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SCIENTIFIC PAPER

Monte Carlo and experimental internal radionuclide dosimetry in RANDO head phantom

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Abstract Monte Carlo techniques are widely employed in internal dosimetry to obtain better estimates of absorbed dose distributions from irradiation sources in medicine. Accurate 3D absorbed dosimetry would be useful for risk assessment of inducing deterministic and stochastic biological effects for both therapeutic and diagnostic radiopharmaceuticals in nuclear medicine. The goal of this study was to experimentally evaluate the use of Geant4 application for tomographic emission (GATE) Monte Carlo package for 3D internal dosimetry using the head portion of the RANDO phantom. GATE package (version 6.1) was used to create a voxel model of a human head phantom from computed tomography (CT) images. Matrix dimensions consisted of $319 \times 216 \times 30$ voxels ($0.7871 \times 0.7871 \times 5$ mm^3). Measurements were made using thermoluminescent dosimeters (TLD-100). One rod-shaped source with 94 MBq activity of ^{99m}Tc was positioned in the brain tissue of the posterior part of the human head phantom in slice number 2. The results of the simulation were compared with measured mean absorbed dose per cumulative activity (S value). Absorbed dose was also calculated for each slice of the digital model of the head phantom and dose volume histograms (DVHs) were computed to analyze the absolute and relative doses in each slice from the simulation data. The S-values calculated by GATE and TLD methods showed a significant correlation (correlation coefficient, $r^2 \geq 0.99, p < 0.05$) with each other. The maximum relative percentage differences were $\leq$14 % for most cases. DVHs demonstrated dose decrease along the direction of movement toward the lower slices of the head phantom. Based on the results obtained from GATE Monte Carlopackage it can be deduced that a complete dosimetry simulation study, from imaging to absorbed dose map calculation, is possible to execute in a single framework.

Keywords Absorbed dose · GATE · RANDO phantom · Internal dosimetry

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Introduction

In vivo measurement of the absorbed dose for a particular radionuclide in nuclear medicine is practically impossible. Advanced geometrical models of a human, such as digital or computerized anthropomorphic phantoms, combined with Monte Carlo programs that simulate radiation transport [1] make it possible to calculate the absorbed fraction of energy or other dosimetric quantities that can be used to explore and predict various biological effects. Several digital phantoms have been developed for general purposes. The Zubal phantom [2] is an early phantom that was obtained from computed tomography (CT) and magnetic resonance (MR) images. Each organ in the Zubal phantom has a unique code

that identifies its voxels. This phantom has previously been used for internal dosimetry calculations with GATE/Geant4 Monte Carlo package and verified with MCNP4C data [3, 4]. Otoko [5], ADELAIDE [6] and Golem [7] are similar examples of computational human models that have been constructed from CT scans of actual patients. These are called voxel tomographic models [8] and have been used to estimate organ doses and other related dose quantities which are either difficult or impossible to measure clinically. More detailed information about these phantom scan be found in the literature [1, 9]. There are numerous physical phantoms such as the RANDO [10] and ATOM [11] phantoms which contain tissue equivalent slices that have anatomical maps and cavities useful for organ dose measurements. These phantoms are typically used for external and internal radiation dosimetry and imaging quality assurance [1].

Monte Carlo techniques have been used for various nuclear medicine applications (i.e., internal dosimetry and pharmacokinetic modeling) to simulate radiation transport inside the human body to improve the accuracy of calculation of three dimensional (3D) dose distributions. These accurate estimations of 3D absorbed dose are most useful for risk assessment of inducing deterministic biological effects and for determining the therapeutic efficiency of radiopharmaceuticals. Accurate 3D absorbed dosimetry could be useful to explore stochastic biological effects (e.g., cancer induction) and risk–benefit ratios of diagnostic radiotracers. Scintigraphic studies have been applied to the different organs such as liver, spleen, lung, bone, kidneys, thyroid and lymph gland using radiotracers in diagnostic procedures in nuclear medicine [12].

