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Thermoluminescent Dosimeters for Exposure Assessment in Gamma or x Radiation Fields with Unknown Spectral Distribution

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The determination of the effective energy of a radiation field using the energy dependence of the response ratio of two dosimeters with different energy dependences is called the "Tandem Method". Having in view the choice of the best pair of dosimeters to be used, the energy response characteristics of LiF:Mg, Ti; $CaSO_4$:Dy; CaF_2:Dy and CaF_2:Mn thermoluminescent (TL) dosimeters were studied. Two different physical forms of TL dosimeters were investigated: hot pressed chips and Teflon disc dosimeters. The calibration factors were obtained for the energy of ^{60}Co γ rays and their energy dependence, normalized to ^{60}Co γ-radiation, was determined using spectral width as a parameter. Tandem systems formed by all TL dosimeters evaluated were compared. It was concluded that the Tandem D–$CaSO_4$:Dy–0.4/LiF:Mg, Ti (TLD-100) determines the effective energy with a maximum uncertainty of only 10 keV and permits the assessment of the energy correction factor for the TLD-100 with a precision of better than 1.7% for the spectral distribution studied in the effective energy range from 30 to 100 keV.

1. Introduction

Every γ or x-radiation dosimeter presents a response which depends on the photon energy. Using such dosimeters for the assessment of exposure in a γ or x-radiation field, it is necessary to know the energies present in the radiation field in order to consider the response characteristics of the instruments as a function of their energy dependence.

The methods used to determine the energy spectrum of a radiation beam are not of practical application routinely. However, some parameters may be used to characterize the energy spectral distribution. This is the case in use of the "Half Value Layer" (HVL) concept. Using this parameter, the energy spectral distribution of a radiation beam is characterized by a unique energy value, namely, the "Effective Energy".

Using two dosimeters with different energy dependences, it is possible to determine the effective energy. This method, called the "Tandem Method", consists of using the energy dependence of the ratio between the values of the energy calibration curves of the dosimeter responses, to determine the effective energy of a radiation beam in order to make the correction of one Tandem dosimeter reading due to its energy dependence, possible.

The accuracy of this method depends not only on the inherent uncertainties of the Tandem dosimeters, but also on how pronounced are the energy dependences of their responses. The more different these dependences, the higher the ratio between them and, consequently, the higher the accuracy in the determination of the effective energy.

For the determination of effective energies below 100 keV, TL dosimeters may be used. The response of these dosimeters depends strongly on the radiation energy, mainly in the range considered here, and different TL phosphors may present very different energy dependences.

The Tandem method demands a detailed knowledge of the energy dependence of the TL dosimeter response. This energy dependence is determined using the effective energy concept obtained from the HVL. Radiation beams with different spectral distributions may present the same HVL value and, thus, the same effective energy. Therefore, in order to discriminate this influence, it is necessary to determine the energy dependence curves of the Tandem TL dosimeter responses for extreme cases; namely, for radiation beams with very wide and very narrow spectral distributions, but with the same effective energies. In

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practice, one can expect that radiation beams encountered will present spectral distributions with widths between these two extremes.

TL materials were firstly employed in the Tandem method in the beginning of the 1960's by Kenney and Cameron[1] who used Al_2O_3 and LiF:Mg,Ti TL phosphors. Since then several investigations using the method have been carried out, particularly by Puite and Crebolder[2] and Rossiter and Wood.[3] Puite and Crebolder[2] describe the dual-phosphor system CaF_2:Mn and LiF:Mg,Ti to be used in a water phantom for beam qualities above 1 mm Cu HVL. They discuss uncertainties in the determination of the radiation quality and the absorbed dose. Rossiter and Wood[3] investigated the possibility of evaluating the effective energy of a x- or γ ray field using a $CaSO_4$:Dy/LiF:Mg,Ti Tandem. They also investigated the dependence of the Tandem ratio on the thickness of the TL dosimeters.

In present work LiF:Mg, Ti; $CaSO_4$:Dy; CaF_2:Dy and CaF_2:Mn, TL dosimeters were investigated in order to determine the best pair to be used in the evaluation of the effective energy of an x- or γ ray field with unknown spectral distribution and, in the assessment of the exposure due to the same radiation field.

