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Effects of computational phantoms on the effective dose and two-dosimeter algorithm for external photon beams

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HIGHLIGHTS

- Two-dosimeter algorithms were developed for external photon beams.
- KTMAN-2, CRAM, MASH, and ICRP male reference phantoms were used for simulations.
- Calculation was performed for different polar and azimuthal angles using MCNP Monte Carlo code.

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ABSTRACT

In this study, the effect of computational phantoms on the effective dose (E), dosimeter responses positioned on the front (chest) and back of phantom, and two-dosimeter algorithm was investigated for external photon beams. This study was performed using Korean Typical MAN-2 (KTMAN-2), Chinese Reference Adult Male (CRAM), ICRP male reference, and Male Adult meSH (MASH) reference phantoms. Calculations were performed for beam directions in different polar and azimuthal angles using the Monte Carlo code of MCNP at energies of 0.08, 0.3, and 1 MeV. Results show that the body shape significantly affects E and two-dosimeter responses when the dosimeters are indirectly irradiated. The acquired two-dosimeter algorithms are almost the same for all the mentioned phantoms except for KTMAN-2. Comparisons between the obtained E and estimated E (E_{est}), acquired from two-dosimeter algorithm, illustrate that the E_{est} is overestimated in overhead (OH) and underfoot (UF) directions. The effect of using one algorithm for all phantoms was also investigated. Results show that application of one algorithm to all reference phantoms is possible.

1. Introduction

The International Commission on Radiological Protection (ICRP) recommended E as the basic quantity in radiation protection (ICRP, 1991). E is the tissue weighted sum of equivalent doses in all specified organs and tissue of the body (ICRP, 1991) that is defined on reference phantoms according to ICRP convention (ICRP, 2007). However, this quantity is not measurable due to impossibility of direct measurement of the absorbed doses in various tissues and organs in the human body. Therefore, radiation monitoring should be performed outside the body. Then, the absorbed dose should be converted to E using a suitable algorithm.

The dose assessment from external exposure is usually performed by individual monitoring using personal dosimeters placed on the body. In general, the absorbed dose in dosimeter (a physical quantity) is converted to Hp (10) (an operational quantity) by applying energy-depended conversion coefficients. In order to know E, only when a personal dosimeter is pointing toward the radiation source, the value of Hp (10) provides an E value sufficiently precise for radiological protection purposes (ICRP, 2007). Applying one-dosimeter algorithm, by means of a dosimeter usually mounted on the chest, may cause underestimations when dosimeter is irradiated indirectly (beam from the back). This problem is solved by using two-dosimeter algorithm (TDA), because one of these two dosimeters is always directly exposed to the radiation source. If a photon beam arrives from the back, then the back dosimeter is directly exposed and it effectively responds to the photon beam. Therefore, the underestimation of the dosimeter on the chest could be compensated.

Several researchers investigated TDA, where a physical quantity, absorbed dose in front and back dosimeter, was converted directly to a protection quantity (E) (Reece et al., 1994; Xu, 1994;

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Claycamp, 1996). TDA was determined over many irradiation geometries for photon beams at energies of 0.08, 0.3, and 1 MeV. A suitable combination of the response of these two dosimeters, therefore, will accurately reflect the E. For the first time, Lakshmanan et al. (1991) used two $CaSo_4$: Dy thermoluminescence dosimeter (TLD) badges to measure H_p (10) on a 30 cm^3 water phantom. They concluded that the sum of dosimeter readings from these TLDs divided by 1.5 provides a conservative estimate of effective dose equivalent (H_E). Then, Reece et al. used the Medical Internal Radiation Dose (MIRD) phantom to simulate readings of personal dosimeters (Reece et al., 1994; Xu, 1994). Several investigators developed the TDA, and optimized dosimeter weighting factors by different methods (ANSI, 1993; Kim et al., 1999b). Recently, Kim et al. have recommended a new TDA using ICRP reference phantoms (Kim et al., 2011).

Several models of reference phantoms have been developed from different ethnic groups such as Caucasian and Asian. In recent years, many countries have constructed reference phantoms, which are adjusted to the anatomical data reported in ICRP Publication 89 (ICRP, 2002) or the 50th percentile of their own countries (Liu et al., 2009a; Lee et al., 2006a, 2006b). Organ masses of the various ethnic groups are different. For instance, the organ masses of Korean Typical MAN-2 (KTMAN-2) have differences up to 40% (e.g., colon, lung, and liver) from those of Asian and ICRP reference phantoms. The different reference phantoms revealed that body shapes of various races are different. Therefore, this study aims to investigate the effect of computational phantoms on the E and TDA. For this reason, several reference phantoms from various ethnic groups (e.g., Caucasian and Asian) were selected. In addition, the possibility of developing a standard TDA was investigated for reference phantoms.

