Monte Carlo study of photoneutron production in the Varian Clinac 2100C linac

A. Ma,1* J. Awotwi-Pratt,2 A. Alghamdi,1 A. Alfuraidh,1 N. M. Spyrou1
1 Centre for Nuclear and Radiation Physics, Department of Physics, University of Surrey, Guildford GU2 7XH, U.K.
2 Medical Physics Department, Norfolk and Norwich University Hospital, Colney Lane, Norwich NR4 7UY, U.K.

(Received January 3, 2007)

Medical linear accelerators (linacs) are used extensively in modern radiotherapy for their flexibility and versatility. As the treatment regime moves from low-energy photon beams to high-energy beams, photoneutrons produced in the linac head components become important. This work used the general purpose Monte Carlo code MCNPX to model the Varian Clinac 2100C linac with a 15 MV photon beam. Simulations are carried out for several field sizes commonly encountered in radiotherapy. Photoneutron productions in various head components are estimated from the photon fluence and the photoneutron production cross sections. The results serve as a basis for further studies on using the linac as an alternative neutron source in BNCT and radiation protection issues arising from photoneutrons in the treatment room.

Introduction

Medical linear accelerators (linacs) are used extensively in modern radiotherapy for their flexibility and versatility. Inside a linac (Fig. 1), a beam of electrons is accelerated to high energy. It is then directed to strike at a high-Z target, usually made of tungsten alloy. The electrons are converted into a beam of bremsstrahlung photons. Since these photons are peaked in the forward direction, a flattening filter of medium-Z materials is used to flatten the beam profile so that the dose distributes evenly in the treatment field. To minimize the exposure of the normal tissues surrounding the tumor site, the photon beam is further shaped by a set of beam modifiers of high-Z materials before being delivered into the patient. The beam modifiers include two pairs of jaws and 40 pairs of multileaf collimator (MLC) leaves. The jaws move orthogonally to each other in an arc focused at the target. Each MLC leaf is doubly focused at the target and moves linearly. All these beam modifiers are capable of independent movements.

Photoneutrons are produced in the giant dipole resonance region (GDR) primarily between 3 and 25 MeV when the incident photon energy is above the production threshold energy. The average threshold energy is about 8 MeV. Therefore, photoneutron production in lower energy linacs, e.g., 6 MV, is usually ignored. However, the production of photoneutrons can be significant in the higher energy linacs (10–25 MV). Besides being produced in the linac head, photoneutrons are also produced in the patient and in the bunker walls, floor and ceiling. The production in the linac head is particularly important because of the presence of a large amount of high-Z materials and their large photoneutron production cross sections. Furthermore, these high-Z materials have low neutron capture cross sections and the generated photoneutrons will escape from the linac head.

The photoneutron production from the high energy linacs is a radiation protection issue. The photoneutron energy spectrum peaks between 100 keV and 1 MeV.1 These neutrons are very effective in damaging tissues and their radiation weighting factor ($w_R = 20$) is at maximum in the calculations of equivalent dose and effective dose.2 Sufficient shielding must be incorporated into the treatment bunker design to reduce the neutron exposure to staff and general public. Recent works have also suggested the possibility of utilising the photoneutrons from the linac as an alternative to nuclear reactors in boron neutron capture therapy (BNCT).3,4 Thus, understanding the process of photoneutron production in the linac head is of high priority. Monte Carlo simulations are used extensively in such studies.1,3–8

A Monte Carlo simulation is a virtual experiment. Particles are generated and tracked through the geometry until they have escaped from it or being absorbed in it. In the process, contributions to the tallies are recorded. Each decision during the generation and the tracking of particles is made using a random number to sample a probability distribution of relevant underlying physics. The convergence of the tallies is guaranteed by the law of large numbers and the central limit theorem provided that all spatial and energy regions are well sampled. Thus a large number of source particles are necessary to avoid undersampling. MCNPX is a general purpose Monte Carlo code developed by the Los Alamos National Laboratory, USA. It allows the user to implement complicated geometries through combination of simple planes and quadratic surfaces. It is capable of tracking 34 types of particles including photons, electrons, neutrons and protons from keV to GeV.

* E-mail: a.ma@surrey.ac.uk
In this study, we are tracking the photons and electrons only. The photoneutron production is estimated from the photon fluence and the photoneutron production cross sections.

**Experimental**

The Varian Clinac 2100C linac head is modeled in detail according to the manufacturer’s specification. It is made of elements specified in the manufacturer’s document. Each element is assumed to have the typical natural abundance of different nuclides (Table 1). The initial electron beam is a uniform beam of 3 mm in diameter striking perpendicularly at the target with a single discrete energy of 15 MeV. Bremsstrahlung splitting is used to speed up the simulation. Photon fluence is tallied in each head component with 100 keV energy bins up to 15 MeV. The photon dose is calculated at the isocentre − 90 cm source-to-surface distance and 10 cm deep in a 60×60×60 cm³ water phantom which is standard in quality assurance works. MCNPX gives the dose in MeV per source electron. It is converted into Gy per source electron by a conversion factor 1.60·10⁻³³ Gy·MeV⁻¹. Three square fields are simulated. They are 1×1, 10×10 and 20×20 cm².

The inclusive \((\gamma,xn)\) yield, \(\sigma\), for a nuclide is the sum of all neutron emission reaction channel cross sections weighted by the number of emitted neutrons:

\[
\sigma(\gamma,xn) = \sigma(\gamma,n) + 2\sigma(\gamma,2n) + 3\sigma(\gamma,3n) + \cdots
\]

(1)

For the maximum incident photon energy of 15 MeV considered in this study, only those reaction channels with threshold energy below 15 MeV are included in \(\sigma\). The threshold energies for the reaction channels are compiled from IAEA\(^10\) and listed in Table 1. The individual cross sections are obtained from EXFOR\(^11\) and combined according to the mixture rule to produce the neutron yield cross section for each material \(m\), \(\sigma_m\).

The number of neutrons produced \(Y_{m,E_0,T}\) is calculated according to the following equation:\(^12\)

\[
Y_{m,E_0,T} = N_{m,T} \int_{E_0}^{E_m} \sigma_m(E) \Phi_{E_0,T}(E) dE
\]

(2)

where \(N_{m,T}\) is the number of atoms of material \(m\) in component \(T\), \(E_m\) is the threshold energy in \(m\), \(E_0\) is the bremsstrahlung end-point energy which is 15 MeV in this study, \(\sigma_m(E)\) is the inclusive photoneutron yield as described above and \(\Phi_{E_0,T}(E)\) is the fluence spectrum of the bremsstrahlung beam in \(T\). The fluence spectrum is not normalized and retains the MCNPX supplied unit of number of photons per cm² per source electron. \(Y_{m,E_0,T}\) thus has the unit of number of photoneutrons per source electron which is ready for conversion into number of photoneutrons per Gy of photon dose.

**Results and discussion**

Table 2 concerns a study on a 1×1 cm² field. The most common nuclide of an element is considered as the sole composition of the element in one set of calculations and the other set considers the relative abundance of different nuclides. The overall photoneutron production is increased primarily due to the larger cross section of \(^{184}\)W than the combined one for the element (Fig. 2).