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PROPOSAL OF A DOSEMETER FOR SHALLOW BETA DOSE ASSESSMENT

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ABSTRACT

Control of the shallow dose is specially important in environments with a large component of soft or low-penetrating radiation. In these situations, specially when the skin dose may be the limiting factor, good quality dosimetry for the skin is essential. The recommendations of the ICRP 26 indicate that the skin dose should be averaged between 5 and 10 $mg.cm^{-2}$. For practical dose assessment purposes the ICRP 26 recommends a determination of the skin dose at a depth of 7 $mg.cm^{-2}$. The shallow dose due to low energy beta rays may be assessed using thermoluminescent (TL) detectors with small thickness. In the present work the reproducibility, lower detection limit, linearity, dependence on beta absorbed dose rate, optical fading, angular and energy dependence, and transmission factors for different thicknesses of tissue equivalent material of ultra-thin detectors made of $CaSO_4$:Dy Teflon were determined for beta radiations from ^{90}Sr - ^{90}Y, $^{204}T\ell$ and ^{147}Pm sources. Based on the results obtained, a dosemeter presenting an energy independence better than 12% is proposed for shallow dose determination.

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1. INTRODUCTION

Recently, there has been a general consensus amongst those concerned with this matter that in the past beta radiation has been neglected in radiation protection(1,2). A change in policy has resulted eventually from the Three Mile Island incident. A number of international activities which have followed this event provide evidence of a new understanding: the CEC Beta Intercomparison Programme 1979/80, followed by a CEC Seminar on the subject of the State-of-the-art in Beta Dosimetry, at Grenoble in October 1980; the informal US Beta Ray Dosimetry Workshop in December 1981 in New York; the International Symposium on Beta Dosimetry in February 1983 in Washington, DC; and a recent study by the Pacific Northwest Laboratory (PNL)(3) to determine the extent to which beta radiation measurements made at NRC licensed facilities are accurate.

As a result of these activities, beta radiation has been recognised as a significant radiation safety problem. It has also been shown that the measuring quantities, area and individual dosemeters, calibration standards and procedures, concepts and conversion coefficients between beta dose indications and body doses were needing improvement. The National Commitee on Radiation Protection, NCRP, has been requested to reavaluate the scientific basis for the current standards and formulate a more realistic one.

Beta rays are far less penetrating than X-rays or gamma rays, and hence beta sources external to the body do not cause significant irradiation of the deeper-lying tissues in the body; but in some cases they can and do contribute significantly to the irradiation of the lens of the eye and, more generally, of the skin. They can be particularly important in causing irradiation of the hands, and specially of the finger-tips.

The International Commission on Radiological Protection(4) has specified a tissue depth of 5-10 mg.cm^{-2} below the skin surface as appropriate for skin dose assessment, and recommends the use of a depth of 7 mg.cm^{-2} as a reasonable mean value. Therefore, a 5 mg.cm^{-2} tissue-equivalent detector beneath a 5 mg.cm^{-2} tissue-equivalent material appears appropriate for skin dose assessment(5).

Thermoluminescent (TL) detectors of small thickness may be used for beta radiation dosimetry, and have been, with this aim, intensively investigated recently(6-11). Among these detectors, ultra-thin discs (6mm in diameter and 20μm in thickness) made of $CaSO_4$:Dy Teflon (Type UT-$CaSO_4$:Dy), commercially available from Teledyne Isotopes Inc., present interesting properties for beta radiation detection(7,8,10,11).

In the present work the reproducibility, lower detection limit, linearity, dependence on beta absorbed dose rate, optical fading, angular and energy dependence and transmission factors for different thicknesses of tissue equivalent material of UT-$CaSO_4$:Dy were determined for beta radiations from ^{90}Sr - ^{90}Y, ^{204}Tℓ and ^{147}Pm sources. Based on the results obtained, a dosemeter presenting an energy independence better than 12% is proposed for shallow dose determination.

2. RADIOLOGICAL PROTECTION IN BETA RADIATION FIELDS

In beta radiation fields, three organs, the skin, eyes and testes are potentially at risk. The skin is the organ at risk from all external beta radiations, and with nuclides of medium or high energy ($E_{max} > 0.8$ MeV) the eye lens and sperm cells in the testicles may be irradiated. The potential sources of such exposures in the nuclear power industry have been reviewed else where(12).

The main characteristics of beta fields which are important in relation to beta dosimetry are(13):

(a) the dose rate very close to a beta source may be very high indeed.

(b) beta fields are grossly non-uniform. The dose rate near to a beta source falls off much more rapidly than it does from a gamma source. The relationship between dose rate and distance contains a component to allow for an absorption on top of the usual inverse square law, this absorption component is energy dependent and highly significant, specially in the case of low energy beta rays, which range in air may be less than a metre.

(c) in many practical cases there are mixed β/γ fields to be considered.

In relation to beta sources, the following considerations are important(13):

(a) the self absorption in the source may be extremely high, and

(b) β sources are often shielded or sealed by a thin layer of plastic foil which reduces the intensity of the β-rays.