2. Experimental Procedures

The TL dosimeters investigated, their relevant characteristics and the annealing procedures used in their regeneration are presented in Table 1. The annealing procedures were carried out in two different ovens, namely, a Jade RP-1100 oven for thermal treatments at 100 C, and a Termolyne 1300 oven, for higher temperature treatments. The TL reader utilized to evaluate the response of the dosimeters was a Teledyne 7300 C.

The TL dosimeters were calibrated in terms of exposure. For this purpose, a ^{60}Co gamma source with an activity of 111 GBq was used. Each dosimeter was irradiated and evaluated 10 times, under identical conditions, in order to determine its individual calibration factor, f_c, and also the reproducibility (1σ) of its response.

The energy dependence of the responses of the TL dosimeters was determined for x-ray beams with effective energies between 33 and 214 keV, generated by a Siemens Stabilipan 250 x-ray machine. The x-ray spectra were characterized by their resolutions. The resolution of an x-ray spectrum is defined, in percent terms, as the ratio between the full width at half maximum and the energy where this maximum occurs. Spectra which presented resolution values below 40% were considered narrow. Those with a resolution above 50% were considered wide. Table 2 presents the characteristics of the spectra used in this work. They are the same spectra which appear in the works of da Rosa[4] and Estrada[5].

Each type of TL detector was submitted to the different qualities of x-radiation in groups of eight samples. The dosimeters received an exposure of 12.9×10^{-5} C kg^{-1}.

The energy dependence, $\gamma(E)$, of the TL response of each type of TL detector, for a certain x-radiation, effective energy E, is given by the mean of the response of the eight detectors. Each response was corrected by the respective calibration factor of the corresponding detector and normalized to the detector response for the energy of ^{60}Co. The uncertainty $\sigma[\gamma(E)]$ associated to $\gamma(E)$ was obtained with a confidence level of 95%.

For each type of TL detector two energy dependence curves were determined; namely, one curve for narrow spectra and one for wide spectra. These curves were obtained by fitting the experimental results with a combined Gaussian and a linear function, having as variable the logarithm of the effective energy E. This fitting took into consideration the uncertainties related to each experimental result. The function used was,

$$\gamma(E) = A \exp[-(\log E - B)^2/C] + D \log E + F \quad (1)$$

where A, B, C, D and F are the parameters to be determined in order to obtain the best fit of the experimental results.

The Tandem curves were obtained from the quotient between the values of the two energy dependent curves, namely, one curve for a detector with a high energy dependence and one for LiF:Mg,Ti. The uncertainties associated with the Tandem ratios were determined from the propagation of the uncertainties associated with the two factors of the quotient.

The precision in the determination of the effective energy using the Tandem curve σ_1, depends not only on the experimental uncertainties, but also on the slope of this curve. Once the effective energy is known, the energy dependence curve of the less

Table 1. Thermoluminescent dosimeters investigated for use in the Tandem method

TL material	Commercial name	Physical form	Dimensions	Manufacturer	Annealing procedures: Pretreatment	Annealing procedures: Post-treatment
LiF:Mg, Ti	TLD-100	Hot-pressed chip	$3 \times 3 \times 0.9$ mm^3	Harshaw Chemical Company	400 C/1 h + 100 C/2 h	100 C/15 min
CaF_2:Dy	TLD-200				400 C/1 h + 100 C/2 h	100 C/1 h
CaF_2:Mn	TLD-400				500 C/1 h	
$CaSO_4$:Dy	D $CaSO_4$:Dy 0.4	Teflon discs dosimeter	12 mm dia. $\times$ 0.4 mm	Teledyne Isotopes	300 C* 15 h + 300 C 3h	100 C 15 min

* This annealing procedure is used only in virgin dosimeters.

