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Comparative study of the TL response of LiF:Mg,Ti and $CaSO_4$:Dy in the clinical electron beams dosimetry applied to total skin irradiation (TSEB) treatments

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ABSTRACT

The commissioning and quality assurance The Total Skin Electron Beam (TSEB) irradiation treatment is based on the AAPM's report 23, which describes the six-dual-field (Standford) technique, and the Hospital Israelita Albert Einstein (HIAE) follows this recommended guidance. The Dosimetric Materials Laboratory of the Instituto de Pesquisas Energéticas e Nucleares (IPEN-LMD) has tradition in research related to thermoluminescent materials and its clinical applications. Thus, aiming to apply the LiF:Mg,Ti, the most common TLD material, and $CaSO_4$:Dy + Teflon produced at IPEN as easy-to-use alternatives to electron beams dosimetry and its parameters applied to TSEB, this paper reports a comparative study of the TL responses of both materials to dose evaluation in TSEB treatments. The TL response of both materials was evaluated in several TSEB parameter tests such as clinical field homogeneity, Monitor Units (MU) calculation, absorbed doses over the reference line and throughout the surface of the skin in a treatment simulation using AldersonRando anthropomorphic phantom. Results show that the field homogeneity measurements remained within ± 8% acceptance limit from AAPM Report 23, little to no energy dependency over the range of 4 o 9 MeV electron beams and, for clinical measurements and MU calculations, both TLDs present compatible results and can be used as alternative tools in TSEB dosimetry.

1. Introduction

One of the modalities of external radiotherapy is the Total Skin Electron Beam (TSEB) irradiation, which aims to deliver a homogeneous dose distribution over the entire skin surface of the patient. It is internationally considered as 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 parts completely, without penetrating the internal organs. If the tumor is detected early, treatment results in the complete disappearance of all signs and symptoms of the disease. In some anatomical regions, the absorbed dose may vary widely due to the angle of treatment, or even the skin surface itself, which is often significantly curved and oblique to the plane of treatment. Certain areas of the patient's skin, as well as some organs (such as nails and eyes), may have to be shielded in order to avoid treatment morbidity. (Strohl, 1994; Jones et al., 1999; Podgorsak, 2005; Bao et al., 2012).

The TSEB irradiations do not use the common external radiation therapy planning softwares. Therefore, the commissioning and quality assurance of this type of application takes place differently. The Hospital Israelita Albert Einstein (HIAE – São Paulo, Brazil), with the objective of commissioning of its TSEB treatments, follows the "six-dual-field" technique (also known as “Stanford” technique) reported by the American Association of Physics in Medicine (AAPM) Report 23 (Karzmack, 1987).

This method reports that ‘dual-fields’ are created varying the gantry rotation of the linear accelerator over ± 17° in the horizontal plane, with reference to the waistline of the patient, creating a very large field over distance. The patient is treated within a two-day cycle, with three dual-fields per day: on the first day, the patient is treated in the anterior position and the posterior right and left obliques; and on the second day, in the posterior position and the anterior right and left obliques. The dual-fields are used to minimize the X-ray contamination of the central axis and the non-uniformity due to the inverse-square of the distance law (Karzmack, 1987).

The Dosimetric Materials Laboratory of the Instituto de Pesquisas Energéticas e Nucleares – LMD/IPEN has tradition in research related to thermoluminescent materials and its clinical applications. The Thermoluminescent dosimeters (TLDs), such as LiF:Mg,Ti TLD-100 and $CaSO_4$:Dy + Teflon pellets produced at IPEN (Campos, 1983; Campos

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and Lima, 1986) have demonstrated great efficiency in clinical photons and electron beams dosimetry (Campos and Lima, 1987; Nunes and Campos, 2008; Matsushima et al., 2011; Bravim et al., 2011, 2014; Villani et al., 2017), and can be useful tools in the detection of errors related to the application of the dose to the patient. The LiF:Mg,Ti is the most used TL material and widely studied in radiotherapy dosimetry due to its near tissue-equivalence and overall reliability (McKeever et al., 1995).

