

Influence of thermoluminescent dosimeters energy dependence on the measurement of entrance skin dose in radiographic procedures*

Influência da dependência energética de dosímetros termoluminescentes na medida da dose na entrada da pele em procedimentos radiográficos

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Abstract **OBJECTIVE:** This study was aimed at evaluating the influence of the energy dependence of thermoluminescent materials on the determination of entrance skin dose in patients submitted to conventional radiographic studies (general radiology, mammography and dental radiology). **MATERIALS AND METHODS:** Three different thermoluminescent materials were utilized: LiF:Mg,Ti, LiF:Mg,Cu,P and CaSO₄:Dy. These materials were exposed to standardized sources of X and gamma radiation and clinical X-ray beams. **RESULTS:** Calibration and energy dependence curves were obtained. All the materials showed a linear response as a function of the air kerma. As far as energy dependence is concerned, the CaSO₄:Dy and LiF:Mg,Ti samples showed the greatest variation on thermoluminescent responses as a function of the effective radiation beam. **CONCLUSION:** The tested materials showed an appropriate performance for detecting X radiation on standard and clinical X-ray beams. Although CaSO₄:Dy and LiF:Mg,Ti samples present a significant energy dependence in the considered energy range, these materials can be utilized for measuring entrance skin doses, provided appropriate correction factors are applied.

Keywords: Thermoluminescent dosimeters; X-ray; Radiation protection; Entrance skin dose.

Resumo **OBJETIVO:** O objetivo do presente trabalho foi avaliar a influência da dependência energética de materiais termoluminescentes na determinação da dose na entrada da pele de pacientes submetidos a exames radiográficos (radiologia geral, mamografia e radiologia odontológica). **MATERIAIS E MÉTODOS:** Três diferentes materiais termoluminescentes foram utilizados: LiF:Mg,Ti, LiF:Mg,Cu,P e CaSO₄:Dy. Estes materiais foram expostos a fontes padronizadas de radiação X e gama, e a feixes clínicos de raios X. **RESULTADOS:** As curvas de calibração e de dependência energética foram obtidas. Todos os materiais apresentaram resposta linear em função do kerma no ar. Com relação à dependência energética, as amostras de CaSO₄:Dy e LiF:Mg,Ti mostraram maior variação da resposta termoluminescente em função da energia efetiva do feixe de radiação. **CONCLUSÃO:** Os materiais testados mostraram desempenho adequado para a detecção da radiação X em feixes padronizados e clínicos. Embora as amostras de CaSO₄:Dy e LiF:Mg,Ti apresentem dependência energética significativa no intervalo de energia considerado, estes materiais podem ser utilizados para medição da dose de entrada na pele se fatores de correção apropriados forem utilizados.

Unitermos: Dosímetros termoluminescentes; Raios X; Proteção radiológica; Dose na entrada da pele.

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INTRODUCTION

The use of ionizing radiation in medicine represents the main cause of human

exposure to artificial radiation sources^(1,2).

If by one side the technological advances in medicine provide for more accurate diagnosis, on the other side the dissemination of such technologies leads to an increase in the collective dose, making it essential that medical practices based on ionizing radiations be optimized, assuring the benefits of such technologies and reducing associated risks.

An important tool for evaluating the optimization of procedures is the measurement of entrance skin dose (ESD) in pa-

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tients submitted to radiographic examinations. This value shall be the lowest the more optimized the employed radiographic technique is, without compromising the imaging quality⁽³⁻⁵⁾. ESD represents the dose on the patient's skin surface added with back scattering radiation.

The ESD can be evaluated by direct methods (measurements with ionization chambers or by using thermoluminescent dosimeters [TLDs]), by indirect methods (by means of the determination of the dose-area product) or also by means of calculations based on the X-ray tube performance⁽⁶⁾.

Thermoluminescent dosimetry presents some advantages: high sensitivity, which allows the use of small-sized dosimeters; response with a low dependence on photon energy and linear response for a wide dose interval; low cost and easy handle; high sensitivity, even for small doses; stable response, even under adverse environmental conditions; good reproducibility, even for small doses; and simple emission curve, with well defined peaks^(7,8).

Such dosimetry is based on the fact that materials will emit light when appropriately heated, after having been irradiated, with the amount of emitted light being proportional to the absorbed radiation energy (in other words, the absorbed dose)⁽⁸⁾.

