Computation of a voxelized antropomorphic phantom from Computer Tomography slices and 3D dose distribution calculation utilizing the MCNP5 Code.

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Abstract. The purpose of this work is to obtain the voxelization of a series of tomography slices in order to provide a voxelized human phantom throughout a MatLab algorithm, and the consequent simulation of the irradiation of such phantom with the photon beam generated in a Theratron 780\textsuperscript{®} (MDS Nordion) \textsuperscript{60}Co radiotherapy unit, using the Monte Carlo transport code MCNP (Monte Carlo N-Particle), version 5. The project provides dose mapping calculations inside the voxelized antropomorphic phantom. Prior works have validated the cobalt therapy model utilizing a simple heterogeneous water cube-shaped phantom [1]. The reference phantom model utilized in this work is the Zubal phantom [2], which consists of a group of pre-segmented CT slices of a human body. The CT slices are to be input into the Matlab program which computes the voxelization by means of two-dimensional pixel and material identification on each slice, and three-dimensional interpolation, in order to depict the phantom geometry via small cubic cells. Each slice is divided in squares with the size of the desired voxelization, then the program searches for the pixel intensity with a predefined material at each square, making a subsequent three-dimensional interpolation. At the end of this process, the program produces a voxelized phantom in which each voxel defines the mixture of different materials that compose it. The output of this code follows the MCNP input deck format and is integrated in a full input model including the \textsuperscript{60}Co radiotherapy unit.

Dose rates are calculated using the MCNP5 tool FMESH, superimposed mesh tally. This feature allows to tally particles on an independent mesh over the problem geometry, and to obtain the length estimation of the particle flux, in units of particles/cm\textsuperscript{2}·s (tally F4). Furthermore, the particle flux is transformed into dose rate by using the conversion factors extracted from the NIST Physical Reference Data.

KEYWORDS: Voxelized phantom, Monte Carlo method, MCNP Simulation, Dosimetry, Biomedical applications of radiation

1. Introduction

Techniques based in Monte Carlo method have introduced significant improvement in the field of Radiotherapy Treatment Planning. These techniques make use of the statistics in order to simulate the stochastic process of particle transport and energy deposition on different tissues or materials. The Monte Carlo algorithms are considered within the most precise and fast methods for dose calculations, with the only limitation of the large computing time cost. Furthermore, the more the computing technology develops, the more accessible they become in the field of medical physics.

The methodology of this work has been developed by using MCNP, a non-analog computer code based in Monte Carlo, for the calculation of the dose given by a photon beam generated in a \textsuperscript{60}Co radiotherapy unit to a voxelized antropomorphic phantom reconstructed from pre-segmented CT slices. The whole MCNP model includes the anthropomorphic phantom and the cobalt therapy unit, which has been validated in previous works [1] by using a heterogeneous water cube-shaped phantom. The Zubal Phantom [2], courtesy of Dr. George Zubal from Yale University, has been used as the reference model in this work. The phantom presented by Dr Zubal consists of a series of pre-segmented CT slices of a human torso and head, with the format of tiff files. The first goal of this project is to provide the voxelization of such phantom by loading the CT slices into the Matlab code, which builds up a 3D voxelized model by means of two-dimensional pixel and material identification and three-dimensional interpolation. Resulting voxels define the mixture of different materials. The output of this code follows the MCNP input deck format and is integrated in the full input model including the \textsuperscript{60}Co radiotherapy unit.
The Matlab algorithm developed here is to be validated by simulating the irradiation of the Snyder Head phantom, from the Massachusetts Institute of Technology [3], and comparing the results with the simulation of the irradiation of the 8 mm Voxelized Surface Snyder Head Phantom model generated by the same authors [4].

The second goal of the project is to simulate the irradiation of the phantom together with the $^{60}$Co unit. The radiotherapy unit is integrated by making use of the surface source SWW/SRR card, and the particle flux obtained at each voxel is converted into absolute dose via conversion coefficients from the NIST database.

