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ARTICLE

Comparison of MCNP5 Dose Calculations inside the RANDO® Phantom Irradiated with a MLC LinAc Photon Beam against Treatment Planning System PLUNC

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MC treatment planning techniques provide a very accurate dose calculation compared to 'conventional' deterministic treatment planning systems. In the present work, PLanUNC (PLUNC), a set of software tools for radiotherapy treatment planning (RTP), is compared with MCNP5 (Monte Carlo N-Particle transport code) by calculating dose maps inside the RANDO® phantom, utilized as the patient model, irradiated with different field sizes with the Multi-Leaf Collimated (MLC) Linear Accelerator (LinAc) Elekta Precise. PLUNC was initially coupled with MCNP5 and so exactly the same patient and plan parameters can be utilized in both dose calculation processes. A MLC Linear Accelerator was commissioned for PLUNC and a MCNP5 model used in the calculations. The coupling of MCNP5 with PLUNC has been achieved via a series of Matlab interfaces, which extract patient and beam information created with PLUNC during the treatment plan and write it in MCNP5 input deck format. A set of Computer Tomography images of the RANDO® phantom was obtained and formatted. The CT slices are input in PLUNC, which performs the segmentation by defining anatomical structures. The Matlab algorithm developed by the authors, validated in previous works writes the phantom information in MCNP5 input deck format. Both calculations result in mapping of dose distribution inside the phantom. MCNP5 utilizes the FMESH tool, superimposed mesh tally, which allows registering the results over the problem geometry. Resulting dose maps are compared.

KEYWORDS: Monte Carlo, MCNP5, PLUNC, radiotherapy, treatment plan, RANDO® phantom

I. Introduction

The purpose of Radiotherapy Treatment Planning systems (RTP) is to estimate the dose absorbed by a patient in a radiotherapy session, so that tumors can be irradiated with the strictly necessary dose. RTP systems still deal with several features that can be optimized, for instance, they do not properly take into account the influence of heterogeneities inside the body against radiation absorption, and they use empirical deterministic algorithms instead of simulating the full stochastic process.[1)]

Monte Carlo (MC) simulation techniques are nowadays considered a very useful aid for patient dose calculation in RTP systems. Many works [1)] have proved MC techniques as a highly accurate dose calculation tool compared to 'conventional' RTP systems, having the only limitation of computing time cost.

The main purpose of this paper is to compare the results obtained from the deterministic calculations of PLanUNC (PLUNC),[2)] a set of software tools for radiotherapy treatment planning (RTP), with those obtained by means of MCNP5 (Monte Carlo N-Particle transport code)[3)] utilizing the RANDO® phantom[4)] as the patient model and the MultiLeaf Collimated (MLC) Linear Accelerator (LinAc) Elekta Precise as the irradiation source.

For this purpose, the simulation of the phantom irradiation with the MLC LinAc has been performed with different field sizes and the results compared via dose distribution, depth dose and dose against skin structure volume curves.

II. Materials and Methods

1. Description of the Coupling of MCNP5 and PLUNC

In order to provide a more detailed calculation algorithm inside the treatment planning system PLUNC, MCNP5 has been coupled via a series of Matlab interfaces, so that the user of PLUNC can proceed with an alternative simulation of the irradiation of the patient with MCNP5. PLUNC software provides a full range of RTP functions, which include image importing and processing, virtual simulation, dose calculation, plan evaluation, and planning for intensity modulated radiotherapy. In addition, PLUNC is complemented with a MC interface package for EGS which provides the code information to be managed by the Matlab interfaces created by the authors of this paper in order to prepare the MCNP5 simulation.

The Matlab interfaces extract patient and beam information created with PLUNC once the treatment plan is complete and write it in MCNP5 input deck format. Once the Monte Carlo simulation is performed, results are input back again in PLUNC in order to evaluate the treatment plan, and, in the case of this paper, to compare the results with the dose calculated by PLUNC's Clarkson Integrated Batho-homogeneity-corrected algorithm.[4-6)] The Batho algorithm uses the principle of the Clarkson method on sector integration to take into account the position and lateral

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extent of the inhomogeneity with respect to the point of calculation, as well as the shape of the irradiating field.

2. MCNP Model of the RANDO® Phantom

The use of anthropomorphic phantoms has been popular within medical physicists and radiation therapists for many years. In this work, the female RANDO® Phantom,[7] provided by the Hospital Clínic Universitari de València, was utilized in this work. It has been constructed with three different materials which allow to overcome the disadvantages of non-uniformity of materials, size and shape. A picture of the Laboratory Phantom can be seen in **Fig. 1**.

