reports of practical oncology and radiotherapy 15 (2010) 138–144

available at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.rpor.eu/

REPORTS OF PRACTICAL ONCOLOGY AND RADIOTHERAPY

A review on photoneutrons characteristics in radiation therapy with high-energy photon beams

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ARTICLE INFO

Article history:
Received 27 May 2010
Received in revised form
9 August 2010
Accepted 19 August 2010

Keywords:
Photoneutron
Radiation therapy
Photon beams
Neutron spectra
Neutron source strength

ABSTRACT

In radiation therapy with high-energy photon beams ($E > 10$ MeV) neutrons are generated mainly in linacs head thorough (γ,n) interactions of photons with nuclei of high atomic number materials that constitute the linac head and the beam collimation system. These neutrons affect the shielding requirements in radiation therapy rooms and also increase the out-of-field radiation dose of patients undergoing radiation therapy with high-energy photon beams. In the current review, the authors describe the factors influencing the neutron production for different medical linacs based on the performed measurements and Monte Carlo studies in the literature.

1. Background

In spite of tremendous developments in cancer treatment methods, radiation therapy using medical electron linear accelerators (linac) still plays an unparalleled role in palliation and treatment of tumors. In radiation therapy with photon beams ($E > 10$ MeV) neutrons are generated mainly in linacs thorough (γ,n) interactions of photons with nuclei of high atomic number materials constituting the linac head and the beam collimation system.[1–3] On the other hand, high-energy photon interactions with patients and treatment room wall could be the other sources of photoneutrons in radiation therapy. Different reaction mechanisms like giant dipole resonance (GDR), quasi-deuteron (QD) delta resonance (DR), etc. are involved in the production of photoneutrons.[4] The neutrons emitted from the GDR mechanism are similar to the evaporation neutrons from a compound nucleus while the QD neutrons have been compared with the pre-equilibrium model. GDR neutrons are of low energy with an isotropic angular distribution.[4] In high-energy accelerators where the photon energy and intensity is high compared to the neutrons, it is difficult to experimentally measure the direct photoneutron component.[5,6]

The NCRP 116 recommends a quality factor of 20 for photoneutrons energy of 0.1–2 MeV which is produced in radiation therapy with photon beams.[7] They are highly penetrating particles with high radiobiological effectiveness (RBE). Their contribution in patient out-of-field dose is smaller than scattered photons but considering their quality factor of 20 gives a significant contribution in patient effective dose and consequently in radiation-induced fatal cancer risk.[8,9]

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doi:10.1016/j.rpor.2010.08.003

2. Aim

In this article, we have tried to review the published studies on photoneutron production in different linacs, including Varian, Elekta and Siemens. Additionally, the effect of different factors on photoneutrons dosimetric features has been reviewed.

3. Materials and methods

3.1. *Photoneutron production in linac head*

The main sources for photoneutrons in a linac head are high atomic number components, including target, primary collimator, secondary collimators, wedges, blocks and multi-leaf collimators. The tungsten (W) and lead (Pb) with high cross sections for (γ,n) reaction are major sources of photoneutrons in medical linacs. Although, other elements such as iron, copper and aluminum are present, their probability for neutron production is negligible. For example, only ^{56}Fe atoms can produce neutrons among the iron atoms. For quantitative comparison, it can be said that the energy threshold of photoneutron production for W and Pb are 6.74 and 6.19 MeV, respectively. Whereas respective thresholds for Cu and Fe have been reported to be 9.91 and 7.65 MeV.[10] On the other hand, the probability of photoneutron interactions increases steeply with photon energy and its maximum value has been found in the therapy range of 13–18 MeV photons for the materials used in the linac head including W, Pb, Cu and Fe.[2,11]

The other noteworthy point is that the main neutron producing materials, tungsten and lead, have very low absorption cross sections for the energy range of neutron produced in linac head. Therefore, photoneutrons have a great chance to penetrate the shielding and reach the patient and bunker walls.

Over recent three decades, many studies have reported neutron dosimetry using different types of dosimeters.[8,12–22] However, the experimental methods have not been able to analyze the origin of neutrons reaching the dosimeter. The proposed method of choice to tackle this problem have been the Monte Carlo methods.[23] By modeling different components of a linac and initiating the primary electron striking on target and then following the history of all particles including photons, electrons and neutrons in different parts of a linac until its death, all information about the interactions and number of generated particles as well as deposited energies in different parts or any defined volume can be tallied and provided at the end of simulation.[24] In several MC studies the contribution of different parts of a linac in neutron fluence received by patient or at the isocenter has been calculated for some commercial linacs.[5,10,23,25,26]

MC methods have been employed extensively to evaluate the photoneutron characteristics in radiation therapy.[26–30] MC studies have shown that neutron source strength or Q value varies with linac model, location of scoring cell, field size and modeling geometry.

Using the MC methods, Pena et al. calculated the contribution of different components of a Primus linac operating in its 15 MeV photon beam for 10 cm × 10 cm field size.[26] The contribution of different components in neutron source strength were reported as primary collimator 52%, secondary collimator jaws 21%, target 12%, Multi-leaf collimator (MLC) 6.6%, shielding 5%, flattening filter 0.41%. A recent study by Becker et al.[13] on the same linac showed results consistent with the previous study of Pena et al. Comparing the results of both studies with the results obtained on a Varian 2100C/2300C linac by Mao et al., Zanini et al. and Howell et al. reveals that in both linacs the overall trend of contribution are identical but there are small discrepancies for different components.[30–32] The results were summarized in Table 1. As seen in Table 1, the target and flattening filter in Varian linac shows higher contribution of 25% and 75% relative to Primus. However, it can be concluded from different MC studies that the primary collimator which is made from tungsten alloys has the highest contribution among different components.[26,32,33] The second contributor is secondary collimator jaws and then target, multi-leaf collimator, shielding and flattening filter as other contributors.

The commonly used quantity for neutron production in different linacs is neutron source strength, Q, which is defined as the number of neutrons at the isocenter coming from linac head per X-ray dose delivered at the isocenter.[2] Neutron source strength of a linac is an important factor used in the neutron dose calculations for both shielding purposes and patient out-of-field dose calculations. A most complete data set of neutron source strength was provided by an experimental study of Followill et al.[17] The results of different studies on neutron source strength of commercially used linacs were summarized in Table 2. A review of Table 2 indicates that the neutron strength for different linacs depends on the photon energy and linac head structures as well as a model. Furthermore, it should be noted that a wide range of Q values reported for a specific model and photon energy result from large uncertainties in neutron measurement methods. Differences in MC modeling and application of different codes for MC calculations could also account for the observed discrepancies.

In the study of Mao et al. the neutron strength of Varian Clinac 2100C/2300C for different energies was estimated

Table 1 – MC calculation of component contribution in photoneutrons from Varian 2100C/2300C linac.[32]

Component	20 MeV	18 MeV	15 MeV	10 MeV
Target	17.2% (W,Cu)	16% (W,Cu)	9% (W,Cu)	0.01% (Cu)
Primary collimator	36% (W)	41% (W)	38% (W)	45% (W)
Flattening filter	10.4% (Fe,Ta)	9% (Fe,Ta)	22% (W)	0.03% (CU)
Jaws	36% (W)	35% (W)	29% (W)	56% (W)
Others (magnet, shielding, etc.)	1%	1.4%	1.2%	1%