The $CaSO_4$:Dy, manufactured and marketed by the Dosimetric Materials Laboratory of the Radiation Metrology Center/IPEN as powder and pellets, offers extensive range of linear response to radiation. This dosimeter has already been used in radiation protection dose assessment due to its high sensitivity (Morato et al., 1982), and recent investigations have assessed its application related to radiotherapy (Nunes, and Campos, 2008; Matsushima et al., 2011; Bravim et al., 2011, 2014; Villani et al., 2017).

The commissioning of TSEB 'six-dual-field' technique reported by AAPM's Report 23 (Karzmack et al., 1987) has been experimentally described by Platoni et al. (2012) in its application at Attikon University General Hospital. The authors used parallel-plate ionization chamber and LiF:Mg,Ti TLD-100 dosimeters to validate the treatments dosimetry.

Aiming to apply the LiF:Mg,Ti and $CaSO_4$:Dy + Teflon dosimeters as easy-to-use alternatives to electron beams dosimetry and verification of parameters applied to TSEB, this paper reports a comparative study of the TL responses of both materials to dose evaluation in TSEB treatments. Measurements were performed using the six-dual-field "Standford" technique and an anthropomorphic phantom.

2. Material and methods

2.1. Dosimetric materials

The dosimetric materials 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;
- LiF:Mg,Ti (TLD-100) TLDs produced by Thermo Scientific: 3.15 mm side, 0.9 mm thick and mass of 2 mg;

Each dosimeter type was divided into five groups and one group was used for background dose control. All samples repeatability were evaluated and it was used samples with response better than ± 5.0%.

2.2. Dosimeters readout and thermal treatments

The TL measurements were performed using a Harshaw 4500 TLD reader in nitrogen atmosphere. For the LiF:Mg,Ti 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 (McKeever et al., 1995). For $CaSO_4$:Dy + Teflon

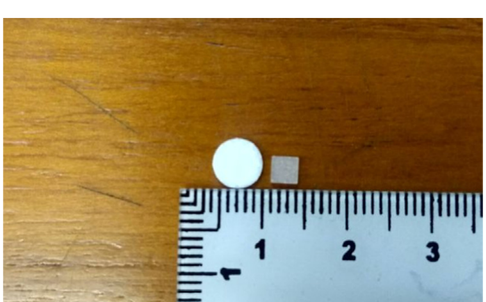

Fig. 1. The thermoluminescent dosemeters used in this study.

Pellets, a TTP with linear heating rate of 10 °C s^{-1} with maximum temperature of 300 °C was used (Campos and Lima, 1986). Each reading cycle was performed within ~40 s. The samples were thermally treated prior and after all irradiations.

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 11200 surgical stove for two hours (McKeever et al., 1995). The $CaSO_4$:Dy + Teflon dosimeters were annealed at 300 °C in a Vulcan® 3–550 PD furnace, for three hours (Campos and Lima, 1986). The readout of both LiF:Mg,Ti and $CaSO_4$:Dy TLDs were performed 24 h after irradiations so all the traps were stabilized.

2.3. Irradiation systems

A 4 π geometry gamma irradiator of ^{137}Cs (Activity of 38,11 GBq in 17 April 2014) from the LMD/IPEN was used to evaluate the TL repeatability of all the dosimeters used. The clinical measurements were carried out using the linear accelerator Varian Clinac 23EX (Varian Medical Systems, Inc., Palo Alto, California) from the Radiotherapy Center of the Hospital Israelita Albert Einstein (HIAE). For TSEB therapy, 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 energy of the produced electron beam of choice for TSEB was 6 MeV. The collimator was opened to 36 × 36 cm^2 after the insertion of a specific tray dedicated for the TSEB practice, providing a great field size over distance.