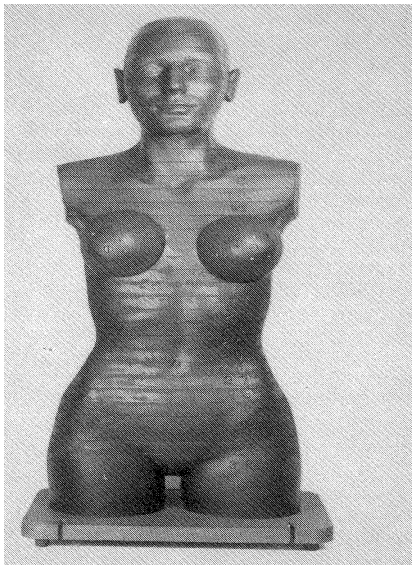

Fig. 1 RANDO® laboratory phantom

The female RANDO® Phantom represents a 163 cm tall and 54 kg female figure. It does not have arms or legs, and the portion utilized in this work corresponds to the head. It has been constructed with a natural human skeleton cast inside soft tissue simulating material. The air space of the head and neck are duplicated. Two tissue-simulating materials comprise the phantom head: the RANDO® soft tissue material (0.997 g/cc), designed to have the same absorption as human tissue at the normal radiotherapy exposure levels, and the skeleton (1.61 g/cc).

A set of 60 Computer Tomography (CT) slices was obtained from the head of the RANDO® Phantom at the Hospital Provincial de Castelló with an image resolution of 512 × 512 pixels and 16 bits per pixel, separated by 0.4 cm one from the other.

The 60 CT images were input in PLUNC, by converting the 60 dicom images into PLUNC's single image file *plan_im*, and subsequently the segmentation of the images was performed via the PLUNC anastruct editor, obtaining two different anatomical structures, the soft tissue, named as *skin* so PLUNC knows where to start performing the calculations, and the skeleton. Once the segmentation is performed, the Matlab interfaces read the phantom information via PLUNC MC Interface and write it in the MCNP5 input deck format, taking into account the size of the segmented phantom and the position where the beam is focused to give 100% of the dose. The MCNP5 lattice card is used to depict de voxel geometry, reducing this way the computing time around 6 times.[8]

The three-dimensional voxelized phantom MCNP5 model of the head of the RANDO® phantom is a 2,441,216 voxels lattice structure.[9]

PLUNC utilizes the Clarkson Integrated Batho homogeneity corrected algorithm, and in this case assuming the densities fixed by the segmentation process instead of the Hounsfield numbers. Dose grid parameters and dose data are stored in a binary file named sum for each treatment plan. Several subroutines (grid_info) are used to read the sum file and print out grid and dose information. Making use of these subroutines, dose grid obtained in the simulation with MCNP5 is input back in PLUNC.

3. MCNP5 MultiLeaf LinAc Model

An MCNP5 Elekta Precise MultiLeaf Collimated Linear Accelerator model was validated in previous works[10-12] at 6 MeV. The MLC LinAc is prepared to give different field sizes at 100 cm from the source. In this work, 5 cm × 5 cm, 7 cm × 7 cm, 10 cm × 10 cm and 12 cm × 12 cm field beams are used to irradiate the phantom. The validation of the simulation of each field size was performed with a phase-space file which stores the particle information so that, in future simulations, the same source file can be used by changing its position, when necessary, according to the gantry, table and collimator angle, significantly reducing the computing time. In the case of the 5 cm × 5 cm field beam, the phase-space file is the starting point of 4,725,581 independent particle histories, resulting from the original 2×10^9 of the treatment head simulation, which were resampled 1,000 times in the simulation of patient irradiation, meaning that the final simulation is performed with 4,725,581,000 particles. The same procedure is used for each field size.

In order for a RTP unit to achieve accurate dose computation in PLUNC, which refers to a physical machine operating at a set energy level and modality, its detailed physical and dosimetric descriptions is established through the PLUNC commissioning process, by which the Elekta Precise Multileaf Linear Accelerator was implemented in PLUNC. This way, PLUNC plan can be performed with the same MLC LinAc model that was validated for the MCNP5 simulations and the Elekta machine appears as an option for the beam settings after the commissioning process.

The spectrum introduced in PLUNC has been obtained after the simulation of the acceleration of a monodirectional electron point source beam upon the tungsten target using a 6.3 MeV initial electron energy with a radial gaussian FWHM spatial distribution of 0.11 (data supplied by *Elekta*). **Figure 2** shows the photon spectrum obtained in that simulation.