A number of commonly used Monte Carlo codes include: Monte Carlo N-Particle (MCNP) [13], Electron Gamma Shower (EGS) [14], PENetration and Energy LOss of Positrons and Electrons (PENELOPE) [15] and GEometryANd Tracking (GEANT) [16, 17]. GATE, which is based on the GEANT4 toolkit [18], is another Monte Carlo package that has become increasingly popular in medical imaging and radiation dosimetry applications. GATE has attractive features in the field of dosimetry for both external and internal dosimetry calculations [19]. GATE is a user friendly code which allows simulations to be designed and controlled using macros and is flexible enough to model many detector designs. Moreover, GATE can handle analytical and voxelised phantoms used for dosimetry. Another innovative feature of GATE is its capability to synchronize all time dependent components in order to allow description of the acquisition process. Hence this code makes it possible to model detector and patient motion, radioactive decay, detector's dead time, and tracer kinetics [18].

Several studies have assessed the applicability of the GATE Monte Carlo package for internal dosimetry of radionuclides and related applications [3, 4, 20, 21]. A brief summary of these studies can be found in a published review by Sarrut et al. [22]. However, assessment of this Monte Carlo package in simulation of voxel base anthropomorphic phantoms in the field of internal radionuclide dosimetry is scarce. In a recent study by Hickson and O'Keefe [23], the GATE Monte Carlo package with the XCAT [24] voxelised phantom was used to investigate the effect of voxel size on absorbed dose calculation. It was found that significantly small voxel sizes and a voxel size of 2 mm or less are required for organ self-dose and cross-dose calculations, respectively. The goal of this work is to experimentally evaluate the application of GATE Monte Carlo package for internal dosimetry in a RANDO head phantom with thermoluminescent dosimeter (TLD) measurements. Quantitative comparisons are made between the absorbed dose calculations from GATE and absorbed dose measurements using experimental techniques in order to achieve this goal.

Materials and methods

Voxelised phantom

The head portion of the RANDO phantom used in this study was developed by Alderson Research Laboratories [10]. The phantom is made of a dried adult human skull surrounded by tissue equivalent materials. The phantom is transected at 2.5 cm intervals and has holes in each slice for placing of TLDs. Voxel-based images of the head RANDO phantom were generated using CT images. CT images were acquired by a Siemens SOMATOM Balance CT scanner (Siemens, Germany) with a 130 kVp tube potential and 60 mAs tube current. The CT images were used as inputs to GATE Monte Carlo package to model source and attenuation voxel phantoms. The matrix dimensions obtained from CT images consisted of $319 \times 216 \times 30$ voxels of $0.7871 \times 0.7871 \times 5$ mm^3 size. It should be noted that the attenuation voxelised map in dosimetry simulation was created by converting the Hounsfield units, from the CT image of the phantom, to tissue type. This conversion was performed using a material range table and the automated Hounsfield material generator function available in GATE Monte Carlo package. Additionally, the voxelised source was created from the segmented CT images, according to the physical dimensions in experimental measurement which will be described in the following section.

TLD measurement

Thermoluminescent dosimeters (TLDs) have been proposed as useful tools for estimation of internal radiation

absorbed dose [25–28] in nuclear medicine and phantom studies. A number of LiF:Mg,Ti (TLD-100) extremity dosimeters from Harshaw with the Harshaw/Bicron Model 3500 TLD reader from Thermo Electronic Corporation (USA) were used for measurement of absorbed doses in the head phantom. The dosimeters were annealed for one hour at 400 °C before any exposure to remove any previously stored energy. A ^{60}Co teletherapy unit in the radiation therapy section of Omid hospital was used following the techniques specified in reader and software manuals along with a Farmer type ionization chamber for calibration of the TLDs [29]. The source was positioned in the brain tissue of the posterior part of the human head phantom in slice number 2 and TLDs were placed randomly at various locations around the source inside slice numbers 2 and 3. The total amount of activity in the rod-shaped source (6.92 mm in diameter and 25 mm in height, with thin plastic walls) was 94 MBq. All TLDs were removed after 48 h following ^{99m}Tc administration. ^{99m}Tc was used for this study because it has a short half-life and is one of the most commonly used radionuclide for diagnostic procedures.