The success in this work aims to the application of the voxelization algorithm to our own pre-segmented CT slices and the calculation of the dose distribution in real-patients-based phantoms applied to the radiotherapy treatment planning.

2. Materials and methods

2.1. Validation of the voxelizing program in Matlab

In order to validate the Matlab program, the Snyder Head [3] numerical head phantom has been utilized. This phantom consists of a series of 125 images, which simulate a human head via three ellipsoids and depict the limits of the three main materials defining the head structure: skin, skull and brain. The original phantom is presented in a multiple-image tiff file.

**Figure 1:** Slice of the Snyder Head multiple-image model.

The 8 mm Voxelized Surface Snyder Head Phantom is an MCNP input deck which describes an 8 mm voxelization of the Snyder Head model, provided by the Nuclear Engineering Department at the ‘Massachusetts Institute of Technology’, [4]. This input is the reference model to which the model created by the Matlab code developed in this work is to be compared. The simulation of the irradiation of these two 8 mm voxel phantoms is performed with the $^{60}$Co radiotherapy unit presented in section . The first step for building up the phantom is to input the Snyder Head images to Matlab. The Matlab code starts the calculations by performing an 8 mm two-dimensional voxelization, continuing with a material-to-pixel identification and three dimensional interpolations, which result in an MCNP input deck. This process is further detailed in the next section. The resulting model is a 3D structure composed by 28 x 24 x 18 voxels of 8 mm x 8 mm x 8 mm each, which define 2854 different material mixtures of the original four materials (air, skin, skull and brain).

The 8 mm Voxelized Surface Snyder Head Phantom consists of 16016 voxels. The difference in the number of voxels compared with the model provided by our program (3920 more than our model) is due to the fact that our developed code has the possibility of joining the outer air voxels in a single geometric element, with the purpose of saving computing time. Also, the different interpolation methods cause a difference in the number of material mixtures: The reference model is composed by 283 material mixtures, 2571 less than our model.
The 8 mm Voxelized Surface Snyder Head Phantom was originally designed to be irradiated with a monodirectional neutron surface source of 10 cm diameter and coaxial with the Z axis of the head phantom. In order to perform both simulations under the same conditions, the $^{60}$Co radiotherapy unit was integrated in the reference model in substitution of the neutron source, by making use of the SSR/SSW surface source card. Both models have been simulated with 940700 particles stored in the surface source file (100000000 original particles in the simulation of the radiotherapy unit), coaxial direction with the X axis.

Particle flux in both phantoms has been compared. The following graphs show the relative error for both XY and YZ central planes.

**Figure 3**: Relative error (%) in each voxel for the XY and YZ central planes.

The results show that in the worst case, a relative error of 4% has occurred, while in most of the cases the relative error is lower than 1%. The bigger differences appear in the boundary regions, due to the different interpolation methods applied to the calculation of the material mixtures in the voxels. In any case, the program offers confident results.
2.2. Voxelization algorithm and the Zubal phantom

The voxelization Matlab code developed in this work is intended to build anthropomorphic phantoms from series of pre-segmented CT images obtained from patients in Radiotherapy Treatment Plans. The previous segmentation of the images provides a relationship between the pixel intensities and the tissue or body structure materials to be identified. Making use of this relation, the process of voxelization starts by dividing the images into squares with the desired voxel size, and evaluating the materials contained in the squares by pixel intensity identification. Then the program labels each square with the proportion of different materials that compose it and makes a 3-dimensional interpolation within all the CT slices, resulting in a voxelized phantom, in which each voxel depicts a mixture of materials. Finally, the whole phantom is output with the MCNP input deck format.

The first goal of this work is to make use of the voxelizing Matlab algorithm to create a voxelized human head phantom from the Zubal phantom. This phantom consists of 243 pre-segmented slices, 42 of which correspond to the ones defining the head. The Zubal phantom is a reconstruction from X-ray CT images of 512x512 pixels with a resolution of 1 mm in the XY plane and 0.5 cm (from the neck to the crown of the head) and 1 cm (for the rest of the body) in the Z-axis. The final phantom is interpolated to create a 128x128x243 bytes volume with isotropic dimensions of 4 mm, and the portion used for this paper is of 128x128x42 that corresponds to the head of the phantom. Each pixel of the volume contains an index number designating it as belonging to a given organ or internal structure; 31 of such index numbers are assigned to the head.