2.4. Dosimetric characterization

The TL dosimeters were characterized for the 6 MeV energy electron beam of the Clinac 23EX. For each sample the calibration factors were determined by means of the individual TL sensitivity to this radiation quality (TL_{Signal}/AbsorbedDose). Irradiations with 150 MU and 250 MU (147.6 cGy and 246.0 cGy respectively) were performed positioning all dosimeters between two polymethylmethacrylat (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 used. These two specific doses were chosen due to the documented linearity of response of all dosimetric materials (McKeever et al., 1995; Campos and Lima, 1986) and to its TSEB practical applicability. The TL energy dependence of response over the range of 4–9 MeV of both materials was also evaluated. One can find more details over this characterization in Almeida et al. (2018). The characterization set-up is shown in Fig. 2.

2.5. Experimental set-up and irradiations

To obtain experimental data on field parameters and treatment absorbed doses, real conditions of TSEB treatment were simulated by using an AldersonRando® anthropomorphic phantom arranged on a turntable and a large PMMA sheet 0.5 cm thickness to module the electron fields. The experimental set-up of field parameters and treatment dosimetry is shown in Fig. 3.

2.5.1. Field homogeneity

The TL responses of the dosimeters were evaluated for the field homogeneity test. A double-field set-up was used varying the gantry angle in ± 17° in the horizontal axis, with the umbilicus (z_{Ref}) as reference. The 0.5 cm PMMA sheet was used between the primary radiation beam and the TLDs, with 50 cm from z_{Ref}. The size of the irradiation field was 36 × 36 cm^2, with 3 m distance from the isocenter. The central axis (vertical) homogeneity was measured positioning the samples 50 and 75 cm superior and inferiorly to the z_{Ref}; and the horizontal homogeneity was measured using the same positions, with a

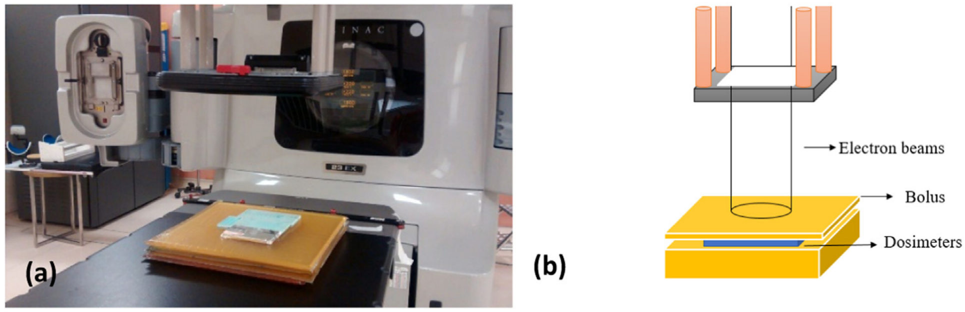

Fig. 2. Positioning of the dosimeters to perform the dosimetric characterization. (a) accommodation of the TLDs between the two PMMA plates and irradiation; (b) set-up for dosimetric characterization with Varian Clinac 23EX.

right displacement of 30 cm (Karzmack et al., 1987).

2.5.2. Absorbed dose in the waistline

In TSEB technique, the patient is treated with six-dual-fields, with the calibration point to umbilicus (z_{Ref}) (Karzmack et al., 1987). To evaluate the response of the TLDs over the z_{Ref} and the entire waist line, the anthropomorphic phantom was used. Dosimeters were placed in five points: (i) umbilicus (z_{Ref}), (ii) posterior, (iii) right lateral (RL), (iv) right anterior (RAO) and (v) right posterior (RPO) obliques. Irradiations were performed simulating a complete two-day cycle of the TSEB treatment, and the TLDs readout presented the integrated absorbed dose at each point.

2.5.3. TSEB treatment: absorbed dose evaluation

To a complete evaluation of the dose-distribution over the patient, the TLDs were placed in 10 different points over the phantom's anatomy, and in the z_{Ref} point. The measurements were performed on two alternate days, as recommended by AAPM (Karzmack et al., 1987), allowing a greater study in sub and/or over dosage.

2.5.4. Monitor Units (MU) Calculation

The monitor unit is a parameter inserted in the linear accelerator console where it indicates the amount of radiation to be emitted. Several factors that are available at the time of planning should be considered so that a value of MU is indicated for the linear accelerator and the correct dose of radiation is delivered. For the determination of the unit monitors all essential parameters and the results of the absorbed dose measurements were used.

