INTERCOMPARISON BETWEEN PHOTOGRAPHIC; THERMOLUMINESCENT AND RADIOPHOTOLUMINESCENT DOSIMETERS

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ABSTRACT

Comparison was made between the responses of three different dosimetric systems, namely, photographic, thermoluminescent (TL) and radiophotoluminescent (RPL) dosimetry. The comparison was divided into two parts. The first one was carried out with known radiation conditions (exposure, normal incidence, energy) in a controlled environment (— 27°C temperature, ~70% relative humidity). Under these conditions, the response as a function of exposure and energy, the relation of the linearity to the energy, the lowest detectable exposure, and reproducibility were studied. The response as a function of exposure at 37 KeVeff and at 1 MeV was found to be linear in the region of interest to routine personnel dosimetry for all dosimeters except the films.

Although the films response are not linear, the ratio between the response at 37 KeVeff and at 1 MeV does not depend on the exposure, and this allows the determination of a simple correction factor for the radiation energy. Such correction is usually necessary since all the dosimeters are strongly energy dependent, except the LiF TL dosimeters. We verified also that TL materials can detect lower exposures than other dosimeters.

In the second part, the relative response of the dosimeters was measured under the uncontrolled condition in personnel dosimetry. Since the $CaSO_4$:Dy is the most sensitive dosimeter, comparisons were made using this dosimeter as the standard, in which case it was found that 20 out of 29 TLD-100 dosimeters gave the same reading within 30%, 13 out of 29 RPL dosimeters agreed within 30%, and only 3 out of 29 films fell within 30%.

INTRODUCTION

The dosimetric system for personnel monitoring used at Instituto de Energia Atômica, São Paulo, Brazil, is the photographic one.

Since there exist other methods of dosimetry, such as those using thermoluminescent (TL) or radiophotoluminescent (RPL) materials, we felt it worth while to carry out an intercomparison between photographic, TL, and RPL dosimetry in order to be able to decide whether we should keep film dosimetry or replace it by another system. Deciding which system is best under our conditions, and gaining experience with each dosimetric system were the aims of the present work.

The study was carried out in two parts: a) Experiments were done with known irradiation and environment conditions, e.g., irradiations at normal X or gamma-ray incidence with known exposure and energy of the radiation, in a controlled environment (~27°C temperature, ~70% relative humidity), b) Experiments were done in the uncontrolled conditions of personnel dosimetry, where the radiation are incident from all possible directions and the energy of the radiations, and the temperature and humidity of the surroundings are unknown.

EXPERIMENTS UNDER KNOWN IRRADIATION AND ENVIRONMENTAL CONDITIONS

1) Response to ^{60}Co gamma-ray exposures and 37 KeVeff x-ray exposures

For these measurements a total of 230 dosimeters was used. This number was composed of 6 types of dosimeters: film badges using a combination of high and low sensitivity films, Toshiba RPL glasses FD-P6-1 and FD-P8-1, Harshaw TLD-100 powder, Harshaw hot pressed TLD-100, and Harshaw $CaSO_4$:Dy powder which are shown in fig. 1. The usual pre-treatment for TLD and RPL materials was given, but, it will not be described here. For irradiation we used the ^{60}Co gamma-ray source at Hospital A.C. Camargo. The exposure varied from 0,010 to 100 R. Each point in the calibration curve of all dosimeters was an average of response of five dosimeters.

Film responses to ^{60}Co gamma-ray exposures for high and low sensitivity films were measured. As was expected, the responses of the films were not linear with exposure. For high sensitivity films, an exposure of approximately 100 R from ^{60}Co gamma-rays produced the maximum readable optical density. The low sensitivity film gave reliable readings only for exposures higher than or of the order of 2 R of ^{60}Co gamma radiation, or higher than 1 R for 37 KeVeff x-radiation. It was found that the standard deviation of the responses increases as exposures decrease.

TL responses for TLD-100 powder, $CaSO_4$:Dy powder, and hot pressed TLD-100 for 0,01 to 100 R gamma-rays were also determined. In the exposure range considered, the TL response is linear with exposure for all of these dosimeters. Equal volumes of TLD-100 and $CaSO_4$:Dy powders were used for readings, and the result shows that calcium sulfate possesses much higher sensitivity. This fact was already reported at Gatlinburg Conference (1968). The errors envolved in these measurements include the error in the source calibration, fluctuation of the powder mass to be read, and the error in the reading itself.

Finally, the responses to gamma-rays exposure of RPL glass dosimeters FD-P6-1 and FD-P8-1 were measured. The FD-P8-1 glass dosimeters were used inside the Toshiba BD-2 badge and their responses are given directly in roentgens. The linear response in the range of exposure studied was observed as expected (Cf. Toshiba Instruction Manual for Model FGD-6 Dosimeter).

The difference between these two kinds of glass dosimeters is their size. The FD-P6-1 is 6 x 6 x 3.3 mm and the FD-P8-1 is8 x 8 x4.7 mm. Their compositions by weight are the same (50% $LiPO_3$, 50 $AlPO_3$, and 7% $AgPO_3$ 3% B_2O_3 additives). These glasses exhibit a pre-dose effect. The higher the pre-dose the larger the minimum exposure that can be measured and the larger the fluctuation of response for low exposures. Another cause for fluctuations in RPL glass readings is the condition of the glass surfaces, which must be as clean as possible.

In every case we observed that the error in the reading increased as the exposure decreased.

2) Energy dependence of dosimeters

Since the response of many commonly used dosimeters is dependent on the radiation quantum energy, and since in actual monitoring the energy of radiation is not known, it was considered important to measure the energy dependence of the dosimeters being studied.

240 dosimeters comprising 6 different kinds were given x-ray exposure of 20 R at energies varying from 12 to 147 KeVeff. They were also given 20 R exposures with ^{137}Cs and ^{60}Co gamma-rays. The results for high sensitivity films, TLD-100 powder, $CaSO_4$:Dy powder, FD-P6-1 and FD-P8-1 RPL glasses show the same energy dependence found by others authors, Becker (1966), Lin and Cameron (1968), Yokota and Nakajima (1965). The measurements with the films were carried out keeping window open (O.W.) and Pb filters. It is found that the responses of all dosimeters except TLD-100 are highly energy dependent, particularly below approximately 200 KeVeff.

The ratios between the responses at about 30 to 50 KeVeff (energy of maximum response) and about 1 MeV (minimum response) are 10.5 for film without filter, 11.0 for $CaSO_4$:Dy, 7.0 for RPL glass, and 1.8 for TLD-100. This factor of 1.8 for TLD-100 differs from the usual value of 1.3 because we used thin walled polyethylene capsules to contain the TLD-100 powder during irradiations. For 1.25 MeV photons the build-up thickness for plastic is about 4.5 mm while we used a plastic thickness of 3 mm. This gave a lower response at this energy by a factor of $\sim$ 0,66. It is well known that the small energy dependence in the response of LiF:Mg is due to the fact that its effective Z value is very close to that of air. Therefore, it is nearly tissue equivalent, and this fact favors the utilization of LiF:Mg for personnel dosimetry where the radiation field is unknown.