The 42 slices defining the head of the Zubal phantom are input into the Matlab program. Several subroutines build up the phantom throughout 3D interpolations, assigning to each voxel the proportion of index numbers contained. Since the Zubal phantom is pre-segmented with dimensions coincident with the size of the voxels (4 mm x 4 mm x 4 mm), each one depicts a single index number. Subsequently, the program identifies each index number with a material and passes the information to the last routine which transforms it into a MCNP input. The 31 index numbers result in 13 different biological materials, which composition is defined in the ICRU REPORT 46 [5] and 44 [6].

In order to reduce the computing time for the MCNP simulation, a reduction of the outer voxels which have an air material assigned is applied in the Matlab algorithm. The resulting MCNP model is a 177828 voxels or cells (excluding the universe) input.

Figure 4: Sketch of the head phantom. Full head and inside cut.
2.3. ⁶⁰Co Radiotherapy Unit and validation

The Radiotherapy Unit utilized in this work is a Theratron 7800®. The main reason for using such Radiotherapy Unit is the fact that ⁶⁰Cobalt gamma spectrum is discrete and well known and therefore easier for modeling purposes. Cobalt units use a ⁶⁰Co radioactive source which is placed in the treatment head. To deliver dose to patients the radiation beam from the source is collimated by jaws.

The validation of the Theratron 7800® (MDS Nordion) ⁶⁰Co Radiotherapy Unit MCNP model has been proved with previous works [1]. These compare the calculations of the energy deposition in a homogeneous and in a heterogeneous phantom with experimental data. The irradiated phantom consists of a water tank with a polystyrene heterogeneity inside.

The model comprises a Theraton Radiotherapy irradiator positioned to give a beam focused on the axis origin of the phantom. The cobalt unit has a leaf collimator to provide rectangular fields of 10 cm x 10 cm. The ⁶⁰Co source is made up of small pellets placed in a cylindrical capsule of stainless steel and surrounded by different materials, such as tungsten and brass. As well as this cylindrical source capsule and its housing geometry description, the Cobalt activity and its 6 different gamma-ray lines spectrum have also been included. A volumetric type source has been applied, which involves realistic cylindrical ⁶⁰Co source capsule.

2.4. Simulation with MCNP

The simulation carried out with MCNP makes use of the resulting voxelized anthropomorphic phantom from the Matlab code, integrated in an input model together with the Radiotherapy Unit. The previous works of validation of the ⁶⁰Co Radiotherapy Unit resulted in a simulation that provides a surface source file, which was written by making use of the SSW/SSR card. This surface source file is the starting point of 940700 particles registered and resampled with 100000000000 (from the original 100000000000 with which the validation was initially simulated). The complete model is designed with a Surface Source Distance of 80 cm, which is the recommended for a ⁶⁰Co therapy unit.

The use of tally cards in MCNP is necessary in order to specify the type of information wanted from the Monte Carlo calculation. The FMESH Tally is utilized in this work with the purpose of defining a mesh tally superimposed over the problem voxel geometry, so that information is reported in each voxel. The FMESH tally calculates by default the track length estimate of the particle flux, averaged over a mesh cell, which in our case corresponds to a voxel, in units of particles/cm²·s. The process of conversion from particle flux to equivalent dose required the card to be organized so that the particle flux in each voxel is divided in 25 bins of energy from 0 to 1.6 MeV, using the EMESH option. This way, two separate MESHTAL files, one for photons and another for electrons, output the results for each Z bin (voxels in the XY plane) and for each energy bin. The tally results are presented with an associated percentage error value.