Table 2. Characteristics of the x-ray spectra

Spectrum	High voltage (kV)	Additional filtration* (mm) Pb	Al	Sn	Ca	First HVL (mm Cu)	Effective energy (keV)	Resolution (%)
Narrow	40				0.20	0.09	33	30
	60				0.60	0.24	47	36
	80				2.00	0.61	66	31
	100				5.00	1.12	84	28
	120			1.00	5.00	1.75	101	27
	150			2.50		2.46	122	36
	200	1.00		3.00	2.00	4.15	172	32
	250	3.00		2.00		5.34	214	30
Wide	70					0.10	34	67
	80				0.10	0.15	39	87
	100		0.97			0.30	50	90†
	120				0.20	0.45	59	95
	150				0.50	0.82	76	93
	200				1.20	1.82	100	81

* The additional filtration includes, in each case, the inherent filtration, 2.7 mm Al.
† The resolution can only be estimated since the spectrum presents characteristic x-ray lines.

energy dependent detector of the Tandem pair is used in order to evaluate the exposure. The exposure, X, is derived from,

$$X = L \cdot f_c \cdot \gamma(E)^{-1} \tag{2}$$

where L is the response of the less energy dependent detector and $\gamma(E)$ is its energy dependence for the effective energy value E determined from the Tandem curve. There are two kinds of uncertainties in the determination of $\gamma(E)$. One uncertainty is related to the determination of the effective energy associated with the slope of the energy dependence curve, σ_2, and the other is related to the experimental determination of the energy dependence curve, σ_3. The total uncertainty, σ_4, is therefore

$$\sigma_4 = (\sigma_2^2 + \sigma_3^2)^{1/2}. \tag{3}$$

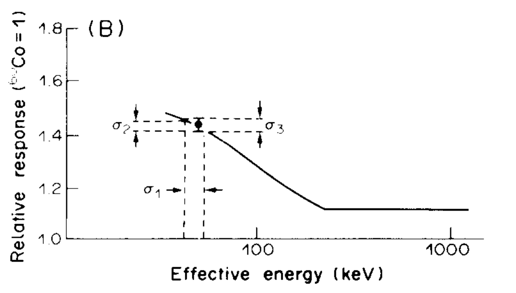

Fig. 1. Uncertainties in the determination of the effective energy and the energy correction factor [$\gamma(E)$]. Tandem curve (curve A). Energy dependence curve of the less energy dependent TL dosimeter (curve B).

Figures 1A and B show the above uncertainties. Considering these uncertainties, the choice of the best Tandem was carried out.

3. Results

Figure 2 presents the results of the reproducibility study of the TL dosimeter responses. It can be seen that 85% of the dosimeters of each type presented calibration factors with a reproducibility better than 1.5%.

Figures 3, 4, 5, and 6 show the energy dependence curves, both for wide and narrow spectra, respectively, for TLD-100, D–$CaSO_4$:Dy–0.4, TLD-200 and TLD-400. For each curve the values of the parameters A, B, C, D and F of formula (1) are presented.

Figures 7, 8 and 9 show respectively the Tandem curves $\gamma(E)$ D–$CaSO_4$:Dy–0.4/$\gamma(E)$ TLD-100, $\gamma(E)$ TLD-200/$\gamma(E)$ TLD-100 and $\gamma(E)$ TLD-400/$\gamma(E)$ TLD-100. For each case, curves for wide and narrow spectra are presented.

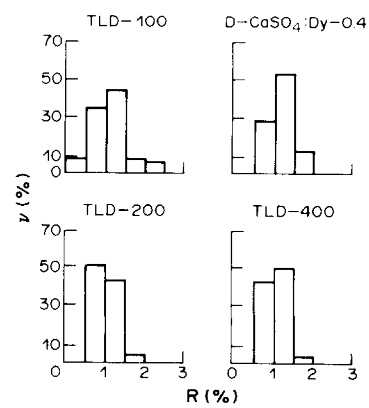

Fig. 2. Histograms relating the frequency of dosimeters (ν) with the individual reproducibility (R) for each group of TL dosimeters studied.