A set of measurements was performed using the anthropomorphic phantom, where the TLDs were positioned in the z_{Ref} with a prescribed dose of 210 cGy for all irradiation fields. The calculations were performed using Eq. (1) (Cox et al., 1990; Poli et al., 2000; Platoni et al., 2012).

$$M_h = \frac{D_{6df\,(pr)}}{D_{w,Q(Z_{Ref})} \bullet \quad C_{(df/hb)} \bullet \quad C_{(6df/df)}} \tag{1}$$

where:

M_h are the Monitor Units to be set;
$D_{6df\,(pr)}$ is the prescribed dose to z_{Ref};
$D_{w,Q(Z_{Ref})}$ is the dose delivered to z_{Ref} by a single horizontal beam per Monitor Unit;
$C_{(df/hb)}$ is a correction factor obtained by the ratio of the dose $D_{df\,(Z_{Ref})}$ delivered to z_{Ref} by a single dual field to $D_{w,Q(Z_{Ref})}$; and
$C_{(6df/df)}$ is a correction factor obtained by the ratio of the dose $D_{6df\,(pr)}$ delivered to z_{Ref} from the six-dual-field treatment to $D_{df\,(Z_{Ref})}$.

The LiF:Mg,Ti TLD-100 dosimeters were used as reference dosimeters, since its results for 6 MeV electron beam dosimetry (Bravim et al., 2011) and similar applications (Platoni et al., 2012) are validated. The presented experimental results of the absorbed doses are the average of four dosimeters measurements and the error bars are the standard deviation the mean. All the calculations were carried out with Microsoft Excel 2016 software, graphics were plotted using OriginPro 8.1, and, the units of the absorbed doses were all expressed in "cGy", due to clinical applications, taking into account the decimal number and the Monitor Units, regarding a better understanding in the Medical Physics field.

3. Results

3.1. Dosimetric characterization

The repeatability measurements were performed free in air at electronic equilibrium conditions placing the TL samples between two 0.3 cm PMMA plates. Irradiation of absorbed dose of 5 mGy, readout and thermal treatments were repeated five times to select the samples with repeatability better than ± 5.0%. The standard deviation after the five readout cycles was lower than ± 4.0% for all selected samples.

The calibration factors of each sample were obtained to 6 MeV electron beam. They varied between 0.167 ± 0.005 C/cGy to

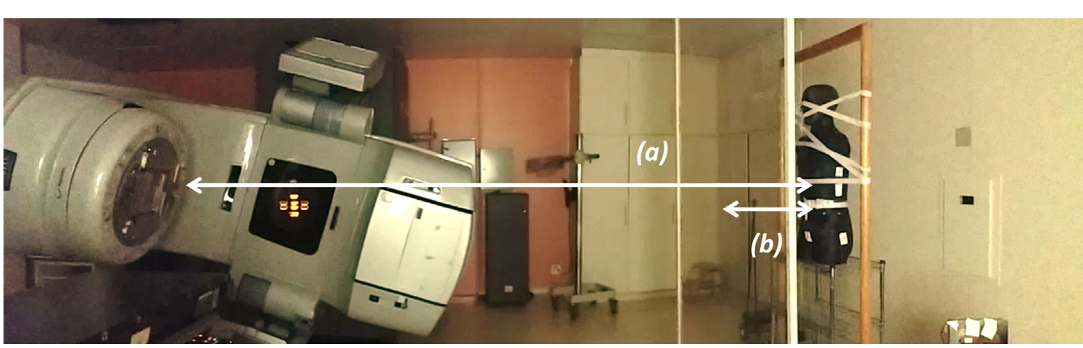

Fig. 3. TSEB experimental set-up of irradiation using the AldersonRando® anthropomorphic phantom. Distance *a* between the phantom and the field isocenter is 3 m; and Distance *b* between the phantom and the PMMA sheet is 50 cm.

