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Distribution of spatial photoneutrons inside a 70 kg water phantom via neutron activation analysis

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ABSTRACT

This study evaluated spatial Φ_{th} inside a 70 kg water phantom using the NAA method. Fifty indium foils were placed inside the water phantom and exposed under 15 MV LINAC for 2.5 min to yield the 10 Gy X-ray dose. The Φ_{th} value at the isocenter of the water was 1.03×10^6 n cm^{-2}/Gy-X, and the maximum quantity of Φ_{th} appeared at the water surface along the z-axis, 3.99×10^6 n cm^{-2}/Gy-X. The thermal neutron dose at isocenter of the water phantom occupied approximately 0.151% of the whole photo and neutron dose.

1. Introduction

This study assesses the thermal photoneutrons inside a 70 kg water phantom via neutron activation analysis (NAA). Although the photoneutrons are byproducts from the linear accelerator (LINAC) during the cancer therapeutic process, the amount of photoneutrons can be determined when the LINAC is operated at a power of over 10 MV. Numerous studies have either measured or calculated the generated photoneutrons within the treatment room. Evaluations were largely proceeded by adopting the TLD-600/700 and the Bonner sphere method, since TLD can count radiation for extended periods and still yield an acceptable confidence level (Barquero et al., 2005; Howell et al., 2005). In addition, Carinou adopted the MCNP code to evaluate the photoneutron dose of LINAC from the theoretical viewpoint (Carinou et al., 1999). Manfredotti applied both 3D-MCNP code calculation and TLD-600/700 coupled with anthropomorphic phantom to measure the in-vivo photoneutron dose (Manfredotti et al., 1992) or other conventional methods such as bubble detectors (D'Errico et al., 1998, 2001; Lin et al., 2007).

However, bubble detector can barely discriminate the thermal neutron energy range from the primary photoneutrons spectrum, implying that the reported value can be evaluated only as neutron dosimeter reflected to the entire neutron spectrum. In contrast, some studies attempt to determine the thermal neutron distribution within the treatment room via the NAA method by using either gold or indium foil since either gold or indium nuclide has a high thermal neutron absorption cross section and is equipped with satisfactory discrimination ability in the entire neutron spectrum (Konefal et al., 2005; Palta et al., 1984; Gur et al., 1978; Uwamino et al., 1986). Moreover, some theoretical calculations based on the MCNP code focus mainly to provide the photoneutron spectra in either air or human body (Cho et al., 2007; Carinou et al., 2005; Adnani, 2002). Those studies have significantly contributed to understand photoneutrons within the treatment room.

The precise thermal neutron distribution inside the water phantom can not only propose the primary information for dose verification from a health physicist's viewpoint but also provide the understanding of neutron distribution inside the body trunk from a radiologist's viewpoint. Conversely, the TLD-600/700 coupled with Bonner sphere can only reveal the original neutron

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spectrum. Furthermore, the Lucite anthropomorphic phantom was also held in this study, since carbon nuclide (the majority part in Lucite) has a comparatively small macroscopic scattering cross section (Σ_s=0.385 cm^{-1}) than water has (Σ_s=3.45 cm^{-1}) for thermal neutron. The scattering process dominates mainly the thermal neutron distribution inside the phantom. Additionally, the macroscopic absorption cross section for thermal neutron in water occupies less than one hundredth to scattering (Σ_a=0.022 cm^{-1}, 0.022/3.45=0.0064) (Glasstone and Sesonske, 1977).

The spatial neutron is estimated by analyzing 50 pieces of thermal neutron induced activated indium foils along the horizontal and vertical axes inside the phantom. Hopefully, the regressed spatial neutron along the two axes can provide valuable data when evaluating the internal neutron absorbed dose for cancer therapeutic patients. The thermal neutron absorbed doses can be evaluated and are not confined to the X-ray field since the quality factor (QF) is assigned to 20 for thermal neutron from the AAPM-19 recommendation (Nath, 1986), implying that the neutron can incur 20 times as much biological damage than a photon can. Namely, neutron quantities should not be sufficiently large to adversely impact humans. However, undertaking such neutron measurements near the LINAC has always been complex owing not only to an intense and pulsed background of photons but also to a limited knowledge regarding the thermalized epithermal/fast neutron spectra originating from the interactions with the LINAC components (D'Errico et al., 1998). The spatial thermal neutron inside the water phantom can be interpreted based on the neutron volume source with a rectangular parallelepiped and integrated from basically two parts of thermal neutrons, i.e. (1) the part from the original photoneutron spectrum and (2) the part from the thermalized epithermal/fast neutron. This study also elaborates on the NAA method, spatial neutron distribution or steady volume source.

