Reduction of uncertainties in radiotherapy assessed by Monte Carlo simulation: spectral analysis applied to absorbed dose correction*

Redução de incertezas em radioterapia utilizando simulação Monte Carlo: análise espectral aplicada à correção de dose absorvida

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Abstract **OBJECTIVE: To calculate spectra of cobalt-60 beam at water depth and correction factors for absorbed dose measurements obtained with lithium fluoride thermoluminescent dosimeters using Monte Carlo simulation. MATERIALS AND METHODS: The simulations of secondary spectra of clinical cobalt-60 sources were performed with the PENELOPE Monte Carlo code at different water depths. Experimental measurements of deep doses were obtained with thermoluminescent dosimeters and ionization chamber under reference conditions for radiotherapy. Correction factors for the thermoluminescent dosimeters detectors were obtained through the ratio between the relative energy absorption for the low energy spectrum and the total spectrum. RESULTS: Deep spectral analysis has demonstrated the presence of secondary low-energy spectra responsible for a significant portion of the dose deposition. Discrepancies of 3.2% were observed among the doses measured with ionization chamber and thermoluminescent dosimeters. The adoption of correction factors has allowed a reduction in the discrepancy among absorbed doses to a maximum of 0.3%. CONCLUSION: Simulated spectra allow the calculation of correction factors for reading of thermoluminescent dosimeters utilized in the measurement of deep doses, contributing for the reduction of uncertainties associated with quality control of clinical beams in radiotherapy.**

Keywords: Monte Carlo simulation; Radiotherapy; Spectrometry; Quality control; Thermoluminescent dosimetry; TLD.

Resumo **OBJETIVO: Determinar, por simulação Monte Carlo, os espectros de feixes de cobaltoterapia em profundidade na água e fatores de correção para doses absorvidas em dosímetros termoluminescentes de fluoreto de lítio. MATERIAIS E MÉTODOS: As simulações dos espectros secundários da fonte clínica de cobalto-60 foram realizadas com o código Monte Carlo PENELOPE, em diversas profundidades na água. Medidas experimentais de dose profunda foram obtidas com dosímetros termoluminescentes e câmara de ionização em condições de referência em radioterapia. Os fatores de correção para os dosímetros termoluminescentes foram obtidos através da razão entre as absorções relativas ao espectro de baixa energia e ao espectro total. RESULTADOS: A análise espectral em profundidade revelou a existência de espectros secundários de baixa energia responsáveis por uma parcela significativa da deposição de dose. Foram observadas discrepâncias de 3,2% nas doses medidas experimentalmente com a câmara de ionização e com os dosímetros termoluminescentes. O uso dos fatores de correção nessas medidas permitiu diminuir a discrepância entre as doses absorvidas para, no máximo, 0,3%. CONCLUSÃO: Os espectros simulados permitem o cálculo de fatores de correção para as leituras de dosímetros termoluminescentes utilizados em medidas de dose profunda, contribuindo para a redução das incertezas associadas ao controle de qualidade de feixes clínicos em radioterapia.**

Unitermos: Simulação Monte Carlo; Radioterapia; Controle de qualidade; Espectrometria; Dosimetria termoluminescente; TLD.

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INTRODUCTION

Quality assurance in radiotherapy must associate high accuracy in the planning and prescribed doses with reproducibility of the planned technique, detailed documentation and a careful dosimetry of both the planned situation and treatment[1–3]. Characteristics such as absorbed dose homogeneity and accuracy are absolutely relevant for the success of clinical treatments in cobalt therapy units, particularly in whole body irradiations, which are normally combined

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with intensive chemotherapy and bone marrow transplantation. Small errors in the determination of depth doses may compromise vital organs, for example, the lungs[4,5].

The determination of uncertainties associated with radiotherapy is absolutely relevant for the assurance of efficiency of clinical treatments. A considerable fraction of such uncertainty resides in intrinsic characteristics of the methods and instrumental apparatuses utilized in the determination of dosimetric parameters, which are directly applied in the calculation for prescription of absorbed dose. In order to minimize the uncertainty associated with dosimetric parameters, it is possible to utilize the Monte Carlo simulation of ionizing radiation interaction with matter in order to identify, quantify and correct inaccuracies from the dosimeters utilized in radiotherapy quality control.

