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Quantification of Body-Reflected Neutron Doses in High-Energy Photon Radiotherapy Using an Albedo TLD Badge System

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ABSTRACT

This study aims to measure albedo neutron doses arising during high-energy photon radiotherapy, using an albedo TLD to check the spatial distribution and dose-dependency of these neutrons across a tissue-equivalent phantom. Irradiations were performed with a 15 MV medical linear accelerator. Alnor-type albedo TLD badges containing MTS-6 (^{6}LiF, neutron and photon sensitive) and MTS-7 (^{7}LiF, only photon sensitive) which were calibrated before Linac irradiation of an Alderson Rando phantom placing the badges at various anatomical sites. The design allows selective measurement of albedo neutrons by a dedicated window exposing a pair of MTS - 6 & 7 crystals, while others remain shielded by boron-loaded plastic. Dose measurements were performed at the lung center, right and left lungs, head-neck, and upper abdomen for delivered photon doses of 100, 200, and 300 cGy. Reflected neutron dose was highest at the beam center (lung center: 440.9 – 520.4 mSv) and decreased steeply at lateral (right/left lung: 33.0 – 66.8 mSv) and peripheral (head-neck, upper abdomen: 4.2 – 13.3 mSv) positions. At all locations, neutron dose increased linearly with delivered photon dose ($R^2 \approx 1$). The dose at the peripheral regions confirms rapid spatial attenuation. The use of albedo TLD badge proves its effectiveness for distinguishing reflected neutrons from direct field and photon doses. Albedo neutrons contribute a measurable amount to total delivered dose particularly within and near the field. Routine assessment of albedo neutron dosimetry is recommended to ensure treatment quality.

1. Introduction

Modern cancer radiation therapy relies heavily on high-energy medical linear accelerators (LINACs), which allow for deeper tissue dose delivery and better tumor control rates [1-2]. Fast (MeV) neutrons are an undesirable product of photonuclear reactions that take place in the accelerator head and treatment accessories when photon beam energies surpass 10 MeV [3–5]. These neutrons have drawn a lot of attention in patient and occupational dosimetry because of their high relative biological effectiveness (RBE), which can raise the risk of secondary cancers [6–8]. After being created, fast neutrons quickly lose energy due to numerous scattering events in treatment head, especially enter the human body, are moderated (slowed down) by collisions, mostly with hydrogen in tissue and then reflected or scattered back toward the surface, which causes them to moderate to thermal energies [1,9-11]. The term "albedo neutrons" refers to those thermalized neutrons that are reflected from the patient or phantom surface instead of absorbed [11–13]. In radiotherapy settings, albedo neutrons contribute significantly to unwanted neutron doses by producing a distinctive flux at the isocenter and surrounding areas [14 - 15]. The neutron dose normally depends on the irradiation geometry, field size, beam energy, patient's and the surrounding materials composition and positioning [9,12,16]. Because of their low energy and the complex, photon-neutron, field neutron mixed radiation fields found in clinical settings, albedo neutrons are difficult to quantify accurately. ^{6}LiF based TLDs, the gold standard for separating direct and albedo neutrons, are often used in albedo badges with selective windows. [17–19]. Recent studies have revealed that although total neutron dose is generally much less than total photon dose, the spatial and depth distribution of albedo neutrons draw clinical attention—especially for patient organs or staff that are near the treatment field [1,7,15,20]. However, the neutron doses measured in this study represent only albedo (reflected, thermalized) neutrons that have been produced by photonuclear reactions in the LINAC head, then scattered, moderated, and reflected by the phantom body, rather than from direct, unmoderated neutron fields. In albedo neutron dosimetry, TLDs made from lithium fluoride (LiF) are generally used in two: MTS-6 (^{6}LiF) and MTS-7 (^{7}LiF). ^{6}Li enriched MTS-6 chip is highly sensitive to thermal (low-energy) neutrons because of the large neutron capture cross-section of ^{6}Li. This feature allows it to detect albedo neutrons reflected from the body or phantom. In contrast, MTS-7 chips are insensitive to neutrons but respond to only photon (gamma and X-ray) radiation and they are also used in the same badge for making it possible to discriminate and separately measure photon and neutron dose components in mixed radiation fields. This dual-chip approach is a global standard in personnel and patient neutron dosimetry for radiotherapy, and is recommended in both clinical protocols and international guidelines [1,7,11,17]. The design of the albedo TLD badge, particularly the boron-loaded plastic encapsulation and dedicated albedo window. Boron-loaded plastic is used in albedo neutron dosimeter badges due to its high absorption cross-section for thermal neutrons, ensures that the MTS-6 detector is selectively exposed to these low-energy, back-scattered neutrons, while being shielded from direct field neutrons [7,11,18,19,21]. Failure to measure these albedo dose risks may undermine patient safety and regulatory compliance. By isolating measurments of albedo neutrons with customized dosimeters, clinicians and medical physicists can better understand, minimize, and manage these risks of secondary malignancy and tissue damage.

