Photon and photoneutron spectra produced in radiotherapy LINACs

H.R. Vega-Carrillo¹, S.A. Martínez-Ovalle², J.L. Benites-Rengifo³ and A.M. Lallena⁴

¹Unidad Academica de Estudios Nucleares
Universidad Autónoma de Zacatecas
C. Cipres 10, Fracc. La Peñuela
98068 Zacatecas, Zac. Mexico

²Grupo de Física Nuclear Aplicada y Simulación
Universidad Pedagógica y Tecnológica de Colombia
Avenida Central del Norte Km.1. Vía Paipa
Tunja, Boyacá, Colombia

³Universidad Autonoma de Nayarit
Postgrado CBAP
Xalisco, Nayarit, Mexico

⁴Dpto. de Física Atómica, Molecular y Nuclear
Universidad de Granada
E-18071 Granada. SPAIN

e-mail: fermineutron@yahoo.com

Abstract

A Monte Carlo calculation, using the MCNPX code, was carried out in order to estimate the photon and neutron spectra in two locations of two linacs operating at 15 and 18 MV. Detailed models of both linac heads were used in the calculations. Spectra were estimated below the flattening filter and at the isocenter. Neutron spectra show two components due to evaporation and knock-on neutrons. Lethargy spectra under the filter were compared to the spectra calculated from the function quoted by Tosi et al. that describes reasonably well neutron spectra beyond 1 MeV, though tends to underestimate the energy region between $10^{-6}$ and 1 MeV. Neutron and Bremsstrahlung spectra show the same features regardless of the linac voltage. The amount of photons and neutrons produced by the 15 MV linac is smaller than that found for the 18 MV linac. As expected, Bremsstrahlung spectra ends according to the voltage used to accelerate the electrons.

Keywords: Neutron, photon, spectrum, LINAC, Monte Carlo
Introduction

Worldwide, the number of cancer cases is growing. Nowadays cancer kills more people than tuberculosis, HIV, and malaria combined. Developing countries, where resources to prevent, diagnose and treat cancer are limited or nonexistent, are worst hit by the cancer crisis (IAEA, 2010).

Cancer patients are treated by radiation alone or combined with surgery and/or systemic therapy including chemical, immunological and genetic treatments. Radiation can be applied as systemic radiotherapy, teletherapy, or brachytherapy. In teletherapy a radiation beam is addressed to the patient aiming at killing cancer cells, unaffected the normal tissues around the tumor. Thus, the classical radiation therapy, CRT, was improved to 3D-CRT, evolving to Intensity-Modulated Radiation Therapy, IMRT. Changes included the multileaf collimator system, MLC, and advanced optimization algorithms (Xu, Bednarz and Paganetti, 2008).

Despite there are several options for cancer treatment, radiotherapy with linacs is the technique most commonly used, either with electron or photon beams (Mesbahi et al., 2010).

A lower skin dose, a higher depth dose, a reduced scattered dose to healthy tissues outside the tissue-target volume, and less rounded isodose curves, are some of the advantages provided by the use of high-energy x-rays instead of low energy photons (Brusa et al., 2008, Hashemi et al., 2007). However using high-energy x-ray machines is a radiation protection issue because besides the therapeutic beam, linacs produce neutrons that induce reactions in materials inside the bunker, such as activation (Polaczek et al., 2010) and prompt γ-ray reactions.
Neutrons deliver an undesirable dose to the patient, this dose can cause secondary cancers.

Working above 8 MV, linacs produce neutrons regardless they operate with electrons or x-rays. In case of electrons, neutrons are produced via virtual photon reactions (e, e'n), while x-rays generate neutrons in (γ, n) nuclear reactions. Cross sections for photoneutron production are roughly between 100 and 200 times larger than for electro-neutron production, therefore studies have been focused in photoneutrons (Martinez-Ovalle et al., 2011, Lin et al., 2001, McGinley 1998, NCRP, 1984).

Photoneutrons are mainly induced in the high-Z materials on the linac head such as the target, the flattening filter, the jaws, the MLC and the head shielding; also, they are produced in the patient body and materials in the treatment hall whose cross sections show the well known Giant Dipole Resonance (Hall et al., 1995, IAEA, 2000)

Photoneutrons are produced when photons collide with a nucleus, its energy is distributed among the nucleons and, eventually, a neutron near the nucleus surface acquires enough energy to emerge as an evaporation neutron. These neutrons are emitted isotropically. Another reaction occurring during photon-nucleus reactions and that contributes also to the neutron production is that in which the photon gives out all its energy to a single neutron that is kicked-out from the nucleus. These neutrons are mostly emitted in the direction of the incoming photon and are known as knock-on neutrons. To describe the photoneutron spectrum Tosi et al., (1991) derived the following expression:
\[ n(E) = \alpha \frac{E}{T} \exp \left[ -\frac{E}{T} \right] + \beta \frac{\ln \left( \frac{E_{\text{max}}}{E+S_n} \right)}{\int_0^{E_{\text{max}}} \ln \left( \frac{E_{\text{max}}}{E+S_n} \right) dE} \]  