A detector response variation as a function of the incident radiation energy depends on the process of interaction between the radiation and the detector. In the energy interval of interest for diagnostic radiology (from 20 to 70 keV⁽⁷⁾), the interaction between radiation and matter predominantly happens because of the photoelectric effect, whose occurrence probability increases with the effective atomic number of the medium⁽⁹⁾. This means that TLDs with higher effective atomic numbers will present overestimated responses to radiation as compared with the readings done with dosimeters with lower effective atomic numbers. Consequently, the dosimeter response variation as a function of incident radiation energy becomes a decisive factor in the choice of the material to be utilized, as without previous knowledge of such behavior, the ESD values might be unreliable.

Amongst the most frequently utilized thermoluminescent materials is the lithium fluoride activated with magnesium and titanium (LiF:Mg,Ti); such material presents some important characteristics such as the effective atomic number ($Z_{\text{ef}} = 8.2$) close to that of human tissue, not compromising the radiographic images, although presenting a very complex thermoluminescent emission spectrum⁽¹⁰⁾. Another lithium fluoride based dosimetric material has more recently been developed, using other dopant agents, the lithium fluoride activated with magnesium, copper and phosphorus (LiF:Mg,Cu,P; $Z_{\text{ef}} = 8.2$). This material presents some advantageous characteristics as compared with LiF:Mg,Ti, among them the 40 times higher sensitivity to gamma radiation. In Brazil, the Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN) produces dosimeters of calcium sulfide activated with dysprosium (CaSO₄:Dy). This material is quite sensitive to radiation, however, it has a high atomic number ($Z_{\text{ef}} = 14.4$) and for this reason it presents a high dependence on the radiation energy, particularly up to 100 keV^(10,11).

The aim of the present study was to evaluate the behavior of three thermoluminescent materials widely utilized in dosimetry of X and gamma radiations (LiF:Mg,Ti; LiF:Mg,Cu,P; and CaSO₄:Dy) on different X radiation beams and the implications in the entrance skin dose estimation in patients submitted to diagnostic radiology procedures (conventional radiology, mammography and dental radiology).

MATERIALS AND METHODS

The following dosimetric materials were utilized in the present study: LiF:Mg,Ti (commercially known as TLD-100), marketed by Thermo Scientific, Massachusetts, USA; LiF:Mg,Cu,P (commercially known as TLD-100H), also marketed by Thermo Scientific, Massachusetts, USA, and CaSO₄:Dy, manufactured by IPEN/CNEN, São Paulo, Brazil. Initially a batch comprising 250 TLDs was gathered; the working batch was selected in such a way that, after five identical thermal treatment, irradiation and readout cycles, the maximum thermoluminescent response varia-

tion was lower than 3%. After this selection, the working batch comprised 24 TLD-100H samples, 36 TLD-100 samples and 39 CaSO₄:Dy pellets.

The thermoluminescent materials were characterized according to their main dosimetric characteristics. For this purpose, they were irradiated with three radiation sources:

- Standard cesium 137 source (¹³⁷Cs) (JLShepherd & Associates, California, USA, with activity of 390 GBq – 1/1/2009) and energy of 660 keV;

- Standard cobalt 60 source (⁶⁰Co) (IPEN, São Paulo, Brazil, with activity of 4.47 GBq – 1/1/2009) and mean energy of 1,250 keV;

- Standard X radiation system, model HF 320 (Pantak Incorporated, Connecticut, USA) operating under the conditions presented on Table 1.

In all exposures to radiation, the samples were individually encapsulated in transparent plastic. This same procedure was utilized in all irradiations. The sensitivity factor for each dosimeter was obtained after five identical irradiation, readout and thermal treatment cycles, by calculating the ratio between each dosimeter's mean response and the mean response of the dosimeter that presented the smallest reading variation after the five measurement cycles.

The calibration curves were obtained by simultaneously irradiating all dosimeters with one of the previously mentioned standard radiation sources, varying the air kerma. The samples were irradiated in the air, at the reference distance (1 m). When exposed to the ⁶⁰Co source, the samples were covered by a 4 mm-thick acrylic plate in order to assure the condition of electronic equilibrium. When exposed to the ¹³⁷Cs source, the electronic equilibrium acrylic plate thickness was 2 mm. Because of the low energy, no electronic equilibrium plates were used when the samples were irradiated by X radiation beams.

