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# GEANT4 simulation of the angular dependence of TLD-based monitor response

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## Abstract

In this work, the response of thermoluminescent (TL) monitors to X-ray beams impinging on them at different angles was investigated and compared with results of simulations performed with the GEANT4 radiation transport toolkit. Each monitor used contains four TL detectors (TLD): two $CaF_2$ pellets and two TLD-100 (one of each type within lead filter and the other without filter). Monitors were irradiated free-in-air with X-ray beams of the narrow and wide spectrum with effective energy of 61 and 130 keV and angles of incidence of 0°, 30°, 45°, and 60°. Curves of TL response relative to air kerma as a function of photon effective energy for each detector, with and without filter, are used to correct the energetic dependence of TL response. Such curves were also obtained from the data of radiation energy stored in the TLDs provided by the simulations. The attenuation increases with the increase of the incidence angle, since the thickness of lead filter traversed by the beam also enlarges. As the monitor calibration is usually performed with the beams impinging the monitor at 0°, changes in the attenuation become a source of error in the energy determination and consequently in the value of dose equivalent obtained with this monitor. The changes in attenuation observed in experiments were corroborated by the Monte Carlo simulations.

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*Keywords:* Thermoluminescence; Monte Carlo method; GEANT4

## 1. Introduction

Individual monitoring is an important safety practice in case of exposure to ionizing radiation. Thermoluminescent (TL) dosimetry is the technique used by the Dosimetry Laboratory of Physics Institute of São Paulo University to monitor workers occupationally exposed to radiation. The badge of TL monitor, made of black plastic with $0.587\,kg\,m^{-2}$ thickness, contains two TLD-100 and two natural $CaF_2$:NaCl detectors, hereinafter referred as $CaF_2$, being one detector of each type within 0.5 mm Pb filter, named (Pb) and in the case of no filter (open). Inside the badge there is also a card of $0.184\,kg\,m^{-2}$ thickness for the user identification.

TLD-100 and $CaF_2$ detectors are heat treated before use at 400 °C/1 h followed by 100 °C/2 h and 400 °C/20 min, respectively. A TL reader based on a photon counting system is used to measure the glow curves. Some of TL characteristics of these detectors have been already presented [1]. Calibration curves are obtained by irradiating monitors free-in-air with gamma rays of $^{60}$Co. The detectors, placed inside the badges, are covered with Pb filter which works as the build up.

The value of air kerma free-in-air is obtained by multiplying the dosimetric peak height of each detector by the respective calibration factor. As the response of both TL detectors (TLD) depends on the energy of the photon, correction must be performed. For this, the curves of TL/air kerma as a function of photon energy from 25 to 1250 keV, experimentally obtained and normalized to the response of detector placed between Pb filter and exposed to $^{60}$Co gamma rays, are used. The energy of radiation

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incident on the monitor is determined from the values of the air kerma of the detector without filter (open) and with filter (Pb). Then, the personal dose equivalent can be evaluated by applying the conversion coefficients from air kerma free-in-air to personal dose equivalent [2]. The performance of these monitors is good for the assessment of dose equivalent in case of workers occupationally exposed to the field of radiation with different energy spectra and normal incidence on the monitor [3].

However, as the angle of incidence of the radiation on the monitor increases, the dose equivalent evaluated with the set of four detectors decreases. This occurs because when the angle of incidence of radiation on the monitor is 60°, for example, the thickness of Pb filter becomes 1 mm, and the attenuation increases, mostly of low-energy X-rays.

The users of radiation monitors are daily exposed to radiation of broad energy spectra and with different angles of incidence. Taking these facts into account, in this work, the X-ray beam qualities were chosen to reproduce, as well as possible, the radiation fields to which the workers are daily exposed. The experimental results were compared with that of Monte Carlo simulations implemented with the GEANT4 radiation transport toolkit [4].

## 2. Monte Carlo method

GEANT4 is a freely distributed package of C++ classes, used to simulate the passage of particles through matter. In this work, the interactions considered were Rayleigh scattering, Compton scattering, photoelectric effect, ionization, and bremsstrahlung using the low-energy electromagnetic extension of the GEANT4 toolkit.

The simulation of the experimental measurements was carried out in three steps: the X-ray generation by the tube, the filtering of the X-ray beam, and the detection of X-ray. The simulation of the X-ray generation comprises an electron gun, a target, and a filter placed in a vacuum chamber. The beryllium window with 2.2 mm thickness and the angle of the electron beam with the anode of 22°, which are characteristics of the X-ray tube employed in the experiments, were used in the Monte Carlo simulation. The spectrum of photons obtained in the first step is used as input for the second step, which is performed by simulating the passage of the beam through the additional filters. More details about these procedures are found in the literature [5]. The simulation of the X-ray detection is performed irradiating the TLD monitors with the beam produced in the second step. The monitors are placed inside a chamber filled with air, with their faces aligned at the desired angle. All dimensions, materials, and irradiation conditions correspond to the ones used in the experimental setup described in the next section. In each step, GEANT4 gives values of kerma: the sum of initial kinetic energies of all the charged ionizing particles liberated by photons in a volume element of unit mass.