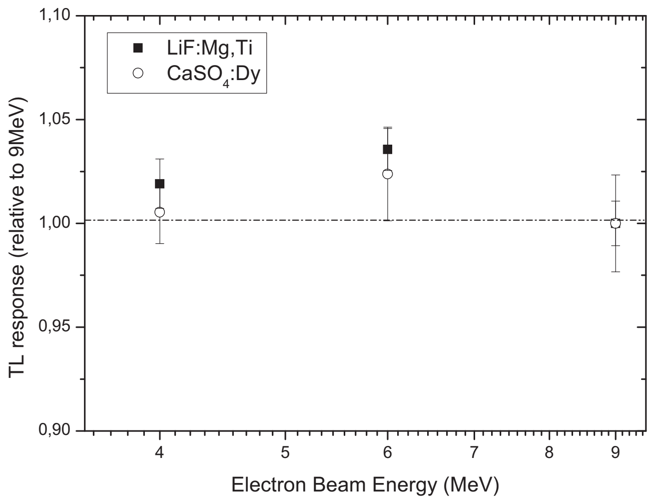

Fig. 4. TL energy dependence response of LiF:Mg,Ti and $CaSO_4$:Dy (adapted from Almeida et al., 2018).

LiF:Mg,Ti TLD-100 and 0.054 ± 0.002 C/cGy to $CaSO_4$:Dy. The results of the electron energy TL dependence for electron beans ranging from 4 up to 9 MeV are presented in Fig. 4. Both TL materials presented average energy dependence better than ± 4.0% over the studied energy range.

3.2. Field homogeneity

Considering the characteristics of the electron field, maximum dose deposition should be delivered within a few millimeters of the skin surface (5–15 mm). The treatment field should be dimensioned to fully cover the patient. The field should have vertical uniformities of ± 8% and horizontal uniformities of ± 4% with respect to the central area of 160 × 60 cm^2 of the treatment plane (Karzmack et al., 1987). Tables 1 and 2 show the experimental results of field homogeneity measured with the TLDs.

For the LiF:Mg,Ti and $CaSO_4$:Dy dosimeters, the results obtained were uniformly within the desired range relative to the treatment plane, so that they could be used for clinical application.

3.3. Absorbed dose in the waist line

Table 3 show the dose at the reference point for each TL dosimeter group, and the dosimetric measurements of the other four points throughout the waistline. The results of the waistline were compared with the dose at the z_{Ref}. The right lateral (RL) showed a greater percentage difference because the incident beam is not directed to this position, obtaining in this way a smaller dose in this place. The posterior region also received a smaller dose because of the anatomical asymmetry.

Table 1
Field homogeneity for inclinations of ± 17° with dual-field irradiation.

Distance from central axis	LiF:Mg,Ti		$CaSO_4$:Dy	
	Absorbed Dose (cGy)	% Difference from z_{Ref}	Absorbed Dose (cGy)	% Difference from z_{Ref}
z_{Ref}	63.7 ± 0.5		62.3 ± 0.2	
50 cm_{sup}	62.3 ± 0.2	− 2.2	61.2 ± 0.2	− 1.7
75 cm_{sup}	61.4 ± 0.4	− 3.7	59.3 ± 0.4	− 5.1
50 cm_{inf}	63.3 ± 0.9	− 0.6	60.2 ± 0.8	− 3.4
75 cm_{inf}	62.1 ± 0.3	− 2.5	58.2 ± 0.2	− 7.0

Table 2
Field homogeneity for inclinations of ± 17° with dual-field irradiation with 30 cm horizontal distancing to the right of the central axis.

Distance from central axis	Absorbed Dose (cGy)	% Difference from z_{Ref}	Absorbed Dose (cGy)	% Difference from z_{Ref}
	LiF:Mg,Ti		$CaSO_4$:Dy	
z_{Ref}	61.3 ± 0.4		62.3 ± 0.8	
50 cm_{sup}	58.2 ± 0.9	− 5.4	57.9 ± 1.0	− 7.6
75 cm_{sup}	56.7 ± 0.3	− 8.0	57.7 ± 1.3	− 8.0
50 cm_{inf}	57.9 ± 0.3	− 5.9	57.8 ± 1.0	− 7.9
75 cm_{inf}	57.9 ± 0.2	− 5.8	57.5 ± 0.4	− 8.2

Table 3
Absorbed doses evaluated at the z_{Ref} and throughout the waistline of the AldersonRando® anthropomorphic phantom.

