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Energy dependence of TLD-900 dosimeters exposed to low energy X-rays

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HIGHLIGHTS

- The energy dependence of TLD-900 dosimeters to low energy X-rays is investigated.
- Values of X-ray to gamma relative TL response are presented.
- This work includes measurements as well as analytical and Monte Carlo calculations.
- Interpretation considers (absorbed-dose)- and (intrinsic)- energy dependence.
- Present results are useful for a proper correction of dose in clinical applications.

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ABSTRACT

This work investigates the energy dependence of $CaSO_4$:Dy (TLD-900) thermoluminescent dosimeters to low energy X-rays. Dosimeters were exposed to X-ray radiation qualities between 30 and 250 kVp for three air kerma values: 100, 250 and 500 mGy. The detector thermoluminescent response as a function of air kerma and the detector's relative kerma sensitivity with respect to ^{60}Co as a function of effective energy were obtained. Monte Carlo and analytical calculations were also performed. A maximum relative kerma sensitivity of 12 is found for a 22 keV effective energy corresponding to the 50 kVp X-ray beam. Monte Carlo and analytical calculations accurately describe trends in the energy dependence curve as a function of photon energy though they predict lower values for the relative kerma sensitivity. Maximum difference is observed at the lowest energy measured (16 keV) where experimental data is 2.1 and 2.3 times greater than Monte Carlo and analytical calculations, respectively. The difference between measurements and Monte Carlo-calculated predictions is attributed to the intrinsic energy dependence of TLD-900. Values of intrinsic energy dependence estimated from the measured relative TL kerma sensitivity together with the MC and analytical calculated values of kerma energy dependence were found to be independent of beam quality in the region from 33 to 142 keV effective energies.

1. Introduction

Thermoluminescence (TL) is a useful tool to determine radiation dose in personal, environmental and medical applications. In clinical practice (diagnostic radiology and radiotherapy) the knowledge of the dosimeter TL response (M_{det}) per unit dose or kerma as a function of beam quality (Q) is relevant. This work investigates the energy dependence of $CaSO_4$:Dy (TLD-900, Thermo-Fisher, Scientific) dosimeters to low energy X-rays. Even though TLD-900 dosimeters are not tissue equivalent and a high Z-material ($Z_{eff} = 15.3$) they have the advantage of exhibiting high sensitivity. A precise knowledge of their TL properties leads to a correct evaluation of the dose.

The energy dependence of the absorbed-dose sensitivity of a detector is composed of two parts: the intrinsic energy dependence (or intrinsic beam quality dependence) and the absorbed-dose energy dependence (Rogers, 2009).

"The intrinsic energy dependence $k_{bq}(Q)$ relates the detector's reading to the average dose to the material of the sensitive detecting element" (Rogers, 2009):

$$D_{det}(Q) = k_{bq}(Q)M_{det}(Q) \quad (1)$$

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“The absorbed-dose energy dependence relates the dose to the detector material to the dose to the medium at the point of measurement of the detector in the absence of the detector” (Rogers, 2009):

$$D_{\mathrm{med}}(Q) = f(Q)D_{\mathrm{det}}(Q) \tag{2}$$

In analogy, the kerma energy dependence relates the dose to the detector material to the kerma in air at the point of measurement, then.

$$K_{\mathrm{air}}(Q) = f(Q)D_{\mathrm{det}}(Q) \tag{3}$$

General purpose Monte Carlo codes calculate only the absorbed-dose or kerma energy dependence of a detector. Microdosimetric Monte Carlo codes could potentially be used to account for linear energy transfer (LET) and thermoluminescence effects, but they are not widely used.

The overall energy dependence of the reading of a detector (often referred to as the energy response) is the product of the intrinsic energy dependence and the absorbed-dose or kerma energy dependence.

In this study, results of TLD-900 TL response as a function of air kerma and the detector's relative kerma sensitivity (often referred as relative TL response) with respect to ^{60}Co as a function of beam quality are presented and discussed in terms of the intrinsic and kerma energy dependence of the detector.

The detector's kerma sensitivity relative to a reference beam quality (^{60}Co in this work) is given by (Rogers, 2009):

$$S^{\mathrm{rel}}_{K,\mathrm{air}}(Q) = \frac{\left(\frac{M_{\mathrm{det}}(Q)}{K_{\mathrm{air}}(Q)}\right)}{\left(\frac{M_{\mathrm{det}}(^{60}\mathrm{Co})}{K_{\mathrm{air}}(^{60}\mathrm{Co})}\right)} \tag{4}$$

The numerator and denominator in Equation (4) are the detector's kerma sensitivity to X-rays of beam quality Q and ^{60}Co, respectively. $S^{\mathrm{rel}}_{K_{\mathrm{air}}}(Q)$ must be measured at low kerma values where the TL response is linear as a function of air kerma.

