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MONTE CARLO CODE APPLICATION TO THE STUDY OF 3D NEUTRONS DISTRIBUTION IN A RADIOTHERAPY BUNKER AND VALIDATION WITH EXPERIMENTAL MEASUREMENTS

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Different methods exist to verify bunkers design for radiation therapy medical facilities; analytical methods based on simplified equations and Monte Carlo methods. One of the main purposes of this work is to present the advantages of using Monte Carlo simulation to verify radiotherapy bunker shielding design. This methodology is more accurate and characterizes not only the fluence and dose three-dimensionally, but also the energy spectrum of particles generated by the LinAc. The other main purpose of the work is to analyze the importance of the generated photoneutrons when the LinAc emits photon beams of high energy (above 8 MeV), since numerous studies have found that they can expose the patient and clinical staff to non-negligible dose. The main novelty introduced by this work, is the creation of more realistic simulation models to represent the radiotherapy facility by using CAD and meshes technologies. Results obtained using these bunker simulation models have been validated experimentally at the Hospital Universitari i Politècnic La Fe de Valencia facilities using two different neutron detectors; the neutron meter LB 6411 (designed between Berthold and Karlsruhe Research Center) and neutron detector model 42 - 41L (Ludlum, Prescila). Results obtained with Monte Carlo and those measured experimentally fit correctly, validating this analysis methodology.

Keywords: bunker, neutrons, Monte Carlo, MCNP6, dose, simulation, radiotherapy

I. INTRODUCTION

Radiation therapy is one of the main treatments used to fight cancer. High-energy treatment photon beams produce lower skin dose, a higher depth delivered dose and a reduced scattered dose to surrounding healthy tissues. However, unwanted and undesirable secondary particle emission is a penalty for better quality and outcome of cancer treatment when operated above 10 MeV. In these situations, LinAcs in radiotherapy have some inconveniences like the induction of photonuclear reactions and the production of activation products. These reactions are mainly generated in the higher density components inside the therapeutic accelerator head, and in air. Neutrons can be transmitted from the massive LinAc shielding and may be found at the maze and the maze entrance.

The photonuclear effect is based on the emission of a neutron from the nucleus, leading to a, in most cases radioactive, nucleus with neutron deficit, and a fast neutron. When the produced nucleus is radioactive, due to the neutron deficit, emission of a positron or decay by electron capture takes place in most cases[1].

International Commission on Radiological Protection (ICRP) publication 103 [2] reported a high (up to 20) radiation weighting factor (W_R) for photoneutrons produced in high energy medical accelerators. The isotropic emission pattern of neutron emission, high W_R and low attenuation have made the neutrons an important issue to be analyzed. International Atomic Energy Agency (IAEA) No. 47 [3] and National Commission of Radiation Protection and Measurements (NCRP) No. 151 have established that photoneutron production becomes important in the bunkers with LinAcs operating at the energy above than 10 MV. Additionally, it was stated that bunker shielding design against neutrons must be considered as well as photons in LinAcs with energy above 10 MV.

This work describes Monte Carlo simulations of such neutrons for a proposed bunker, which emits a 15 MV treatment beam. Neutron fluence and absorbed dose due to neutrons were scored tridimensionally inside the whole bunker. In this work, the study of the 3D neutron distribution generated by the photonuclear reactions at the LinAc has been analyzed, in order to check that the induced dose to patients and clinical radiotherapy staff is below legislation limits. In addition, an accurate and realistic methodology for the design of the radiotherapy bunkers with the MCNP Monte Carlo code is presented.

II. METHODS AND MATHERIALS

II.A. Varian Clinac 2100C accelerator

The collaboration of the *Hospital Universitari I Politécnic La Fe de València* has been required for this work. In this hospital, the Varian Clinac 2100C linear accelerator is used. This medical LinAc is one of the most used in the world and presents a 120 separate sheets multileaf collimator with intensity-modulated. This makes the adjustment to the tumor more accurate and less damaging to nearby organs.

II.B. Neutron detectors

Neutron detection is a complicated task since neutrons do not produce ionization in materials. Neutrons transmit energy by means of elastic scattering or nuclear reactions to ionize materials. Two detectors were used to detect the neutrons that are generated in the radiotherapy bunker of the *Hospital Universitari i Politècnic La Fe de València*.