4. MCNP Simulation

MCNP5 has been coupled with PLUNC via a series of

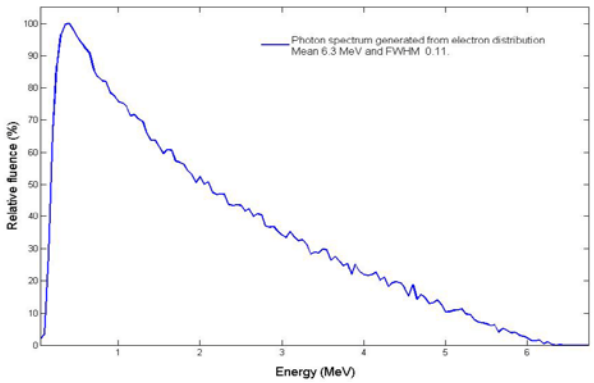

Fig. 2 Photon spectrum generated after an electron energy distribution with mean = 6.3 MeV and FWHM = 0.11

Matlab interfaces, so the simulation of the irradiation of the patient with different field sizes provides the radiophysicist with an alternative accurate Monte Carlo simulation. PLUNC software includes a full range of RTP functions including image importing and processing, virtual simulation, dose calculation, plan evaluation, and planning for intensity modulated radiotherapy.

Patient and beam information created with PLUNC can be translated to MCNP5 code and the simulation performed with the desired field size. Once the Monte Carlo simulation is finished, results are input back again in PLUNC in order to evaluate the treatment plan.

The accuracy of the results very much depends on the strictness of the simulation model and parameters, which include the physics, material properties, geometry specifications, source characteristics, variance reduction techniques, detector tallies and the set of the number of particles to track. The radiation transport is calculated following individual photon and electron histories along the geometry. A detailed photon physics treatment, including photoelectric effect with fluorescence production, incoherent and coherent scattering and pair production, has been considered in the energy range between 0.001 and 7 MeV. The photon energy cut-off considered for this study was 1 keV, the default value in MCNP, while for electrons it was set to 100 keV. An importance ratio of 4 was forced in the voxels within the phantom, so the statistical error would be reduced in the regions where most collisions occur.

The FMESH tally is utilized to define a mesh tally superimposed over the problem geometry. Adding the conversion factors for photons and electrons, this feature calculates the dose averaged over a mesh cell, which in our case corresponds to each phantom voxel. In the end, we obtain the dose distribution maps inside the phantom, which can be input back in PLUNC and can be compared with results of relative dose calculated with PLUNC algorithms.

MCNP code has been parallelized in an HP Proliant DL 580, utilizing the MPI parallel protocol, using 16 processors for our simulation. Furthermore, MCNP code has been modified in order to allow geometries up to 2,900,000 lattice voxels[9] with the Intel Fortran Compiler 11.1, on the Linux parallel computing machine. In the simulation of the irradiation with the 5 cm × 5 cm field beam, the final simulation real CPU time was 444 minutes with MCNP5 version 1.40, for 4,725,581,000 particles.

III. Results and Discussion

Next figures present MCNP and PLUNC relative dose map calculations, visualized by PLUNC RTP tools. The dose map presented corresponds to the 5 cm × 5 cm beam. At 100 cm from the source the 100% of the dose is delivered. This point is called the isocenter of the beam. All dose values are normalized so that the 100% of the dosed is delivered at such isocenter. The final setup provides a Surface Source Distance of 91 cm. In the MCNP simulation, the beam is centered and focused to the axes origin, coinciding with the isocenter in PLUNC's coordinates, along with the positive *x* axis.

Figure 3 shows the relative dose distribution for a 5 cm × 5 cm beam calculated by PLUNC, with the homogeneity correction set by taking into account the anastructures density. The isocenter is called *iso of r-lat*. The isodose curves provide the percentage indicated at the top-left of the graph. The maximum relative dose in the slice is 154.9%.

Figure 4 shows the relative dose distribution for a 5 cm × 5 cm beam calculated with MCNP5 and returned to PLUNC graphical interface for comparison purposes. This way the plan evaluation can also continue. The maximum relative dose in the slice is 163.0%.

It is observed that both relative dose distributions follow a very similar pattern, though MCNP calculations offer a more precise distribution. It is clear that MCNP5 takes into account the dose absorption where a change of material density appears, like from skull to skin or from skin to air. MCNP5 simulation averaged a statistical dispersion of less than 5%.

The comparison of the computed doses with both methods gives a maximum dose relative difference of 4.97%, which can be attributed to the inaccuracies of the PLUNC homogeneity corrected algorithm.

