Physica Medica 48 (2018) 1–5

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Original paper

Monte Carlo simulation of neutron dose equivalent by photoneutron production inside the primary barriers of a radiotherapy vault

Chang Heon Choi[a,b,c], So-Yeon Park[a,b,c], Jong Min Park[a,b,c,e], Minsoo Chun[a,d], Jung-in Kim[a,b,c,*]

[a] Department of Radiation Oncology, Seoul National University Hospital, Seoul, Republic of Korea
[b] Institute of Radiation Medicine, Seoul National University Medical Research Center, Seoul, Republic of Korea
[c] Biomedical Research Institute, Seoul National University Hospital, Seoul, Republic of Korea
[d] Interdisciplinary Program of Radiation Applied Life Science, Seoul National University College of Medicine, Seoul, Republic of Korea
[e] Center for Convergence Research on Robotics, Advanced Institutes of Convergence Technology, Suwon, Republic of Korea

ARTICLE INFO

Keywords:
Neutron shielding
Neutron dose equivalent
Photoneutron dose
Primary barrier

ABSTRACT

Purpose: To evaluate the neutron dose equivalent produced by photoneutrons inside the primary barriers of a radiotherapy vault.

Methods: Monte Carlo simulations were performed for investigating the production of photoneutrons as well as neutron shielding requirements. Two photon beams of 15 and 18 MV struck sheets of steel and lead, and the neutron doses were calculated at the isocenter (P_{iso}) and at a distance of 50 cm from the inside wall (P_{wall}) while delivering 1 Gy to the patient. The proper thicknesses of borated polyethylene (BPE) and concrete were simulated to reduce neutron contamination.

Results: When the primary barrier consisted of a concrete alone, the neutron doses at P_{iso} were 0.5 μSv/Gy and 12.8 μSv/Gy for 15- and 18-MV, respectively. At P_{wall}, the neutron doses were 15.8 μSv/Gy and 318.4 μSv/Gy for 15- and 18-MV, respectively. When 15 MV photons interacted with metal sheets, the neutron doses were 0.4–22.2 μSv/Gy at P_{iso} and 15.8–812.5 μSv/Gy at P_{wall}, depending on the thickness and material of the metal sheets and neutron shielding. In the case of 18 MV photons with the same configuration, the neutron doses were 0.9–59.5 μSv/Gy and 73.9–5006.1 μSv/Gy for P_{iso} and P_{wall}, respectively. The neutron dose delivered to the patient was reduced to the level of the dose delivered with a concrete barrier by including a 10-cm-thick BPE for each beam.

Conclusions: When the primary barrier shielding is designed with a metal sheet inside for high energy, proper neutron shielding should be constructed to avoid undesirable photoneutron dose.

1. Introduction

Medical linear accelerators (LINAC) that have the ability to generate photon beams have been widely used for radiation therapy [1]. In most radiation therapy facilities, older low-energy linacs have been replaced with new dual-energy linacs that can generate both low- (6 MV) and high-energy (≥10 MV) photon beams. With high-energy linacs, photoneutrons could be produced in the metallic components of the treatment head, such as the target, flattening filter, and collimator [2–5]. In these situations, the shielding design of the bunker should be modified to consider both high-energy photons and neutrons [6,7] according to the National Council on Radiation Protection and Measurements (NCRP) Report 151, which addresses the structural shielding design for high-energy linacs [7].