GATE Monte Carlo simulation

The dosimetry simulation was performed using the GATE Monte Carlo package (version 6.1) which was built on Geant4.9.3p01 [18]. To simulate the physical processes, standard model was used for the electromagnetic interactions of photons and electrons. The energy cutoff (i.e., the limit at which the energy is regarded to be locally absorbed) and the range cutoff were set to 1 keV and 0.1 mm for photons and electrons in all simulations, respectively. This range for electrons is regarded as sufficiently small compared to the size of a voxel (0.7871 mm). In this study 9.4×10^7 photons were tracked in the simulation. Compton scattering, photoelectric absorption, and Rayleigh scattering were considered in the photon tracking. A personal computer with 3.5 GHz Intel(R) Core(TM) i7-4770 K processor and 8.0 GB RAM was used in the running for Monte Carlo simulation. Total run time for the GATE simulation dosimetry was $\sim$8.5 h.

Dose calculation

A dose actor was used in the GATE Monte Carlopackage to acquire a dose output file. This output file contained dose voxels values (in cGy) that were calculated as the energy deposited per unit mass in the corresponding anatomic voxels of the RANDO head phantom. At the end of simulation, GATE also generates a dose uncertainty file which is corresponding to the absorbed dose file, with the same dimensions as the input image. The dose output results were normalized per source disintegration to obtain an S value. The S value is defined for each pair of source (r_s) and target (r_t) regions as follows:

$$S \text{ value}\left(r_t \xleftarrow{E} r_s\right) = \frac{\textit{mean absorbed dose in } r_t}{\text{radioactive disintegration } \textit{in } r_s} \quad (1)$$

where E is the mean (or individual) energy of the nuclear transition [30]. For calculation of S value in the TLD method, the mean absorbed dose in each region was divided by the total number of nuclear transformations in the source region over the dose integration period ($\tilde{A} \approx 1.443 A_0 T_{\text{eff}}$).

Results

The mean absorbed dose per cumulative activity (S values) derived from GATE Monte Carlo package and TLD measurements are listed in Table 1. The first column of the Table 1 represents the ID of the positions in the head portion of the RANDO phantom where the TLDs were placed. In the next two columns the S values derived with GATE and TLD measurement are presented, respectively. The relative percentage differences between the S-values derived by GATE and TLD measurement are presented in the fourth column. Figure 1 represents the scatter plot of S values data and a linear curve fitted to them. The Pearson's correlation coefficient showed an excellent linear correlation between the GATE and TLD results ($r^2 \geq 0.99$). Figure 2a, b illustrate the absorbed dose distribution (normalized to the maximum dose) resulting from the GATEMonte Carlo package calculations for the axial slice numbers 2 and 9, respectively. Meanwhile, lateral and coronal slice images of the absorbed dose distribution from the human head scans of the RANDO phantom are shown in Fig. 2c, d, respectively. The lateral slice number 109 and coronal slice number 200 were approximately the central slices in the head anatomy, and therefore chosen for this illustration. In addition to the dose distribution figures, differential and integral dose volume histograms (DVHs) were plotted for each slice and total slices to determine the overall dose distribution within the RANDO human head phantom. The DVHs in Fig. 3a–c represent the volume of each and whole slices that received at least a given dose.