2. Materials and Methods

The experiment employs a 15 MV medical linac using an Alderson Rando phantom (served as an anatomical surrogate). Albedo TLDs; MTS-6 and MTS-7 crystals were used as dose detector. The calibrations and data analysis were performed in Secondary Standard Dosimetry Laboratory (SSDL), Atomic Energy Research Establishment (AERE), Bangladesh, and the Linac were used from Enam Cancer center, Savar, Bangladesh.

2.1. Albedo Badge and TLD Calibration

The study employed five Alnor-type albedo badges, each housing a TLD. Each card included two MTS-6 (LiF:Mg,Ti, enriched in ^{6}Li, sensitive to both photons and neutrons) and two MTS-7 (LiF:Mg,Ti, enriched in ^{7}Li, only photon sensitive) chips. The unique feature of the Alnor albedo badge is the albedo window: a dedicated thin section of the badge, positioned so that the sensitive MTS-6 crystal is directly exposed to low-energy neutrons (reflected from the phantom or patient surface), while surrounding filters or metallic shields attenuate other forms of radiation. Only the crystals positioned behind the albedo window (usually the MTS-6 chips) are directly exposed to reflected (albedo) neutrons. This design allows selective measurement of albedo (reflected, thermalized from body) neutron dose by maximizing the response of the ^{6}LiF chip to back-scattered neutrons. The other crystals (often the MTS-7 chips and sometimes an MTS-6 behind a shield) are placed behind Boron Loaded Plastics encapsulation. These filters are designed to block or significantly attenuate thermal neutrons, so those crystals mainly measure field neutron dose, not the reflected (thermalized) neutron dose. In this dosimeter design, boron-loaded plastic serves as the neutron filter, effectively blocking thermalized (albedo) neutrons from reaching all TLD positions except the one directly behind the dedicated albedo window. All cards were oven-annealed at 400 °C for 1 h then 100 °C for 2 h for clearing residual signals. A zero-dose about (± 0.02 mSv) was read immediately afterward established the background. Five "gold-standard" cards were irradiated to 1 mSv in a ^{137}Cs source. The Reader Calibration Factor (RCF) varied by no more than ±1.3 %, which demonstrates excellent reproducibility. To account for slight differences in individual LiF chips, each TLD card was exposed to a series of known gamma doses (1, 2, 3, 4, and 5 mSv from a ^{137}Cs source, and 100, 200, and 300 cGy from a ^{60}Co teletherapy unit) and 0.1 to 0.3 mSv from ^{241}Am-Be source). From these readings, chip-specific sensitivity factor for each MTS-6 and MTS-7 element were defined for dose calculation.