Figures 5, **6**, **7**, and **8** show the dose against volume curve comparison for MCNP5 and PLUNC, inside each of the

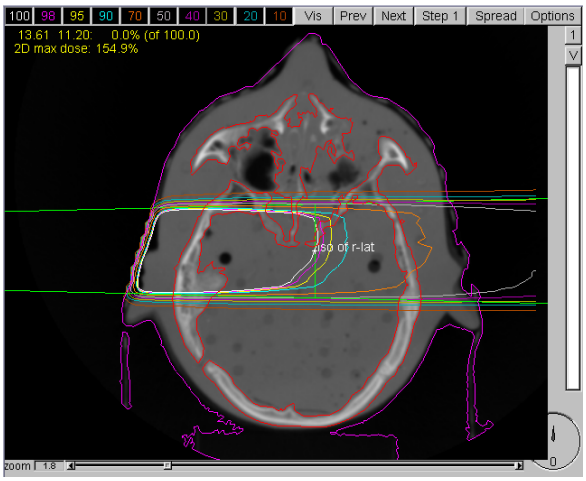

Fig. 3 Relative dose distribution calculated with PLUNC

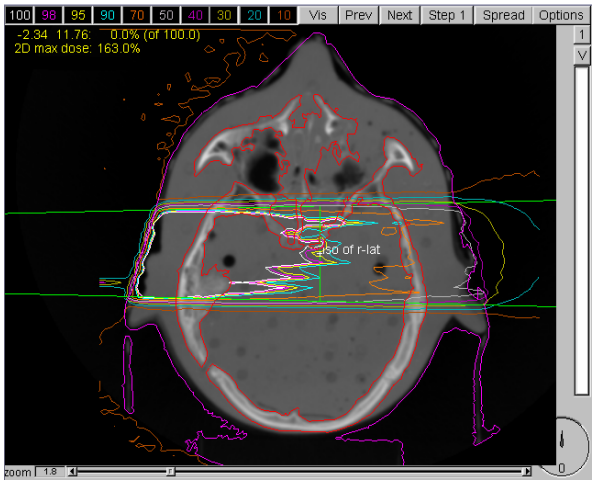

Fig. 4 Relative dose distribution calculated with MCNP5

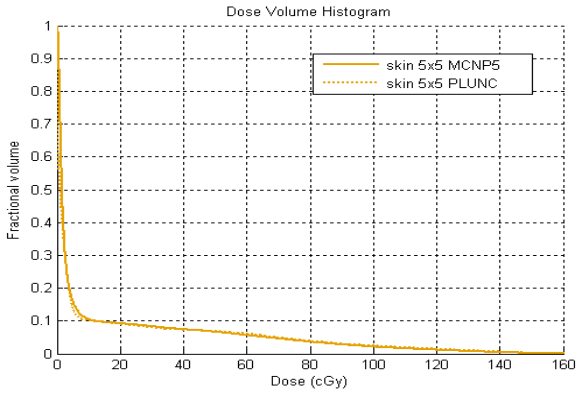

Fig. 5 Dose against skin volume, 5 cm × 5 cm field

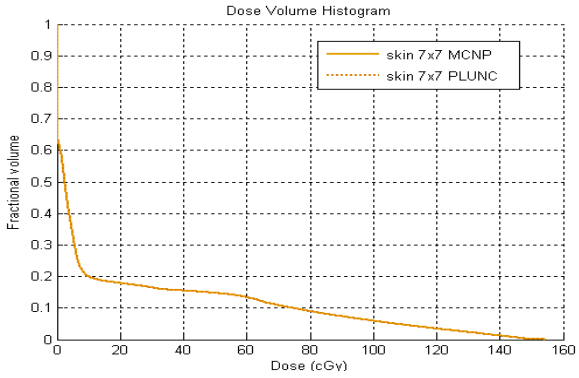

Fig. 6 Dose against skin volume, 7 cm × 7 cm field

anastructures defined in the segmentation process, that is, skin and skull, and is presented for each of the field sizes, that means 5 cm × 5 cm, 7 cm × 7 cm, 10 cm × 10 cm and 12 cm × 12 cm.

Almost no differences can be observed in terms of dose given in a volume percentage of each structure.

Figure 9 shows the relative depth dose curve comparison for MCNP5 and PLUNC calculation. In this case, the irradiation field presented is 5 cm × 5 cm.

