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TL and OSL dosimetric characterization of different luminescent materials for clinical electron beams application in TSEB treatments

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ABSTRACT

Thermoluminescent dosimeters (TLDs) play an important role in radiotherapy for the dosimetry of ionizing radiation. This type of dosimeter presents advantages that makes them a useful tool for measurements in anthropomorphic phantoms and in vivo dosimetry. Several dosimetric materials have been used in the radiotherapy sectors such as LiF, µLiF, $CaSO_4$:Dy. The OSL dosimetry has also been widely applied using Aluminum Oxide (Al_2O_3:C). These dosimeters have advantages over TLDs due to their high sensitivity, extensive linearity in response to the dose, faster reading, possibility of multiple readings and the need to perform the heat treatment of the samples. The aim of this work was to compare and characterize, using TL and OSL techniques, different luminescent dosimeters (LiF, µLiF, $CaSO_4$:Dy and Al_2O_3:C) to be applied in clinical electron beam used to TSEB treatments. Measurements were performed in order to study the applicability of these detectors as easy-to-take alternatives to calibration and measurements of TSEB treatments. Parameters such as dose-response curves; average sensitivity to radiation, intrinsic efficiency and energy and angular dependences were evaluated. The results show good agreement within $CaSO_4$:Dy and TLD-100 measurements and, applying energy and angle dependence factors over the other two materials, all the four detectors can be applied as alternative easy-to-take dosimetric tools for commissioning and quality assurance of 6 MeV clinical electron beams used in TSEB treatments.

1. Introduction

The Total Skin Electron Beam (TSEB) Irradiation is one of the modalities of external radiotherapy. The technique aims to deliver a homogeneous dose distribution over the entire skin surface of the patient and it is the treatment of choice for cutaneous T-cell lymphoma, for either curative or palliative purposes. Electron irradiation penetrates a few millimeters into the skin, reaching the affected ill parts completely, without penetrating the internal organs [17,2,18].

The TSEB irradiations do not use the common external radiation therapy planning softwares. Therefore, its commissioning and quality assurance must be handled another way. The Hospital Israelita Albert Einstein (HIAE – São Paulo, Brazil), aiming the commissioning of its TSEB treatments following the "six-dual-field" technique (also known as "Stanford" technique) reported by the American Association of Physics in Medicine (AAPM) Report 23 [8], is investigating alternative dosimeters to perform this type of measurements.

The Dosimetric Materials Laboratory of the Instituto de Pesquisas Energéticas e Nucleares – LMD/IPEN has been developing research related to clinical dosimetry of electrons and photons. The thermoluminescent detectors (TLDs) used are, mainly, the LiF:Mg,Ti TLD-100 from Thermo Scientific and $CaSO_4$:Dy + Teflon pellets produced at IPEN. Optically stimulated luminescence (OSL) dosimetry with Al_2O_3:C (Landauer Inc.) have demonstrated great efficiency as well [12,15,20,3–7], and can be used as alternative dosimetry methods.

The LiF:Mg,Ti TLD-100 is the most used TL material and widely studied in radiotherapy dosimetry due to near tissue-equivalence of the material, along with its overall reliability [13]. The $CaSO_4$:Dy is manufactured and marketed by the Dosimetric Materials Laboratory of the Radiation Metrology Center/IPEN as powder and pellets and offers extensive range of linear response to radiation. This dosimeter has already been used in radiation protection applications due to its high sensitivity [14,5–7], and recent investigations were performed for its application in radiotherapy [11,12,15,20,3,4]. The latest research of the Institute has involved the same dosimeters for Intensity Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) dosimetry using Al_2O_3:C as well, with the Optically Stimulated Luminescence (OSL) [11,19,20].