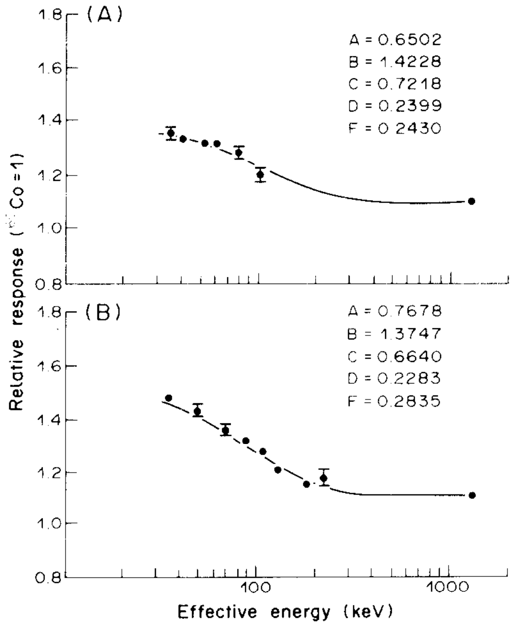

Fig. 3. Energy dependence curve for TLD-100. Wide spectrum (curve A). Narrow spectrum (curve B.)

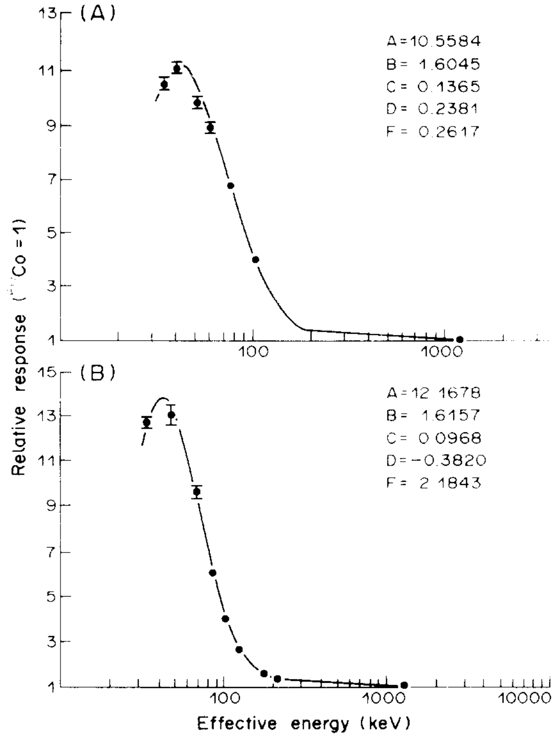

Fig. 5. Energy dependence curve for TLD-200. Wide spectrum (curve A). Narrow spectrum (curve B).

4. Discussion

Tandem D–CaSO$_4$:Dy–0.4/TLD-100

The uncertainties in the determination of the Tandem ratios obtained with D–CaSO$_4$:Dy–0.4 and TLD-100 TL dosimeters, using x-ray beams with wide spectral distribution (curve 7A) were less than $\pm 2\%$. Considering both these uncertainties and the fitting curve obtained for the experimental results, it is possible to determine the effective energy of an x- or γ ray beam, with a wide spectral distribution and

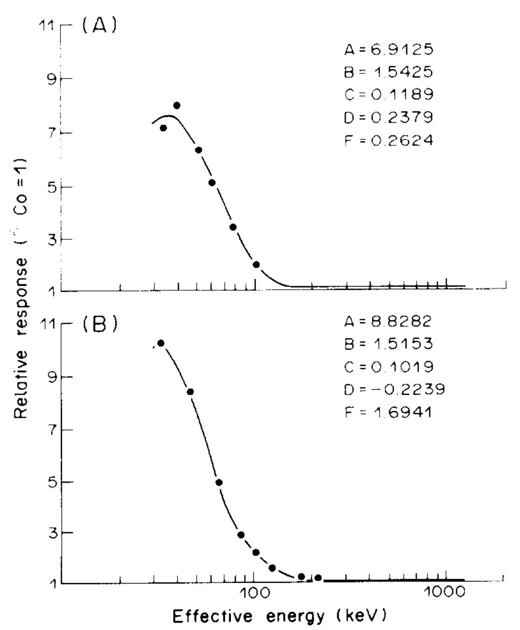

Fig. 4. Energy dependence curve for D–CaSO$_4$:Dy–0.4. Wide spectrum (curve A). Narrow spectrum (curve B).

