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Examination of general cavity theory for magnesium and titanium doped lithium fluoride (TLD-100) of varying thicknesses in bone and lung

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HIGHLIGHTS

- Investigated the accuracy of Burlin cavity theory for clinically used thin TLDS.
- Provided values of d for Burlin cavity theory calculations in bone and lung.
- Provided MC simulated $(f)_{med}^{TLD}$ to be used by thse radiation measurement community.
- MC method can be successfully used instead of stheoretical calculations of $(f)_{med}^{TLD}$.

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ABSTRACT

Purpose: To evaluate the accuracy of Burlin cavity theory for TLDs in bone and lung, the two most relevant heterogeneities in radiological physics.
Methods: Theoretical calculations and Monte Carlo (MC) simulations of dose to TLD to dose to medium correction factor, $(f)_{med}^{TLD}$, were performed and compared in bone and lung. MC simulations included virtual irradiation of TLDs with varying thicknesses (0.015, 0.038, and 0.089 cm) in bone, lung, and water phantoms. Theoretical calculation of Burlin cavity theory requires calculation of fractional dose contribution from photon interactions (d) from mass effective attenuation coefficient (β) and average path length of electrons penetrating in the cavity from the wall (g). Different theoretical formulations of g and β were used to calculate 18 different values for d and $(f)_{med}^{TLD}$. Further, the impact of mean energy approximation used in theoretical calculations was evaluated using full spectrum MC simulations.
Results: While the values of d differed as much as by a factor of 2, $(f)_{med}^{TLD}$ agreed well (SD = 0.1%) in water, bone and lung. The TLD thickness ranging 0.015–0.089 cm was not a significant factor (SD = 0.2%). Dose correction factors calculated using mean energy approximation agreed within the 2% with full spectrum MC simulations. Uncertainty associated with theoretical calculation of $(f)_{med}^{TLD}$ was 7.2% compare to 0.5% with MC simulation.
Conclusion: The $(f)_{med}^{TLD}$ calculated with Burlin theory agreed well with MC results for 6 MV photon beam. Nevertheless, the difficulty and the ambiguity in the determination of β and g in a given medium and the energy spectrum under investigation limited the theoretical calculations and resulted in large uncertainty. This study suggests the use of MC for easy and accurate estimation of $(f)_{med}^{TLD}$, which is required in radiological applications to convert TLD measured dose to dose in medium.

1. Introduction

Detectors often constructed of a different material than the medium in which they are used to measure dose thereby forming a cavity (Mobit et al., 1997). The relationship between the absorbed

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dose in a medium (D_{med}) and the average absorbed dose in the cavity (D_{cav}) is given by the general cavity theory (Carlsson, 1985).

$$(f)_{med}^{cav} = \frac{D_{cav}}{D_{med}} = \frac{\left(\frac{\bar{S}}{\rho}\right)_{cav}}{\left(\frac{\bar{S}}{\rho}\right)_{med}} \quad (1)$$

where $(f)_{med}^{cav}$ is the dose to cavity to dose to medium conversion factor and $\frac{\bar{S}}{\rho}$ is the mean mass collision stopping power. Both vary with energy, radiation type, medium, size and composition of the medium and cavity. The Bragg–Gray cavity theory provided the first relationship between the absorbed doses in the dosimeter to that in medium, when the cavity dimension is much smaller than the range of the secondary electrons (Horowitz and Dubi, 1982). Burlin proposed a general cavity theory (Burlin, 1966) that is applicable to all cavity sizes to predict the energy deposition from a source of ionizing radiation to a cavity of arbitrary size and composition (Kearsley, 1984). The size of the cavity is defined relative to the range of the secondary electrons (Attix, 1986). If the cavity dimension is comparable to the range of secondary electrons, the cavity is called intermediate cavity whereas a large cavity has a dimension greater than the range of secondary electrons. Burlin cavity theory accounts for the size of the cavity using the following relationship:

$$(f)_{med}^{cav} = \frac{D_{cav}}{D_{med}} = d\left(\frac{\bar{S}}{\rho}\right)_{med}^{cav} + (1-d)\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{med}^{cav} \quad (2)$$

where $\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{med}^{cav}$ is the ratio of mean mass energy absorption coefficients of the cavity to the medium and $\left(\frac{\bar{S}}{\rho}\right)_{med}^{cav}$ is the ratio of mean mass collisional stopping power of the cavity to that of medium. The weighting factor d varies between unity for small (or Bragg–Gray) cavity and zero for large cavity.

Ogunleye et al. (Ogunleye et al., 1980) performed one of the most detailed experiments to date in order to verify Burlin cavity theory for TLDs in polystyrene, LiF, aluminum, copper, and lead holders. Burlin cavity theory showed good agreement with experimental results in polystyrene but overestimated the TLD dose in media with high atomic number such as aluminum, copper, and lead. Further, both d and the $(f)_{med}^{cav}$ decreased with increasing thickness of TLD and Z of the medium. A steeper drop was observed with increasing atomic number, Z, of the medium. For instance, the $(f)_{med}^{TLD}$ decreased by 20% and 3% in lead and aluminum, respectively, when the TLD thickness is doubled.