The TSEB 'six-dual-field' technique reported by AAPM's Report 23 [8] has been experimentally commissioned and described by Platoni

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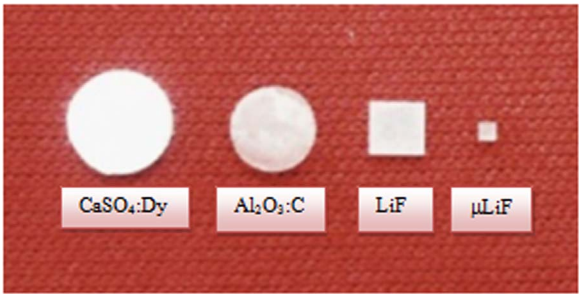

Fig. 1. The luminescent dosimeters used in this study.

et al. [16] at Attikon University General Hospital (AUGH – Athens, Greece). The authors used parallel-plate ionization chamber and LiF:Mg,Ti TLD-100 dosimeters to validate the treatments dosimetry. Aiming to apply luminescent dosimeters as easy-to-take alternatives to calibration and parameters evaluation of the TSEB dosimetry, this paper reports a comparative study of the luminescent responses of TLD-100, μTLD-100, $CaSO_4$:Dy + Teflon and Al_2O_3:C detectors to dose evaluation in electron beams.

2. Material and methods

2.1. Dosimetric materials

The dosimetric detectors used in this study are presented in Fig. 1 and specified below.

- $CaSO_4$:Dy + Teflon TLDs produced by IPEN: 6.0 mm diameter, 0.8 mm thick and mass of 50 mg;
- Al_2O_3:C (TLD-500) dosimeters supplied by Rexon TLD Systems & Components Inc. (EUA): 0.5 mm diameter and 0.9 mm thick and mass of 72 mg.
- LiF:Mg,Ti (TLD-100) TLDs produced by Thermo Scientific: 3.15 mm diameter, 0.9 mm thick and mass of 2 mg;
- μLiF:Mg,Ti (TLD-100) TLDs produced by Thermo Scientific: 1 mm side, 1 mm thick and mass of 1 mg;

Each dosimeter type was divided into groups to be used for dosimetric measurements and background dose control. All samples repeatability was evaluated and it was used only samples with response better than ± 5.0%.

2.2. Dosimeters readout and annealing treatments

The TL measurements were performed using a Harshaw 4500 TLD reader in nitrogen atmosphere. For both TLD-100 dosimeters it was selected the recommended Time Temperature Profile (TTP) of preheating at 80 °C, linear heating hate of 5 °C s^{-1} with maximum temperature of 400 °C [13]. For $CaSO_4$:Dy + Teflon Pellets, a TTP with linear heating rate of 10 °C s^{-1} with maximum temperature of 300 °C was used [6]. Each reading cycle was performed within ~ 40 s.

The LiF;Mg,Ti detectors were annealed in a Vulcan® 3–550 PD furnace at 400 °C for one hour, followed by rapid cooling to ambient temperature and then placed at a 100 °C preheated Fanen® 315-IEA 11,200 surgical stove for two hours [13]. The $CaSO_4$:Dy + Teflon dosimeters were annealed at 300 °C in a Vulcan® 3–550 PD furnace, for three hours [6]. The readout of both LiF:Mg,Ti and $CaSO_4$:Dy TLDs were performed 24 h after irradiations so all the traps were stabilized.

The TLD-500 were evaluated in a RISØ TL/OSL-DA-20 reader from LMD/IPEN. The reader is equipped with the standard PMT tube bialkali EMI 9235QB, 90% intensity of blue LED light source was used as OSL stimulation, and Hoya U-340 (7.5 mm thick, 45 mm diameter) filter. Each reading cycle was performed within 50 s. The optical bleaching for reutilization of the samples were fulfilled using a Ourolux® 1.3 W of power lamp, composed of 30 blue LEDs, with the samples exposed to the blue light for ~24 h [21]. In order to keep all TLD-500 dosimeters protected from any light exposure, the pellets were covered using aluminum paper during manipulation and irradiations.

