Radiation Measurements 116 (2018) 40–45

Contents lists available at ScienceDirect

Radiation Measurements

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

Improvement of neutron spectrum unfolding based on three-group approximation using CsI self-activation method for evaluation of neutron dose around medical linacs

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ARTICLE INFO

Keywords:
Photoneutrons
Medical linacs
Self-activation method
Unfolding
^{128}I
Three-group approximation

ABSTRACT

We previously evaluated ambient neutron dose equivalent by using the self-activation of a CsI scintillator around a high-energy medical linear accelerator (linac) ^{128}I saturated activities were successfully converted to neutron spectrum and ambient neutron dose equivalent by neutron spectrum unfolding with the “three-group approximation.” The principle of the three-group approximation is based on the assumption of fixed shapes of neutron energy spectra for each of the three energy regions to evaluate the neutron spectrum effectively. However, such a neutron dose evaluation with the unfolding method might be affected by the difference between the actual fast neutron energy spectrum and the assumed spectrum. In the present work, we modified the unfolding method by taking into account the differences in the shapes of fast neutron energy spectra for various medical linacs. We verified the unfolding method using Monte Carlo simulation with several neutron spectra obtained from published research articles. The modified three-group approximation evaluates the neutron doses more accurately than the conventional unfolding method.

1. Introduction

The use of high-precision X-ray therapy such as intensity-modulated radiotherapy, which allows delivery of a high dose to a tumor while minimizing the dose delivered to normal tissue, has grown recently. However, in the process of X-ray therapy, the photoneutrons are generated from high-*Z* materials such as the target and collimators (Mao et al, 1997), and possess high biological effectiveness, with the risk of causing secondary cancer (Hall et al, 1995). So, in our opinion, it is desirable to evaluate the neutron dose for each patient who receives X-ray therapy.

We recently proposed a novel neutron detection method that uses the self-activation of an iodine-containing scintillator such as NaI or CsI (Wakabayashi et al, 2015; Nohtomi and Wakabayashi, 2015; Nohtomi et al, 2016a; Nohtomi et al, 2016b; Honda et al, 2017). This method may be applied for neutron detection around medical linear accelerators (linacs) in terms of highly sensitive neutron detection with online readout.

In a previous study (Nohtomi et al, 2016b), we evaluated the ambient neutron dose equivalent around a 10 MV medical linac by using a CsI scintillator with several filtering conditions; the neutron spectrum unfolding was performed by assuming fixed neutron energy spectra for each of the three energy regions (referred to as the *three-group approximation*). By the proposed unfolding method, the neutron spectrum and ambient neutron dose equivalent were evaluated effectively. However, in the previous evaluation, although the approximated spectrum in the fast neutron region was estimated by the fitting of a simulated spectrum based on Monte Carlo calculation for a 10 MV medical linac (Yabuta et al, 2014), the difference in actual shape of fast neutron spectra may be because of different experimental conditions, such as different medical linac manufacturers, accelerator voltages, and measuring points. So, the fixed neutron spectrum approximation in fast region might result in the wrong evaluation on neutron spectrum.

Fig. 1 shows the neutron-fluence-to-ambient-dose-equivalent conversion coefficients given by the International Commission on Radiological Protection (ICRP, 1996). The conversion coefficients curve shows a steep change in the fast neutron region (0.1–1 MeV). Thus, an unexpected slight spectral distortion in this region might cause a large error in the neutron dose evaluation. Therefore, for neutron dose evaluation, it is important to approximate the appropriate shape of the fast neutron spectrum in the three-group approximation.