The relative depth dose graph provides us with a broader view of the difference between MCNP5 and PLUNC calcu-

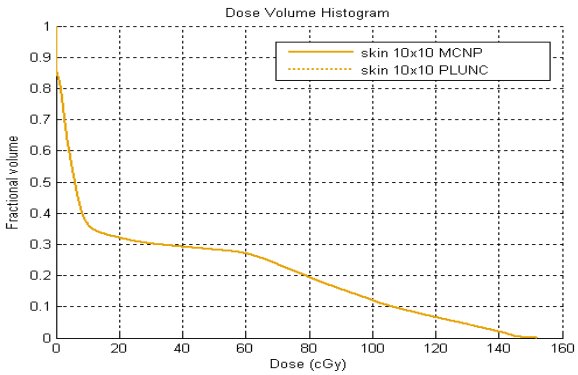

Fig. 7 Dose against skin volume, 10 cm × 10 cm field

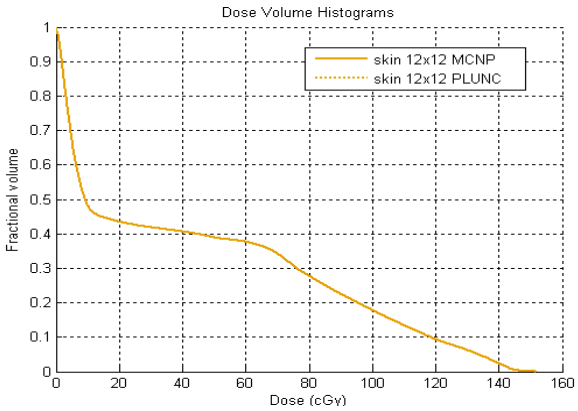

Fig. 8 Dose against skin volume, 12 cm × 12 cm field

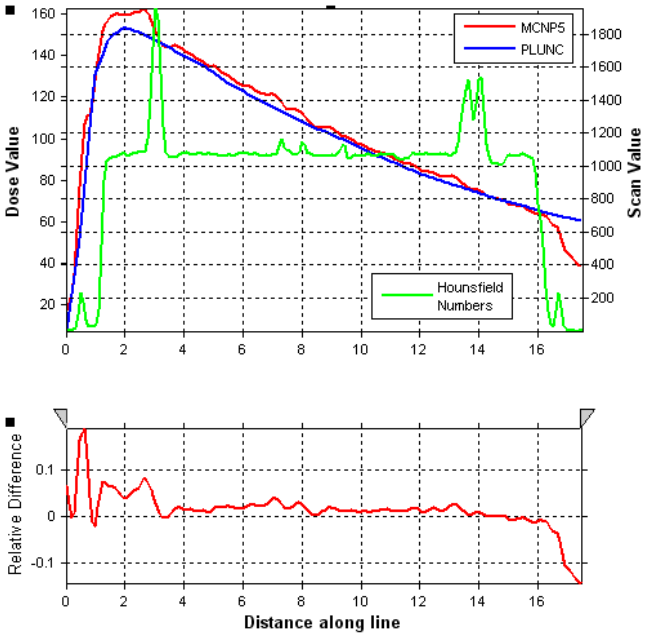

Fig. 9 Relative Depth Dose for the 5 cm × 5 cm field

lations inside the phantom. As the photon beam encounters the first material, the dose is absorbed at a high rate, until the maximum is reached, and then it begins to decay. In the MCNP5 curve, a change of slope is found at 2.5 cm in the

graph, when the skull is reached by the beam, as can be seen through the Hounsfield Numbers curve. PLUNC does not register such change. Afterwards MCNP and PLUNC curves decay at a similar rate, and at the last part the curve shows that PLUNC does not take into account the change to air material after the phantom.

IV. Conclusion

This work offers a valid methodology for precise Monte Carlo calculations during Radiotherapy Treatment Plans. The Monte Carlo simulation takes approximately 444 minutes working with a multiprocessor CPU and utilizing 16 processors each time. This still makes the methodology unfeasible for real therapy plans, though as transport codes and computer technologies develop the computing time becomes more and more realistic, still proving it an optimal tool to evaluate calculations of commercial deterministic planning systems. The required calculation time for a real treatment would be less than 5 minutes, best around 2 minutes. Such calculation times, from the point of view of the number of processors, at this moment, cannot be achieved.

Technology development as well as further research in this field aim to the implementation of Monte Carlo techniques in radiation treatment planning systems for patient dose calculations in realistic computational times. The Monte Carlo method implemented in RTPs allows the radiophysicist to calculate accurate dose maps inside complex geometries with many different material densities and to validate the deterministic computations on a regular basis. It could also be used as a second opinion for a complex planning.

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