The irradiations with radiodiagnostic clinical beams were made using the Rando-Alderson (Alderson Research Laboratories Inc.; Connecticut, USA) anthropomorphic phantom, the breast phantom with a thickness of 5 cm and composition equivalent

Table 1 Specification of radiodiagnostic qualities established in the Pantak 320kV X radiation system.

Quality	First HVL* (mmAl)	Second HVL† (mmAl)	Effective energy (keV)	Air kerma rate (mGy/min)
RQR2	1.43	1.84	25.0	10.83
RQR3	1.79	2.34	27.2	19.62
RQR4	2.08	2.75	28.8	29.40
RQR5	2.32	3.39	30.0	39.86
RQR6	2.60	3.96	31.4	51.30
RQR7	2.87	4.55	32.7	64.07
RQR8	3.17	5.11	34.1	76.81
RQR9	3.74	6.25	36.6	104.86
RQR10	4.59	7.82	40.2	152.26

* The first half-value layer (HVL) corresponds to the thickness of material required to reduce the radiation beam intensity to one half (50%) of its original value (100%). † The second HVL corresponds to the thickness of material required to reduce the radiation beam intensity from one half (50%) to a quarter (25%) of its original value (100%).

to 50% fat and 50% glandular tissue, developed by Oliveira et al.⁽¹²⁾, and the following equipment:

- Polymat 30/50 Plus general radiology equipment, manufactured by Siemens, Erlangen, Germany;

- M III mammography equipment, manufactured by Lorad Corporation, Connecticut, USA;

- Intraoral dental radiology equipment, with two tube heads, manufactured by Indústrias Reunidas Rhos Ltda., Rio de Janeiro, Brazil.

In all irradiations with clinical beams, the TLDs were positioned in the center of the radiation field, on the phantom, with a pair of each thermoluminescent material being simultaneously irradiated. The parameters utilized in the irradiations simulating chest, abdomen and skull studies are presented on Table 2. In the irradiations made with the mammography equipment, the parameters were the following: semi-automatic exposure control, 28 kVp and 37.6 mAs. On the other hand, in the irradiations with the dental radiology beams, the following parameters were used: 80 kVp and 1.2 s; with a 22cm-long collimator with 6 cm in diameter.

Table 2 Summary of radiographic techniques utilized to simulate chest, abdomen and skull radiographic studies, all of them performed anteroposterior projection.

Study	Distance (cm)	Voltage (kVp)	Product mAs	Current (mA)	Field size (cm ²)
Thorax	180	77	8	200	36 × 36
Abdome	150	81	32	200	51 × 34
Skul	150	81	20	200	20 × 26

The thermoluminescent readout system used was a model 5500 manufactured by Thermo Electron Corporation, Massachusetts, USA. For the thermal treatment of the samples a PTW-TLDO annealing oven, manufactured by PTW, Freiburg, Germany, was utilized.

With the CaSO₄:Dy samples, a pretreatment at 150°C for 20 seconds was performed. The readings were integrated from 150°C to 300°C with a heating rate of 10°C/s. After the reading, a thermal treatment was performed in the oven during 15 minutes at 300°C. In the case of LiF:Mg,Ti (TLD-100), a pretreatment was performed in the oven, before the reading at 100°C for one hour. The reading was integrated from 50°C to 300°C, with a heating rate of 15°C/s. After the reading, a thermal treatment was performed in the oven at 400°C for three hours and at 100°C for 1 hour. With the LiF:Mg,Cu,P (TLD-100H) samples, a pretreatment at 145°C was performed for 10 seconds. The reading was integrated from 145°C to 260°C, with heating rate of 10°C/s.

From the reading values of each thermoluminescent sample, ESD was calculated using the following equation (1):

$$ESD(mGy) = (L - L_{BG}) \times S_i \times C_f \quad (1)$$

where: L is the average of the irradiated dosimeter readings under the same conditions (in nC); L_{BG} is the reading of non-irradiated dosimeters (background radiation); S_i is the sensitivity factor for each sample; C_f is the calibration factor (mGy/nC) obtained from each one of the obtained calibration curves.

RESULTS

Initially, the calibration curves were obtained (thermoluminescent response versus absorbed dose in air) for the tested dosimetric materials, in the radiation energies described in Materials and Methods. Because of the low air kerma rate of the ⁶⁰Co source, the calibration curve at this energy was obtained for absorbed dose in air < 10 mGy. For the other energies (¹³⁷Cs and X-radiation qualities) the calibration curves were obtained for values up to 50 mGy. These curves are shown on Figures 1 and 2.

