Pediatric personalized CT-dosimetry Monte Carlo simulations, using computational phantoms

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Abstract. The last 40 years Monte Carlo (MC) simulations serve as a “gold standard” tool for a wide range of applications in the field of medical physics and tend to be essential in daily clinical practice. Regarding diagnostic imaging applications, such as computed tomography (CT), the assessment of deposited energy is of high interest, so as to better analyze the risks and the benefits of the procedure. The last few years a big effort is done towards personalized dosimetry, especially in pediatric applications. In the present study the GATE toolkit was used and computational pediatric phantoms have been modeled for the assessment of CT examinations dosimetry. The pediatric models used come from the XCAT and IT’IS series. The X-ray spectrum of a Brightspeed CT scanner was simulated and validated with experimental data. Specifically, a DCT-10 ionization chamber was irradiated twice using 120 kVp with 100 mAs and 200 mAs, for 1 sec in 1 central axial slice (thickness = 10mm). The absorbed dose was measured in air resulting in differences lower than 4% between the experimental and simulated data. The simulations were acquired using ~10¹⁰ number of primaries in order to achieve low statistical uncertainties. Dose maps were also saved for quantification of the absorbed dose in several children critical organs during CT acquisition.

1. Introduction
Patient specific dosimetry is of high interest in pediatric applications where exposure to ionizing radiation is widely debated. The development of accurate anatomical virtual anthropomorphic models has reached a mature state for clinical exploitation. X-rays used in computed tomography (CT) for diagnosis can damage DNA directly or indirectly [1]. Although the radiation exposure per scan is decreased, the contribution of CT exams to collective dose is increasing rapidly due to the continuous rising in the frequency of CT examinations [2]. Pediatric patients are more susceptible to radiation-induced risks than are adult patients owing to their more rapidly growing tissues, their wider and increased cellular distribution of skeletal active marrow, and their greater post-exposure life expectancy. Recent studies conducted on a large pediatric population concluded that an increase in cancer incidence could be attributed to CT ionizing radiation, although the radiation doses are relatively small [3]. For that reason, the accurate calculation of pediatric radiation doses is vital in order to optimize CT protocols and to better understand the potential radiation risks of CT examinations. CT radiation doses are
currently estimated by the volume computed tomography dose index (CTDIvol) and the dose length product (DLP) dose indices.

Monte Carlo (MC) simulations is a widely recognized and well validated technique to study the particle interactions within the matter in nuclear medicine, radiology and radiation therapy. A plethora of MC codes have been developed especially since the early 90s. All the developed codes are mainly divided in two main categories, the “generic” and the “dedicated” codes. EGS, MCNP and GEANT4 are three of the most widely used and validated general purpose codes, while there are several MC tools for specific imaging or therapy simulations such as SIMSET, PET-SORTEO, TOPAS, GAMOS. GATE is a dedicated MC toolkit based on the Geant4 generic code [4]. Initially, it was designed for imaging single photon emission tomography (SPECT), and positron emission tomography (PET) applications while more recently it has been extended in Radiotherapy (RT) and CT imaging. We decided to use GATE in the present study, because it offers additional precision considering physics modeling and it has been extensively validated both on simple and realistic geometries in both dosimetry and imaging applications [5].

The use of anthropomorphic computational phantoms is rapidly gaining interest in medical sciences for the optimization of the acquisition and the processing protocols used in clinical practice. CT scans have a relatively high radiation exposure with associated long-term cancer risk, so computational anthropomorphic models provide an accurate and effective way to test and optimize the maximization of image quality and the minimization of absorbed dose per organ.

2. Materials & Methods
In the present study, the GATE open-source MC toolkit (v6.2) was used for modeling a 16 multidetector CT scanner Brightspeed, GE Healthcare. A DCT-10 ionization chamber was modeled in GATE in order to validate the simulated X-ray source. Furthermore, clinical pediatric CT data were processed (segmented) to be imported in GATE and the XCAT [6] and IT’IS [7] anthropomorphic phantoms were used as reference models for the dosimetric simulations.

In order to have accurate and realistic simulations the need of high number of simulated particles (a clinical study is in the order of \(\sim 10^{13}\) particles) as well as fine resolution on the voxelized model \(\leq 2.0\) mm is apparent. The main limitation for acquiring such simulations is the computational cost. The final simulations were executed in the GateLab grid using 500 CPUs per simulation [8]. The execution time was almost 1 day per simulation (with \(\sim 10^{10}\) simulated particles). The output of the simulations was 3D dose-maps, where the absorbed dose was stored in each voxel of the phantom. The dose-map loaded in MatLab as 3D matrix, and the dose per organ was calculated, according to the initial phantom.