$CaSO_4$:Dy has a sensitivity about 14 times that of TLD-100 for 1 MeV gamma radiation and 86 times for 40 KeVeff x-rays. This high sensitivity of calcium sulfate makes it a very useful material for personnel monitoring, in spite of its large energy dependence.

The response of Toshiba FD-P8-1 glass, when used in the Toshiba BD-2 badge, is energy independent above approximately 90 KeVeff, due to the 0,9 mm Sn filter contained in the badge.

3) Variations of sensitivity of dosimeters to exposure, for each radiation energy

This part was carried out by exposing four dosimeters of each type to between 300 mR and 20 R of 37 KeVeff x-rays. This energy was chosen because it is approximately the energy at which the dosimeters present the highest sensitivity. If the ratio between the response at 37 KeVeff and 1 MeV is independent on exposure, then the results presented in Section 2 cam be assumed to be applicable to the entire range of exposures studied, and an energy correction factors can be calculated from them. Having these factors, which will be explained below, and knowing the energy of the radiation, the exposure can be determined using a calibration curve for the ^{60}Co gamma-rays.

The ratio mentioned above was measured for several exposures below 20 R. The results shows that it is exposure independent for all dosimeters. Furthermore, it shows that the sensitivity is constant for exposures up to 20 R at constant photon energy (37 KeVeff in the present case), for all dosimeters, except for films.

4) Responses to exposures lower than 100 mR

Since personnel monitoring, usually involves only very low exposures we carried out the following experiment in order to determine the lowest exposure detectable within a given error for each kind of dosimeter. 32 samples of each of the following types, $CaSO_4$:Dy powder, hot pressed TLD-100, TLD-100 powder, FD-P8-1 RPL glass, and high sensitivity film, were divided into 8 groups. Each group was exposed to ^{60}Co gamma-rays with one of the following exposures: 2, 5, 7.5, 10, 20, 30 and 50 mR. 4 additional $CaSO_4$:Dy samples were irradiated to 1 mR.

Their responses were read and the standard deviations were computed. Figure 2 shows the standard deviation as a function of exposure. In order of reading reliability, up to 100 mR, the tested dosimeters can be ordered as shown in table 1.

For exposures greater than 100 mR all the dosimeters are almost equally reliable. It is fair to say, however, that above approximately 500 mR RPL glasses yield more accurate readings than other dosimeters.

5) Reproducibility of dosimeter response

To mesure the reproducibility of the dosimeter responses, the reading of the previous sections were used. In those sections the standard deviation was related to the known exposure received by the dosimeters, while in this section they were computed taking into account only the variations of the dosimeters readings. The results are shown in Table 2, where it can be seen that, for exposures lower than approximately 200 mR, the dosimeters can be classified in order of decreasing reproducibility as it follows.

1. $CaSO_4$:Dy
2. Hot pressed TLD-100
3. TLD-100 powder
4. RPL glasses
5. Films

Above 200 mR the order was found to be

1. $CaSO_4$:Dy
2. RPL glasses
3. TLD-100
4. Film

EXPERIMENTS UNDER UNKNOWN IRRADIATION AND ENVIRONMENTAL CONDITIONS

1) Effective energy determination

The dosimeters were distributed among the employees at the Instituto de energia Atômica as well as placed at several points inside the building housing the Institute's reactor. Since the energies of radiations involved were not known, their effective energy was determined using films and/or TL materials.

The determination of the effective energy with films was carried out by measuring the ratio of the optical density with open window (O.W.) to the density with lead filter. This ratio was compared to Fig. 3 which was obtained from results discussed in Section 2 concerning energy dependence. After the effective energy determination, an energy correction factor was also determined from Fig. 4 which also was obtained from the results of section 2. This was done by calculating the ratio between the optical density with lead filter at 1 MeV and the optical densities with lead filter at energies below 1 MeV.

Determination of effective energy by TL materials was done measuring the ratio between the TL reading in $CaSO_4$:Dy and that in TLD-100 using Fig. 5. The curve in this figure obtained by calculating, for each energy, the ratio between the TL reading in $CaSO_4$:Dy and that in TLD-100.

The energy correction factor was determined using Fig. 6 for TLD-100 and Fig. 7 for $CaSO_4$:Dy. These figures represent the ratio between TL reading for a given photon energy E and TL reading for Cobalto 60 gamma-ray, versus E.

The exposures measured with RPL glasses (FD-P6-1) were also corrected for the radiation energy, using the effective energy values determined from the films and the energy correction factors from Fig. 8 which was obtained from the results of section 2 the same way as for the film and TL dosimeters.

2) Comparison between $CaSO_4$: Dy and other dosimeters

As it was verified, $CaSO_4$:Dy is the most sensitive one among of the dosimeters used. It presented low standard deviation in the low exposure region. Because of that a comparison between the response of all the dosimeters with that of the $CaSO_4$:Dy was carried out. The results are shown in Fig. 9. One observes in this figure that 20 out of 29 TLD-100 dosimeters presented readings within 30% of that of $CaSO_4$:Dy, and only 2 read no exposure while the $CaSO_4$:Dy read 36 and 46 mR. As explained earlier, the responses of the hot pressed TLD-100 dosimeters were not corrected for energy, and their readings are higher than those of the $CaSO_4$:Dy. For the RPL glasses, type FD-P8-1, 13 out of 29 responded within 30% deviation with respect to the $CaSO_4$:Dy readings, and only 2 read no exposure when the $CaSO_4$:Dy read 73 and 80 mR. From 29 RPL glasses type FD-P6-1, 9 presented error within 30% and 6 read zero exposure when the exposures were in the 32 to 80 mR range , as read by the $CaSO_4$:Dy. For the films only 3 out of 29 read exposure within 30% deviation in comparison to $CaSO_4$:Dy and 4 read zero exposure when the $CaSO_4$:Dy readings were between 70 and 150 mR.

DISCUSSION AND CONCLUSIONS

Table 3 shows a summary of the present work. One can see that the films are the dosimeters that show the worst characteristics. They have the following disadvantages:

a) large minimum detectable exposure
b) strong energy dependence
c) non linear response with exposure
d) latent image fading
e) fogging
f) dependence of sensitivity on the direction of radiation incidence

g) nonequivalence to human tissue
h) high cost in the long run for those depending on importation from abroad

However, they do show some advantages, such as offering a long lasting document of the exposure, since they can be read again and again.