Thermoluminescent dosimeters (TLDs) are among the dosimeters most frequently utilized in radiotherapy, with characteristics of effective atomic number ($Z_{effective}$ = 8.2) close to that of water, high spatial detector resolution (0.9 mm) and low cost associated with their use[6–8]. TLDs with lithium fluoride (LiF) present energetic dependence for photons with energies < 662 keV[9], which implies the necessity to correct readings performed with such dosimeters as they are exposed to low energy radiation. In measurements of depth absorbed dose[10], for example, those applied in quality control of whole body irradiation[8], the spectrum of therapy beams at depths of clinical interest is composed by high energy fractions, to which LiF presents a linear response, and also by low energy fractions, in which there is energetic dependence[9].

The simulation of clinical treatments based on the Monte Carlo method has been widely utilized in radiotherapy mainly due to the accuracy associated with its use[11]. The Monte Carlo PENELOPE simulation code is a well established and efficient tool for spectrometry and clinical beam dosimetry, allowing the faithful geometrical representation of several types of radiotherapy apparatuses[12]. The PENELOPE code uses material cross section libraries based on international standards[13], thus assuring a faithful representation of characteristics interaction between materials of dosimetric interest.

The present study presents the energy spectra of a cobalt-60 (Co-60) clinical beam simulated in water depth, using the Monte Carlo PENELOPE simulation code. By means of quantitative analysis of dose contribution of primary and secondary components of such beam, it is possible to calculate correction factors for LiF-100 TLDs readings at several water depths. The contribution of the use of correction factors in absorbed doses in TLDs can be attained by comparison between the depth dose rate (DDR) curves built with experimental data collected with an ionization chamber and with TLDs, whose responses were corrected by these factors.

MATERIALS AND METHODS

Monte Carlo simulation

The computer simulations of ionizing radiations interaction with matter were performed by using the Monte Carlo PENELOPE simulation package, which comprises the PENELOPE particles transport code and the geometry package PENGEOM. In these simulations, the source was positioned at 80 cm from the phantom, with an aperture of 3.57°, which provided a radiation field of 10 × 10 cm^2 on the surface of the phantom. The primary photon spectrum is composed by two peaks of equal occurrence probability, with 1.17 MeV and 1.33 MeV[12] energies, respectively. The phantom was a homogeneous water cube with a 30 cm edge.

The photon spectra at depths were obtained by means of virtual impact detectors: virtually drawn pellets, simulating the TLDs experimental geometry at depth inside the phantom, with 150 energy channels uniformly distributed between 10 KeV and 1.33 MeV. The impact detectors have the function of counting the photons that reach the depth in which the detector is positioned, separating into channels and storing their respective energies[13]. So, the response generated at the end of each simulation, comprises the probability density function associated with the photon occurrence, separated by energy, at each depth. Based on the data in the response files, the total and low energy spectra were built at several depths of the phantom. Also, a simulated DDR curve in the central axis of the phantom was obtained, for determining the PENELOPE code accuracy in this type of simulation, by means of comparison with experimental data of depth dose.

Experimental data

The DDRs were experimentally obtained with a Farmer type 0.6 cm^3 cylindrical ionization chamber with LiF-100 TLDs, both positioned at depth, within a cubic, homogeneous water phantom, with an edge of 50 cm, analogous to that in the computer simulation. The field projected on the surface of the phantom was 10 × 10 cm^2, and was at a source-surface distance (SSD) of 80 cm.

The phantom was irradiated in a Siemens Gammatron II S-80 cobalt therapy system, at the Radiotherapy Unit of Hospital das Clínicas da Faculdade de Medicina de Ribeirão Preto da Universidade de São Paulo. The TLDs were treated and read at the Center of Instrumentation, Dosimetry and Radioprotection of Universidade de São Paulo (Cidra-USP).

Determination of correction factors by energetic dependence

For each depth, the summatories of spectrum energies multiplied by the ratio between the respective LiF and water mass absorption coefficients (μ_{en}/ρ)[14] were calculated in two parts: one with energies in the 10 keV to 670 keV interval and another comprising all the energies in the spectrum, i.e., from 10 keV to 1.33 MeV. The calculation of the correction factors was made as presented in equation 1.