In the present study, the unfolding method with the three-group

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https://doi.org/10.1016/j.radmeas.2018.06.021
Received 23 January 2018; Received in revised form 16 June 2018; Accepted 21 June 2018
Available online 22 June 2018
1350-4487/

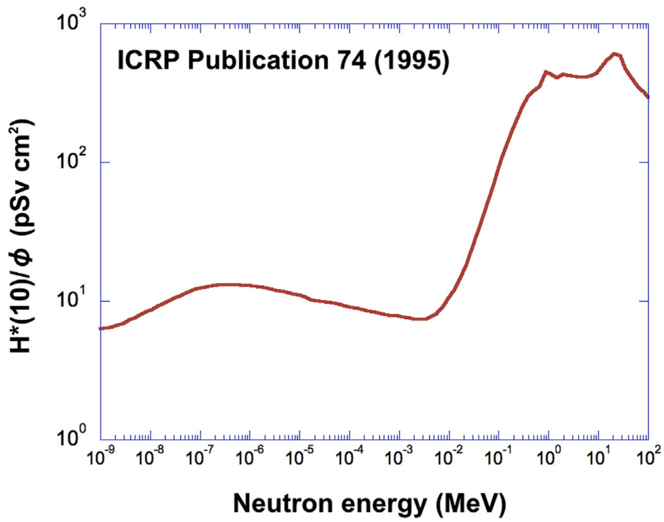

Fig. 1. Neutron fluence-to-ambient-dose-equivalent conversion coefficients (ICRP, 1996).

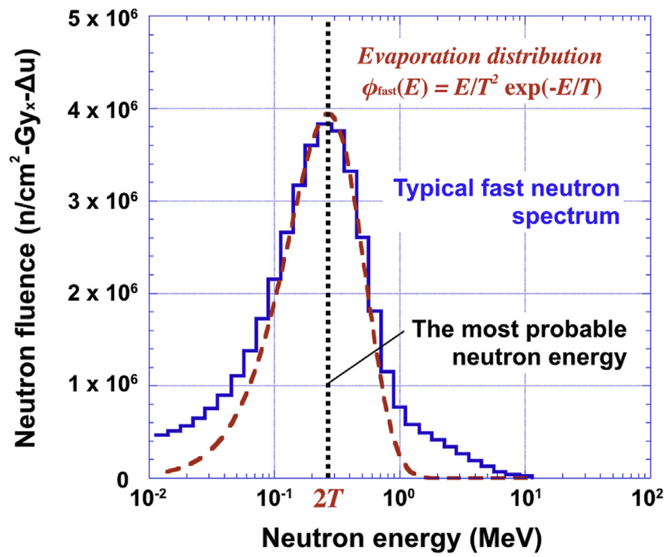

Fig. 2. An example of comparison between an approximated spectrum and a typical spectrum. The typical spectrum was obtained from (Domingo et al, 2010).

approximation was modified. The evaluation of ambient neutron dose equivalent with the modified unfolding method is compared with that with the conventional method using Monte Carlo simulation for verification.

2. Unfolding procedure with modified three-group approximation

The ^{128}I saturated activity ($A_{\rm sat}$) (Bq) generated in the self-activation method with a CsI scintillator can be expressed as follows:

$$A_{\rm sat} = \phi N\sigma VS \tag{1}$$

where ϕ is the neutron fluence rate (n/cm^2-s), N is the number density of iodine atoms in the CsI scintillator (1/cm^3), σ is the neutron capture cross section of the reaction ^{127}I (n,γ)^{128}I (cm^2), V is the volume of the CsI scintillator (cm^3), and S is the self-shielding correction factor. σ and S in Eq. (1) depend on the shape of the neutron energy spectrum and the detector dimensions. Thus, detector response R (cm^2) = $N\sigma VS$ can be calculated if the neutron energy spectrum is already known. In general, typical shapes of neutron spectra at medical linacs are almost unchanged for each of the two energy regions (thermal, epithermal regions), slight distortions of neutron spectra appear in fast region, and the ratio of neutron fluences among the regions vary depending on the experimental conditions (Esposito et al, 2008). On the basis of this tendency, in the modified three-group approximation, the neutron energy spectra $\phi(E)$ are approximated by the following equations for energy regions corresponding to thermal, epithermal, and fast neutrons:

$$\phi_{\rm thermal}(E) = E^{0.5}\exp\left(-\frac{E}{2.53}\times 10^{-8}\right) \; E(MeV) < 5\times 10^{-7} \tag{2}$$

$$\phi_{\rm epi}(E) = 1/E$$
$$5\times 10^{-7} \le E\,(MeV) < 1\times 10^{-2} \tag{3}$$