The RPL glasses have almost the same lower detection limit as the films. They have the following disadvantages:

a) large lower detection limit
b) strong energy dependence
c) dependence of the sensitivity on the direction of radiation incidence
d) nonequivalence to human tissue
e) washing procedure is tiresome and if not carefully done can cause considerable error in the readings

Their advantages are following:

a) linear response to exposure up to 3 KR
b) small fading (~1%/3 months)
c) low cost in the long run because they can be reused several times
d) the reading method is simple
e) the stored exposure effect in the glass is not destroyed by reading, therefore glass dosimeters are a long lasting record of the actual exposure

The TL dosimeters possess the following properties:

a) the detection limit for low exposures is very low
b) little energy dependence for low Z phosphors
c) the response is linear for the entire range of exposure values of interest in personnel dosimetry
d) small fading (5%/month)
e) simple reading technique
f) dosimeters can be reused after a given heat treatment, hence they are material of relatively low cost in the long run
g) small size dosimeters can be used, such that they are convenient for in-vivo measurement.

However they have the disadvantage of erasing the radiation effect after the reading process, but this can be overcome by using more than one dosimeter at a time.

In sumary one can say that, according to the present work, TLD is the most suitable dosimetric system for personnel monitoring.

Table 1

Standard Deviation (%)

	1 mR	2 mR	5 mR	10 mR	20 mR	30 mR	50 mR	100 mR
1. $CaSO_4$:Dy	50	20	10	9	9	9	9	9
2. Hot pressed TLD-100	-	280	70	30	19	16	14	-
3. TLD-100 Powder	-	∞ (*)	80	38	25	21	19	18
4. RPL glass FD-P8-1	-	-	1000	300	120	70	40	20
5. Film	-	∞	∞	∞	160	80	40	20

(*) ∞ means that the dosimeter readings are equal to the background readings.

Table 2

Reproducibility - Standard Deviation (%)

Exposure	1 mR	2 mR	5 mR	10 mR	20 mR	30 mR	50 mR	100 mR	200 mR	500 mR	1 R	2 R	5 R	10 R	20 R	50 R	100 R
Films	-	∞	∞	∞	150	80	35	19	13	9.3	7.2	6	5	4.5	4	3.5	3
TLD-100 Powder	-	120	65	32	21	18	14	11	8.5	6.5	5.6	5.5	4	3.6	3.4	3.2	3
Hot Pressed TLD-100	-	60	30	20	13	10	8	-	-	-	-	-	-	-	-	-	-
$CaSO_4$:Dy	50	11	3	2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
RPL Glasses FD-P8-1	-	-	250	110	60	40	25	14	8.5	5	3.5	2.7	1.9	1.5	1.3	1	0.9

Table 3

	Linearity	Reading error for 20 mR exposure	Minimum exposure with 20% error	Minimum exposure with reproducibility within 20% error	Nº of readings within 30% error compared to $CaSO_4$:Dy reading (total; 29 dosim.)	Exposure ratio at ~40 Kev and 1 Mev without filter
$CaSO_4$:Dy	Linear	9%	2 mR	1.5 mR	–	11.0
Hot pressed TLD-100	Linear	19%	18 mR	10 mR	–	–
TLD-100 Powder	Linear	25%	35 mR	22 mR	20	1.8
RPL glass FD-P8-1	Linear	120%	100 mR	65 mR	13	7.0
Film	nonlinear	160%	100 mR	90 mR	3	10.5

FIGURES' CAPTION LIST

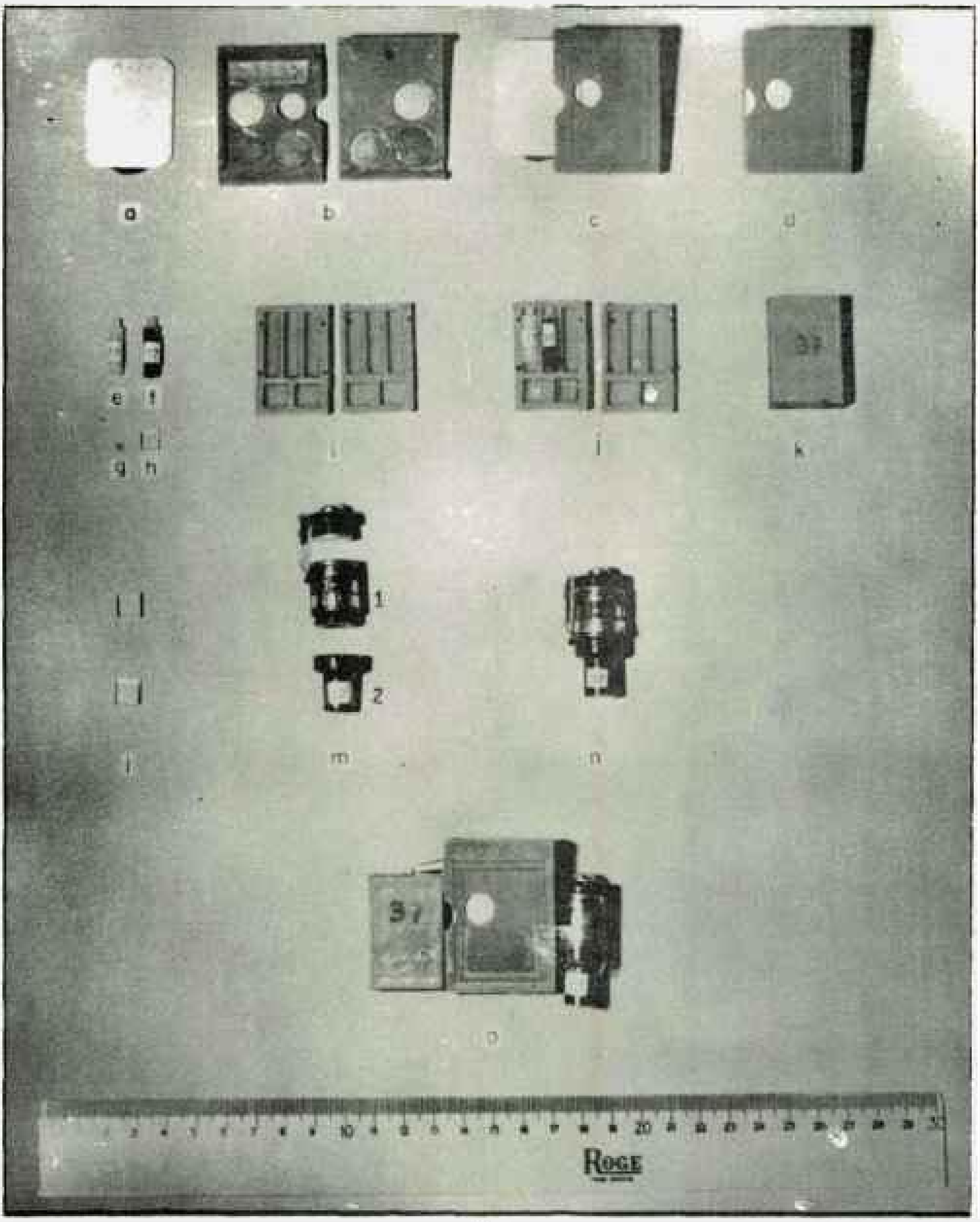

FIG. 1 a) Agfa Gevaert film model Structurix D2 e D10. **b) Open film** badge showing the filters (Pb, Cd, Cu and open window). c) Film being introduced into the badge. d) Closed film badge. e) TLD-100 dosimeter. f) $CaSO_4$:Dy dosimeter. g) LiF (hot press). dosimeter. h) RPL glass FD-P6-1. i) Open badge. j) Badge containing dosimeters. k) Closed badge. l) RPL glasses FD-P8-1. m) Open BD-2 badge from Toshiba. The glasses are introduced **in parts 1 and 2 shown.** n) Closed BD-2 badge. o) Composite badge.