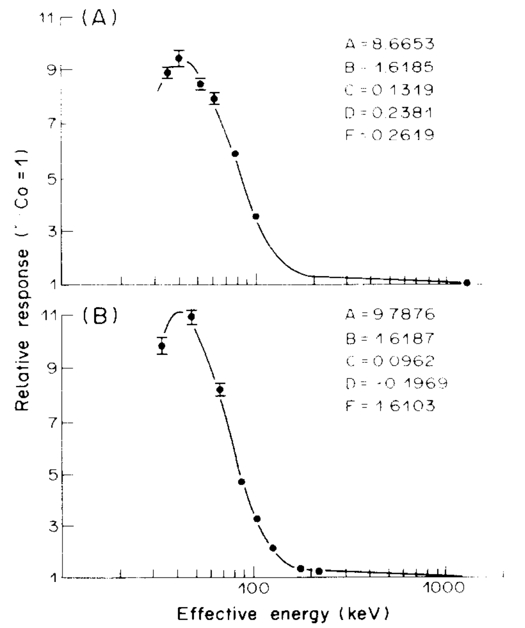

Fig. 6. Energy dependence curve for TLD-400. Wide spectrum (curve A). Narrow spectrum (curve B).

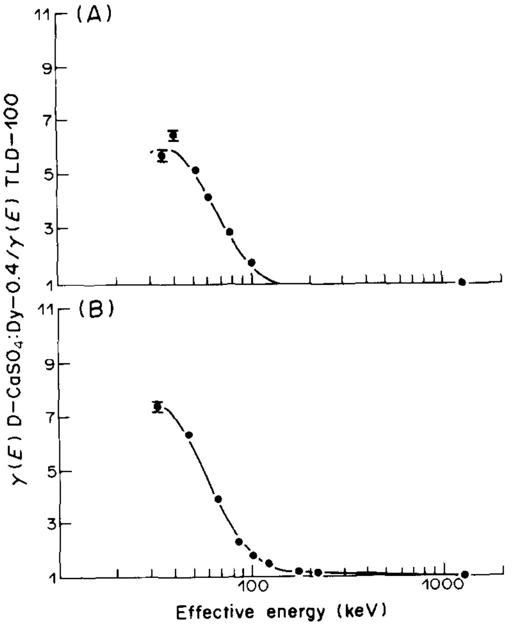

Fig. 7. Tandem curve D–CaSO$_4$:Dy–0.4/TLD-100. Wide spectrum (curve A). Narrow spectrum (curve B).

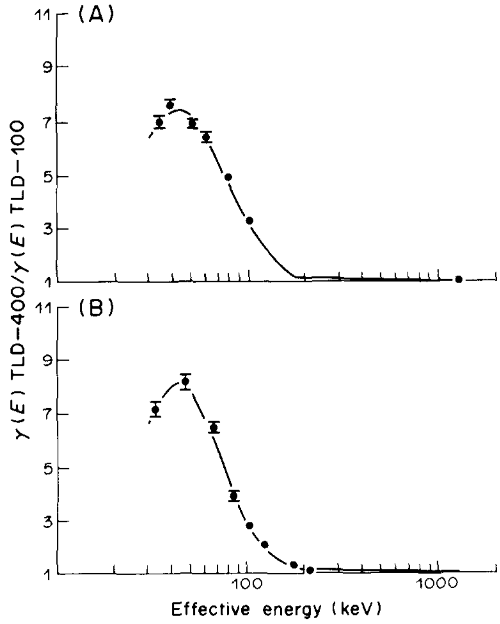

Fig. 9. Tandem curve TLD-400/TLD-100. Wide spectrum (curve A). Narrow spectrum (curve B).

an effective energy between 100 and 50 keV, with an uncertainty of about 1 keV. If the effective energy of the radiation beam has a value between 30 and 50 keV, the uncertainty in its determination is greater and may equal 10 keV. In this effective energy interval, the maximum of the Tandem curve is located and