Ordinary concrete has been used as the standard material for shielding radiotherapy bunkers because of its low cost and structural strength [6]. However, the tenth-value layer (TVL) of ordinary concrete is 44 cm and 45 cm for 15-MV and 18-MV photon irradiation, respectively [7]. Therefore, when ordinary concrete is used to shield rooms for high-energy photons, the necessity of thick primary barriers can reduce the available space. Space is one of the key factors for bunkers, and bunker shielding design and should be efficiently configured [8]. When sufficient space is not available for a bunker, it is necessary to consider laminated barrier shielding, which is composed of concrete and metal sheets, as an alternative to reduce the thickness of the primary barrier design [7]. In most cases, steel or lead are used as metal shielding materials due to their good structural support and effective TVL [6]. However, if the metal portion of the primary barrier is attached on the inside wall of the bunker and the metal shield is irradiated by photon beams with energies of 10 MV or higher, the patient

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* Corresponding author at: Department of Radiation Oncology, Seoul National University Hospital, Seoul 110-744, Republic of Korea.
E-mail address: madangin@gmail.com (J.-i. Kim).

https://doi.org/10.1016/j.ejmp.2018.03.009
Received 8 March 2017; Received in revised form 6 March 2018; Accepted 13 March 2018

may be exposed to neutron radiation due to the production of photoneutrons. If the patient was located near a primary wall, which might occur during total body irradiation (TBI), the patient could be exposed to additional photoneutrons [9].

Photoneutrons are highly penetrative particles with high radiobiological effectiveness [10,11]. Considering their quality factor, photoneutrons have a significant contribution to the patient effective dose [12,13]. Exposure to such an unexpected extra dose can increase the risk of delayed secondary malignancies [14]. Therefore, additional shielding must be considered to minimize undesired neutron doses.

NCRP 151 reported the mathematical model for calculating the neutron dose equivalents outside the barrier for the protection of radiation workers or public. However, the model can be considered an inadequate model by Monte Carlo (MC) evaluation [1]. A. Facure et al. investigated the photoneutron dose of the isocenter in laminated barriers using the MC method for a 10-MV photon beam [8]. However, this study has not reported results for near the wall and 15- and 18-MV beams. McGinley investigated the increase in neutron dose to the patient using the neutron dose equivalent rates for lead and steel barriers in an 18-MV linac vault [6]. The results were derived from the neutron measurement. However, the neutron measurements are sensitive experiments because of uncertainties in the photon background and a lack of information about the neutron spectrum inside the bunker [15]. Thus, the MC method has been considered the most accurate method for calculating the neutron dose.

In this study, we calculated the neutron dose produced from the interaction of 15- and 18-MV photon beams with a primary barrier containing metal (lead or steel) using Monte Carlo simulations at the isocenter and near the inside wall (TBI condition). The neutron ambient dose equivalents delivered to patients were simulated to evaluate the neutron shielding effect for neutron shielding materials (borated polyethylene (BPE) plate and concrete) [6,16]. The neutron fluences were calculated to evaluate the effect of the material and the thickness of additional shielding depending on the energy distribution.

2. Materials and methods

Monte Carlo (MC) simulations were performed using both the EGSnrc/BEAMnrc code and Monte Carlo N-Particle Extended (MCNPX) 2.7.0 code [17–19]. The EGSnrc/BEAMnrc code was selected to model the clinical linac by adjusting component module specifications. A clinical linac can be modeled with EGSnrc/BEAMnrc code efficiently [13]. The initial photon energy spectrum generated from BEAMnrc was provided to MCNPX as the input source. In turn, MCNPX code was used for neutron dose calculation since EGSnrc/BEAMnrc code cannot calculate the neutron dose [20].

2.1. Monte Carlo simulations (EGSnrc/BEAMnrc code) for modeling the initial photon energy spectrum

The initial 15-MV and 18-MV photon spectrum was modeled using the EGSnrc/BEAMnrc code. The parameters of the linac and the incident electron beam were adjusted to match the factory beam data of the Varian 21iX linac (Varian Medical Systems, Palo Alto, CA) [21]. Percent depth dose (PDD) values were evaluated at the depth of the maximum dose deposition (d_{max}) at 5 cm, 10 cm, and 20 cm (D_5, D_{10}, and D_{20}) for benchmarking. One rectangular plane—located 100 cm from the source and placed perpendicular to the central beam axis—was used to collect the phase space information generated by the BEAMnrc code. The spatial distributions and energy spectra of the photon beams were extracted from these phase space files. The extracted energy spectra information was used as input data for neutron dose simulation performed with the MCNPX code.

