Delivered dose from photoneutrons in a head phantom during therapeutic radiation

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Abstract

Regularly, radiation oncologic treatment plannings do not take into account dose received by patients due to induced neutron radiation resulting from high energy radiotherapeutic beams. This information is especially important to estimate health risks, including the possibility of developing secondary cancers. The consideration of neutron dose would permit an optimized management of patient treatment logistics, improving timing, sequencing of treatment and overdosing.

The advantages of using Monte Carlo simulations in this issues is that it is particularly suited to trace all interactions contributing to the dose of modeled patients body, including photoneutron production, providing the most versatile and reliable tool for studying these effects.

This work has developed a comprehensive MCNP5-model [1] simulation to study computed dose distributions obtained using multileaf collimation (MLC) photon therapy beam. Points of dose calculation are located in a head phantom, where the primary irradiation has been pointed out, but also in the superior portion of the torso. The female Rando anthropomorphic phantom has been chosen in this study.

The work is devoted to dose computation, including contribution from photoneutron interactions that would not have been accounted for by conventional radiation therapy planning systems.

Keywords

Radiation treatment planning, photoneutron, multileaf collimation (MLC)

1. INTRODUCTION

High-energy medical electron accelerators (*Linac*) can produce undesirable neutron radiation [2]. Neutrons are mainly produced by resonance reactions in the high atomic number materials constituting the accelerator head and beam modifiers when the incident photon energy is higher than the (γ,n) reaction threshold energy.

The present work is centered on the development of a *Linac* treatment head computational model using the Monte Carlo code MCNP (version 5). The model includes the major components of an accelerator head as well as anthropomorphic RANDO phantom representing the patient head. The model was used in order to estimate the neutron absorbed dose distribution within the phantom.

To exploit the potential of MCNP5 code in radiotherapy applications a project between ISIRYM (*Institute for Industrial, Radiophysical and Environmental Safety)* and *Hospital Clínic Universitari de València* has been initiated. The goal of the project is to design a comprehensive set of MCNP5 simulations, and to collect and interpret data of these simulations for the purpose of evaluating all therapeutic and radiation protection risks associated with neutron overdoses.

To be consistent with the above objective, simulations of the *Elekta Precise* unit head emitting a 15 MeV photon beam under clinical conditions has been developed.

The MCNP5 Monte Carlo dose calculations presented in this work seem to be the first Monte Carlo simulations in which photonuclear interactions and its corresponding dose distribution in a head phantom has been investigated.

A particular example of these simulations is provided for the brain treatment by a typical lateral beam with a 10 cm x 10 cm field size. To this end, the 15 MeV photon beam with the defined characteristics are set on the RANDO phantom and its penetration from the surface of the head inside is simulated with the MCNP5 code.

2. METHODS AND METHODOLOGY

2.1. RANDO phantom MCNP model

Medical physicists and radiation therapists have designed anthropomorphic phantoms for many years. The female RANDO® Phantom, provided by the *Hospital Clínic Universitari de València*, was utilized in this work. It is made with three different materials in an effort to overcome the disadvantages of non-uniformity of materials, size and shape. A sketch of the Laboratory Phantom can be seen in Figure 1.

Figure 1. Head and neck female RANDO laboratory phantom.

The female RANDO® Phantom represents a 163 cm tall and 54 kg female figure. It does not have arms nor legs, and the portion utilized in this work corresponds to the head and neck. It is constructed with a natural human skeleton which is casted inside soft tissue simulating material. Two different tissue-simulating materials comprise the phantom head: the RANDO® soft tissue material (0.997 g/cm^3), designed to have the same absorption as human soft tissue at the normal radiotherapy exposure levels, and the skeleton (1.61 g/ cm^3).

A set of 60 Computer Tomography slices of the RANDO® Phantom was obtained with an image resolution of 512 x 512 pixels and 16 bits per pixel, separated by 0.4 cm one from the other.

This set of images was segmented [3] obtaining two different anatomical structures, the soft tissue and the skeleton. Once the segmentation is performed, a Matlab program reads the phantom information and writes 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 the voxel geometry, reducing the computing time around 6 times [4].

The three-dimensional voxelized phantom MCNP5 model can be seen in Figure 2, visualized with Sabrina code. The final model of the head of the RANDO phantom [5] is a 2,441,216 voxels lattice structure.