Others used Monte Carlo (MC) methods to evaluate cavity theories. MC technique is accepted as the gold standard for estimating absorbed dose in or near heterogeneities (Haraldsson et al., 2003). Mobit et al. (Mobit et al., 1997) used EGSnrc to examine general cavity theories for LiF, $Li_2B_4O_7$, CaF_2 and $CaSO_4$ dosimeters irradiated with megavoltage photon and electron beams in several materials including perspex, water, Al, Cu, and Pb. Alike experimental studies, they too observed a disagreement between the various theories and MC simulations for TLDs in high Z materials. For instance, the difference between dose to TLD and dose to medium was as much as 12% for lead. They noted that the $\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{med}^{cav}$ and $\left(\frac{\bar{S}}{\rho}\right)_{med}^{cav}$ vary more rapidly with energy in high-Z than it does in low-Z materials.

All previous studies aimed at the evaluation of Burlin cavity theory for TLDs in water (Miljanic and Komor, 1997) or metals such as aluminum, copper, and lead (Paliwal and Almond, 1975; Evans, 1955; Loevinger, 1956; Burlin and Chan, 1969; Janssens et al., 1974). Nevertheless, accurate measurement of the dose in heterogeneous tissues in the body is of great importance in radiological physics. To date, no study has evaluated the Burlin cavity theory for clinically used TLDs in lung and bone. This work aims to study and compare Burlin cavity theory in bone and lung using theoretical calculations and MC simulations.

2. Materials and methods

2.1. MC simulations

Three virtual phantoms were constructed for MC simulations as shown in Fig. 1. The first phantom consisted of a 15 cm water phantom with TLDs placed at 10 cm depth at a source to skin distance (SSD) of 90 cm. The second phantom consisted of 22 cm lung equivalent material with TLDs placed at 6 cm depth at 94 cm SSD. The third one was constructed from 5 cm bone equivalent material with TLDs placed at 2 cm depth at 98 cm SSD. The depths of TLDs were chosen such that the corresponding water equivalent depths were beyond the depth of maximum dose (d_{max}). MC calculations were performed using 6 MV photons and 10 × 10 cm^2 field size from a Varian Clinac 2100 Linear accelerator (Varian Medical Systems Inc., Palo Alto, CA).

MC simulations were carried out with EGSnrc (Electron Gamma Shower, National Research Council Canada). DOSXYZnrc (Walters et al., 2005) was used to calculate dose distribution in phantoms while the BEAMDP was utilized to derive the energy fluence spectrum and mean energy distribution from the phase space data published by Cho et al. (Cho et al., 2005).

The material properties H2O521ICRU, LUNG521ICRU, and ICRPBONE521ICRU were assigned to water, lung, and bone, respectively. Magnesium and titanium doped lithium fluoride TLD-100 was constructed in PEGS4. The TLD-100 has a density of 2.64 g cm^{-3} and is composed of 26.70% Li, 73.28% F, with 0.001% Mg and 0.02% Ti dopant by weight (Berger et al., 2005; Davis, 2003). NIST (National Institute of Standards and Technology) (Hubbell and Seltzer, 2004; Siebers et al., 2000) provides mass collision stopping power $\left(\frac{S}{\rho}\right)$ and mass energy absorption coefficient $\left(\frac{\mu_{en}}{\rho}\right)$ for only LiF not for TLD-100. Mobit et al. suggested that concentrations as

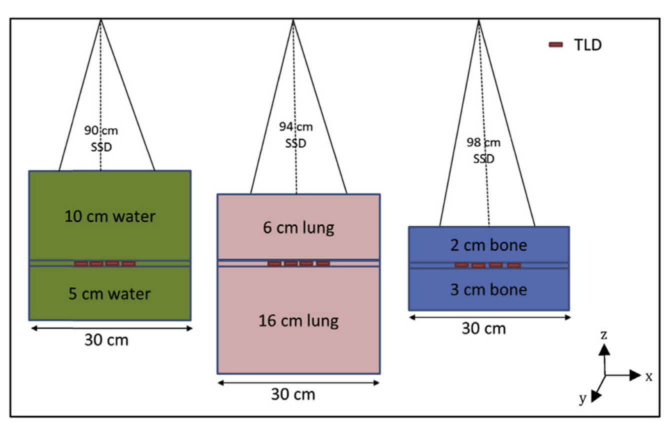

Fig. 1. Phantoms used in MC simulations. Phantom dimensions were 30 × 30 × 15 cm^3, 30 × 30 × 22 cm^3 and 30 × 30 × 5 cm^3 for water, lung and bone, respectively. Illustrations were not drawn to scale.