2.2 Phantom Setup and Irradiation

All Albedo TLD cards placed inside badge were laid flat on the Alderson Rando phantom (served as an anatomical surrogate) surface keeping their sensitive side facing the beam. The central "target" badge was defined as 0 cm off-axis and located midway between the two lung's positions. The badges on the lung region were positioned at ±2.5 cm laterally (right and left of center). The head-neck, upper-abdomen region badges were placed at 10 cm superior (toward the head) of the target, and 15 cm inferior (toward the feet) of the target respectively. Phantom alignment was as central badge at beam isocenter, SSD = 100 cm. A standard open field (jaw and MLC) for thoracic/head–neck treatments was used here Maintaining all the geometric parameters constant, delivered doses of 100, 200, and 300 cGy were applied sequentially at field size (10 cm × 10 cm).

3. Results & Discussion

Measured albedo neutron doses, using the MTS-6 crystal behind the albedo window, show a distinct spatial and dose-dependent profile across the phantom surface. **Fig. 1** and **Table 1**. show that the neutron dose is noticeably highest at the lung center (0cm, in-field) for all delivered doses reaching 440.9 mSv at 100 cGy, 475.7 mSv at 200 cGy, and 520.4 mSv at 300 cGy. This is generally expected, as the primary photon beam generates the greatest density of photoneutrons and their moderation or scattering occurs predominantly under the beam. Neutron dose is highest at the in-field position because it is directly under the photon beam, because target region is receiving the greatest flux of primary neutrons. By contrast, there is a steep drop in neutron dose even just 2.5 cm away (right/left lung) which illustrates rapid geometric attenuation of neutron flux with distance. Beyond 2.5 cm, doses fall down and are lowest at the periphery (10, 15 cm: head-neck and upper abdomen), indicating that only a small fraction of reflected neutrons reach these distant sites. As distance from the beam increases, geometric attenuation, tissue scattering, and neutron absorption rapidly decay the neutron flux. For example, according to **Table 1**, at 300 cGy, the right lung receives only ~12.8% of the lung center's neutron dose, and the upper abdomen just ~1.2%, reflecting attenuation of over 88% and 98% respectively. This trend of changing neutron dose with respect to spatial variation is aligned with the previous studies by both experimental and Monte Carlo [6,7,9,11]. Further, **Fig. 2 & Fig. 3** displays the linear fit of neutron dose at different locations as a function of delivered dose. The near-unity R^2 confirms that, neutron dose is linearly proportional with photon dose over the 100 – 300 cGy range, regardless of distance which also aligns with previous studies [2,5,7,14].

Table 1. Reflected neutron dose of MTS crystal irradiated in different dose delivery with field sizes of 10×10 cm^2.

Region on Phantom Surface	Distance (cm)	Neutron Dose at 100 cGy (mSv)	Neutron Dose at 200 cGy (mSv)	Neutron Dose at 300 cGy (mSv)
Right lung	2.5	33.01554	54.18321	66.76419
Left lung	2.5	34.63784	44.20185	59.39427
Head neck	10	7.186007	9.235525	13.34
Upper abdomen	15	4.222049	5.252072	6.105682
Lung Center	0	440.9053	475.6547	520.439

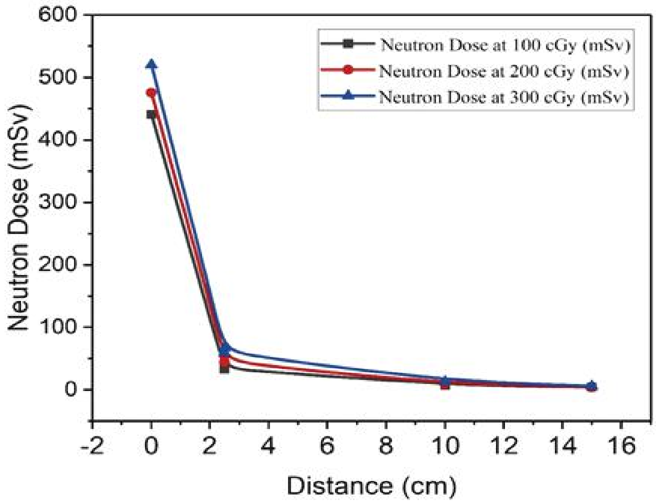

Fig. 1: Spatial distribution of reflected (albedo) neutron dose as a function of location on the phantom surface (lung center, right lung, left lung, head-neck, upper abdomen) for three delivered photon dose. The neutron dose is highest at the beam center and decreases sharply with lateral and peripheral distance, demonstrating rapid spatial attenuation of albedo neutrons.

