials (53 including air). The phantom tissues/materials are implemented in the Geant4 application using their chemical formula and density as provided in the ICRP publication 110 [13], which can differ between the male and female models. The information of the voxels and their associated material IDs are saved in a dedicated array in the Detector Construction class.

Once the information of the voxels and their associated material IDs is saved, an air-filled container is dynamically implemented with dimensions equal to that of the phantom (whole or partial). A 3D voxelised geometry is created and housed within this phantom container, with each voxel initially filled with air. The Geant4 Nested Parameterization functionality [15] is used to fill each voxel, identified by copy number, with a material as specified in the dedicated array. This functionality is advantageous over other Geant4 geometry parameterisation solutions in that it requires much less memory for geometry optimisation and additionally provides much faster navigation for applications harnessing a very large number of voxels [16].

The G4ICRP110PhantomPhysicsList class defines the physics processes to be modelled in the simulation. By default, the G4EmStandardPhysics_option4 is used to describe electromagnetic (EM) interactions as it is deemed to be the most accurate EM constructor for medical physics applications [17]. Additional physics processes which have been activated include G4RadioactiveDecayPhysics and
G4DecayPhysics to describe decay processes, and G4HadronElasticPhysicsHP and G4HadronPhysicsQGSP_BIC_HP to describe elastic and inelastic hadronic interactions, respectively. The threshold of production of secondary particles is fixed to 0.2 mm, corresponding to approximately 10% of the voxel dimensions; secondary particles with a range smaller than the cut are not tracked and instead their associated energy is recorded as a local energy deposition.

The scoring of the dose in each phantom voxel is performed by means of the Geant4 scoring mesh functionalty [15]. The output of the simulation, consisting of the dose in each voxel and the voxels position along x, y, and z, are saved in an ASCII file.

A C++ application named Analysis is included as part of ICRP110Phantoms to calculate the total absorbed dose in each organ from the simulation’s output ASCII file, along with the total dose absorbed over all phantom voxels. In addition, the Analysis application produces a series of files which contain 2D dose distribution within each phantom slice constructed during the simulation, for further analysis of the results.

3. Results
A 3D rendering of the ICRP Reference Male and Reference Female voxel phantoms as produced in Geant4 via the G4ICRP110Phantoms application is displayed in figure 1. Figure 1 identifies easily visible organs in the phantoms that are universal amongst both the male and female phantoms such as the heart, lungs, stomach, and bladder, as well as the testes for the male phantom. In order to visualise the internal anatomy of the phantoms (figure 1), external tissues such as skin, adipose and muscular tissues have been made invisible.

As an example application of G4ICRP110Phantoms, a pencil beam of 125 MeV protons (10^5 histories) was simulated incident to the left breast, directed along the sagittal axis (or y-axis) of a partial male chest phantom and passing through the lungs and heart. The chest was constructed from slices AM_slice141.g4dat to AM_slice190.g4dat for the male phantom. A birds-eye view of the beam trajectory and a 3D rendering of the male chest is shown in figure 2a. The beam is generated at a point in cartesian space at coordinates (8.00, -13.57, 0.00) cm, where the origin is at the centre of the phantom, positive x coordinates lie to the left of the phantoms centre in figure 2a and positive y coordinates lie above the centre of the phantom (i.e. towards the back of the phantom). The proton pencil beam travels along the y-axis (sagittal axis) in a positive direction (i.e from the front to the back of the phantom). It should be noted that this simulation set-up does not represent a clinical proton therapy treatment scenario, but rather is used simply to demonstrate the dose retrieval capability of the ICRP110Phantoms application.

The dose per incident proton deposited in the partial male chest phantom at various depths was recorded via the scoring mesh of the ICRP110Phantoms application and the resulting Bragg peak is shown in figure 2b.

Table 2 reports the average dose and associated statistical uncertainty (standard deviation) in specific organs, calculated by means of the post-simulation data processing application Analysis. The average values and standard deviations were obtained from the dosimetric results of several simulations executed with different random seeds.