In the equation 1 $(\mu_{en}(E_i)/\rho)$ corresponds to the ratio between the LiF and water mass absorption coefficients (μ_{en}/ρ) for an energy E_i; $P(E_i)$ is the probability density of the occurrence of particles with energy E_i at the x depth, relative to the total spectrum; $P_{sec}(E_i)$ is the probability density of occurrence of particles with energy E_i, renormalized for the secondary spectrum at the x depth; FC_x is the correction factor for the TLD reading calibrated in dose at the x depth of the phantom.

$$FC_x = \frac{\sum_{i=10\,keV}^{i=670\,keV} P_{sec}(E_i)\,.\,E_i\,.\left(\frac{\mu_{en}(E_i)}{\rho}\right)_{água}^{LiF}}{\sum_{i=10\,keV}^{i=1,33\,MeV} P\,(E_i)\,.\,E_i\,.\left(\frac{\mu_{en}(E_i)}{\rho}\right)_{água}^{LiF}}$$

Equation 1. LiF-100 reading correction factors by contribution in dose of the secondary spectrum of a Co-60 clinical beam in water depth.

RESULTS

Spectra were obtained at 24 different depths in the phantom, at 2 mm intervals in the first centimeter to observe the behavior at the build-up region, and at every 1 cm in depth after the build-up region, scanning the whole phantom extent. The total spectrum simulated at a depth of 0.5 cm shown on Figure 1, presents a low energy spectral component with a peak at 220 keV (2.5%) with a total expression rate of 5.5%.

The secondary spectra simulated for the depths of 5.5 cm, 10.5 cm 20.5 cm and 25.5 cm along the phantom central axis are presented on Figure 2. The relative intensities of the simulated spectra reach a maximum at the 5.5 cm depth, where the low energy spectra peak represents 7% of the total spectrum. After this depth, the contribution of the energy peak, centered at 220 keV, goes to 5% at 10.5 cm, decreasing to 1.4% and 1.2% at 20.5 cm and 25.5 cm respectively. However, the contribution in dose deposition increases, as the relative expression of energies > 220 keV grows.

In order to obtain the FC_x, the depths at which there were DDR data with both dosimeters (TLD and ionization chamber), were considered. Figure 3A graphically presents the DDR values measured by the TLDs, with and without response correction, together with the DDR measurements performed with the ionization chamber and the DDR curve calculated by means of integration of simulated energy spectra with the PENELOPE code. The percentage differences between the absorbed dose readings with the TLDs, with and without the application of the FC_x, and measurements with the ionization chamber are presented on Figure 3B.

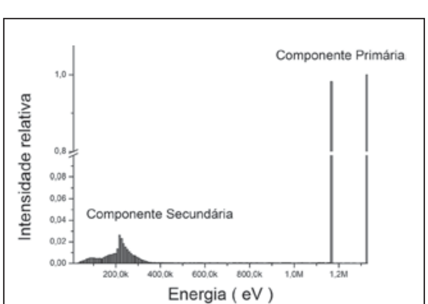

Figure 1. Total energy spectrum at the depth of maximum dose of Co-60 in water.

The chart presented on Figure 3A demonstrates the PENELOPE code as appropriate and accurate for simulating spectra in water depth, co-validating the spectral analysis presented in the present study. Based on the analysis of Figure 3, it is possible to observe how much the readings with TLDs become less accurate at greater depths, because of the presence of low energy radiation, which confirms the need to apply the FC_x. On Figure 3B, it is clear that the FC_x approach the measurements performed with the TLDs to those performed with the ionization chamber, reducing discrepancies from up to 3.3% to a maximum of 0.38%. The numerical data of the FC_x can be observed on Table 1.

DISCUSSION

The clinical practice of radiotherapy with high quality indexes is primarily based on rigorous, periodic and reproducible reference dosimetry[14,15] as corroborated by