Position	LiF:Mg,Ti		$CaSO_4$:Dy	
	Absorbed Dose (cGy)	% Difference from z_{Ref}	Absorbed Dose (cGy)	% Difference relative to LiF:Mg,Ti
z_{Ref}	214.5 ± 1.2		204.9 ± 1.1	− 4.7
Posterior	199.8 ± 1.2	− 7.4	191.2 ± 1.3	− 4.5
RAO	212.6 ± 1.1	− 0.9	196.4 ± 3.0	− 8.3
RPO	210.1 ± 0.9	− 2.1	195.3 ± 3.9	− 7.6
RL	196.7 ± 1.0	− 9.1	186.9 ± 1.7	− 5.2

3.4. TSEB treatment: dose delivering

Many electrons that penetrate the skin surface are incident at large angles relative to the treatment plane and the surface of the skin itself is often significantly curved and oblique to this plane. Consequently, the dose distribution on the skin may vary widely. In some regions such as thorax, posterior region, right lateral and right thigh varies only in a small percentage as predicted by the dose distribution in the air. However, for many other parts of the body, doses are measured more than 20% different to abdomen (z_{Ref}) (Karzmack et al., 1987).

For treatment simulation, 470 MU were selected in the console control of the Varian Clinac 23EX to deliver 210 cGy to z_{Ref}. TLDs were positioned at z_{Ref} and disperse in 10 other points throughout the anthropomorphic phantom to evaluate the hole-body dose distribution and compare the LiF:Mg,Ti results with the $CaSO_4$:Dy. The readout of all TLDs was carried out after a two-day cycle of irradiation, resulting in the integration of dose received at each point of measurement. Table 4 presents the experimental results obtained with LiF:Mg,Ti and $CaSO_4$:Dy.

The agreement between the two dosimetric materials in each point

Table 4
Experimental results using LiF:Mg,Ti TLD-100 and $CaSO_4$:Dy dosimeters.

Position	LiF:Mg,Ti		$CaSO_4$:Dy	
	Absorbed Dose (cGy)	% Difference from z_{Ref}	Absorbed Dose (cGy)	% Difference relative to LiF:Mg,Ti
z_{Ref}	205.0 ± 1.0		205.0 ± 1.7	+ 0.01
Thorax Center	205.30 ± 1.2	+ 4.0	203.7 ± 2.0	− 0.8
Thorax Right	189.6 ± 1.1	− 12.6	193.4 ± 0.8	+ 2.0
Thorax Left	193.2 ± 1.7	− 10.5	203.2 ± 0.7	+ 5.2
Posterior	206.4 ± 0.9	+ 3.5	212.7 ± 1.9	+ 3.2
Right Lateral	196.6 ± 1.8	− 8.6	198.6 ± 0.7	+ 1.0
Right Thigh	204.4 ± 2.6	− 4.5	200.4 ± 4.1	− 2.0
Perineum	202.2 ± 0.9	− 5.6	195.7 ± 2.4	− 3.4
Forehead	200.9 ± 0.7	− 6.3	206.4 ± 2.0	+ 2.7
Scalp	155.8 ± 2.8	− 37.0	141.3 ± 9.5	− 10.3
Right Axilla	86.2 ± 2.4	− 142.7	103.8 ± 4.5	+ 20.3