Discussion

In this work, the GATE Monte Carlo package was used to obtain acceptable estimates of 3D voxelised dosimetry in a voxel version of the human head phantom. Absorbed dose was directly calculated using the GATE Monte Carlo package and compared with measured TLD data. The

Table 1 The *S* values (mGy MBq^{-1} s^{-1}) derived with GATE simulation and TLD measurement (^{99m}Tc,E_{Photon} = 140 keV)

Target ID	TLD method (mean ± SD)	GATE Monte Carlo (mean ± SD)	Percentage difference (%)
9A	$1.95 \times 10^{-4} \pm 7.87 \times 10^{-6}$	$1.89 \times 10^{-4} \pm 1.77 \times 10^{-6}$	3.2
9B	$2.87 \times 10^{-6} \pm 1.23 \times 10^{-7}$	$2.60 \times 10^{-6} \pm 1.02 \times 10^{-7}$	9.2
9D	$5.29 \times 10^{-6} \pm 1.04 \times 10^{-6}$	$5.02 \times 10^{-6} \pm 1.72 \times 10^{-7}$	4.9
9E	$1.44 \times 10^{-6} \pm 3.41 \times 10^{-7}$	$1.24 \times 10^{-6} \pm 5.30 \times 10^{-8}$	14.0
9F	$4.30 \times 10^{-7} \pm 2.02 \times 10^{-7}$	$3.81 \times 10^{-7} \pm 9.84 \times 10^{-9}$	11.0
9I	$5.63 \times 10^{-06} \pm 7.10 \times 10^{-7}$	$5.20 \times 10^{-6} \pm 1.70 \times 10^{-7}$	7.5
9G	$2.80 \times 10^{-6} \pm 1.56 \times 10^{-7}$	$2.66 \times 10^{-6} \pm 3.80 \times 10^{-8}$	5.2
9 J	$6.67 \times 10^{-6} \pm 3.41 \times 10^{-7}$	$5.97 \times 10^{-6} \pm 1.04 \times 10^{-7}$	10.0
10A	$5.84 \times 10^{-6} \pm 1.80 \times 10^{-6}$	$5.35 \times 10^{-6} \pm 6.50 \times 10^{-8}$	8.5
10B	$1.09 \times 10^{-6} \pm 5.21 \times 10^{-8}$	$9.44 \times 10^{-7} \pm 2.10 \times 10^{-8}$	14.0
10D	$3.46 \times 10^{-6} \pm 5.21 \times 10^{-7}$	$3.03 \times 10^{-6} \pm 3.56 \times 10^{-8}$	12.0
10E	$6.38 \times 10^{-6} \pm 5.21 \times 10^{-7}$	$5.90 \times 10^{-6} \pm 1.02 \times 10^{-7}$	7.6
10F	$2.81 \times 10^{-6} \pm 7.10 \times 10^{-8}$	$2.61 \times 10^{-6} \pm 1.14 \times 10^{-7}$	7.1
10G	$1.55 \times 10^{-6} \pm 1.42 \times 10^{-7}$	$1.35 \times 10^{-6} \pm 8.33 \times 10^{-8}$	13.0

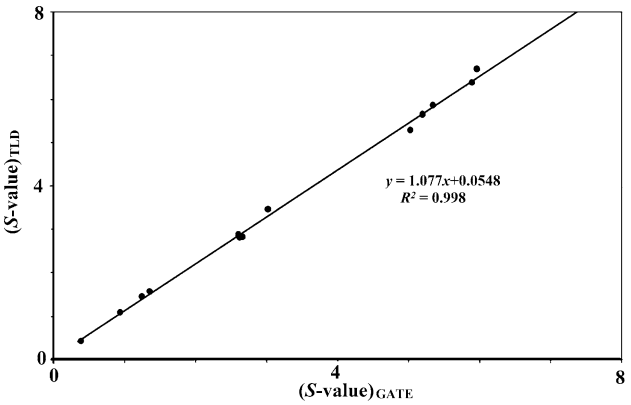

Fig. 1 The scatter plot of TLD and GATE *S* value (10^{-6} mGy MBq^{-1} s^{-1}) data

standard electromagnetic processes (SEP) were utilized in GATE simulation. The greatest discrepancy between the simulated and measured S-values was 14 %. Lower deviations were observed for most cases. In a study, Yaşar and Tuğrul [31] placed several TLDs in a RANDO phantom to measure the absorbed dose in the critical organ and compared the results with MIRD methodology. They have produced similar results and the difference level was reported within 15 %. In another study, Sahebnasagh et al. [32] mentioned the same agreement between TLDs measurement and the MCNP and MIRD results.

