Neutron Activation Processes simulation in an Elekta Medical Linear Accelerator head

B. Juste, R. Miró, G. Verdú, S. Díez, J.M. Campayo

Abstract— **Monte Carlo estimation of the giant-dipole-resonance (GRN) photoneutrons inside the *Elekta Precise* LINAC head (emitting a 15 MV photon beam) were performed using the MCNP6 (general-purpose Monte Carlo N-Particle code, version 6). Each component of LINAC head geometry and materials were modelled in detail using the given manufacturer information. Primary photons generate photoneutrons and its transport across the treatment head was simulated, including the (n, γ) reactions which undergo activation products.**

The MCNP6 was used to develop a method for quantifying the activation of accelerator components. The approach described in this paper is useful in quantifying the origin and the amount of nuclear activation.

I. Introduction

High-energy treatment photon beams produce lower skin dose, a higher depth delivered dose and a reduced scattered dose to surrounding healthy tissues. However, when operated above 10 MV the LINACs in radiotherapy have some inconveniences like the induction of photonuclear reactions and the production of activation products. These reactions mainly are generated in the higher density components inside the therapeutic accelerator head, and in air.

Several studies have studied activation isotopes and measured or calculated resulting dose rates [1],[2] and from these works, it is known that resulting doses are not negligible.

The release and capture of neutrons produce radioactive nuclei that can irradiate even when the accelerator is not operating. The objective of this work is to develop a methodology for quantifying the activation of accelerator components using MCNP6. To that, a simulation was performed in order to characterize the induced activity in an *Elekta* treatment head, as well as the quantity and location of activation products.

From this work it can be demonstrated that the target and the primary collimator are dominant radiation sources. It has been shown also that jaws, leaves and other treatment accessories like the flattening filter regions are activated as well.

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II. Methods and materials

This paper identifies the activation products generated in the accelerator components of the *Elekta Precise* LINAC. Detailed knowledge of the radioisotopes generating during radiotherapy by the high energy photon beams is extremely important for the radiological protection of staff operating accelerators as well as for medical LINAC constructors.

A. Theoretical physics background

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.

$$ {}^{A}_{Z}A_N\ (\gamma, n)\ {}^{A-1}_{Z}A_{N-1} \tag{1} $$

with A = number of nucleons, Z = atomic number and N = number of neutrons.

When the produced nucleus is radioactive, due to the neutron deficit, will be a positron emitter or decay by electron capture in most cases.

The produced neutron is able to undergo nuclear reactions itself. In the energy range encountered in medical accelerators, the most important reaction is the neutron capture:

$$ {}^{A}_{Z}A_N\ (n, \gamma)\ {}^{A+1}_{Z}A_{N+1} \tag{2} $$

The produced nucleus is again radioactive in most cases and will most probably decay in β- mode due to its excess in neutrons.

The target, primary collimators and jaws of the *Elekta Precise* are made mostly of tungsten alloy (W-Ni-Fe). The flattening filters consist of steel alloy. These atoms can be activated by exposure to high energy photons. As a result, many isotopes can be produced during the exposure time. Some candidates of isotopes with long life times and large branching fractions are listed in Table 1.

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Table 1. Induced radioactivity for *Elekta LINAC*

Isotope	Half-life	Gamma energy (keV)	Branching ratio (%)	Production
^{187}W	23.7 h	479/686	23/27	186W(n,γ)187W
^{28}Al	2.24 m	1778	100	27Al(n,γ)28Al
^{56}Mn	2.58 h	847	99	55Mn(n,γ)56Mn
^{58}Fe	45 d	1095/1292	56/44	58Fe(n,γ)Fe59
^{65}Ni	2.56 h	368	4.5	64Ni(n,γ)65Ni
^{51}Cr	27.8 d	320	9	50Cr(n,γ)51Cr

B. Monte Carlo Simulation

Direct measurements of photon fluence and spectra in a medical accelerator room involve complex measurement techniques, and can be frequently long time-consuming and rigorous. Monte Carlo methods, on the other hand, have become alternative methods since they are faster and more flexible than making measurements. To characterize the photon and neutron activation in medical accelerators using Monte Carlo methods, precise cross-section data are needed.