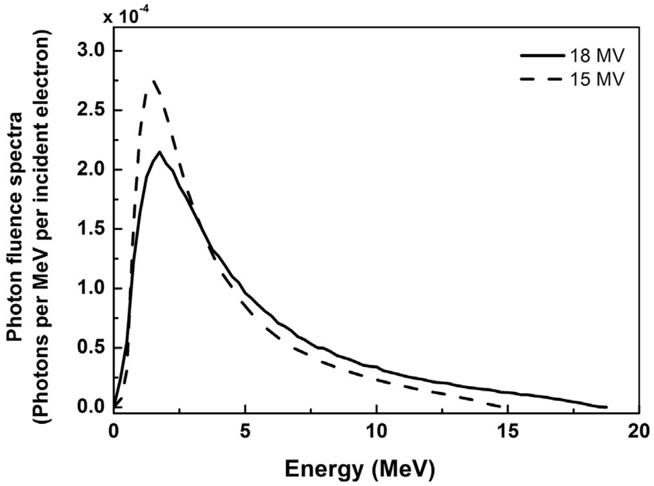

Fig. 1. Photon spectrum described as the input of the MCNPX source for 15-MV (dashed line) and 18-MV (solid line) photons.

2.2. Monte Carlo simulations (MCNPX) for photoneutron calculations using a metal sheet and neutron barrier

The neutron mode of the MCNPX code was used to investigate the neutrons induced by photons [22–24]. Nuclear data for interactions with neutrons were taken from the ENDF66 library [25]. The F5 tally was used to assess neutron fluence at the detector point [25]. Detector points were set at the isocenter (P_{iso}) and at a distance of 50 cm from the inner wall (P_{wall}). The radius of the detector was set to 10 cm. The points P_{iso} and P_{wall} were used for evaluating the dose to a patient undergoing general radiation therapy and TBI treatment, respectively.

The energy spectrum calculated by the EGSnrc/BEAMnrc code (Fig. 1) was used as the input data in this simulation. The incident photon distribution was set to a divergent beam with a 40 × 40 cm^2 field size at the isocenter. The distance from the isocenter to the outer surface of the primary barrier was set to 5 m. The primary barrier was divided into three parts: the neutron shielding barrier, metal sheet shielding barrier, and concrete wall. The barrier design is shown in Fig. 2. Boron-10 loaded polyethylene and concrete were used as neutron shielding materials [6]. Borated polyethylene, which is made from high-density polyethylene plastic with 5% boron content by weight, is typically used in the medical field for neutron shielding. Metal sheets of lead and steel are typically used for photon shielding [26]. The composition of materials used in MNCPX simulation is summarized in Table 1.

All neutron ambient dose equivalents were calculated at both P_{iso} and P_{wall}. The thicknesses of the metal sheet in the shielding barrier were 1 TVL and 2 TVL in the simulations. The TVL of lead and steel is 5.7 cm and 11 cm, respectively [7]. For each case, the neutron shielding

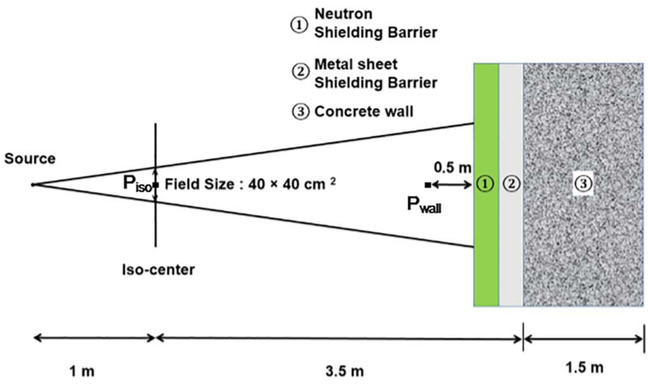

Fig. 2. Illustration of the described geometry in Monte Carlo simulation.