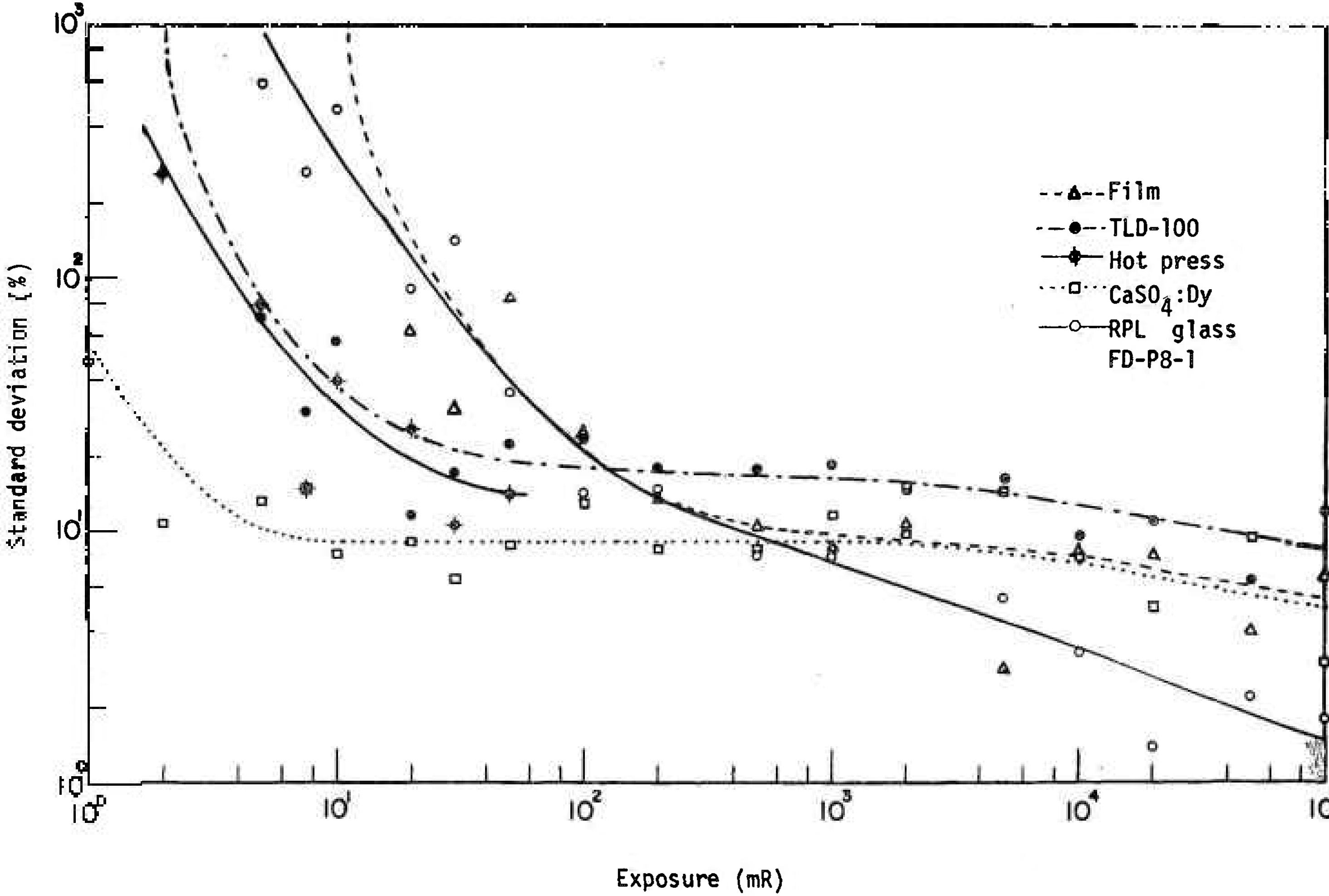

Figure 2 - Reading's standard déviation

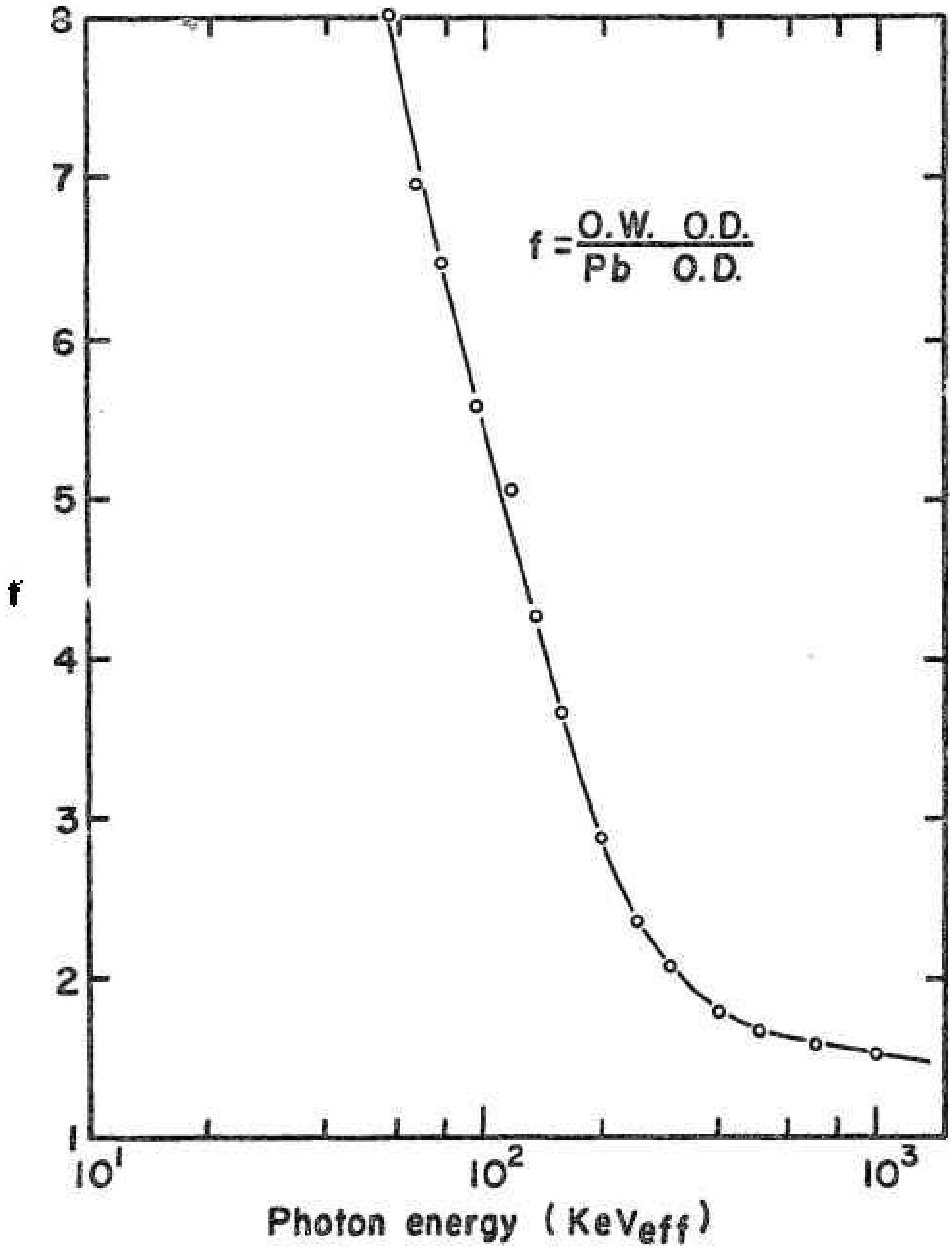

Figure 3 - Curve for energy determinations