It is clear from Table 1, the maximum and the minimum *S*-values are related to target points 9A and 9F, respectively. The difference between the *S*-values is related to the difference in the distance to the source region. The target point 9A is located nearest to the source region (i.e. above the source region). The measured S values generally are higher than those calculated with GATE. The reason for this is that the experimental measurement was performed in the realistic conditions and the readings measure the environmental scattering effects which may have influence on its results [33]. Axial, lateral, and coronal slice images of the dose distribution of the RANDO head phantom visually depict that most of the ^{99m}Tc gamma radiation is absorbed in the brain and surrounding tissues (shown in Fig. 2). From these figures,a linearity of the absorption of radiation is found with a maximum distribution of the dose at the center of the source region with a gradual decrease with distance. Similarly, according to dose curves in the DVHs, the dose decreased along the direction of movement toward the lower slices of the head phantom, as shown in Fig. 3b, c. The differential DVHs visually reveal the variations of mean absorbed dose per administrated activity at voxel level for each slice and total slices. In the Fig. 3a, in contrast with the lower slices, the upper slices of the head phantom such as slices 2 and 6 received slightly higher absorbed dose, in accordance with the values reported in the S values of Table 1. The fluctuations also exhibited in the differential DVHs, especially for the upper slices, could be related to the variety in attenuation properties of voxels in proximity of source voxels of the RANDO phantom.

As it can be seen in Fig. 3b, c, the integral DVHs derived using the GATE calculation experience a monotonically descending trend, which is theoretically expected. The overall statistical uncertainty was around 7 % for all voxels; a statistical uncertainty less than 2 % was found for the nearest voxels from the source. The statistical uncertainties were estimated according to the approaches