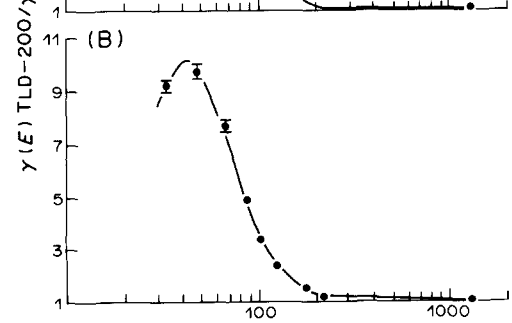

Fig. 8. Tandem curve TLD-200/TLD-100. Wide spectrum (curve A). Narrow spectrum (curve B).

this fact contributes to a higher uncertainty in the determination of the effective energy.

Using the energy dependence curve of TLD-100 obtained with wide x-ray spectra (curve 3A) and considering the uncertainties in its determination and in the determination of the effective energy with curve 7A, it is possible to establish the energy correction factor, $\gamma(E)$, with an uncertainty less than $\pm 1.7\%$ in the effective energy range 30–100 keV.

Uncertainties in the determination of the Tandem ratios obtained with D–CaSO$_4$:Dy–0.4 and TLD-100 TL dosimeters, using x ray beams with narrow spectral distribution (curve 7B) were also less than $\pm 2\%$. Considering both these uncertainties and the fitting curve obtained for the experimental results, it is possible to determine the effective energy of an x- or γ ray beam, with a narrow spectral distribution and an effective energy between 100 and 30 keV, with an uncertainty of less than 4 keV.

Using the energy dependence curve of TLD-100 obtained with narrow x-ray spectra (curve 3B) and considering the uncertainties in its derivation and in the determination of the effective energy with curve 7B, it is possible to determine the energy correction factor, $\gamma(E)$, with an uncertainty less than $\pm 1.7\%$ in the effective energy range 30–100 keV.

Tandem TLD-200/TLD-100

In the case of the Tandem TLD-200/TLD-100, obtained with a broad x-ray spectra (curve 8A) the ratio uncertainties vary between ± 1 and $\pm 2.5\%$. The uncertainties in the determination of the effective energy of a wide x-ray spectrum with this Tandem, in

Table 3. Maximum uncertainties in the determination of the effective energy and the energy correction factor $\gamma(E)$ using the Tandem systems studied

Tandem	Uncertainty in the effective energy (keV)				Uncertainty in the factor $\gamma(E)$ (%)			
	Wide spectrum		Narrow spectrum		Wide spectrum		Narrow spectrum	
	30–60 keV	60–100 keV	30–60 keV	60–100 keV	30–60 keV	60–100 keV	30–60 keV	60–100 keV
$\gamma(E)$ D–$CaSO_4$:Dy–0.4/$\gamma(E)$ TLD-100	10	1	4	4	1.0	1.7	1.7	1.7
$\gamma(E)$ TLD-200/$\gamma(E)$ TLD-100	25	5	30	4	1.8	2.0	7.0	2.0
$\gamma(E)$ TLD-400/$\gamma(E)$ TLD-100	30	2	30	5	2.0	2.0	7.0	2.0

the effective energy range from 100 to 55 keV, is less than 5 keV. If the effective energy to be determined has a value between 30 and 55 keV, the uncertainty in its determination may be greater than 20 keV, since this is the region of the maximum of the Tandem curve. Using curve 3A, it is possible to determine the energy correction factor, $\gamma(E)$, with an uncertainty less than $\pm 2\%$ in the effective energy range 30–100 keV.