On the one hand, it has been used a neutron meter LB6411 designed between Berthold and the Karlsruhe Research Center. The instrument has an extremely high sensitivity of approximately 3 counts/nSv and therefore measuring times are low in areas of weak neutron population. In addition, they have an excellent energy response ± 30% from 50 keV to 10 MeV, which is 5 times better than that obtained in conventional detectors. This detector detects the slow neutrons using a detector of ^{3}He focused on a sphere of 250 mm diameter.

On the other hand, a gamma/neutron meter has been also used. This neutron dose counter combines meter Ludlum model 2363 with the neutrons detector model 42-41L Prescila. This detector detects the recoil of the protons. For this reason, the detector provides excellent results with a lighter tool. The following figure shows the system used for neutron dose measurement.

Fig. 1. Dose neutron detector LB6411 (left side) and Ludlum Prescila 42-41 (right side)

II.C. Radiation therapy bunker

The *Hospital Universitari i Politècnic La Fe de València* provided all the necessary information for the design of the radiation therapy bunker. These facilities must be appropriately designed according to dose limits legislation.

The hospital has also provided information about the composition of the materials that have been used for the construction of the bunker. Walls, floors, ceilings and door of the bunker should be shielded with suitable material and sufficient thickness so that the dose outside the room rate is below the limits.

Figure 2 shows a plan view of the proposed bunker.

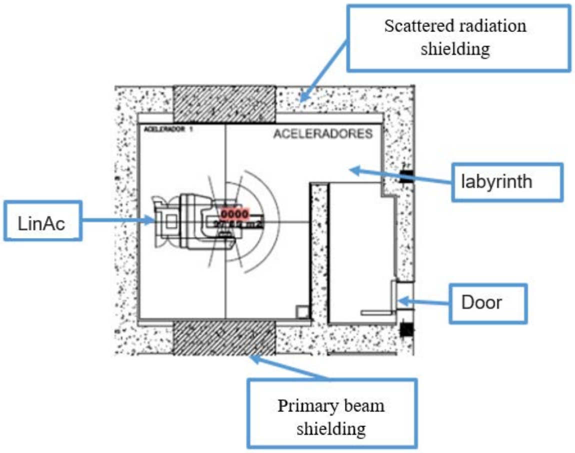

Fig. 2. *Hospital Universitari i Politècnic La Fe de València*. bunker drawing.

The primary barriers are intended to arrest the accelerator's beam, while the secondary barriers are designed to stop leakage and scattered radiation. In this case, ordinary concrete is used for the construction of the primary and secondary barriers. The maze is intended to reduce the radiation that reaches the door. The maze accomplishes this by allowing radiation to be attenuated and absorbed in an increased amount of concrete and air[4]. This reduces the amount of radiation that the door is required to shield; thus, allowing the door to be made lighter compared to a door in a design without a maze. In fact, with some maze designs, the radiation is attenuated so much by the maze that no door is even needed

Table I shows the different materials composing the bunker.

TABLE I. Bunker materials and corresponding densities.

PARTS	**MATERIAL**	**DENSITY (g/cm^3)**
Scattered radiation	Concrete	2.35

shielding		
Primary beam shielding	Barite concrete	3.245
Door	Lead	11.35
	Ledite_Xn_240	3.84
	Polyethylene	0.98

III. MONTE CARLO MODEL AND SIMULATION

III.A. Bunker facility design

In this work different programs that allow modeling and meshing the radiotherapy bunker and the different materials have been used to generate the simulation model. First, a CAD software as[5] to model the bunker in three dimensions, as figure 3 shows.

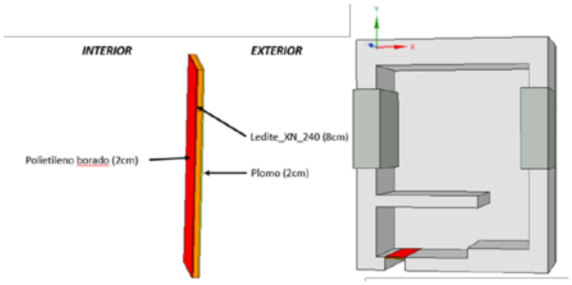

Fig. 3. Radiation therapy room created with a CAD software.

Once the model is created, it is exported to Abaqus [6] software to perform the mesh process.