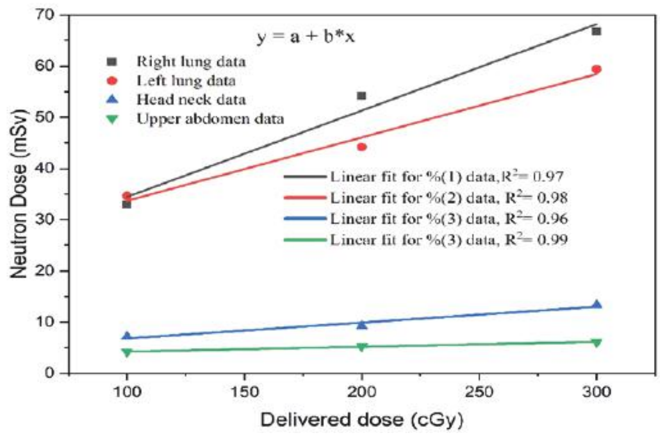

Fig. 2: Relationship between delivered photon dose and reflected neutron dose at outfield position on Phantom surface. Linear fits (shown as lines) confirm a strong proportionality ($R^2 \approx 1$) between neutron dose and clinical dose.

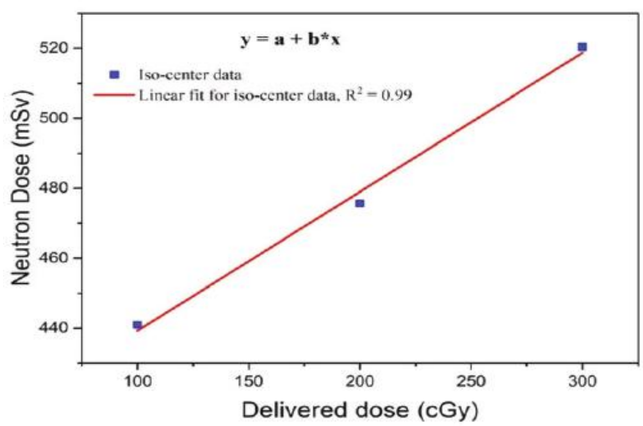

Fig. 3: Relationship between delivered photon dose and reflected neutron dose at inside-field on phantom surface. Linear fits (shown as lines) confirm a strong proportionality ($R^2 \approx 1$) between neutron dose and clinical dose.

4. Conclusions

This study provides a systematic evaluation of reflected neutron doses from patient body during high-energy photon radiotherapy by employing an albedo TLD badge with an MTS-6 detector positioned behind the neutron window of the badge. The measured data confirm that albedo neutron dose is highest at the beam center and diminishes rapidly at peripheral positions which highlights the spatial dependence of neutron reflection and moderation within tissue-equivalent materials. An obvious linear fit observed between delivered photon dose and albedo neutron dose at all measurement points indicates the direct influence of clinical dose delivery parameters on secondary neutron dose. Importantly, the detection of neutron dose by the albedo TLD badge at multiple positions across the phantom ensures that the patient's body is exposed to neutron doses, not just within the primary irradiation field but also at out-of-field and inside-field sites.

The use of the albedo TLD badge allowed for selective and accurate quantification of these low-energy, reflected neutrons, distinguishing them from direct field neutron and photon doses. These results emphasize the need of routine assessment of albedo neutron dose to ensure comprehensive protection for patients and staff.

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