For the narrow x-ray spectra, the TLD-200/TLD-100 Tandem ratio uncertainties vary between ± 1 and $\pm 2\%$ (curve 8B). Uncertainties in the determination of the effective energy of a narrow x-ray spectrum in the effective energy range 100–60 keV, is less than 4 keV. If the effective energy to be determined has a value between 30 and 60 keV, the uncertainty in its determination may be as large as 30 keV, since this is the region of the maximum of the Tandem curve. Using curve 3B, it is possible to determine the energy correction factor, $\gamma(E)$, with an uncertainty less than $\pm 2\%$, in the effective energy range from 100 to 60 keV. For an effective energy value less than 60 keV, the uncertainty in the $\gamma(E)$ factor determination is $\pm 7\%$.

Tandem TLD-400/TLD-100

For the Tandem curve TLD-400/TLD-100, obtained with wide x-ray spectra (curve 9A) the ratio uncertainties lies between ± 1 and $\pm 3\%$. The uncertainties in the determination of the effective energy of a wide x-ray spectrum with this Tandem, in the effective energy range 100–60 keV, is less than 2 keV. If the effective energy to be determined has a value between 30 and 60 keV, the uncertainty may be as large as 30 keV, since this is the region of the maximum of the Tandem curve. Using curve 3A, it is possible to determine the energy correction factor, $\gamma(E)$, with an uncertainty less than $\pm 2\%$ in the effective energy range from 100 to 30 keV.

In the case of narrow x-ray spectra, the TLD 400/TLD-100 Tandem ratio uncertainties vary between ± 1 and $\pm 3\%$ (curve 9B). Uncertainties in the determination of the effective energy of a narrow x-ray spectrum with this Tandem, in the effective energy range 100–60 keV, vary from 2 to 5 keV. If the effective energy to be determined has a value between 30 and 60 keV, the uncertainty in its determination may be as large as 30 keV, since this is the region of the maximum of the Tandem curve. Using curve 3B, it is possible to determine the energy correction factor, $\gamma(E)$, with an uncertainty less than $\pm 2\%$, in the effective energy range from 100 to 60 keV. For an effective energy value below 60 keV, the uncertainty in the $\gamma(E)$ factor determination is $\pm 7\%$.

5. Conclusions

The analysis of uncertainties in the determination of the effective energy and the energy correction factor $\gamma(E)$, using the Tandem method, was based on a knowledge of the type of radiation beam spectral distribution defined in terms of its width. This information is not difficult to obtain. For example, in the case of a filtered x-ray beam, the filter and the maximum energy can give this information. In Table 3, the maximum uncertainties in this determination are presented. It can be observed that there is no great difference in the uncertainties in the determination of the effective energy of an x- or γ ray beam with known spectral distribution and with an effective energy between 60 and 100 keV. However, a better precision is obtained with the Tandem D–$CaSO_4$:Dy–0.4/TLD-100.

For effective energy values below 60 keV, the Tandem D–$CaSO_4$:Dy–0.4/TLD-100 is undoubtedly preferable, since it permits a determination of the effective energy with a higher precision. As the D–$CaSO_4$:Dy–0.4 TL dosimeters have a small thickness (0.4 mm) the low-energy x- or γ ray beam is less attenuated in these dosimeters and, therefore, the maximum of the Tandem curve is dislocated to energies lower than 35 keV.

The Tandem D–$CaSO_4$:Dy–0.4/TLD-100 also permits the most precise determination of the exposure. In the effective energy interval from 30 to 100 keV the uncertainty in the determination of the energy correction factor, $\gamma(E)$, is better than $\pm 1.7\%$ for any type of spectral distribution.

Therefore, among the pairs of dosimeters studied, the D–$CaSO_4$:Dy 0.4 and TLD-100 present the best properties for the determination of the effective energy of an x- or γ ray beam with an unknown spectral distribution. This Tandem also permits the most precise determination of exposure for the same radiation beam. However, the spectral distribution in terms of being "wide" or "narrow", should be known.

All the Tandem systems studied were calibrated in air. If they are intended for use inside a material for effective energy and absorbed dose measurement, it is necessary to consider the modification of the spectrum by the material involved. If the material and the spectrum of the incident radiation beam are known, it is possible to anticipate, qualitatively, the type of modification that will occur in the spectrum as a function of the material thickness. Thus, uncertainties encountered in a measurement inside a material are not expected to be much different from those obtained for measurements in air.

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