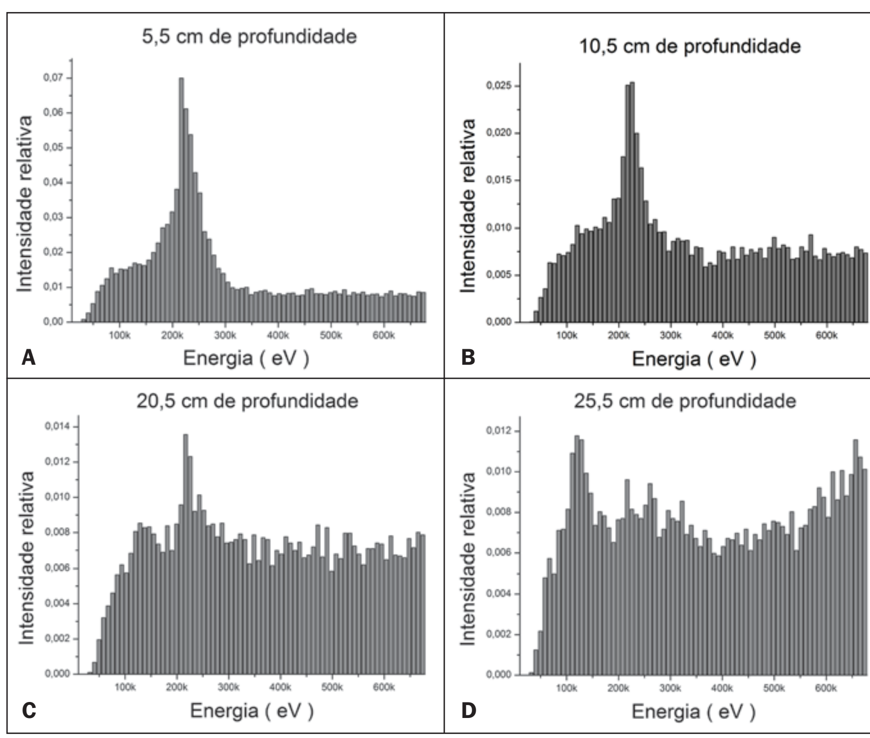

Figure 2. Energy spectra at water depths, obtained by the Monte Carlo simulation, for a Co-60 beam on a 10 × 10 cm square field on the phantom surface. **A:** Secondary spectrum of the Co-60 clinical beam at a depth of 5.5 cm in water: 220 keV peak with 7% representativeness. **B:** Secondary spectrum of the Co-60 clinical beam at a depth of 10.5 cm in water: 220 keV peak with 2.4% representativeness and 600 keV peak with 0.6% representativeness. **C:** Secondary spectrum of the Co-60 clinical beam at a depth of 20.5 cm in water: 220 keV peak with 1.3% representativeness and 600 keV peak with 0.8% representativeness. **D:** Secondary spectrum of the Co-60 clinical beam at a depth of 25.5 cm in water: 220 keV peak and 600 keV peak, both with 0.95% representativeness.

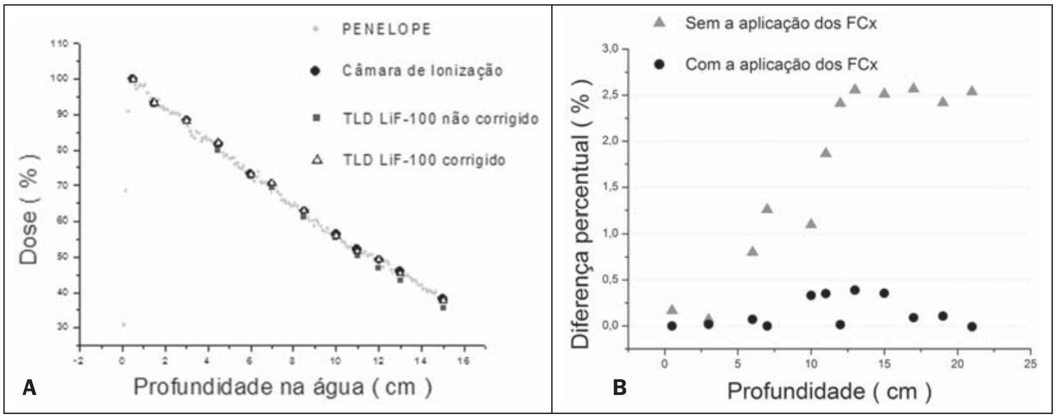

Figure 3. A: DDR curve in water for the Co-60 beam simulated with PENELOPE, obtained with ionization chamber and with LiF TLDs before and after the application of correction factors. **B:** Percentage differences between measurements by the ionization chamber and TLDs before and after the application of FC_x. The percentage difference interval is reduced from up to 2.6% to 0.3%..

Table 1 Comparison between the DDR values obtained with the TLDs corrected by response energetic dependence, and values measured with the ionization chamber.