with film (Agfa Gevaert Model Structurix D10).

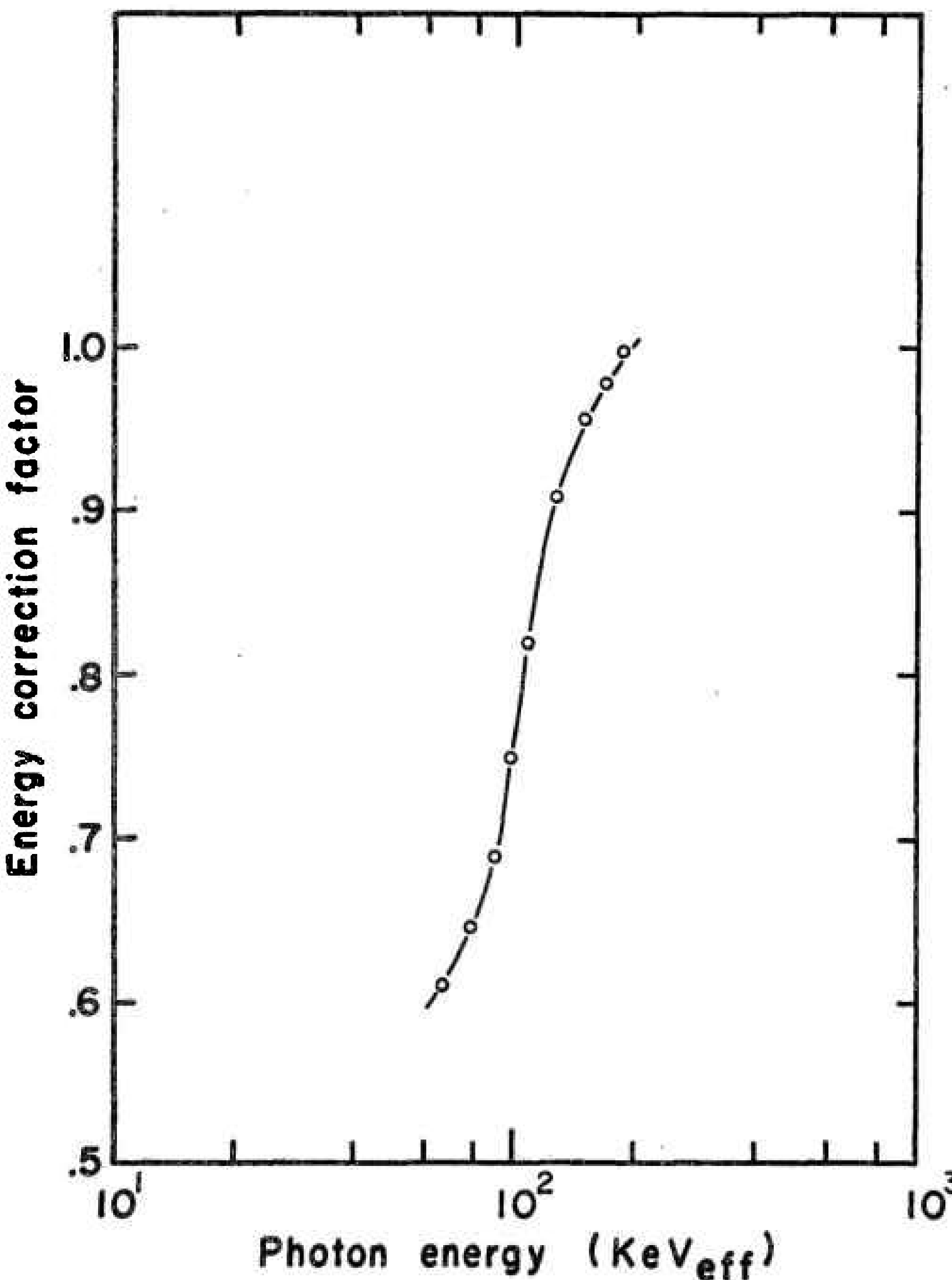

Figure 4 - Curve for determining the energy corrections factor with film.