The energy dependence was obtained by irradiating all tested thermoluminescent materials with the same value of absorbed dose in air (50 mGy), under the same geometric conditions, and varying only the radiation beam energy. The results are shown on Figure 3.

In order to determine the patients' ESD, phantoms were exposed to general radiology, mammography and dental radiology beams, as described in Materials and Methods. The ESD values are presented on Table 3, using three different methods:

- method 1: determination of ESD using the calibration factor C_f for the ⁶⁰Co energy;
- method 2: determination of ESD using the calibration factor C_f for the ¹³⁷Cs energy;
- method 3: determination of ESD using the calibration factors C_f for the mean energies (determined by HVL values) of the utilized X-radiation beams.

With respect to uncertainties estimation, the factors in equation (1) utilized to determine ESD were considered. The standard deviations only estimate the uncertainties in L and L_{BG} .

The uncertainties regarding S_i are in the order of 3% and in relation to C_f , 15%.

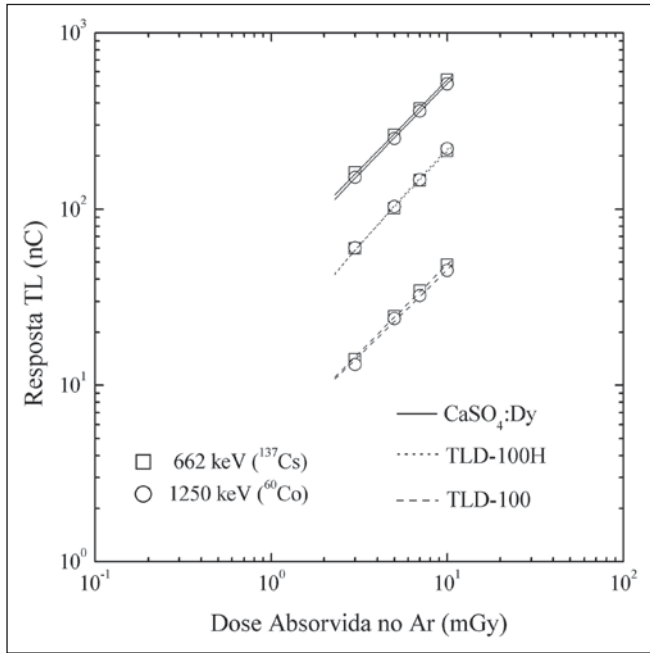


Figure 1. Thermoluminescent response as a function of absorbed dose in air for the energies of 662 keV (^{137}Cs) and 1250 keV (^{60}Co) for the three thermoluminescent materials (CaSO₄:Dy, TLD-100 and TLD-100H).

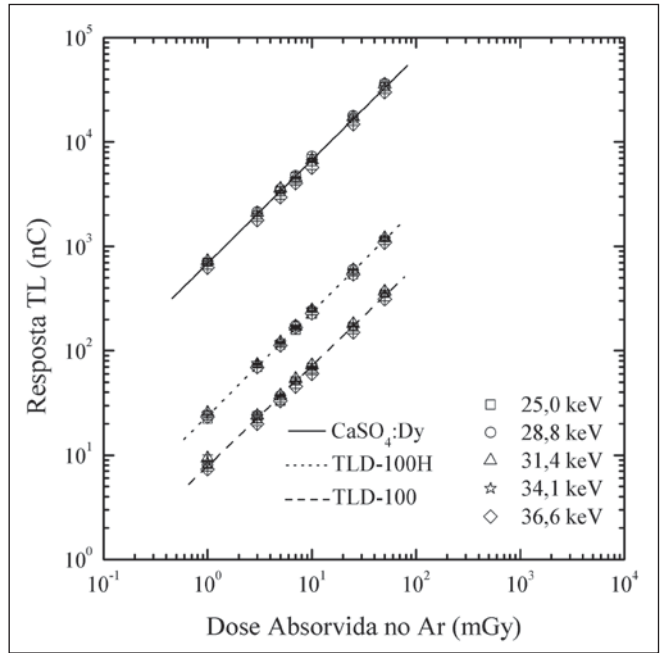


Figure 2. Thermoluminescent response as a function of absorbed dose in air for different X-radiation energies for the three thermoluminescent materials (CaSO₄:Dy, TLD-100 and TLD-100H).