## 3. Experiment

The X-ray beam was produced by a Philips MG 450 tube and the monitors with four TLD detectors were exposed free-in-air at a distance of 218 cm from the focal point. Two X-ray beam qualities were used: N-80, corresponding to the narrow spectrum series [6] with effective energy of 61 keV, and the other with wide spectrum with effective energy of 130 keV (250 kVp, thoraeus filtration: 8 mm Sn + 0.25 mm Cu + 1.0 mm Al). The monitors were exposed to X-ray beams with angle of incidence on the monitor of 0°, 30°, 45°, and 60°. The readout of TLD detectors by thermal stimulation releases the energy stored in metastable states, which is proportional to the absorbed dose. This is equal to kerma in the range of X-ray energy considered here. The experimental results are compared with that of simulated with GEANT4.

## 4. Results

In the results presented in Figs. 1–3, all the TL responses were corrected by using the energy dependence factor [3],

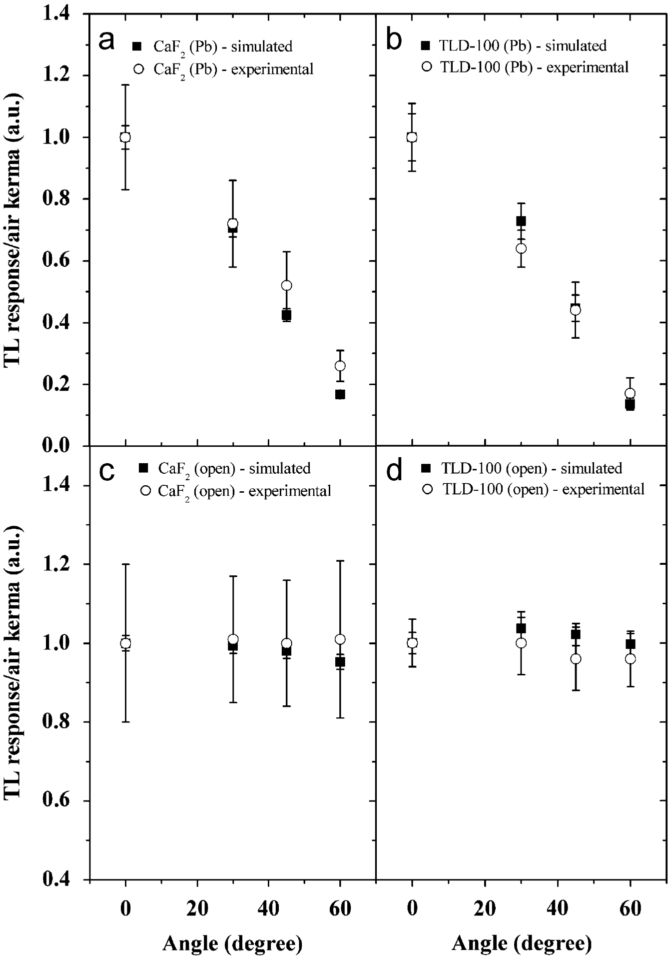

Fig. 1. Angular dependence of experimental and simulated values of TL response/air kerma of the monitors $CaF_2$ and TLD-100, with Pb filter and without filter, for several angles of incidence, normalized to 0°. X-ray beam was N-80 [6].

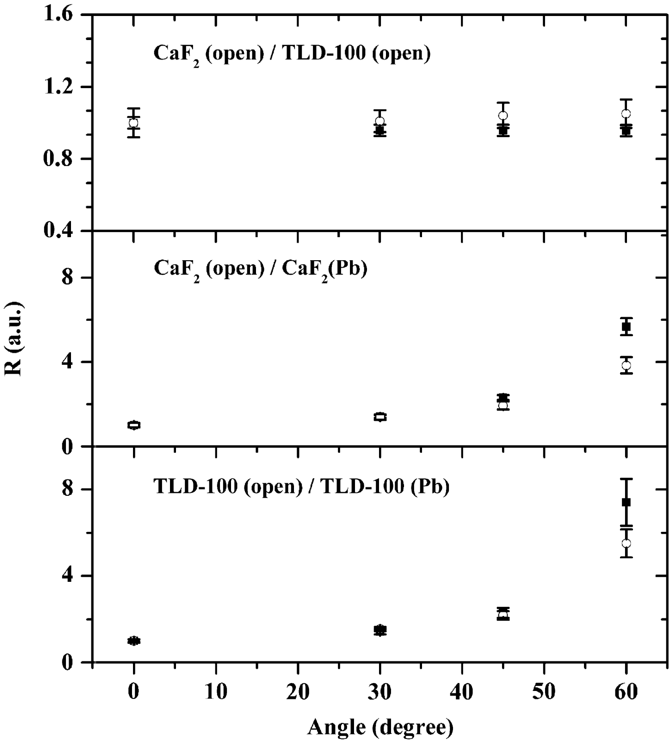

Fig. 2. Experimental (○) and simulated (■) ratio $R$ of $CaF_2$(open)/TLD-100(open), $CaF_2$(open)/$CaF_2$(Pb), and TLD-100(open)/TLD-100(Pb) for several angles of incidence, normalized to 0°, irradiated with X-ray beam of 61 keV effective energy (N-80).