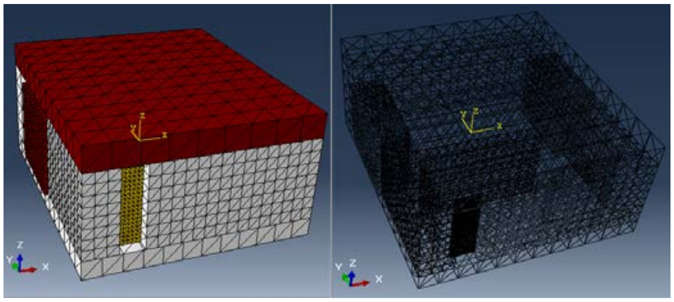

Fig. 4. Meshed model created in Abaqus.

To complete the simulation model, it was necessary to include a reliable model of the clinical LinAc head operating at 15 MeV. Therefore, manufacturers of the medical linear accelerator provided all necessary data of the geometry and materials of the LinAc machine and the beam spectrum (energy, spatial and angular distribution of the particles in the beam). The accelerator is placed in the bunker such that it rotates about the isocentre; which is found in the beam's rotational plane.

The beam forming parts of the LinAc, i.e., the target, absorber, primary collimator, flattening filter, ion chamber, mirror, jaws and multileaf collimator (MLC), were modelled in detail using the confidential data provided by Varian. The created model has been validated experimentally in previous studies with depth dose measures in a water tank using an opening of the MLC and jaws of 10×10 cm^2 field size at the isocentre [7].

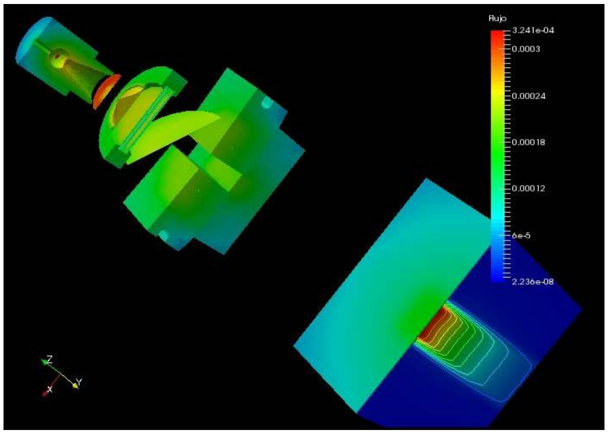

Fig. 5. Clinac simulation model and isodose curves in a water tank.

III.B. Surface source orientation and neutron register.

The 15 MeV spectrum was unfolded in previous works and it was used to generate a phase space file to be included as surface source for MCNP6 input [8,9,10]. This surface source has been oriented to different angles, in order to study the neutron distribution in several irradiation conditions.

In the full Monte Carlo running, biased photonuclear production enabled by setting the forth entry of PHYS:P card (which controls the energy and physical aspect of photoneutron production) to 1, so as to speed up calculations.

Resulting neutron absorbed dose and fluence were scored, using MCNP registration card (F4:n and *F4:n). This tally allows obtaining neutron fluence in each cell (particles/cm^2) and/or energy fluence (MeV/cm^2). Final standard deviations were below 10% for dose and fluence energy bins. Up to 10^9 histories were run for each simulation in order to achieve this level of statistical uncertainty.

IV. RESULTS

Paraview software allows visually analyzing data that have been obtained in the simulations carried out by MCNP6.1.1. This three-dimensional representation of neutron dose at the bunker allows analyzing the neutron dose dispersed through the air (walls, floor, ceiling, door...). Next figures represent different beam orientations results. As it can be seen, the reduction in neutron dose at the maze entrance, achieved by cladding concrete maze walls was determined, as well as the dose barrier of the whole bunker walls.

In figure 6 and 7 neutron fluence results at 1 meter high from soil are displayed when the accelerator’s beam is directed toward the isocentre, where patients are normally positioned.

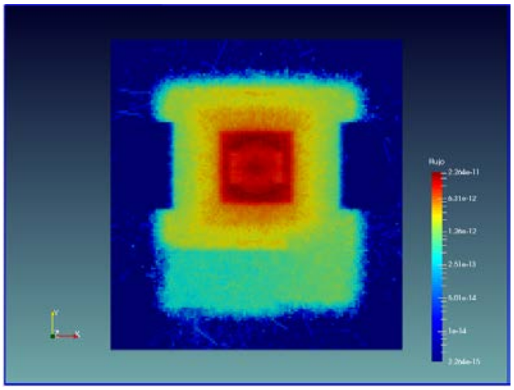

Fig. 6. Neutron fluence distribution with floor beam orientation (MCNP6.1.1) (parts/cm^2 per emitted particle).