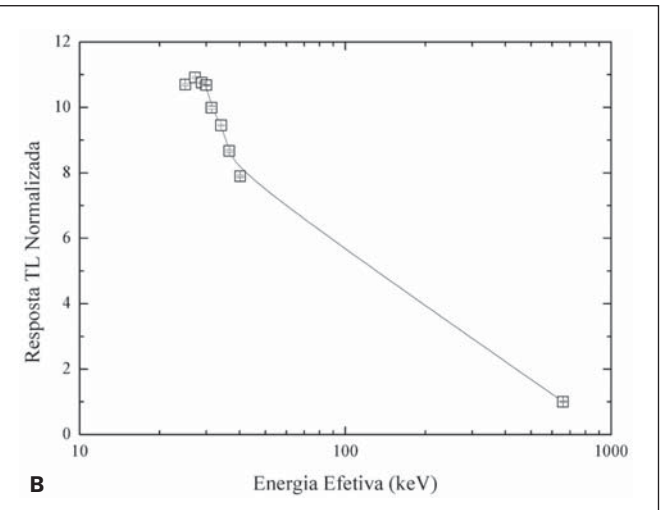
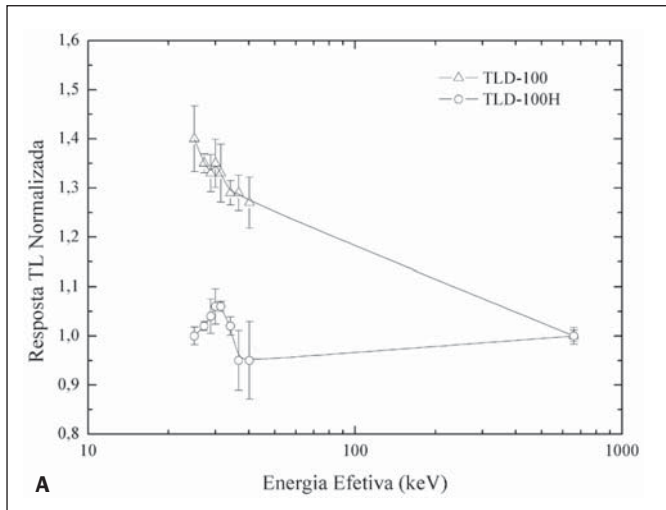


Figure 3. Energy dependence for: (A) LiF:Mg,Ti and LiF:Mg,Cu,P samples; and (B) CaSO₄:Dy pellets. In this figure, the thermoluminescent response is normalized for the energy corresponding to ^{137}Cs .

Thus the combined uncertainty ($k = 1$) is in the order of 19%.

DISCUSSION

The excellent calibration curves linearity (evaluated by the linear coefficients of the adjustment applied to the experimental points) shows the applicability of the tested materials for dosimetry of X-radiation in the considered air kerma interval. It is im-

portant to note that, in terms of magnitude, such interval corresponds to the values of reference dose for typical adult patients in conventional radiodiagnostic, mammography and dental radiology studies, according to the Order (Portaria) 453 of the Brazilian Ministry of Health, published in 1998, which is up to 10 mGy for the most common studies⁽¹³⁾. However, according to the literature, ESD values between 0.01 and 100 mGy⁽⁷⁾ may be found.

With respect to the TLDs energy dependence (Figure 3), LiF:Mg,Cu,P (TLD-100H) was the material that presented the lowest response variation in the considered energy interval (less than 10% as compared with the response with ^{137}Cs energy). However, the LiF:Mg,Ti (TLD-100) and CaSO₄:Dy samples presented a more significant variation; for such materials, the normalized thermoluminescent responses as compared with the response for to ^{37}Cs energy were

Table 3 ESD for general radiology, mammography and dental radiology studies on phantoms. In this table, the mean values and corresponding standard deviations are shown.