The Monte Carlo method is extensively used for simulating particle transport through different materials, and storing tallies (results) of the particles interactions. The code used in this work is Monte Carlo N-Particle (MCNP version 6) [3], which is a general purpose Monte Carlo transport code developed at Los Alamos National Laboratory.

As a neutron travels through a material, MCNP uses a succession of steps to characterize the interactions. First, a selection process dependent on the macroscopic cross section is used to identify the nuclide in the material with which the collision takes place. Then the program verifies to see if thermal cross section tables, S(α, β), are available for the particular nuclide. The S(α, β) tables pertain to neutron energies generally below 4 eV in order to account for the thermal motions of the atom relative to the neutron. Next, neutron capture probabilities are modeled for the nuclide. If the neutron is not captured, the final process models the collision via elastic or inelastic scattering.

Inelastic scattering does not conserve energy and momentum. Instead, the target nucleus captures the neutron, becomes excited, and undergoes one of the following reactions: (n, n'), (n, 2n), (n, γ), (n, n'α).

1) Elekta model

The detailed geometry of the radiotherapy treatment head unit *Elekta Precise* equipped with 80-leaf MLC (operating with a 15 MeV photon beam), has been accurately implemented in the Monte Carlo model according to the manufacturer data. The validation of MLC LINAC MC model was previously validated using depth dose curves in a water phantom [4], [5].

Figure 1 presents a sketch of the multileaf geometry of the *Elekta* modeled with MCNP6.

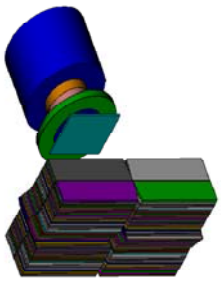

Figure 1. Elekta Precise geometry model.

The gantry angle was set to 0 degrees, the field size formed by MLC was a rhombus and the one formed by jaws was 10 x 10 cm, as figure 2 shows.

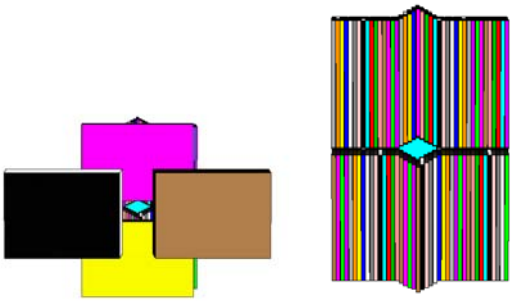

Figure 2. Rhombus-shaped field collimation and jaws at 10 cm x 10 cm.

Tallies have been selected by the user to calculate and display volume flux. The volume flux tally determines the track length of a particle integrated over time, volume, and energy. The output is then divided by the total volume of the cell, resulting in units of particles/cm^2. The estimation of the track length is reliable since there are often many tracks in a cell resulting in many contributions to the tally.

The volume flux tally can be modified by using a multiplier card (FM card) to obtain activated atom volume concentrations. The FM card allows several different multipliers to be used with the neutrons/cm^2 output. First an atom concentration in the volume is determined.

10^9 particles were simulated in order to obtain tally uncertainties below 3%.

III. RESULTS

1) The Validation of Elekta Accelerator Modeling

Before studying the activation mechanisms, the Monte Carlo model of the LINAC was verified. As first validation, the depth dose curve in a water phantom obtained by simulation was compared with the experimental measures taken at the *Hospital Clínic Universitari de Valencia*, (figure 3), showing a root mean square difference lower than 3%. As

it can be seen, the simulation gives a good representation of the depth dose curve.