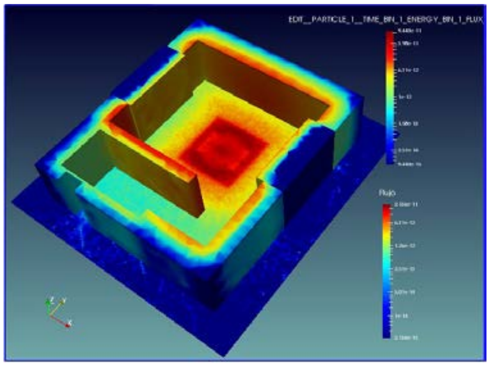

Fig. 7. Neutron fluence 3D distribution with floor beam orientation (MCNP6.1.1) (parts/cm^2 per emitted particle).

Figure 8 displays neutron fluence distribution inside the bunker for four different beam orientations.

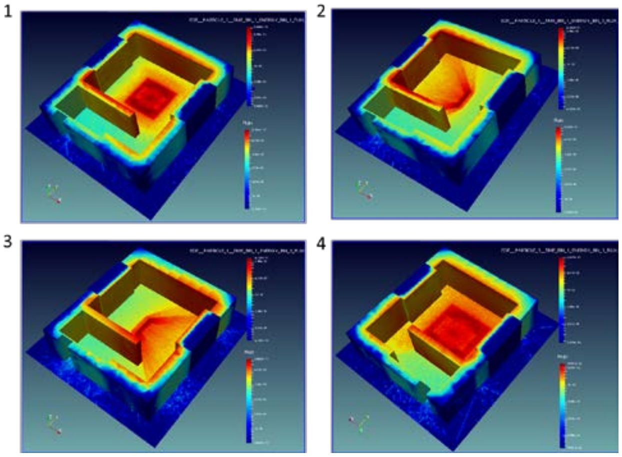

Fig. 8. Neutron fluence 3D distribution with four different beam orientation (MCNP6.1.1) (parts/cm^2 per emitted particle).

Simulations results validates the shielding design of the radiotherapy room for neutrons. On the other hand, these models have been validated experimentally with the data collected in the *Hospital Universitari i Politécnic la Fe de València* with neutrons detectors LB 6411 (Berthold) and 42 - 41 L (Ludlum, Prescila), obtaining less than 10% percentage difference.

To measure the neutron dose rate distribution at the LinAc room, a 4 x 4 grid covering the entire surface has been studied. Each discretized measurement point dimensions are 2.22 meters on the X axis and 2.6 meters in the Y axis, and the detectors were placed at the center of each resulting cell.

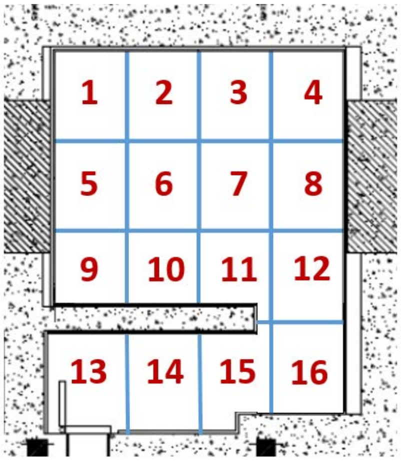

Fig. 9. Neutron measuring points

Once discretized the room in 16 cells, 15 MeV irradiation during 5 minutes was performed for each of the cells in the mesh, locating both neutron detectors in the center of the grid division. In these irradiations, the radiation beam was set with 0º gantry orientation i.e. to the floor of the bunker with an energy of 15 MeV, with an almost closed secondary collimator configuration (0.5 cm x 0.5 cm) and open MLC, and setting 600 UM/min.

Neutron doses in mSv/h with both detectors were obtained for each detection point, the maximum difference between measures being below 5%. The mean value of both detectors in each point has been compared with simulation results.

Fig. 10. Experimental measurements with neutron detectors.

Figure 11 represents the normalized neutron dose rate comparison between Monte Carlo results and experimental values at the 16 different measuring point cells. Normalization has been calculated to the maximum dose value.