2. Materials and methods

In this study, KTMAN-2 (Lee et al., 2006a, 2006c, Lee and Lee, 2006; Lee et al., 2007a, 2007b), CRAM (Liu et al., 2009a, 2009b; Zhang et al., 2007), ICRP (ICRP, 2008), and MASH (Cassola et al., 2010a, 2010b; Kramer et al., 2010) adult male reference phantoms were used for the simulations. The TDA was calculated for each phantom separately. To this end, the E data and response of dosimeters, which were positioned on the chest and back of phantom, were derived using MCNP code Monte Carlo simulations (Briesmeister, 2000) for hundreds of incident beam directions, according to the new definition of the E at photon energies of 0.08, 0.3, and 1 MeV (ICRP, 2007). Furthermore, a new TDA was developed by averaging over all weighting factors obtained from all phantoms. Then, the results of this algorithm were compared with those of the TDA specified for each phantom.

2.1. Specification of beam directions

A specific coordinate system was used to indicate the direction of the incident photon beam (Fig. 1). In the aforementioned coordinate system, polar angles were varied from 0° (beams irradiated from overhead to underfoot) to 180° (beams irradiated from underfoot to overhead) and azimuthal angles were varied from 0° (beams irradiated from front to back of the body) to 180° (beams irradiated from back to front of the body) and back to 360° (beam irradiated from front to back of the body) in the clockwise direction. By this way, the anterior–posterior (AP), right lateral (RLAT), posterior–anterior (PA), and left lateral (LLAT) were defined in 90° polar angle and in 0°, 90°, 180°, and 270° azimuthal angles, respectively, and OH and UF directions were determined in 0° and 180° polar angles, respectively.

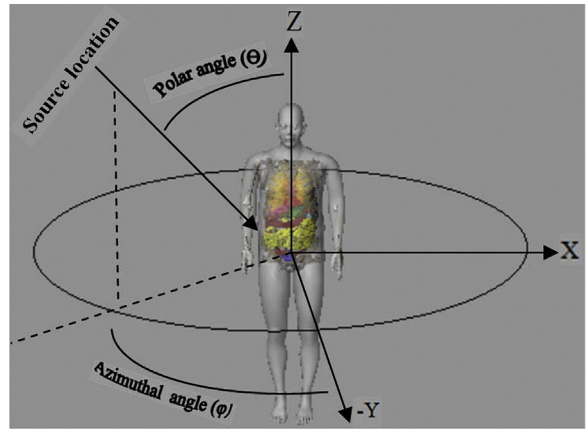

Fig. 1. Polar azimuthal angle system used in this study to specify incident beam direction. The phantom is centered on the z-axis facing the negative y-direction.

2.2. Characteristics of the TDA

In this study, the algorithm should be optimized according to the method used by Kim et al. (2011) for ICRP reference phantoms. First, E and the responses of the chest and back dosimeters were determined for hundreds of incident photon beam directions through Monte Carlo simulation using the MCNP code. Variations in polar and azimuthal angles were selected 30° for photon irradiations (15° and 165° polar angles were also investigated). Then, a TDA with trial weighting factors (w) was applied in the calculation of the estimated E (E_{est}) for each beam direction:

$$E_{est} = wR_f + (1 - w)R_b, \quad (1)$$

where R_f and R_b are responses of front and back dosimeters, respectively, which were obtained by MCNP. Weighting factors (W) were selected from (0, 1) interval and it was increased by a step size of 0.1. Newton–Raphson method was used to find the optimal combination of w. For each w, E_{est} was estimated using Eq. (1). Then, the ratio of E_{est} to E was computed, defined by r, for all beam directions (117 irradiation geometries for each energy). In total, 351 values of r were calculated for each w, using FORTRAN program. Then, the maximum and minimum values of r were calculated and the ratio r_{max}/r_{min} was determined over the beam directions. The process was repeated for each w. The algorithm should show the least fluctuations in the distribution of E_{est} ratios for all irradiation geometries to be optimized. This study used the r_{max}/r_{min} value as an index for the fluctuation in the distribution of E_{est} ratios (Kim et al., 1999b, 2011). To this end, the optimal w was obtained based on the minimum value of r_{max}/r_{min}. Finally, the optimal algorithm was acquired after suitable normalization using the dosimetry result of AP irradiation geometry. The normalization factor, h(E),[1] was computed for each energy by Eq. (2):

$$h(E) = \frac{0.9E(AP)}{E_{est}(AP)}. \quad (2)$$

Results of AP calculation were applied to derive h(E), because the highest underestimations occur in this geometry. Indeed, h(E) is used to avoid underestimating E by $> 10\%$, so that 90% of the E(AP) value is considered in the h(E). Therefore, a factor of 0.9 was applied in Eq. (2). Finally, the average value of h(E), obtained by

[1] In the published papers, h(E) has been introduced as a normalization coefficient or normalization factor (Kim et al., 1999b, 2011). For this reason, we also use this expression, so there is no conflict for the readers. However, h(E) adjusts the underestimation and may be the expression of “underestimation regulator” is better than normalization factor.