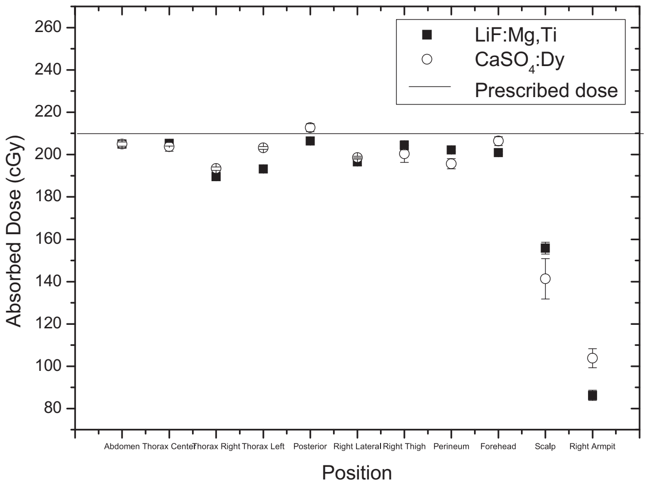

Fig. 5. Agreement between TL dosimeters measurements in each point studied.

Table 5
Experimental results using both TLDs for Dose/MU calculations and respective correction factors.

TLD	$D_{w,Q}(z_{Ref})$ (cGy/MU)	$D_{df}(z_{Ref})$ (cGy/MU)	$D_{6df(pr)}$ (cGy/MU)	$C_{(df/hb)}$	$C_{(6df/df)}$
LiF:Mg,Ti	0.128	0.139	0.449	1.087	3.228
$CaSO_4$:Dy	0.132	0.139	0.450	1.057	3.236

of measurement can be better observed in Fig. 5.

3.5. Monitor Units (MU) calculation

Using Eq. (1), along with the results showed in Table 5, it was obtained that if 210 cGy is delivered in the z_{Ref} ($D_{6df(pr)} = 210$ cGy), the monitor units to be selected in the linear accelerator console for each field must be 470 MU.

4. Discussion

The TSEB six-dual-field technique is quite complex, as is its dosimetry and quality assurance. The evaluation and measurement of absorbed doses in the cutaneous region of the patient can present variations up to 10% over the dose in the reference point (Karzmack et al., 1987). The TLDs have demonstrated excellent results in assessing dose uniformity in both field parameters and patient's skin. It is found that, both materials were able to evaluate the field homogeneity and results showed good agreement among themselves, considering dosimeter's differences in geometry, energy dependence and effective density.

For the abdomen region (z_{Ref}), the agreement with the prescribed 210 cGy dose was 97.62% for LiF,Mg,Ti and 97.61% for $CaSO_4$:Dy. Over the waistline, the right lateral (RL) showed the greater percentage difference (up to 9.0%) and all the deviations can be explained by anatomical asymmetry and field's incident angles. For the clinical simulation, the dose distribution varied within the expected 20% reported by AAPM (Karzmack et al., 1987) at almost all points measured. The greater deviations were at scalp and right axilla, the resulting sub dosage can also be explained by the incident angles and phantom's anatomy. Both TLDs were capable to express experimental results for Monitor Units calculation and respective correction factors.

Well-known and established in clinical dosimetry are the protocols and measurements using ionization chambers and diodes due to their physical characteristics and electronic systems. As a routine dosimetric system, the LiF:Mg,Ti TLD-100 dosimeters have been widely used in the last decades and both their behavior and performance in clinical dosimetry are validated by the vast literature available; it being the TL dosimeter of choice for validation of the experimental data obtained in our laboratory.

As previously mentioned, many works have already been developed in order to validate also the performance of the $CaSO_4$:Dy dosimeter produced in IPEN with good results. As Platoni et al. (2012) used LiF:Mg,Ti TLDs for dose distribution evaluation over a treatment simulation, this paper reports the feasibility of its use for commissioning measurements as well, helping validating the $CaSO_4$:Dy results, so one can choose the dosimeter according to its availability.

5. Conclusions

Through analysis of the experimental results it can be concluded that both LiF:Mg,Ti and $CaSO_4$:Dy TLDs presents good results for clinical electron beam dosimetry. Field parameters, MU calculation and clinical applications were tested. The TLDs are small, easy to handle and position for measurements, no cables needed and, specially $CaSO_4$:Dy, widely available in Brazil. All obtained experimental results agreed with recommended guidelines (Karzmack, 1987; Podgorsak, 2005) and both materials can be used as easy-to-use alternative tools to perform TSEB six-dual-field measurements.

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