2.1. Modelling the X-ray source
The initial goal was to set up and standardize the CT scanner model in GATE platform. There are three basic requirements in order to set up a whole simulation study for dosimetric applications. The exact source definition (energy, particles, angle, rotation, etc.) is necessary for the particle generation, and then the phantom description should be done taking into account its geometric characteristics and the material composition for particle tracking within it. Finally, the output file, i.e. “Dose Actor”, should be defined in order to store the deposited energy in each voxel within the phantom.

The source energy spectrum was calculated using the commercial software SpekCalc [9]. The calculated beam spectrum was inserted in the GATE platform as a general particle source (GPS), handled by Geant4. Specifically it was defined as a gamma-particle point source with an isotropic angular distribution equal to:

\[
89.4^\circ \leq \varphi \leq 90.6^\circ \quad \text{and} \quad 152.5^\circ \leq \theta \leq 207.5^\circ,
\]

where \(\varphi\) and \(\theta\) stand for the spherical angle coordinates.

The energy photon spectrum was defined using a manual histogram of the energies (in MeV) and their intensity value in each respective histogram point (energy). In order to model the rotational movement of the CT X-ray beam, an extra file was prepared in the GATE simulator. In order to achieve an almost continuous movement of the source the 360\(^\circ\) were divided in 800 steps of 0.45\(^\circ\) angle rotation in each
step (1.25 msec per step, for a full rotation of 1 sec). Defining more parameters in this file (Time, RotationAngle, RotationAxis and Translation in mm), a helical movement of the source was realistically modeled. In order to be as more realistic as possible, no variance reduction techniques (VRTs) were used in the modeling of the physical processes, nor cuts on the simulated physical volumes. All the appropriate physical processes that are taking place were modeled using the standard model of Geant4.

2.2. Methodology of absorbed dose in pediatric phantoms
In the current study 2 computational pediatric phantoms were modeled in GATE; a 5 years old girl from the IT’IS foundation and a 5 years old girl from the XCAT pediatric population. Both models were used as a reference for the quantification of the difference absorbed dose per organ between these different anatomical models (same age and gender). Clinical CT data were used to create computational models of individualized patients in order to move to personalized dosimetry. Specifically, 40 patients were used, 20 of which underwent head CT scans, while the rest underwent abdomen-pelvis CT examinations. After a semi-automated segmentation method the clinical data were converted to head and abdomen-pelvis phantoms for the simulator.

Our goal was to create a simulated pediatric population based on clinical data, which will be irradiated in GATE (helical irradiation) and the absorbed doses per organ (in mGy) in several groups of children will be given for reference to the scientific community.

3. Results
3.1. Verification of CT-source
The calculated energy spectrum compared to the simulated one is presented in figure 1.

Simulations were applied to quantify the absorbed dose a) in air, using a DCT-10 ionization chamber, and b) in PMMA, using a CTDI body phantom. Both in experiment and simulation irradiation was done in axial scans and in the center of the phantom. The results are shown in Table 1.

| Phantom | kVp | mAs | Experimental abs. Dose (mGy) | Simulated abs. Dose (mGy) | Difference (%) |
|---------|-----|-----|-----------------------------|--------------------------|----------------|
| Air     | 120 | 200 | 109.30                      | 113.01                   | 3.28           |
|         | 120 | 100 | 54.50                       | 56.51                    | 3.56           |
|         | 120 | 200 | 12.10                       | 12.90                    | 6.20           |
|         | 120 | 350 | 22.90                       | 24.10                    | 5.02           |
| PMMA    |     |     |                             |                          |                |

3.2. Individualized pediatric dosimetry per organ
The methodology on extracting absorbed doses per organ was standardized. The output of GATE simulations is a 3D “Dose map” where the deposited energy per voxel (in MeV) is stored. Having the anatomical map of the model (attenuation map), the borders of the organs can be accurately defined in the dose output as shown in Figure 2.
All the simulations run with $\sim 10^{10}$ primaries as they resulted in statistical uncertainties lower than 8% per organ of interest. The 2 computational models (5 years old XCAT and IT’IS) were irradiated in head, resulting in absorbed dose differences lower than 7% in brain.

4. Conclusion & Discussion

This is an ongoing study for optimization of pediatric dosimetry based on personalized clinical CT data. The verification of the CT scanner was completed, with high accuracy comparing clinical and simulated results, both in air and PMMA. The highest recorded difference was 6.20% in PMMA while the lower 3.28% in air. Initial dosimetric simulations were applied using standard pediatric phantoms, while a pediatric population was created based on clinical data. Our next step is to irradiate several children phantoms (head and abdomen-pelvis) in order to extract the absorbed doses in the most critical organs, taking into account the differentiation of the anatomy of each patient.

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