2. Materials and methods

2.1. Foil activation method

Foil activation has been extensively adopted to determine Φ_{th} (n cm^{-2}/Gy-X) in the recent decades. Thermal neutrons can be identified by selecting appropriate foil materials including gold (Au-197) or indium (In-115), for performing thermal neutron absorption. The spatial Φ_{th} is evaluated by activating the indium foils via $^{115}In(n,\gamma)^{116m1}In$ reaction, which has high absorption cross section (162 barns) for the thermal neutrons and an adequately short half-life ($T_{1/2}$=54.2 min) (Nath, 1986). In this study, the indium foil (purity > 99.999%; 25 × 25 mm^2 and 1 mm thickness, Goodfellow Cambridge, Ltd., UK) has an average mass of 4.86 ± 0.07 g to be applied.

Consider a thin indium foil of mass m exposed for time t_i. Following irradiation, the foil is allowed to cool for time t_d and then counted for time t_c by using a high-purity germanium (HpGe) detector (GC3520) (Canberra Industries, Meriden, CT, USA). The HpGe detector has an active volume of 145.3 cm^3, 35% relative efficiency to a 2" NaI detector and resolution of 2.0 keV at 1332 keV, where Φ_{th} can be derived as

$$\Phi_{th} = \frac{N_{In}}{\varepsilon\gamma\sigma K}$$
$$K = \frac{n(1-e^{-\lambda t_i})(e^{-\lambda t_d})(1-e^{-\lambda t_c})}{\lambda} \quad (1)$$

where N_{In} denotes the number of activated nuclides $^{116m1}In$. λ represents the decay constant (=0.693/$T_{1/2}$). ε is the detection efficiency, and σ is the microscopic cross section. $T_{1/2}$ is the half-life of $^{116m1}In$, and γ is the absolute γ-ray intensity (29.2%)

$$n = \frac{\theta m N_A}{M} \quad (2)$$

where n is the number of ^{115}In, and θ is isotopic abundance of ^{115}In, the indium nuclide (95.7%). N_A is Avogadro's number (6.022×10^{23} in atoms/g-atom), and M is molar mass of the foil material, and m represents indium foil mass.

The measured γ-ray spectra were collected using a multi-channel analyzer (10^+) (Canberra Industries, Meriden, CT, USA). The foils were immediately placed on the detector face. Notably ε, at the characteristic γ-ray energy of 417 keV, was emitted from the isomeric transition of $^{116m1}In$ and calibrated as to 4.0%. Furthermore, the detector efficiency was also revised from the gamma peak coincidence correction in practical measurement. The coincidence effect was extremely high for close source–detector configuration (the distance between source and detector was 0.0 cm in this study). When two γ-rays were released simultaneously from the β-decay (Co-60, 1,17 and 1.33 MeV adopted as one of the standard sources in this study), and were recorded as one pulse within the resolving time of the detecting system, coincident detection of these γ photons appeared. The coincidence correction factor was assigned as 1.16 on the basis of the evaluation of Dr. Abbas (Abbas, 2007). Dr. Abbas measured the correction factor using an axial isotropic point source placed on the surface of the HpGe detector with an active volume of 75 cm^3. The GC3520 HpGe detector evaluated the efficiency of a series of γ-energy using calibrated standards for ^{60}Co, ^{133}Ba, ^{137}Cs, and ^{152}Eu. In addition, the well calibrated detection efficiency agreed well with other similar arrangements. For instance, Dr. Chao adopted the activated indium foil to measure the Ar-41 and reported that the HpGe detection efficiency reached 4.0% (Chao et al., 2007), and Lin surveyed the stray neutron in cyclotron vault room using the activated indium foil with a similar HpGe system of 4.92% detection efficiency (Lin et al., 2009). Following exposure, the activated indium foils were allowed to decay for an appropriate time interval. The integrated errors were systematic and consist of detector energy responses. Spectra acquired were identified and calculated using Micro SAMPO-90 software and a personal computer. Details of the experimental conditions can be found elsewhere (Chen et al., 2003; Lin et al. 2009). Statistical errors were within 9–12%. The experimental layout is depicted in Fig. 1. As clearly illustrated, the indium foil was laid closely toward the HpGe head for increasing the detection efficiency since most indium foils were irradiated beneath the water surface and thus the activation process was barely achieved.

2.2. Self-absorption factor of indium foil

Indium is an extremely strong absorber for thermal neutrons; therefore neutron field has been changed and the neutron flux has been decreased inside the thick (1 mm) indium foil. These effects are taken into account by using a "self-shielding factor" compensation in the activation formula. The ratio between the reactions rates per atom in the real sample and with a similar one infinitely dilute is defined as G_{th}. The practical G_{th} can be derived for a given element with fixed geometry and sample dimension as expressed by Idiri et al., 2007; Martinho et al., 2004

$$G_{th}(z) = \frac{1}{1+(z/z_0)^p} \quad (3)$$

where z_0 and p are particular constants and equal to 0.682 and 0.990, respectively, for indium foil as applied herein. z is the dimensionless variable that is expressed as

$$z = t\Sigma_t\left(\frac{\Sigma_a}{\Sigma_t}\right)^k \quad (4)$$