Thermoluminescent material	Study	ESD (mGy)		
		Method 1	Method 2	Method 3
LiF:Mg,Ti	Thorax AP	0.325 ± 0.011	0.305 ± 0.010	0.229 ± 0.012
	Abdome AP	2.178 ± 0.086	2.043 ± 0.074	1.584 ± 0.060
	Skull AP	1.31 ± 0.10	1.228 ± 0.095	0.952 ± 0.074
	Breast	1.22 ± 0.22	1.14 ± 0.21	0.82 ± 0.15
	Periapical 1	6.08 ± 0.22	5.71 ± 0.19	4.08 ± 0.23
	Periapical 2	5.80 ± 0.17	5.44 ± 0.14	3.89 ± 0.20
LiF:Mg,Cu,P	Thorax AP	0.315 ± 0.037	0.323 ± 0.038	0.304 ± 0.036
	Abdome AP	1.638 ± 0.040	1.677 ± 0.033	1.645 ± 0.040
	Skull AP	0.904 ± 0.037	0.926 ± 0.036	0.908 ± 0.037
	Breast	0.733 ± 0.030	0.751 ± 0.028	0.743 ± 0.027
	Periapical 1	4.02 ± 0.22	4.12 ± 0.22	4.12 ± 0.22
	Periapical 2	4.06 ± 0.10	4.153 ± 0.086	4.16 ± 0.10
CaSO ₄ :Dy	Thorax AP	2.598 ± 0.066	2.477 ± 0.057	0.248 ± 0.034
	Abdome AP	17.22 ± 0.65	16.42 ± 0.59	1.738 ± 0.053
	Skull AP	9.17 ± 0.30	8.75 ± 0.26	0.926 ± 0.022
	Breast	7.27 ± 0.25	6.93 ± 0.23	0.635 ± 0.017
	Periapical 1	47.8 ± 2.5	45.6 ± 2.3	4.26 ± 0.20
	Periapical 2	47.2 ± 1.4	45.0 ± 1.3	4.20 ± 0.10

ESD, entrance skin dose; AP, anteroposterior.

1.4 and 10.9 for TLD-100 and CaSO₄:Dy, respectively. These results are in agreement with those reported in the literature^(7,14-16).

According to Ministry of Health Order (Portaria) 453⁽¹³⁾, the minimum HVL values as a function of peak voltage (kVp) applied to the X-ray tube for general radiology equipment should range between 2.1 and 3.5 mmAl for single phase equipment, and 2.3 and 4.9 mmAl for three-phase equipment. For mammography equipment, the HVL value must be between kVp/100 and kVp/100 + 0.1 mm aluminum equivalent; and in the case of dental radiology equipment the minimum HVL must range from 1.2 to 2.5 mmAl, as a function of kVp. Such HVL values are in agreement with the HVL values of the X-radiation beams (Table 1) in which the thermoluminescent materials were characterized. This means that in the commonly utilized energies in clinical radiodiagnostic beams, because of its effective atomic number, a material may present greater or smaller response as demonstrated on Figure 3.

Table 3 shows the ESD values for radiographic studies utilizing the three thermoluminescent studied materials calculated by means of equation (1). In the case of the

CaSO₄:Dy pellets and LiF:Mg,Ti (TLD-100) samples, there is a huge discrepancy between the ESD values determined from the calibration curves for the ⁶⁰Co or ¹³⁷Cs energy as compared with the ESD values obtained by knowing the effective beam energy and the behavior of such materials in the energy interval of interest. Only for the LiF:Mg,Cu,P (TLD-100H) samples, the differences between the ESD values determined from any of the calibration curves revealed to be in the same magnitude of uncertainties associated with the measurement. In this case, it is important to note that, although LiF:Mg,Ti and LiF:Mg,Cu,P have the same effective atomic number ($Z_{ef} = 8.2$), LiF:Mg,Cu,P presents an anomalous response to radiation, according to Olko et al.⁽¹⁷⁾, which explains the smaller variation in the thermoluminescent response in the studied energy interval.

CONCLUSIONS

The present results demonstrate the need of knowing the effective beam energy and the behavior of the thermoluminescent materials utilized for the correct determination of the desired quantity.

Of the three tested materials, only LiF:Mg,Cu,P did not present a significant response variation (which was in the same magnitude as the uncertainties) as a function of the effective X-radiation beam energy. On the other hand, CaSO₄:Dy and LiF:Mg,Ti presented significant variations in response to X-radiation beams as compared with the responses obtained in the ¹³⁷Cs or ⁶⁰Co energies. This, however, does not impair the use of such materials. Besides being produced in Brazil, CaSO₄:Dy, is very sensitive, being particularly useful for low dose measurements. On the other hand, LiF:Mg,Ti has an effective atomic number which is very close to that of human tissue, and for this reason it does not cause artifacts on radiographic images, therefore being very useful in measurements directly performed by placing the TLD on the patient's skin.

The three studied thermoluminescent materials can be utilized for patients dosimetry in clinical beams. However, for the correct determination of ESD in patients submitted to radiographic studies (general radiology, mammography or dental radiology), the dosimeters must be previously calibrated for the energies corresponding to those utilized in the clinical practice.

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