Here, \( \alpha \) is the fraction of evaporation neutrons, \( T \) is the target nuclear temperature, \( \beta \) is the fraction of knock-on neutrons, \( E_{\text{max}} \) is the maximum energy of accelerated electrons and \( S_n \) is the separation energy of neutrons in the target nucleus. For W, \( \alpha = 0.8929, \beta = 0.1071, T = 0.5 \text{ MeV}, \) and \( S_n = 7.34 \text{ MeV}. \) For the Bremsstrahlung Cu target, \( S_n = 10.56 \text{ MeV and } T = 1 \text{ MeV} \) (Agosteo and Foglio, 1994, Agosteo et al., 1995).

The actual geometry and composition of the linac head are not always available. For neutron transport studies around a linac using Monte Carlo methods, some simplifications are usually assumed. Thus a point-like photoneutron source whose energy distribution is given by Equation (1) is located at the centre of a 10 cm-thick spherical shell, with 20 cm external radius, for W head, and 15 cm-thick spherical shell for Pb head (Agosteo et al, 1995). According to the American Association of Physics in Medicine (AAPM, 1986), the W head is preferred, because the Pb head provides a dose enhancement of a factor 2.

This simple head model has been successfully used (Facure et al., 2005, Followill et al., 2003) even with a thicker W sphere and different models for knock-on photoneutrons (Barquero et al., 2005). In particular, it has been pointed out that the results obtained using this simple model in Monte Carlo calculations show no significant differences with those found for detailed geometries of the linac head (Agosteo et al., 1995, Carinou, Kamenopoulou and Stamatelatos, 1999). On the other hand, photoneutron features, such as thermal fluences, spectra, absorbed
dose, and ambient dose equivalents have been investigated either using experimental procedures or Monte Carlo calculations (Barquero et al., 2005, Kry et al., 2009, Hernandez-Adame et al., 2011, Vega-Carrillo and Baltazar-Raigoza, 2011).

The aim of this work is to calculate, using Monte Carlo methods, the photon and neutron spectra of two linac heads, and to compare the neutron spectra with the analytical function of Tosi et al., (1991).
Materials and methods

Spectra were calculated using the Monte Carlo code MCNPX code (Pelowitz, 2005). Detailed head models of the 15 MV Siemens Primus and the 18 MV Varian Clinac 2100 C/D were used. Figures 1 and 2 show the geometry of the main components of both linacs.

![Diagram of linear accelerator components]

Figure 1. Target, compensator, flattening filter and jaws models for the 15 MV Siemens Primus linac

In the calculations an electron beam hits the 0.1 cm-diameter target. Electron energies were sampled from a Gaussian distribution with a mean energy of 15.3 MeV and a standard deviation of 1.5 MeV. These values were fixed by comparing the calculated percentage depth dose, PDD, with the experimentally measured in a water phantom (Martinez-Ovalle et al., 2011). This procedure was also used for the 18 MV Varian Clinac 2100 C/D where a 18.3 MeV electron beam was used. Figure 3 shows the comparison between calculated and measured PDDs for both linacs.
The geometry of both linacs included the shielding cover that was built up using Pb and Fe.

![Image](image.png)

Figure 2. 18 Varian Clinac 2100 C/D geometry model

Neutron spectra were tallied using point-like detectors located below the flattening filter and at the isocentre. In order to reduce the computational time, calculations were carried out in two steps. First a unidirectional electron beam was made to collide with the target and the Bremsstrahlung spectrum was calculated in both detectors, using the mode e/γ. Second, the x-ray spectrum obtained in the detector located under the flattening filter was used as source term, in mode e/γ/n, and the photoneutron spectrum was estimated in both detectors.

For all calculations the amount of histories was large enough to have uncertainties below 1%. Spectra were calculated using two energy arrays with 47 (MB) and 26 (FB) energy groups.
In order to compare the Tosi’s function with the photoneutron spectra obtained here, lethargy spectra, $E \phi_E(E)$, were calculated. In the case of the Tosi’s function the lethargy spectrum was obtained using equation 2.