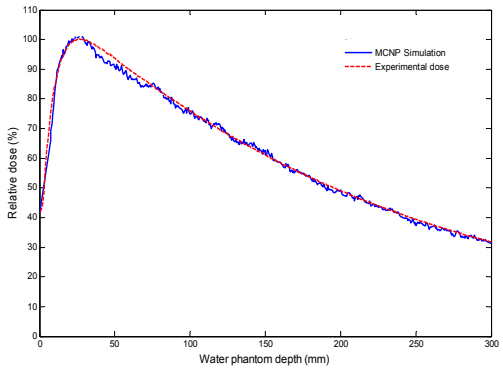

Figure 3. Depth dose curve obtained with a 15 MeV photon spectrum.

Measures were performed with a high resolution detector placed in a motorized guide inside the 50 cm side phantom ("RFA-300 Water Phantom"). The water cube was irradiated with a 10 cm x 10 cm field size maintaining the source-to-surface distance (SSD) equal to 100 cm.

2) Activation products analysis

Figure 4 presents the simulation results obtained with the MCNP6 code. It presents the comparison of tallies using the activation FM card associate to F4 volumetric tally for each reaction. Results are presented in relative count rate in order to compare the importance of the activation products generated. It can be seen that the reaction W186(n,γ)W187 is the one which generates the highest radionuclide activity peak. Tungsten is the main component of target, primary collimator, jaws and leaves. In comparison, other important activated product is Mn56, although it has two orders of magnitude lower tan W87. This last isotope is generated mainly in the flattening filter.

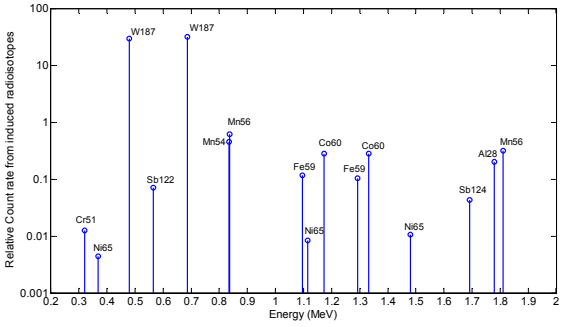

Figure 4. Activated products generated in the LINAC head and calculated by Monte Carlo simulation.

Activity products in air (41Ar) have also taken in to account in the simulation, but results obtained demonstrated that its consideration can be negligible.

Figure 5 presents the W187 peaks classified by the accelerator head part where they were generated. It can be seen that the majority is generated in the target. The primary collimator is also an important source of induced radioactivity (although it is one hundred times lower than those created at the target).

Jaws and leaves display similar level of generation of W186. From these results it has been also observed that the activation in the closed leaves is one quarter lower than in the opened ones.

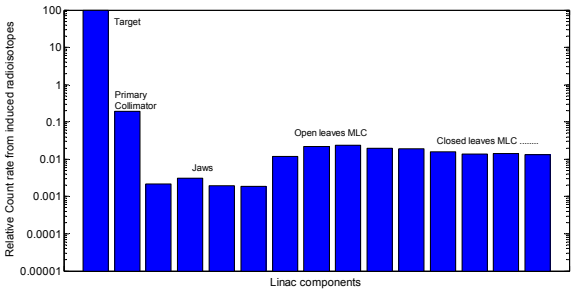

Figure 5. 186W(n,γ)187W reaction quantity at LINAC head components.

IV. CONCLUSION

This study shows that the MCNP6 code can be used to simulate nuclear activation. Using detailed models of medical accelerators, the photon and neutron activation in any location in the treatment room can be calculated. This tool can be used to quantify the origin and the amount of nuclear activation produced during medical accelerator operation.

Future works will be addressed towards the determination of the dose to the patient or medical personnel from this activation. Future studies will include also experimental measures to confirm Monte Carlo simulation

ACKNOWLEDGMENT

We would like to thank the "*Hospital Clínic Universitari de Valencia*" for the given help.

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