2.3. Irradiation systems

It was used a 4 π geometry gamma irradiator of ^{137}Cs (Activity of 38,11 GBq in April 17th 2014) from the LMD/IPEN to evaluate the repeatability of all the dosimeters used. The dosimeters were annealed and irradiated in electronic equilibrium conditions (0.3 cm thickness plates of polymethylmethacrylate - PMMA) with absorbed dose of 2 mGy and read. The process was repeated five times to define, through the mean read value, the sensitivity and the repeatability of each sample.

The clinical measurements were carried out using a linear accelerator Varian Clinac 23EX (Varian Medical Systems, Inc., Palo Alto, California) of the Radiotherapy Center of the Hospital Israelita Albert Einstein (HIAE). The High Dose Rate Total Skin electron mode (HDTSe-) was selected from the control console, in which the Monitor Units (MU) for dose delivering where also selected. The nominal energies of the produced electron beams for this work were 4, 6 and 9 MeV.

2.4. Experimental set-up and measurements

The dosimeters were characterized for the 6 MeV energy electron beam of the Clinac 23EX. Dose response curves were obtained ranging from 28.7 cGy up to 382.8 cGy. Irradiations were performed positioning all dosimeters between two PMMA plates 0.3 cm thick and depth of 1.30 cm obtained with solid water bolus for electronic equilibrium conditioning. Field size of 20 × 20 cm^2, source-surface distance (SSD) of 100 cm and 5 cm of solid water bolus for electron backscatter were also used. The average sensitivity for this type and quality of radiation were tested. The energy dependence of their luminescent response over the range of 4–9 MeV was also evaluated. The experimental set-up of irradiation is showed in Fig. 2.

The experimental results of the absorbed doses presented in this paper are the average of four dosimeters measurements and the error bars, when visible, are the standard deviation the mean. All the calculations were performed with Microsoft Excel 2013 software, graphics were plotted using OriginPro 8.1, and, the units of the absorbed doses were all expressed in "cGy", due to its clinical applications.

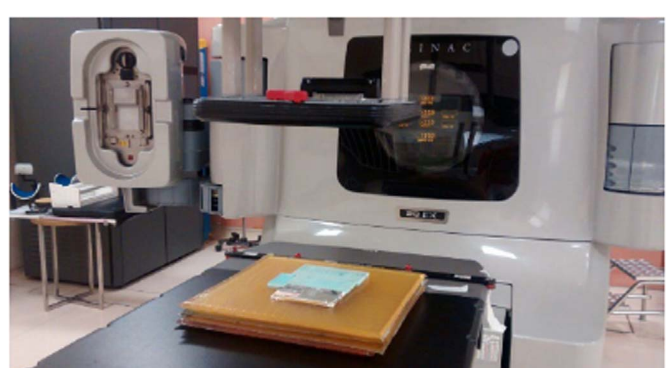

Fig. 2. Positioning of the dosimeters: accommodation of the TLDs between the two PMMA plates and irradiation set-up for dosimetric characterization with Varian Clinac 23EX.