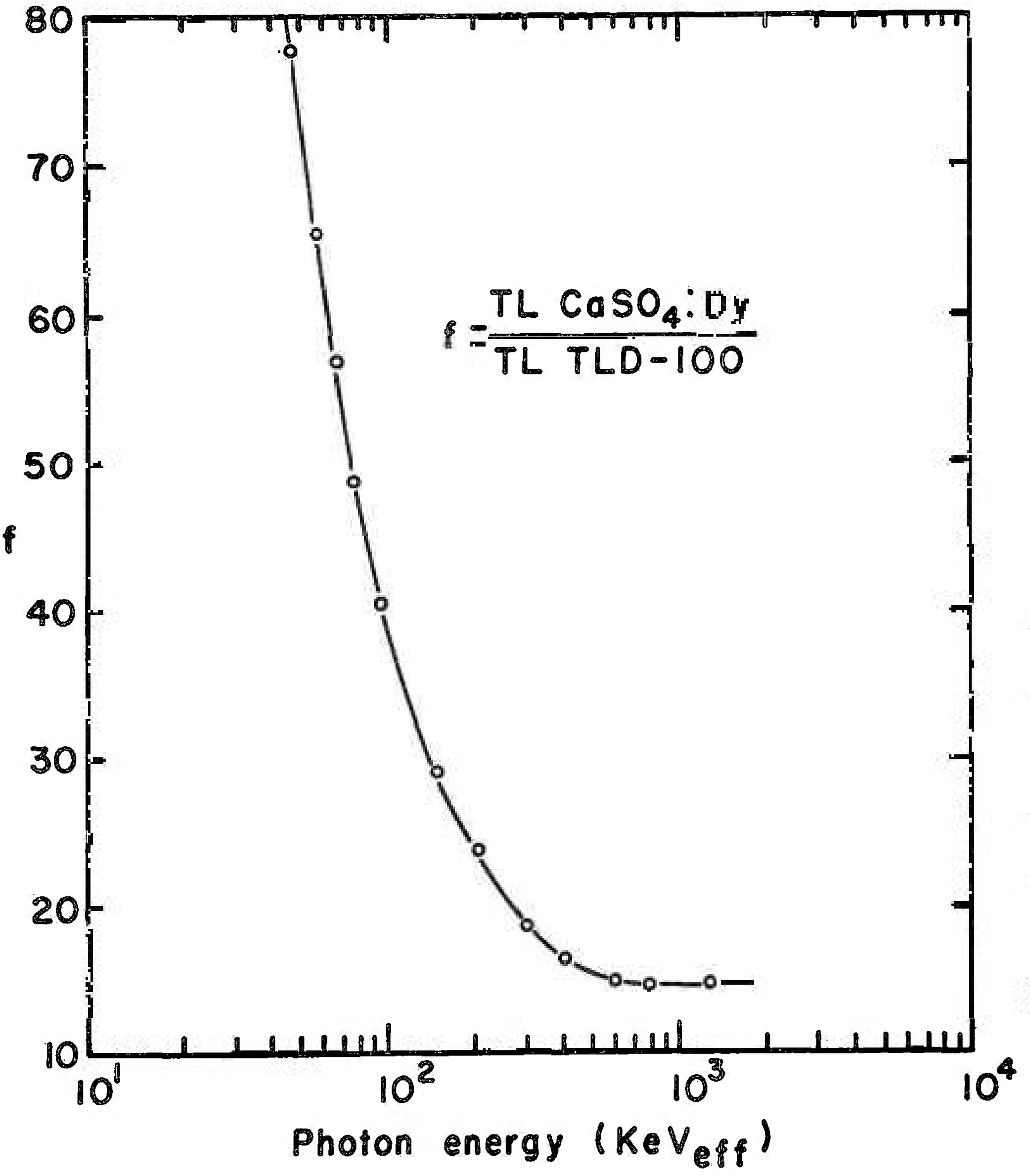

Figure 5 - Curve for energy determination with TLD-100 and $CaSO_4$: Dy.

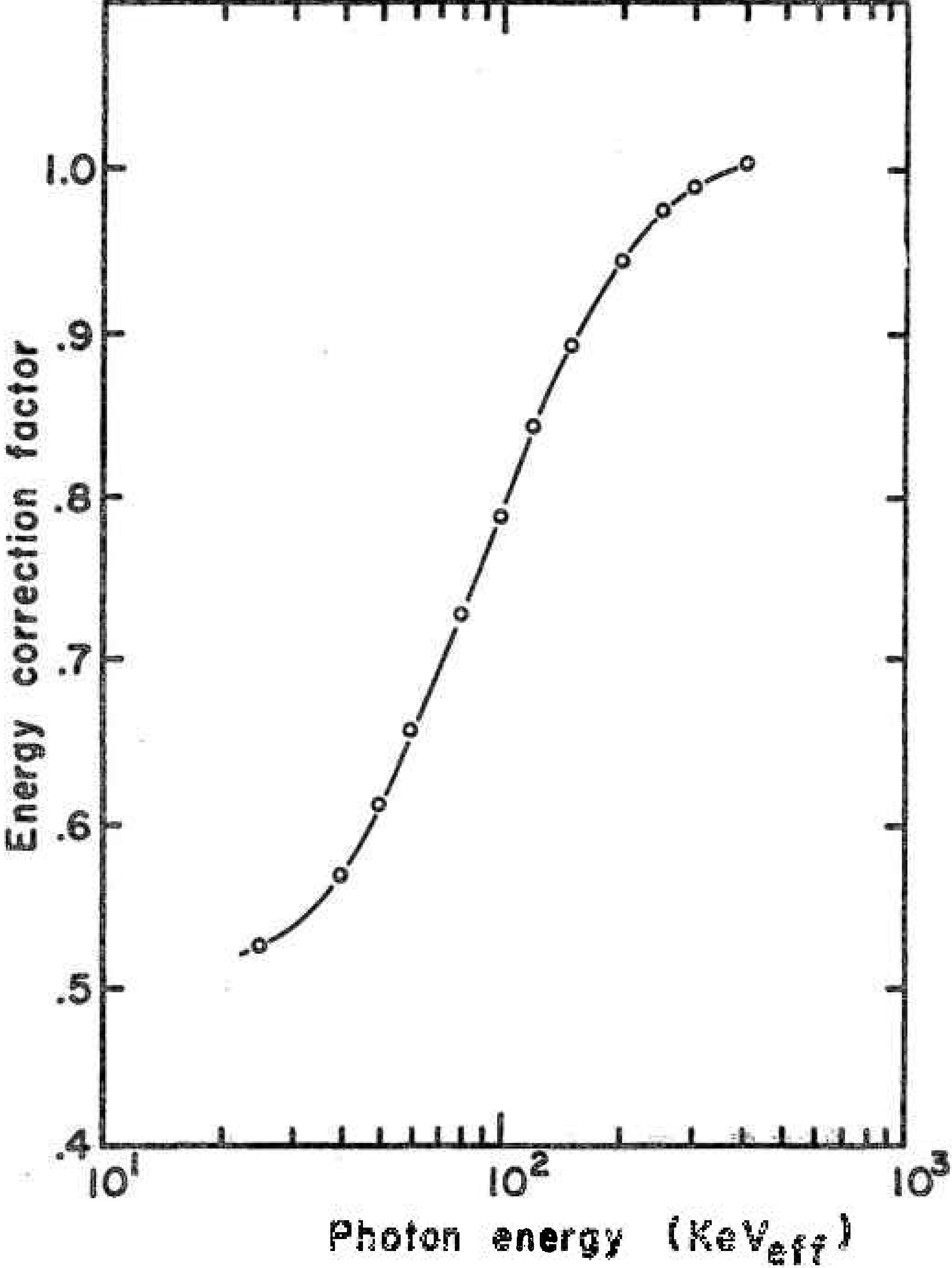

Figure 6 - Curve for determining the energy correction factor with TLD-100.