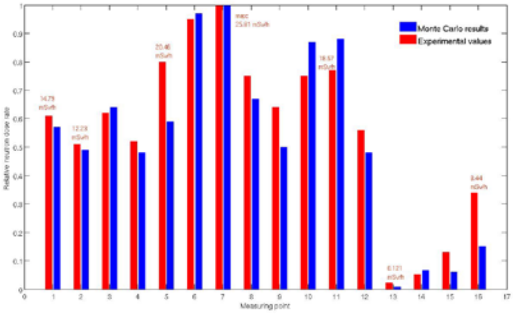

Fig. 11. Normalized neutron dose comparison between Monte Carlo results and experimental values

According to the results obtained, it can be concluded that the Monte Carlo simulation has been validated by experimental measurements. In addition, this work has shown the main advantage of the Monte Carlo simulation, the rapidity and detailed map of the fluence and neutron doses distribution inside a radiotherapy bunker. The difference between the experimental measures and MCNP6 results does not exceed 10%.

V. CONCLUSIONS

High energy radiation therapy is associated with fast and thermal photoneutrons. Adequate shielding against the contaminant neutrons has been recommended by IAEA and NCRP new protocols.

Usually, the methods used to verify the design of bunkers for radiation therapy are analytical methods, which are based on simplified equations that are associated with many concerns. Simple closed equations makes designing quick, less error-prone, and insightful. Unfortunately, they also oversimplify radiation physics to the point where it is not unusual for radiation measurements to be significantly different from what the equations predicted. Moreover, as the conventional method is normally conservative in its calculation methods, it is common for bunkers to be over-shielded in areas, increasing budgets.

Recently, NCRP No. 151 and IAEA No. 47 have recommended analytical methods for the shielding calculation against photon, photoneutron and capture gamma ray radiations in the high energy radiation therapy facilities. Additionally, NCRP No. 144 has recommended the Monte Carlo simulation as a reliable method for the shielding calculations[11]. In the present work, a radiation therapy bunker design was verified using Monte Carlo simulation.

One of the main objectives of this work is to create an accurate methodology for the design of these facilities. Models created with the MCNP Monte Carlo code, estimate accurately the dose and the spectrum of particles generated by the LinAc radiotherapy treatment.

Results have been validated with data obtained at the Hospital Universitari i Politècnic la Fe de València using Berthold and Ludlum neutron detectors.

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REFERENCES

[1] C. Ongaro, A. Zanini, U. Nastasi, Analysis of photoneutron spectra produced in medical accelerators. Phys Med Biol. 45 (2000) 55–61.

[2] International Commission on Radiological Protection (ICRP) 2007. ICRP, No. 103. The 2007 recommendations of the International Commission on Radiological, Protection. Report.

[3] International Atomic Energy Agency (IAEA) 2006. Radiation protection in the design of radiotherapy, facilities. Safety reports series, No. 47 (Vienna: IAEA).

[4] P.H. Ginley, E.K. Butker, Evaluation of neutron dose equivalent levels at the maze entrance of medical accelerator treatment rooms. Med Phys. 18 (1990) 279–281.

[5] SpaceClaim 3D Modeling Software http://www.spaceclaim.com/en/default.aspx.

[6] Dassault Systèmes, 3DExperience Company, ABAQUS 6.14, ABAQUS/CAE User´s Guide, 2014.

[7] V. Abella, et al., Use of MOSFET dosimeters to validate Monte Carlo radiation treatment calculation in an anthropomorphic phantom. Radiation Physics and Chemistry 116 (2015).

[8] L. Roger, The MCNP6 Book On Unstructured Mesh Geometry: User's Guide, LA-UR- 11-05668 Rev. 8, MCNP6 code release to RSICC, Oak Ridge.

[9] N. Mohammadi, et al., A Monte Carlo Study for Photoneutron Dose Estimations around the High-Energy LinAcs, Biomed Phys Eng., 4 (2014) 127–140.

[10] S. Morató, et al., Experimental validation of neutron activation simulation of a varian medical linear accelerator”. Conf Proc IEEE Eng Med Biol Soc. (2016).

[11] National Council on Radiation Protection and Measurements (NCRP) 2003. NCRP, No. 144. Radiation protection for particle accelerator, facilities. Report.