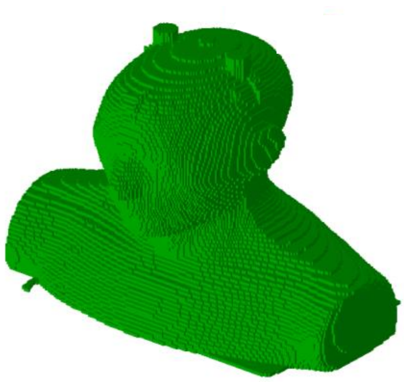

Figure 2. Voxelized RANDO phantom, visualization by Sabrina code.

2.2. MLC LinAc simulation

The *Linac* unit head model includes the major components of the MLC accelerator head. Dose calculations with this model involve collimated beams by a large number of small leaves. Since such calculations are very sensitive to the detailed structure of the multileaf collimator, the 80-leaf MCL *Elekta Precise* was implemented in a geometric developed model, as shown in Figure 3.

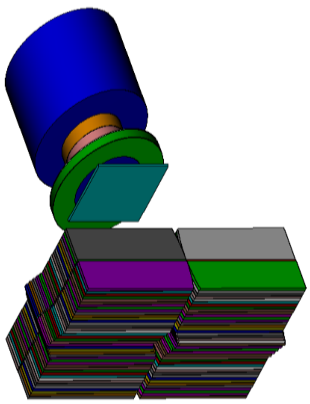

Figure 3. MCNP5 *Linac* unit head model including the MLC collimator.

The simulation of the validated model with different field sizes provides a series of phase-space files located at the exit of the last collimator. This phase-space file store the particle information so that, in future simulations, these source files can be used by changing the gantry, table and collimator angle, significantly reducing the computing time. The simulation utilized for this work corresponds to squared 10 cm x 10 cm at 100 cm from the source. The phase-space file is the starting point of 2,555,629 independent particle histories, which were resampled 100 times in the simulation of patient irradiation.

The accuracy of the calculated results is highly dependent on the strictness of the Monte Carlo simulation model, including 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 going through the whole geometry. A detailed photon physics treatment, including photoelectric effect with fluorescence production, incoherent and coherent scattering, pair production and photoneutron production, has been considered in the energy range between 0.001

and 15 MeV. The photon and neutron energy cut-off considered for this study used the default value in MCNP, 1 keV, while it was set to 10 keV for electrons.

The FMESH tally is utilized to define a mesh tally superimposed over the problem geometry. Adding the conversion factors for photons, electrons and neutrons, 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 (an adaptable and extensible software system for radiation treatment planning) algorithms [6].

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 with the Intel Fortran Compiler 12.1, on the Linux parallel computing machine. The final simulation real CPU time was 1882 minutes with MCNP5 version 1.40, for 1E9 initial particles. All simulations have been run until the Monte Carlo associated error was less than 3%.

This MCNP5 Elekta Precise MLC model was previously validated at 15 MeV. The used photon energy spectrum was obtained using a TSVD gradient methodology reconstruction based on unfolding techniques [7]. To validate the reconstructed spectra a complete Monte Carlo simulation was developed in order to generate the depth dose curve in a water phantom using the reconstructed spectra as input source.

Figure 4 shows the reconstructed 15 MeV photon spectrum used in this work [7].

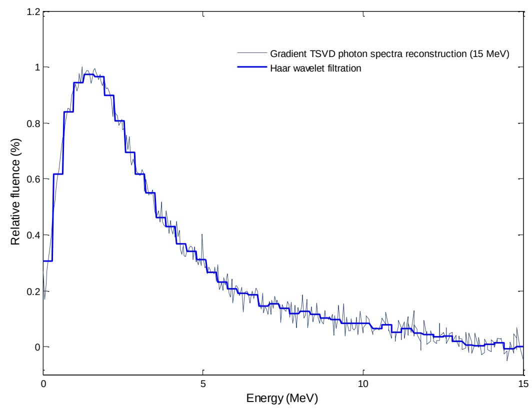

Figure 4. 15 MeV photon spectrum used in the simulation.

The generated depth dose curves using this spectrum have been compared with the experimental dose data measured at the hospital, showing a root mean square difference of 2% (Figure 5).