Several studies of the energy dependence have been performed for LiF:Mg,Ti dosimeters in the effective energy range between 6 and 250 keV: (Tochilin et al., 1968), (Davis et al., 2003), (Nunn et al., 2008), (Nariyama et al., 1993), (Das et al., 1996), (Edwards et al., 2005) (Olko et al., 2002) and (Carlsson Tedgren et al., 2011). The work by (Nunn et al., 2008) found up to a 13% difference between the measured relative TL response and the MC calculations and attribute the difference to complications of the solid state physics not included in the simulation. The work by (Olko et al., 2002) proposes a microdosimetric model and states that the 10% over-response of LiF:Mg,Ti detectors to X-rays in the energy range between 20 and 200 keV can be explained as an ionization density effect related to the generation of short electron tracks produced by low energy X-rays which locally deposit a high radiation dose.

No detailed studies were found in the literature which include MC calculations for the energy dependence of $CaSO_4$:Dy dosimeters though a great quantity of publications have been reported on their properties. The book by McKeever et al. (McKeever et al., 1995 and references therein) provides a summary of studies by several authors who report measurements on $CaSO_4$:Dy investigating dose response curves, sensitivity with respect to TLD-100 dosimeters (LiF:Mg,Ti, Thermo-Fisher, Scientific), reproducibility and energy dependence. More recent investigations on different properties, such as the effect of co-dopants and the performance of nanocrystalline and microcrystalline phosphors of $CaSO_4$:Dy include the work performed by (Atone et al., 1995) (Salah et al., 2006) and (Maia and Caldas, 2010). Regarding the energy dependence of this material it is worthwhile to point out the works by (Pradhan and Bhatt, 1982) and (Yang et al., 2002) who published results of $CaSO_4$:Dy phosphor-embedded Teflon powder prepared at their respective laboratories. The work by Pradhan and Bhatt reports measurements of relative TL response normalized to ^{60}Co finding a maximum value of 11.5 at 13 keV effective energy. Yang et al. also report relative response normalized to ^{137}Cs finding a maximum value of 9.6 at 34 keV.

The present study intends to provide a better understanding of the behavior of TLD-900 dosimeters subjected to low energy X-rays. To attain this objective, dosimeters were exposed to X-ray radiation qualities between 30 and 250 kVp for three air kerma values: 100, 250 and 500 mGy and compared to predictions given by MC and analytical calculations.

2. Method

2.1. Experiment

TLD-900 (Thermo Fisher Scientific, Inc., USA) $3.1 \times 3.1 \times 0.89$ mm^3 chips were used for gamma and X-ray measurements. As a reference, TLD-100 dosimeters were also exposed. Four dosimeters were used for each irradiation. After applying an individual correction factor for each dosimeter the corrected TL responses (M_{det}) of the batch were within 2% of the mean reading after exposure to a ^{60}Co known dose.

The applied experimental procedures are described:

i) Thermal treatment: TLD-900 dosimeters were oven annealed in air for 30 min at 400 °C (Driscoll et al., 1986). TLD-100 dosimeters were oven annealed in air, for 1 h at 400 °C, followed by sudden cooling at room temperature for 10 min, followed by a second annealing for 2 h at 100 °C (Gamboa-deBuen et al., 1998).
ii) 24–48 h later, dosimeters were irradiated. X-ray irradiations were performed in air while for the ^{60}Co irradiations dosimeters were introduced in acrylic containers to approximate charged particle equilibrium conditions.
iii) After a 24–48 h interval TL readings were performed using a 3500 Harshaw reader (Thermo Fisher Scientific, Inc., USA) at a heating rate equal to 10 °C s^{-1} under nitrogen flow. Readout was performed integrating from room temperature to 350 °C for TLD-900 and TLD-100.

X-ray exposures were performed using a Phillips MCN 321 X-ray tube at the X-ray laboratory of the Ionizing Radiation Secondary Laboratory, Instituto Nacional de Investigaciones Nucleares (ININ), Mexico.

Dosimeters were exposed at the available air kerma values of 100, 250 and 500 mGy within an 8.3 cm diameter radiation field at a 1 m distance from the tube. Alignment was performed with the aid of a laser beam. An aluminum square holder was used to frame a 13×13 cm^2 free space where scotch tape was placed going from top to bottom at the middle of the holder. The central irradiation area was established by visualizing the field with the aid of Radiochromic XR-QA2 films. Dosimeters were placed on top of the scotch tape at the center of the irradiation area; four dosimeters separated 1 mm from each other, two of them 1 mm above and other two 1 mm below the center. A previous test was performed in order to ensure the tape did not leave any residue on the dosimeters or affect their TL response. Prior to irradiations, air kerma was measured with a farmer PTW 0.6 cm^3 ionization chamber calibrated at “Laboratoire d'Etudes des Combustibles Irradiés” (LECI), France.