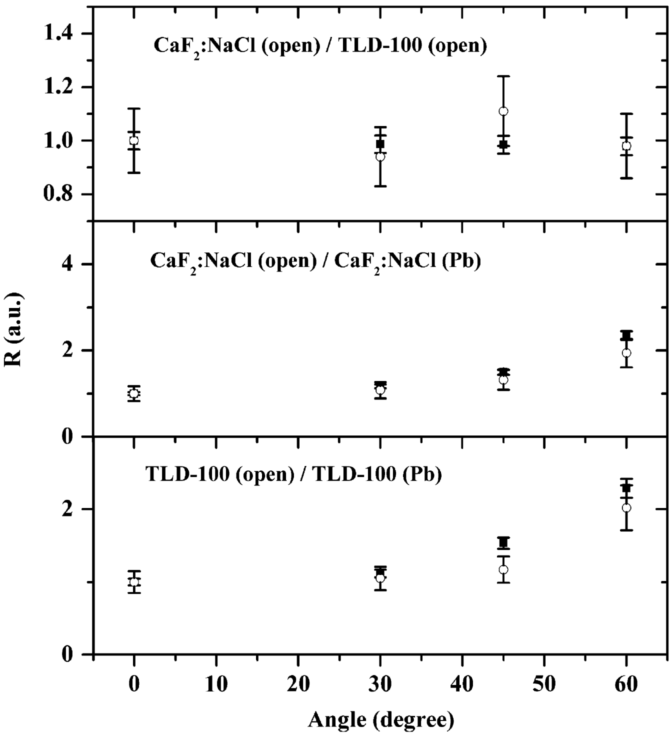

Fig. 3. Experimental (○) and simulated (■) ratio $R$ of $CaF_2$(open)/TLD-100(open), $CaF_2$(open)/$CaF_2$(Pb), and TLD-100(open)/TLD-100(Pb) for several angles of incidence, normalized to 0°, irradiated with X-ray beam of 130 keV effective energy.

and divided by the value of air kerma free-in-air. They are indicated as $CaF_2$ (Pb) or $CaF_2$ (open) when the fluorite detector is placed within Pb or without filter and as TLD-100 (Pb) or TLD-100 (open), similarly.

Fig. 1 shows the experimental (empty circles) and simulated (filled squares) values of TL response/air kerma of the detectors $CaF_2$ and TLD-100 with Pb filter (a and b) and without filter (c and d) for several angles of incidence, normalized to the value measured at 0°. The X-ray beam used was N-80 [6]. Each experimental point on the graphs is the average value of three measurements and the error bars correspond to the uncertainties, which were calculated by propagating the standard deviations of the mean value. The error bars of the simulated data correspond to statistical deviations only. Similar behavior was obtained for X-ray beams of 130 keV effective energy.

From Fig. 1, one observes that the effect of Pb filter in the attenuation of the beam on both TLDs reaches 80% for incidence angle of 60° in relation to 0°. Assuming that for this angle the effective thickness of the Pb filter is twice as for 0°, the expected value for attenuation is around 50%. This assumption should be valid for monochromatic beam and thin filter, where each photon suffers only one interaction. The larger attenuation observed in the experiment indicates that this hypothesis is inadequate in this case. The reasonable agreement between the simulated and experimental results shows that the Monte Carlo calculation inherently takes into account the effects which are relevant to describe the irradiation of dosimeters with beams of narrow and broad spectra at different angles of incidence. Figs. 2 and 3 show the experimental and the Monte Carlo simulated results of ratio $R$ for the detectors combination as indicated in the caption of figures.

As expected, experimental and simulated values of the ratio $R$ for detectors of different types without filter are around 1.0, for all angles of incidence. For the detectors of the same type with and without filter, the ratio $R$ increases for large angles; this increase is less pronounced for X-rays of higher energies. The increase from 0° to 60° in the value of $R$ is due to the decrease in the TL response of the detector within lead filter, which is in the denominator of $R$. The experimental and simulated results agree within the statistical errors in most of the cases. The discrepancies, observed mainly at large angles of incidence, are probably originated in the thickness of the Pb filter, which is considered uniform in the simulation, although this does not correspond to the experimental situation, since it is malleable and can be slightly deformed after many uses.

## 5. Conclusion

The experimental results show that the response of the detectors with filter is strongly dependent on the angle of incidence of the radiation. It was observed that the detected attenuation cannot be described by considering only the variation in the distance that the radiation cross through the filter. The overall agreement between the experimental and simulated results shows that the Monte Carlo method employed in this study is adequate to describe the response of the detectors for different conditions of irradiation.

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