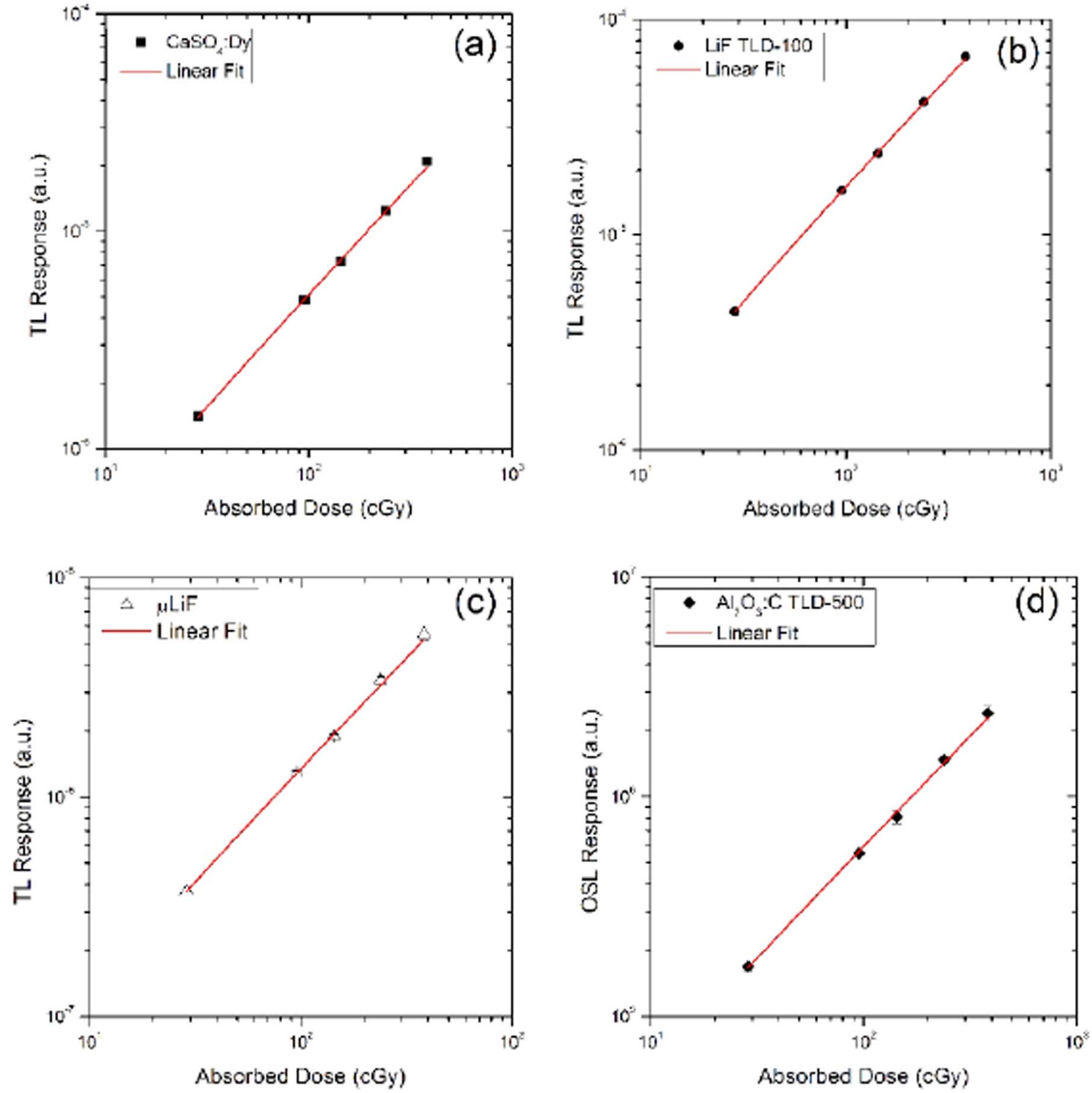

Fig. 3. Experimental dose-response curves for (a) $CaSO_4$:Dy (b) LiF:Mg, Ti TLD-100 (c) µLiF:Mg, Ti and (d) Al_2O_3:C TLD-500 dosimeters to 6 MeV electron beam with doses ranging from 28.7 cGy up to 382.8 cGy.

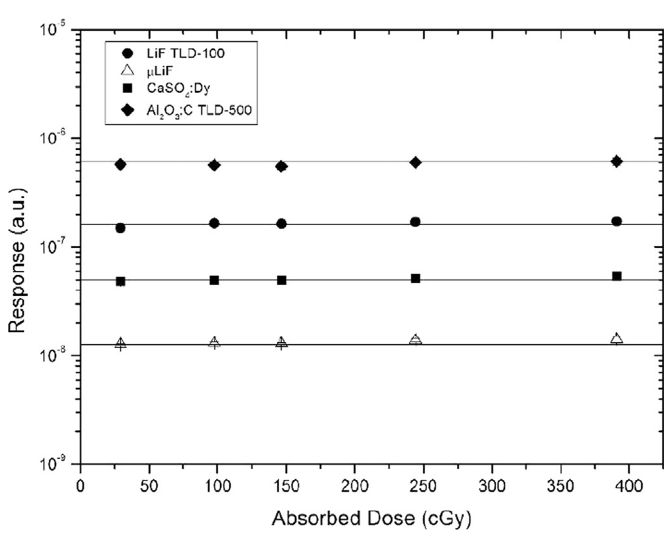

Fig. 4. Experimental results of the average sensitivity of the detectors to 6 MeV.