Depth dose rate and correction factors for LiF-100						
X (cm)	IC*	TLD†	Δ%*,†	FC_x	$TLD_{corrected}$‡	Δ%*,‡
0.5	100.0	100.00	0.166	1.0017	100.00	0.001
3	88.4	88.33	0.069	1.0096	88.38	0.018
6	73.2	72.40	0.800	1.0101	73.13	0.073
7	70.6	69.34	1.257	1.0181	70.60	0.001
10	56.4	55.30	1.100	1.0199	56.07	0.332
11	52.0	50.17	1.864	1.0302	51.68	0.351
12	49.2	46.79	2.410	1.0412	49.19	0.014
13	45.8	43.24	2.557	1.0501	45.41	0.389
15	38.1	35.59	2.512	1.0606	37.74	0.356
17	32.5	29.93	2.568	1.0828	32.41	0.089
19	29.3	26.88	2.418	1.0860	29.19	0.107
21	27.0	24.46	2.536	1.1040	27.01	0.008

* IC, experimental measurements with ionization chamber; † TLD, experimental measurements with LiF-100 TLDs; Δ%, percentage difference; FC_x, correction factors calculated with PENELOPE; ‡ $TLD_{corrected}$, measurement of absorbed dose in the TLD corrected by the FC_x factors .

the utilization of TLDs as a complementary alternative to reference dosimetry, allowing more frequent quality control tests with relative simplicity, without excessive cost and interference in the clinical routine[16].

The reduction of uncertainties and errors associated with dosimetry in radiotherapy is the central theme of several scientific and clinical studies, all of them facing the challenge the fact that precision and accuracy are not easily found in a single dosimeter[17]. The use of Monte Carlo simulation, combined with experimental measurements with TLDs for directly determining dosimetric parameters is a precise and viable alternative to face the need of reducing uncertainty and errors in radiotherapy. With the correction factors presented in the present study, it is possible to utilize LiF TLDs for DDR measurements in water, with an error interval relative to the ionization chamber coherent with the indexes recommended by the reference literature on quality control of radiotherapy beams.

The spectral analysis based on total and secondary photon spectra at water depth, simulated with the PENELOPE code[18,19], allows the calculation of correction factors that can be applied in a relatively simple manner. Photons spectra in water depth allow to observe the presence of low energies at the maximum dose depth, distributed between 30 and 350 keV, region in which the LiF response has a non-linear behavior alternating between a relatively descending response at energies from 30 to 100 keV and mildly increasing at energies in the 100 to 300 keV interval, approximately.

In all simulated spectra up to 15.5 cm within the phantom, the low energy peak is kept at 220 keV and the expression of portions with energies from 30 to 300 keV is predominant, which does not happen at depths below the middle of the phantom, at which the probability of occurrence of low energy particles are equally distributed in a larger interval, from 30 to 670 keV.

As the depth increases, the total spectra present a higher number of lower energy particles, which dislocates the mean energy of the simulated beam reaching that depth to a lower value than the mean energy of the incident Co-60 beam, that would be 1.25 MeV, commonly considered for the calculation of absorbed energy at water depth.

It is possible to observe that the area of secondary spectra with energies between 10 keV and 670 keV remains approximately the same after the build-up depth, therefore dislocating the effective energy of the secondary spectrum which increases the dose in each detector. Such an increase is not duly observed in experimental measurements performed with LiF TLDs, as a function of their response energetic dependence in this energy range, which can be observed in the DDR curves obtained with these dosimeters (see Figure 3A).

In spite of the decrease in energy with depth be easily visualized from the observation of simulated spectra, a more precise study of absorbed dose at a given depth must consider the (μ_{en}/ρ) corresponding to each discrete set of particles with a given energy, that are, by their turn, differently absorbed by water and by the LiF, generating different deposited doses in each one of these mediums. It is exactly by observing the low energy portions and their significance at each depth that it is possible to relate the differences in absorption among the medium of interest, the water, and the dosimeter material, LiF, applying the FC_x determined in the present study.

When compared, the PDDR curves obtained with an ionization chamber and with TLDs presented a percentage difference that increases with depth, from 0.2% to 3.2%, and remaining approximately constant, at around 2.5% for depths > 10 cm. Also, when observing that the relative probability of the low energy particles increase with depth in the phantom (analysis on Figure 2), and considering that the total number of simulated particles in each interaction remains the same, it is easy to observe that the FC_x must increase with depth, as shown on Table 1.

CONCLUSION

The spectral analysis of a clinical Co-60 beam based on the Monte Carlo simulation allows the calculation of satisfactory correction factors for the absorbed dose readings in LiF TLDs. The application of the correction factors FC_x in TLD readings contributes for the increase in accuracy in the determination of dosimetric parameters, intimately associated with the quality control of clinical beams in radiotherapy.

The results of the present study may be extended for several clinical protocols, with the objective of making the use of TLDs more accurate and common.

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