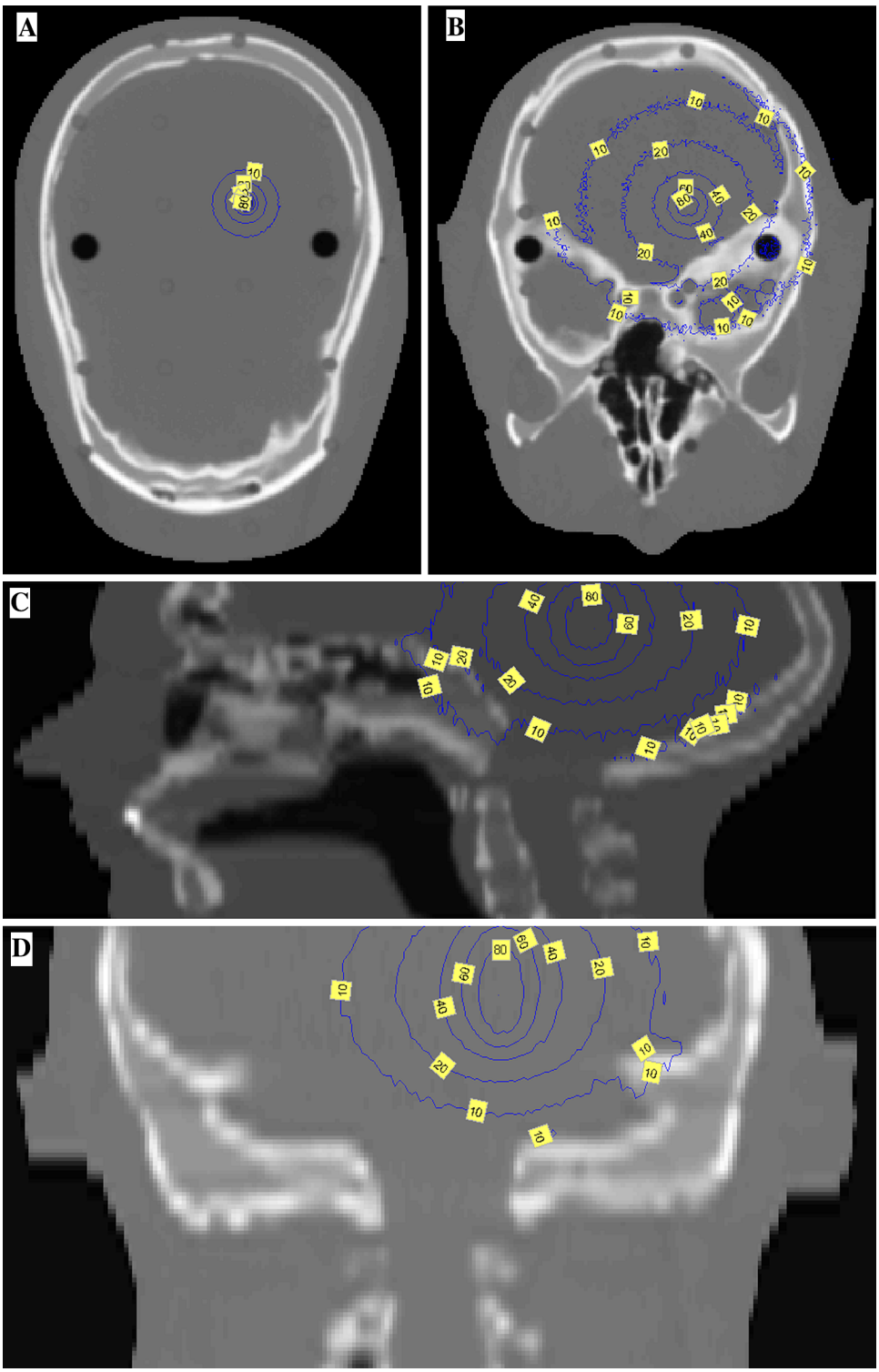

Fig. 2 Absorbed dose distribution (normalized to the maximum dose) overlaid on the RANDO head CT images for: **a** Trans-axial slice No. 2, **b** Trans-axial slice No. 9, **c** Lateral slice No. 109 and **d** Coronal slice No. 200, computed using GATE, obtained from a rod ^{99m}Tc source

presented by Stabin [34] and Pacilio et al. [35]. The *S*-value for the absorbed dose due to the local depositionfor ^{99m}Tc in this work was 1.74×10^{-4}mGy MBq^{-1} s^{-1}. Hindorfet al. [36] demonstrated that the mass and the shape of the organs and their locations relative to each other are important parameters for self and cross-absorbed *S* values.

Conclusions

This work indicates a possibility to conduct imaging-based dose calculation using the GATE Monte Carlo package together with a voxel model of a physical human phantom. The agreement of experimental measurements with GATE