3. Results

3.1. Dose-response curves

The repeatability of all dosimeters was better than ± 4.0%. The standard deviation of the mean after the five readout cycles was lower than ± 4.0% for all selected samples. Fig. 3 *a* to *d* presents the dose-response curves obtained to 6 MeV electron beam. The experimental calibration factors (given by the ratio of emitted signal – Coulomb or counts – and the absorbed dose) were 0.167 ± 0.005 $C.cGy^{-1}$ to TLD-100; 0.011 ± 0.001 $C.cGy^{-1}$ to µLiF:Mg,Ti; 0.054 ± 0.002 $C.cGy^{-1}$ to $CaSO_4$:Dy; and 6.03 ± 1.07 × 10^3 $counts.cGy^{-1}$ to Al_2O_3:C.

3.2. Average luminescent sensibility to the absorbed dose

The average sensibility of the luminescent signal (S) as a function of the absorbed dose for the 6 MeV electron beam was calculated using the Eq. (1)

$$S = \frac{\overline{R}}{D} \quad (1)$$

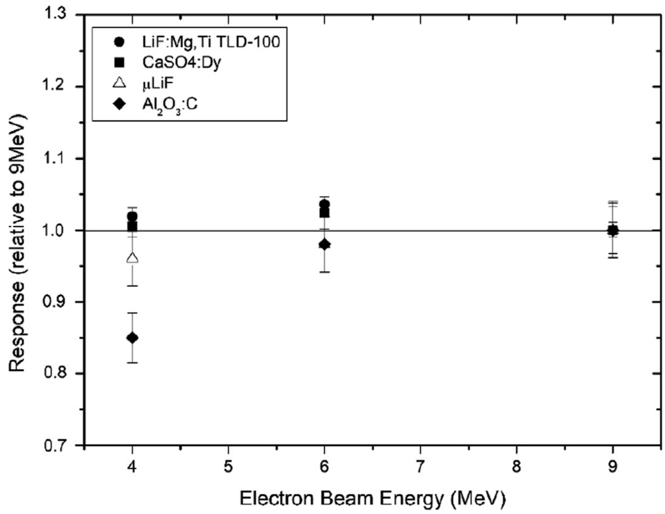

Fig. 5. Energy dependence of response of the dosimeters studied.

where $\overline{R}$ is the mean response of the dosimeter (TL or OSL), and D the absorbed dose. The experimental results are showed in Fig. 4.

3.3. Energy dependence

The results of the electron energy dependence ranging from 4 up to 9 MeV are presented in Fig. 5. As can be observed, the μLiF and Al_2O_3:C TLD-500 detectors presented relevant energy dependence. The most likely hypothesis is the dimensions and thicknesses of the respective detectors.

Fitting a function over the experimental data, this dependency of response (R_E) with the energy (E) can be corrected for μLiF and Al_2O_3:C dosimeters, respectively, with Eqs. (2) and (3).

$$R_E = 0.19(6)\bullet \ln 25(42)E \tag{2}$$

$$R_E = 0.05(2)\bullet \ln 3.1(24).\ 10^7 E \tag{3}$$

3.4. Angular dependence

Fig. 6 shows the angular dependence of the TL and OSL responses of each dosimeter analyzed. The incident angles studied varied from 0° to 40°. One can observe a significant angular dependence for the Al_2O_3:C