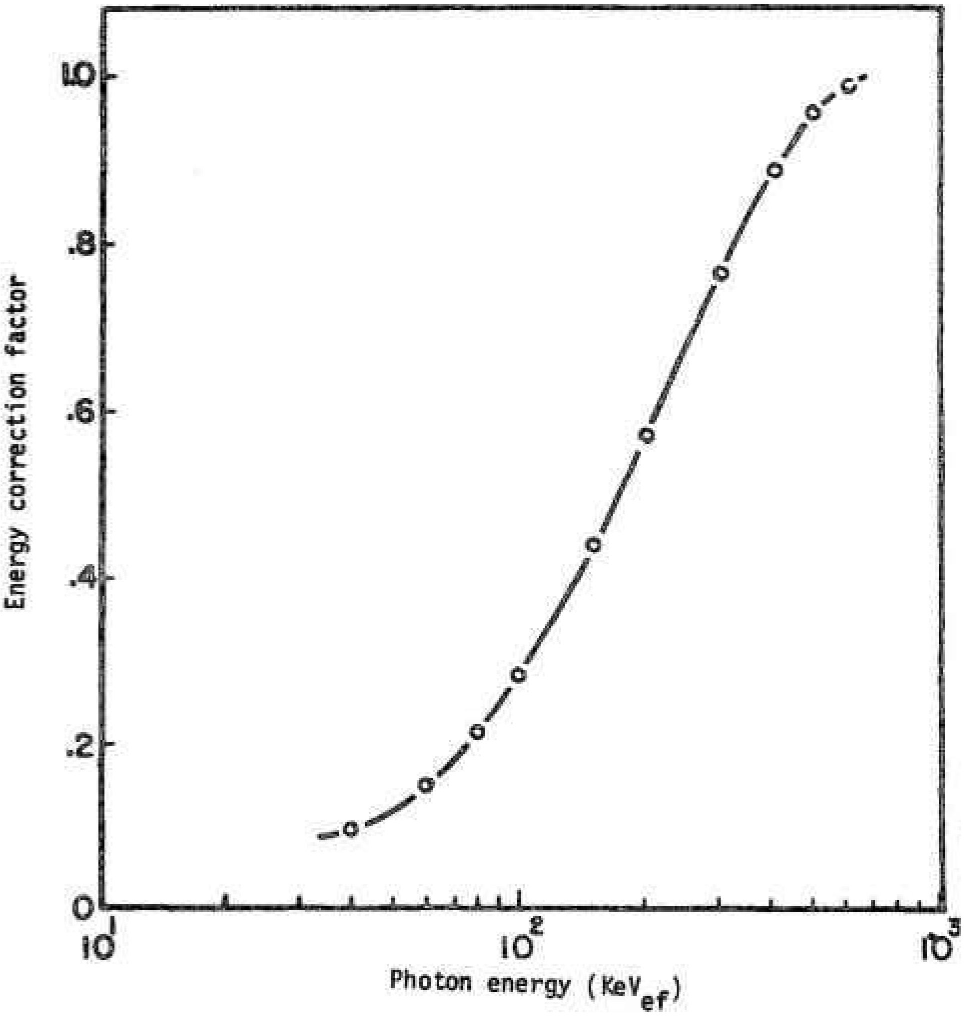

Figure 7 - Curve for determining the energy correction factor with $CaSO_4$: Dy.

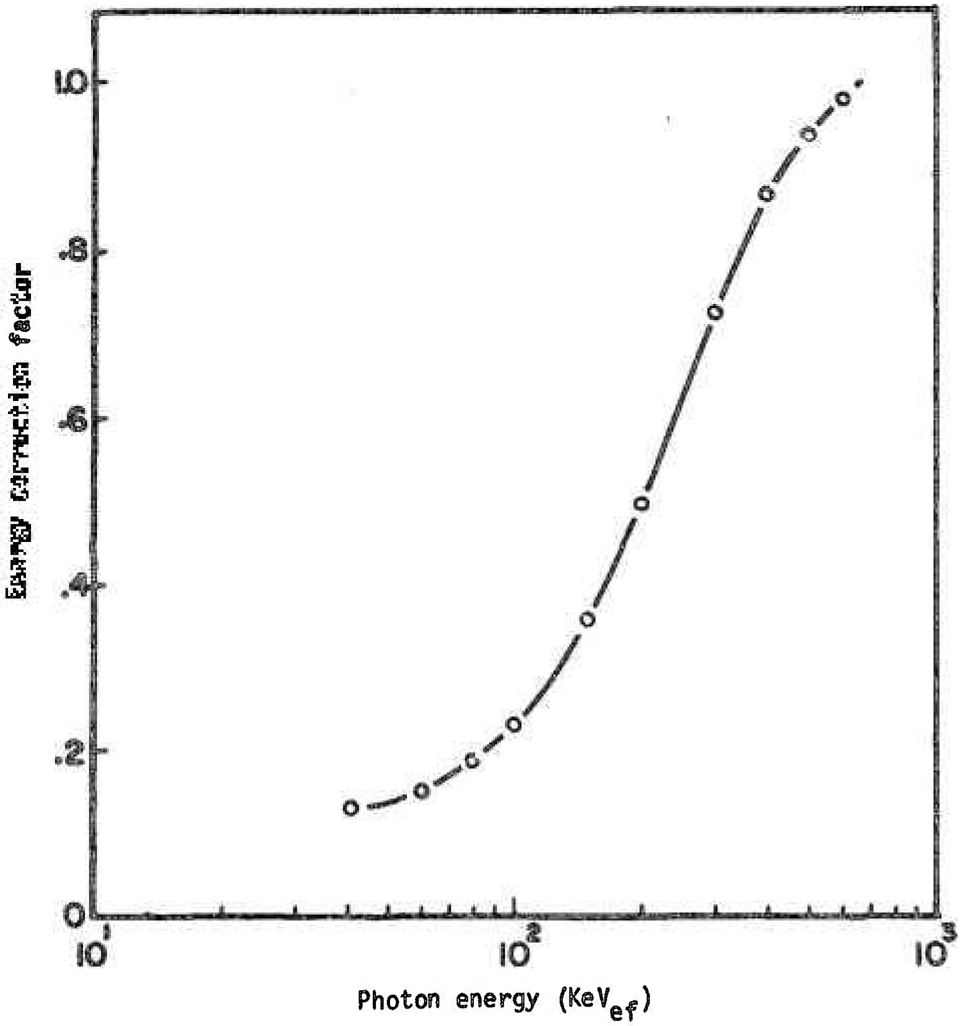

Figure 8 - Curve for determining the energy correction factor with FD-P6-1.