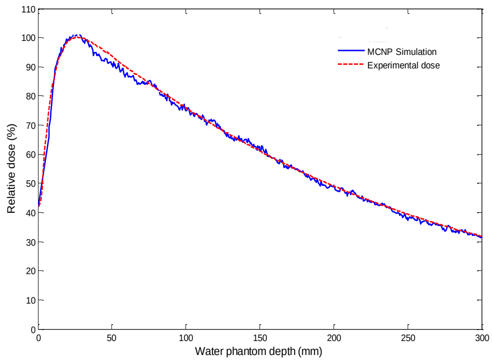

Figure 5. Depth dose curve obtained with a 15 MeV photon spectrum.

3. RESULTS

In this work doses from photons and electrons and those obtained from photonuclear reactions have been calculated for the head and torso. This has been done for regions directly exposed to the primary beam of photons and also for regions that lay at some distance from the primary beam trajectories.

The fraction of neutron dose relative to photon and electron dose, for particles originated from interactions in the human head had been calculated for brain and skull.

According to NCRP Report 116 [8], the radiation weighting factor WR for neutron ranging from 5 to 20 MeV are quite large and would expect quite significant dose equivalent to these parts.

Figure 6 shows the relative absorbed dose (percentage data %) at the central plane of the RANDO head phantom generated by photon and electron contribution.

On the other hand Figure 7 represents the absorbed dose distribution generated by photoneutron contribution and relative to the maximum total absorbed dose. As it can be seen in this figure, the treated part of the head is receiving by photoneutron contribution an extra dose which ranges between 0.5 to 0.05 per cent of the total photon and electron absorbed dose established in treatment.

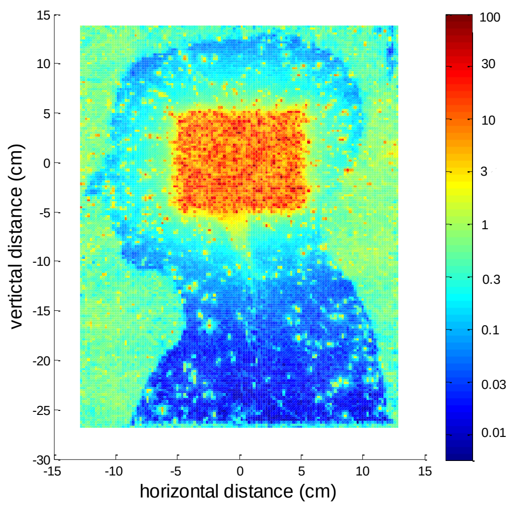

Figure 6. Absorbed (and equivalent) relative dose (%) distribution at the central plane of the RANDO head phantom generated by photon and electron contribution.

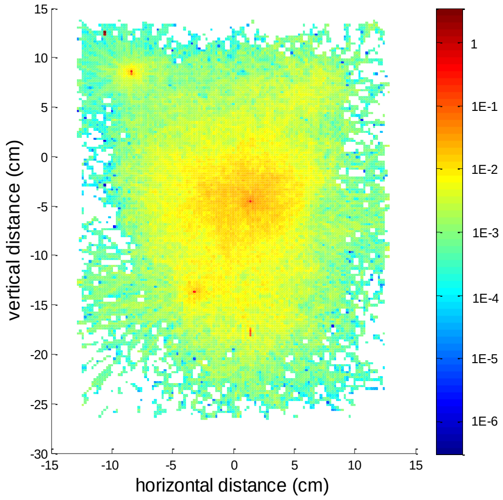

Figure 7. Absorbed relative dose (%) distribution at the central plane of the RANDO head phantom generated by photoneutron contribution.

These calculations, made for an operational therapy facility, show that in the course of a typical treatment the neutron contribution (round 0.5% of the total absorbed dose) is non-negligible and could represent a late risk for surrounding healthy tissues.

Considering that in a normal treatment a patient could receive over 60 Gy, the dose equivalent from phtoneutrons (taking into account its corresponding weighting factors from 5 to 20 MeV) could reach 6 Sv. This quantity needs to be considered by conventional radiation therapy planning systems.

It has been demonstrated in this paper that MCNP5 code is an appropriate tool for calculating comprehensive data on the photonuclear component of the dose distribution in photon radiation therapy and that the geometry of the human body can be closely modeled for the purpose of these dose calculations.

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