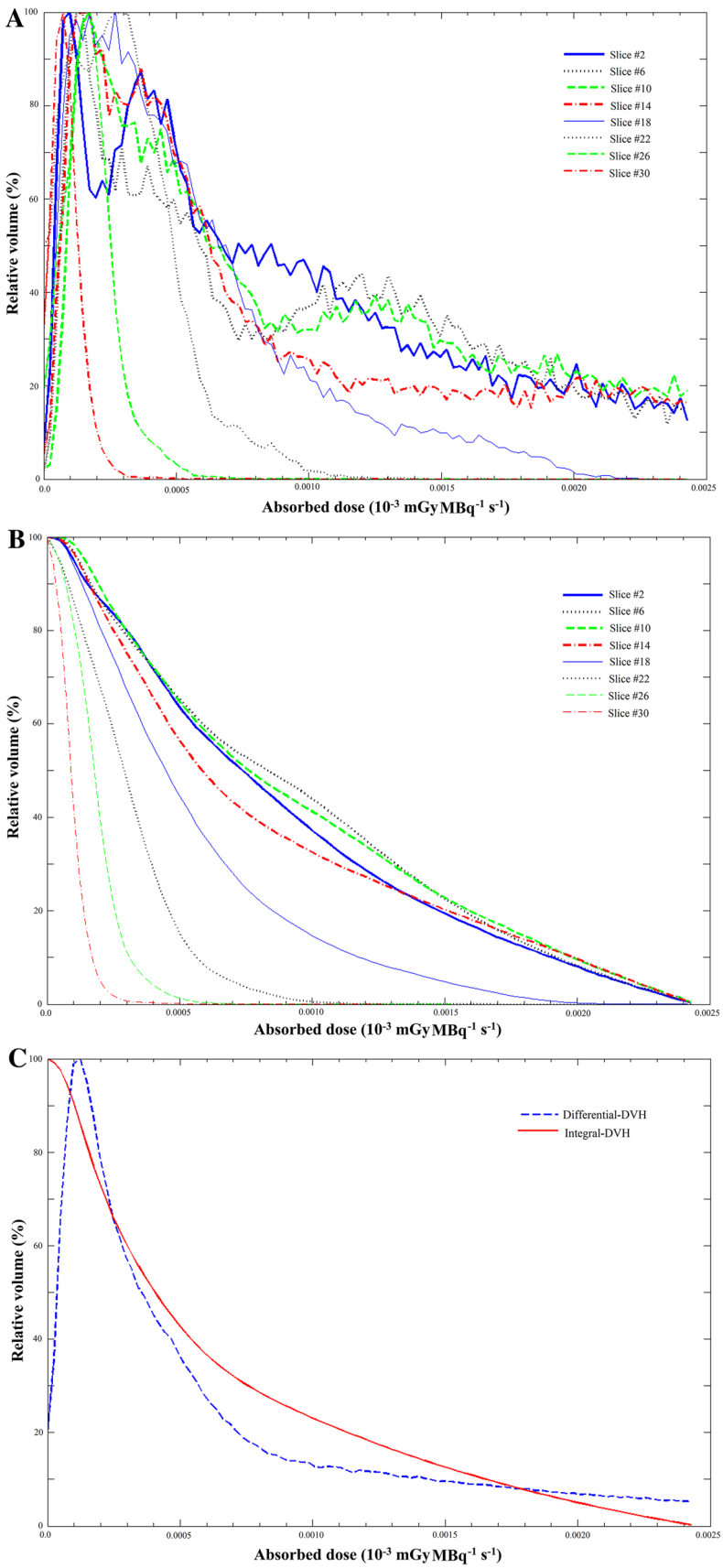

Fig. 3 Differential and integral dose-volume histograms (DVHs) calculated by voxel-based analysis of the dose images for RANDO head phantom: **a** Differential DVHs in slice No. 2–30, **b** Integral DVHs in slice No. 2–30 and **c** Differential and integral DVHs for overall head slices

computation for a portion of a humanoid phantom also demonstrates the usefulness and applicability of GATE Monte Carlo package for voxel level dose calculations in non-uniform media by use of the attenuation and emission maps. This is a step to ward patient-specific radionuclide dosimetry in diagnostic and therapeutic procedures in nuclear medicine from CT and scintigraphic data. It can be deduced that a complete dosimetry simulation study, from image generation to absorbed dose maps calculation, is possible to execute in a single framework using the GATE Monte Carlo package. It is expected that in the near future, GATE Monte Carlo package will play an increasingly important role in both domains of imaging and therapeutic dose assessment in medicine.

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