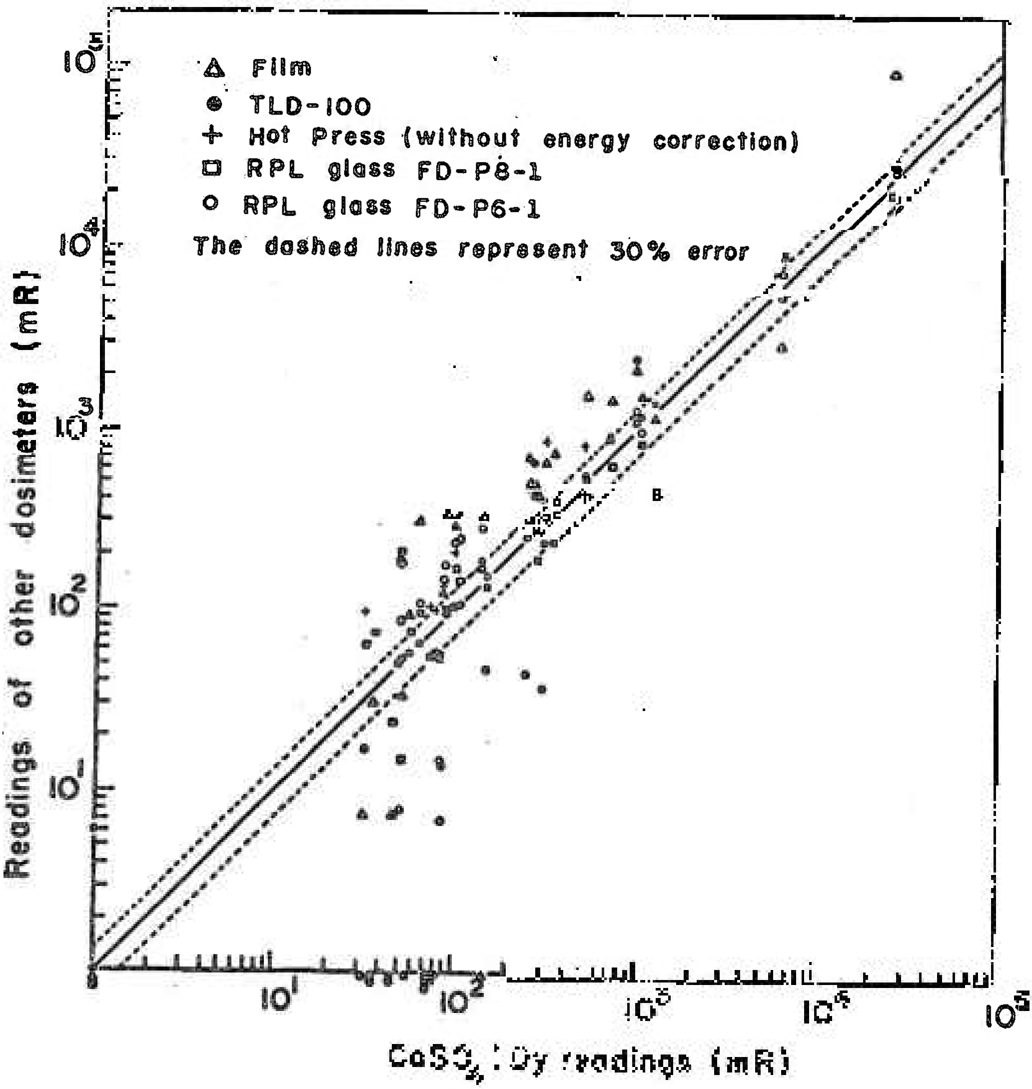

Figure 9 - Comparison between $CaSO_4:Dy$ readings and those of other dosimeters.

RESUMO

Foi feita uma comparação entre as respostas de três sistemas dosimétricos diferentes, a saber, fotográfico, termoluminescente (TL) e radiofotoluminescente (RPL). O trabalho foi divido em duas partes. Uma foi efetuada sob condições conhecidas de radiação (exposição, incidência normal e energia) num ambiente controlado (temperatura de 27°C e umidade relativa de cerca de 70%). Debaixo destas condições, foram estudadas a resposta em função da exposição e energia, a relação da linearidade para diferentes energias, a exposição detetável mais baixa e a reprodutibilidade. A resposta em função da exposição para radiação gama de 37 KeVef e 1 MeV é linear na região de interesse à dosimetria pessoal para todos os dosímetros, exceto os filmes.

Embora a resposta de filme não seja linear, a razão entre a resposta em 37 KeVef e em 1 MeV não depende da exposição, o que permite a determinação de fator simples de correção para a energia da radiação. Tal correção é normalmente necessária, pois, todos os dosímetros são fortemente dependentes de energia com exceção dos dosímetros TL de LiF. Foi verificado, também, que os materiais TL conseguem detetar exposições mais baixas do que os outros dosímetros.

Na segunda parte, a resposta relativa dos dosímetros foi medida em condições incontroladas na dosimetria de pessoal. Como o $CaSO_4$:Dy é o dosímetro mais sensível, foram feitas comparações da sensibilidade de outros dosímetros em relação a este. 20 dos 29 dosímetros TLD-100 deram leituras dentro de 30% 13 dos 29 RPL, dentro de 30% e somente 3 dos 29 filmes tiveram leituras dentro de 30%.

RÉSUMÉ

On a fait la comparaison entre les rèponses de trois systèmes dosimetriques differents: phtographique, thermoluminescent (TL) e radiophotoluminescent (RPL). Le travail a été divisé en deux parties. L'une a été effectuée pour des conditions connues d'irradiation (exposition, incidence normale et énergie) dans une ambiente controllée (temperature d'ordre de 27°C et humidité relative de 70%). Sous ces conditions, on a étudié la réponse en fonction de l'exposition et de l'énergie, la rélation de linéarité pour différentes energies, la plus basse exposition détectable et la reproductibilité. La réponse en fonction de l'exposition pour le rayonnement gama de 37 KeVef et de 1 MeV est linéaire dans la région d'interêt à la dosimetric personnelle pour tous les dosimètres à l'exception du film.

Bien que la réponse du film ne soit pas linéaire, la raison entre les réponses à 37 KeVef et à 1 Mev ne dépend pas de l'exposition; ceci permet de determiner un facteur simple de correction pour l'énergie de la radiation. Cette correction est normalement necessaire, puisque tous les dosimetres sont fortement dependants de l'énergie, à l'exception des dosimetres TL de LiF. On a trouvé, aussi que les materiaux TL sont capables de détecter les expositions plus basses que les autres.

Dans la second partie, on a mésuré la réponse relative de dosimètres en conditións incontrollées pendant la dosimetrie de routine. Comme le $CaSO_4$:Dy est le dosimètre le plus sensible, les sensibilités des autres dosimètres ont été comparées avec celle de $CaSO_4$:Dy. 20 des 29 dosimètres TLD-100 donnèrent les lectures dans une marge de 30%, 13 des 29 RPL, dans la même marge et seulement 3 des 29 filmes dosimetriques présenterent lectures TL dans cette méme plage 30%.

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