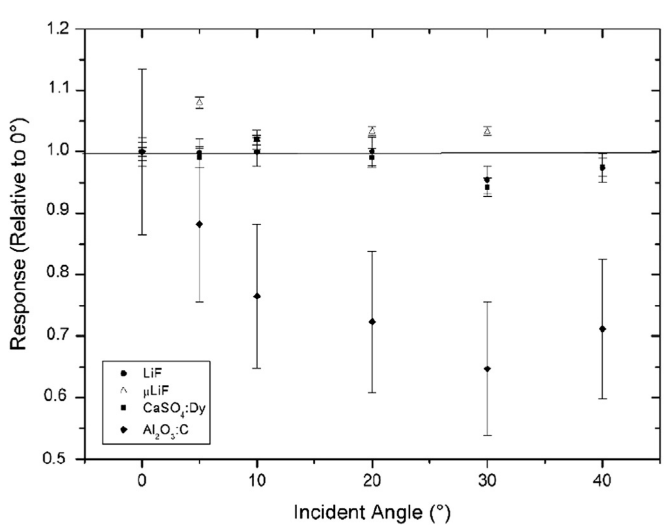

Fig. 6. Angular dependence of the detectors studied with incident angles from 0° up to 40°.

TLD-500 detectors.

Fitting an exponential function over the experimental data, a correction can be performed for the response ($R_{(\theta)}$) given from an incident angle θ using the Eq. (4).

$$R_{(\theta)} = 0.33(14)e^{-0.12(12)\theta}+0.68(8) \tag{4}$$

An angular dependence around 4.0% is a well-known fact of the Al_2O_3:C dosimeters for clinical photon beams and reported by several authors [9,10]. Antonio and Caldas [1] studied this property using beta radiation from $^{90}Sr + ^{90}Y$. The obtained results in our experiments agree with the reported, and the causes can be attributed to the geometry and size of the dosimeter and the irradiation geometry [9,10].

3.5. Intrinsic efficiency

The intrinsic efficiency of the luminescent materials (I_E) can be calculated using the Eq. (5)

$$I_E = \frac{\overline{R}}{D.\ m} \tag{5}$$

where $\overline{R}$ is the mean luminescent response of the material over a absorbed dose (D), and m is the dosimeter's mass. The experimental results of the intrinsic efficiency are presented in Table 1.

4. Discussion

The dose-response curves to 6 MeV electrons of all detectors tested presented linear behavior over the dose range studied, with slight superlinearity tendency for absorbed doses close to 400 cGy for Al_2O_3:C TLD-500 dosimeters. The repeatability values are better than 4.0%. $CaSO_4$:Dy and LiF:Mg,Ti TLD-100 showed negligible energy and angular dependences over the range of energies studied and incident angles from 0° to 20°. Different results were found with μLiF and Al_2O_3:C TLD-500 dosimeters, presenting several energy and angular dependences, probably because of its commercial geometry and dimensions.

According to the results obtained all dosimeters present differences in the efficiency of providing luminescent signal from the absorbed doses of 6 MeV electron beam, as one can observe in Table 1. As documented [6], $CaSO_4$:Dy presents higher sensitivity in comparison with other two TLDs, and Al_2O_3:C TLD-500 was also very sensitive in our study.

5. Conclusions

Electron beam dosimetry is quite complex, specially applied to TSEB radiation therapy measurements. Through analysis of the experimental results, it can be concluded that all luminescent detectors studied can be used as easy-to-take dosimetric tools for commissioning and quality assurance of 6 MeV clinical electron beams used in TSEB treatments. Some correction factors regarding of energy and angular dependencies may be required for μLiF and Al_2O_3:C TLD-500 dosimeters to ensure that the uncertainties of the measurements remain below the radiotherapy acceptable levels.

Table 1
Intrinsic efficiency of the luminescent materials to electron beam absorbed dose.

Dosimeter	**TL intrinsic efficiency (C/cGy mg)**
TLD – 100	(6.83 ± 0.04) x 10^{-3}
μLiF	(3.21 ± 0.04) x 10^{-3}
$CaSO_4$:Dy	(10.51 ± 0.09) x 10^{-4}
Dosimeter	**OSL intrinsic efficiency (counts/cGy mg)**
Al_2O_3:C TLD – 500	(85 ± 4)

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