4. Conclusions
This paper describes the implementation of the ICRP110 adult Reference Male and Reference Female voxelised phantoms within a dedicated Geant4 application called ICRP110Phantoms. This application can be used in radiation protection, nuclear medicine, radiography and radiotherapy. The ICRP110Phantoms application, described in this paper, is planned to be distributed as a Geant4 Advanced Example starting from December 2020. The next step of the project will consist in the validation of the ICRP110Phantoms application for dosimetry in radiotherapy and nuclear medicine.
Figure 1. 3D rendering of whole body ICRP110 Reference Female (left) and Reference Male (right) voxel phantoms as modelled in the Geant4 application ICRP110Phantoms, in which skin, muscle, cartilage and adipose tissue are not visualised.
Figure 2. a) 3D rendering of partial male phantom from a top-down angle, with a pencil beam of $10^5$ 125 MeV protons incident on the left breast and travelling parallel to the sagittal axis (or y-axis). b) Bragg peak resulting from the irradiation of the male partial chest phantom. The dose values have been normalised per incident proton.

Table 2. Average absorbed dose per incident proton in selected organs due to a 125 MeV proton pencil beam ($10^5$ histories) incident on a male partial chest phantom.

| Organ/Tissue                        | Average Dose per incident proton (nGy/particle) |
|-------------------------------------|-----------------------------------------------|
| Heart (Wall + Contents)             | 36.71 ± 0.09                                  |
| Lung Tissue, Trachea and Bronchi    | 3.35 ± 0.05                                   |
| Breast Tissues (Glandular + adipose)| $(1.3 ± 0.4) \times 10^{-2}$                  |
| Stomach (Wall + Contents)           | $(4.6 ± 0.7) \times 10^{-2}$                  |
| Skin, muscles and residual tissues  | 12.07 ± 0.02                                  |
| Total Phantom Dose*                 | 52.27 ± 0.07                                  |

*Note that total dose is calculated over all partial phantom voxels and is not simply the sum of the organ doses listed.

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6. References
[1] Guatelli S et al 2006 IEEE Nuc. Sci. Symp. Conf. Rec. 3 1359-62
[2] Rodrigues P et al 2004 App. Rad. Isotopes 61 1451-61
[3] Stadtman H 2001 Rad. Prot. Dosimetry 96 21-6
[4] Caon M 2004 Rad. Env. Biophys. 42 229-35
[5] Snyder W S et al 1969 Estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom (Oak Ridge National Lab, TN).
[6] Valetin J 2002 ICRP vol. 32 (Oxford: Elsevier) 1-277
[7] Valetin J 2007 ICRP vol 37 (Oxford: Elsevier) 1-133
[8] Griffiths H J 1989 Radiology 173 202
[9] Sato K et al 2007 Rad. Prot. Dos. 123 337-44
[10] Martins M C et al 2014 Rad. Phys. and Chem. 95 309-12
[11] Franck D et al 2001 Radioprot. 36 77-86
[12] Costa G C A et al 2015 Biomed. Phys. and Eng. Express 1
[13] Zankl M 2010 ICRP vol 39 (Oxford: Elsevier) 1-165
[14] Agostinelli S et al 2004 Nuc. Instrum. Meth. A. 506 250-303
[15] Geant4 Collaboration 2012 Geant4 User's Guide for Application Developers. Accessible from the GEANT4 web page: https://geant4.web.cern.ch/support/user_documentation.
[16] Asai M 2007 Geometry II Lecture presented at Geant4 SLAC Tutorial (SLAC, Stanford, USA, 14-18 May 2007). Accessed at: http://geant4.in2p3.fr/2007/prog/MakotoAsai/Geometry2.pdf.
[17] Arce P et al 2020 Report on G4-Med: a Geant4 benchmarking system for medical physics applications developed by the Geant4 Medical Simulation Benchmarking Group Spec. Iss. Med. Phys. (accepted for publication on the 17th April 2020).