$$\phi_{\rm fast}(E,T) = \frac{E}{T^2}\exp(-E/T)\; 1\times 10^{-2} \le E\,(MeV) \tag{4}$$

where Eq. (2) is the Maxwell distribution at room temperature (0.0253 eV), Eq. (3) is from (Yamaguchi et al, 1982), Eq. (4) is an evaporation distribution, and T (MeV), known as the *nuclear temperature* (National Council of Radiation Protection, 1984), is a key parameter for the determination of the shape of the fast neutron spectrum. The fast neutron lethargy spectrum $\phi_{U\,\rm fast}(E)$ is obtained by using the following equation (Vega-Carrilo et al, 2012):

$$\phi_{U\,\rm fast}(E,T) = E\cdot\phi_{\rm fast}(E) = E^2\exp(-E/T) \tag{5}$$

In Eq. (5), the most probable neutron energy of the evaporation distribution is located at $2T$ (MeV). In general, the most probable neutron energy of the fast neutron spectrum around medical linacs depends on the experimental conditions such as medical linac manufacturers, accelerator voltages, and measuring points, and the neutron energy ranges from 0.2 to 1 MeV (Esposito et al, 2008; Vega-Carrilo et al, 2012; Domingo et al, 2010; Amgarou et al, 2011). The typical fast neutron spectrum can be fitted well with the approximated lethargy spectrum of Eq. (5) with an optimal value of the parameter $2T$ for the most probable energy, as shown in Fig. 2. The choice of optimal value of $2T$ might result in more accurate evaluations of ambient neutron dose equivalent compared to those from the conventional three-group approximation which fixes the fast neutron spectrum. However, there is no straightforward way to know the actual value of $2T$ from our measurements. For this reason, the optimal value of $2T$ was estimated by an alternative method as presented below.

^{128}I saturated activities, $A_{\rm sat}$ (Bq), in a self-activated CsI scintillator with several filtering conditions can be converted to the neutron fluence rate ϕ (n/cm^2-s) for each of the three energy regions using the following equation:

$$\begin{bmatrix}\phi_{\rm thermal}(2T)\\ \phi_{\rm epi}(2T)\\ \phi_{\rm fast}(2T)\end{bmatrix} = \begin{bmatrix} R^{\rm F1}_{\rm thermal} & R^{\rm F1}_{\rm epi} & R^{\rm F1}_{\rm fast}(2T)\\ R^{\rm F2}_{\rm thermal} & R^{\rm F2}_{\rm epi} & R^{\rm F2}_{\rm fast}(2T)\\ R^{\rm F3}_{\rm thermal} & R^{\rm F3}_{\rm epi} & R^{\rm F3}_{\rm fast}(2T)\\ R^{\rm F4}_{\rm thermal} & R^{\rm F4}_{\rm epi} & R^{\rm F4}_{\rm fast}(2T)\end{bmatrix}^{+} \begin{bmatrix} A^{\rm F1}_{\rm sat}\\ A^{\rm F2}_{\rm sat}\\ A^{\rm F3}_{\rm sat}\\ A^{\rm F4}_{\rm sat}\end{bmatrix} \tag{6}$$

where the plus sign associated with the response function matrix indicates its pseudoinverse, and F1–F4 are filtering conditions. The responses can be calculated with a Monte Carlo code for each energy region and each filtering condition. Furthermore, response function matrix elements for the fast region are calculated by changing the $2T$ value to arrive at the optimal value. Hence, the neutron fluence rate ϕ evaluated using Eq. (6) depends on $2T$. To determine the optimal value of $2T$, the residual sum of squares (RSS) of ^{128}I saturated activities was calculated using the following equation for several values of $2T$.

$$\mathrm{RSS}\left(2T\right) = \sum_i ((A_{\rm sat})_i - (A_{\rm cal}(2T))_i)^2 \tag{7}$$

where the value of i indicates the filter condition and $(A_{\rm cal}(2T))_i$ represents the recalculated ^{128}I saturated activities for each $2T$