MCNP calculates the radiation transport following individual photon and electron histories going through the whole geometry of the phantom. There has been considered, in the energy range between 0.001 and 2.6 MeV, a detailed photon physics treatment including photoelectric effect with fluorescence production, incoherent and coherent scattering and pair production. For the simulation of the ⁶⁰Co unit a ‘photon and electron’ model (MODE PE) has been used, in which all photon collisions except coherent scattering can create electrons which are banked for later transport.

The MCNP code has been parallelized in as SGI Altix 3700, using the MPI parallel protocol, in this case with 6 processors. This way, the problem is divided in 6 problems reducing the computerized time in the same proportion. Furthermore, the MCNP code has been adapted to the problem geometry by increasing the maximum number of cells allowed in the input geometry description to 200,000 with the Intel Fortran Compiler 9.0, on the Linux parallel computing machine [7].
The final total computing time for the tallied photons is of 703.75 minutes (11.72 hours), and for the tallied electrons is 713.66 minutes (11.89 hours).

2.5. Flux to Dose conversion

The FMESH tally provides the results in units of particle flux. The conversion to dose is managed separately with a Matlab program, due to the complexity of the whole procedure. The NIST Physical Reference Data web page [8] was used in order to calculate both photon cross sections and electron stopping power for the different tissue materials. The information obtained from the NIST is stored in matrices to be called by the dose calculation algorithm. The other information used by the Matlab code is the group of matrices where the particle flux is given at each plane and energy bin, obtained from the MESHTAL file.

The Matlab program begins the calculation by first identifying the different materials that compose each voxel located at the voxel plane where the calculation is desired. Each material is associated with the corresponding cross section coefficient for the photons and with the stopping power for the electrons. Then the corresponding particle flux results for photons and electrons, taken from the MESHTAL file, are also input. The program effectuates a matrix entries multiplication and addition following the formula for flux to dose conversion. In the end, the dose given by photons is added to the dose given by electrons and converted to Grays. Results are presented in the form of relative dose profile curves and relative depth dose curves, for each desired plane.

3. Results

This work was intended to present the results by first giving absolute dose graphs for the central Z plane (from 0.4 cm to 0 cm of the origin of axis) in the form of isodose curves and an additional graph presenting the dose in each voxel. The results are given in Gray units:

**Figure 5:** Absolute dose isodose curves for an XY voxel plane situated at the center of the phantom.
Figure 6: Absolute dose in each voxel of the XY voxel plane situated in the center of the phantom.

Secondly, an absolute depth dose was calculated at the same Z bin and for a central point in the x axis, X=26. This result is presented in the following graph, also in Grays:

Figure 7: Absolute depth dose for the central XY plane and X=26.

An average relative error of 0.0693 is estimated for the photons at the Z plane and X point mentioned before. For the electrons, the average relative error at the same location is estimated to be 0.123.

4. Conclusions

The implementation of Monte Carlo based methods in the field of Radiotherapy Treatment Plans is a new methodology utilized in this paper, with great future aspirations. Also, anthropomorphic
Numerical phantoms are of great need in such treatment plans. The results obtained in this paper prove computerized voxelized human phantoms to be a valid tool for the calculations of irradiated patients absorbed dose. The results of the simulation of an irradiation with a photon beam focused on a patient tumor provide depth dose curves with a relative error of around 5% for photons and 10% for electrons, and this has been proved for a 4 mm voxelized anthropomorphic phantom.

The use of voxelizing methods in building up human phantoms from pre-segmented CT images has been described and successfully validated in this work. Future scopes to the voxelization of non-pre-segmented images making use of more complex interpolation and identification methods. Also, smaller voxel sizes would lead to a more precise geometry description, even though the computing times would increase. This will develop along with the computing technologies.

The future development of this methodology scopes to the coupling of the voxelization of non-pre-segmented CT images with the MCNP simulations and with the flux-to-dose conversion algorithm. This work is a step forward in the increasing necessity for a user friendly radiotherapy treatment planning program based on Monte Carlo and for specific patient-based anthropomorphic phantoms in the medical physics field.

REFERENCES