Figure 3. Calculated and measured PDDs for the 15 MV Siemens Primus and the 18 MV Varian Clinac 2100 C/D linacs
\[ E \Phi_E(E) = E n(E) , \quad (2) \]

Here, \( n(E) \) is given by equation (1). For the spectra here calculated, that are discrete, we used:

\[ E \Phi_E(E) = \frac{\Phi_E(E)}{\ln\left|\frac{E_u}{E_l}\right|} \quad (3) \]

In equation (3), \( E_u \) and \( E_l \) are the upper and lower energy bounds of the class interval for each energy group.
Results

As said above, photoneutron spectra in linacs include the contribution of evaporation and knock-on neutrons, with a smaller contribution coming from \((\gamma,nn)\) and \((\gamma,pn)\) reactions. In figure 4, the neutron spectra for the 15 MV LINAC, in the detectors below the filter (in red) and at the isocenter (in blue) are shown.

![Figure 4. 15 MV linac photoneutron spectra below the filter and at the isocenter](image-url)

In the region between 0.1 and 10 MeV, two peaks with maxima around 0.3-0.5 MeV and 1.2-2 MeV are present. Neutrons with energies between 1 eV and 1 MeV are the evaporation neutrons while knock-on neutrons appear above 1 MeV.
The upper energy in these spectra is 6 MeV. In figure 5 the corresponding spectra for the 18 MV linac are plotted. They show the same features as those found for the 15 MV linac, except that in this case the upper energy is 9 MeV. Also, a larger amount of neutrons per photon are produced in this case.

Figure 5. 18 MV linac photoneutron spectra below the filter and at the isocenter

For both linacs, the difference between the spectra below the flattening filter and at the isocenter is mainly due to the distance between both detectors' locations.

In figure 6, the lethargy spectrum calculated with the function of Tosi et al. is compared to those obtained in our simulations. Both MB and FB spectra are shown.
Figure 6. Photoneutron lethargy spectra below the flattening filter for the 15 MV linac. The spectra obtained from the function of Tosi et al. is shown in red. The MB and FB Monte Carlo results are shown in blue and black, respectively.

The Tosi et al. spectrum shows evaporation neutrons from 1 eV up to 4 MeV, with a maximum for 1 MeV; the small tail above 4 MeV corresponds to knock-on neutrons. Both Monte Carlo spectra have the maximum shifted towards slightly lower energies having a larger contribution for all energies below that of the maximum.
In figure 7, the results found for the 18 MV linac are shown. Similar features, as those for 15 MV linac, are noticed; however differences are larger in this case in agreement with the findings of Huang et al. (2005).

Figure 7. Same as figure 6 but for the 18 MV linac

In figure 8 the photon spectra for 15 and 18 MV linacs calculated below the flattening filter and at the isocentre are shown. For both linacs the Bremsstrahlung spectra estimated under the flattening filter have a peak near 0.5 MeV and a continuous energy spectrum up to the incident electron energy (Patil et al., 2011). As the electrons colliding with the target are slowed down producing heat and
Bremsstrahlung x-rays that are continuous. Due to the distance between the target and the isocenter, the number of photons that reach the isocenter is strongly reduced and this effect is most visible in case of the lower energy photons. Regardless of the linac voltage, the photon maximum energy at the isocenter is approximately 1.5 MeV. Spectra at this position are into agreement with spectra reported in literature (Patil et al., 2011, Sheikh-Bagheri and Rogers, 2002).

Figure 8. Photon spectra below the filter and at the isocenter for both linacs
Conclusions

Detailed models of 15 MV Siemens Primus and 18 MV Varian Clinac 2100C/D heads were used to estimate the photon and neutron spectra below the flattening filter and at the isocenter. The spectra were calculated using the Monte Carlo code MCNPX. The features of the incident electron beam were tuned by comparing the PDDs calculated with the measured ones.

For both linacs, and for both locations, neutron spectra has the same features: they present two peaks around 0.3-0.5 MeV and 1.2-2 MeV. Evaporation neutrons appear between 1 eV and 1 MeV, whilst knock-on neutrons are beyond 1 MeV. Spectra at the isocenter are reduced with respect to those below the filter mainly due to the distance between both locations.

Neutron lethargy spectra were compared with those obtained from the function of Tosi et al. that has its maximum at 1 MeV. In both linacs, the agreement is reasonable above 1 MeV, though the spectra found for the function of Tosi et al. underestimate the Monte Carlo spectra below this energy.

For both linacs, Bremsstrahlung spectra calculated below the flattening filter have a peak near 0.5 MeV and a continuous spectra that, as expected, end at the maximum electron energy. At the isocenter, Bremsstrahlung spectra have the maximum between 1 and 2 MeV, regardless the accelerating voltage. The 15 MV-linac continuous spectrum is smaller than the 18 MV spectrum.
References