Since dose rates near to beta sources can be high, two important conclusions can be drawn(13):

(a) in general, steps should be taken to ensure that people do not bring any part of their body into close proximity to a beta source; when people are handling β-sources of high activity, a minimum distance to the source should be recommended;

(b) if there is any chance that some part of the body might accidentally (or even deliberately, in spite of all advice) be brought close to a beta source, then an appropriate personal dosemeter should be worn on that part of the body. It is of no use to put it on some other part of the body, in view of the large variations of dose rate which can and do occur over distances of a few centimeters. The greatest risk is that people will bring their hands close to a beta emitter. Where this risk exists, a dosemeter should be worn on an appropriate part of the hand. In special cases of very inhomogeneous radiation fields, dosemeters should be worn on different parts of the body, fingers and head, for example.

3. EXPERIMENTAL PROCEDURES

The UT-$CaSO_4$:Dy 20μm thick detectors were tested in beta radiation fields. The irradiations were carried out using the Beta Secondary Standard System of the Calibration Laboratory at the Instituto de Pesquisas Energéticas e Nucleares, São Paulo, with ^{90}Sr - ^{90}Y, $^{204}T\ell$ and ^{147}Pm sources. This system consists of a source stand, a control unit with timer and different interchangeable sources. Compensation filters of plastic foils provide for field homogeneity within a diameter of 11cm at the calibration distances. The sources were calibrated in terms of absorbed dose rates to air, in air, at Physikalisch-Technische Bundesanstalt (PTB), FRG, with a Primary Standard System using an extrapolation chamber. The detectors were always placed on a 12mm thick phantom (lucite) during the irradiations. The standard thermal treatment used for UT-$CaSO_4$:Dy consisted of pre-irradiation annealing at 300°C for 3h and a post-irradiation annealing at 100°C for 15 min. The detectors were measured at the Instituto de Radioproteção e Dosimetria, Rio de Janeiro, using a Teledyne 7300C thermoluminescent reader with a special planchet, to avoid triboluminescent effects. This planchet guarantees a good thermal contact between its surface and the detector surface without damaging the detector surface.

The reproducibility of the detector TL response was initrally investigated. Groups of ten detectors were irradiated with 1.5, 7, 35 and 75 mGy (^{90}Sr - ^{90}Y) three times. Batch non-uniformity corrections were applied. The detectors lower detection limit, which may be defined as three times the standard deviation of its zero-dose reading(14), was also determined.

Absorbed dose calibration curves (TL relative to absorbed dose) were obtained for ^{90}Sr - ^{90}Y, $^{204}T\ell$ and ^{147}Pm radiations. The UT-$CaSO_4$:Dy detectors irradiated by the ^{90}Sr - ^{90}Y source received between 0.145 and 300 mGy. In the case of $^{204}T\ell$, the TL response was measured from 0.1 to 100 mGy, while for ^{147}Pm the detectors were exposed to radiation between 0.1 and 45 mGy.

The dependence on beta absorbed dose rate was investigated for the UT-$CaSO_4$:Dy TL response using a ^{90}Sr - ^{90}Y source. In another experiment, the ^{90}Sr - ^{90}Y irradiated detectors were exposed to the ultraviolet (UV) radiation of a high pressure mercury lamp (250nm) provided with a monochromator and a radiometer, to study the possibility of optical fading. The radiant exposure was varied between 2.6×10^2 and 24.8×10^2 $J.m^{-2}$.

The angular dependence of the TL response was obtained for ^{90}Sr - ^{90}Y, $^{204}T\ell$ and ^{147}Pm sources at angles of 0°, 30°, 45°, 60°, 90°, 120°, 135°, 150° and 180°. 0° incidence angle means a frontal irradiation.

Transmission factors for different thicknesses of tissue-equivalent material were obtained for UT-$CaSO_4$:Dy using the three available beta sources. Hostaphan foils with thicknesses of tissue-equivalent material varying from

0.32 up to 4.6 mg.cm^{-2} and from 0.32 up to 25.9 mg.cm^{-2} were used in the case of the ^{147}Pm and ^{204}Tℓ irradiations respectively. For the ^{90}Sr - ^{90}Y irradiations, Hostaphan foils and Plexiglas plates were used as absorber materials. The maximum thickness obtained with the Hostaphan foils was 38.9 mg.cm^{-2}. With Plexiglas plates it was possible to vary the thickness from 163.5 up to 326.9 mg.cm^{-2}. The source-detector distance was 30, 15 and 15cm respectively for ^{90}Sr - ^{90}Y, ^{204}Tℓ and ^{147}Pm sources. The transmission factors for Hostaphan foils and Plexiglas plates were converted to transmission factors for soft tissue by assuming relative attenuation factors to tissue equal to 0.92 and 1.01 respectively(15).

The energy dependence of the UT-$CaSO_4$:Dy TL response per unit beta absorbed dose in air was also determined for ^{90}Sr - ^{90}Y, ^{204}Tℓ and ^{147}Pm radiation fields.

4. RESULTS AND DISCUSSIONS

For beta absorbed dose values greater than 1 mGy, UT-$CaSO_4$:Dy presented a reproducibility of better than 3%. Figure 1 shows the reproducibility curve for UT-$CaSO_4$:Dy. This curve can be described by a two-parameter fit(14,16):

$$S = \left[\frac{A^2}{D^2} + B^2\right]^{1/2} ,$$

where S is the reproducibility of the TL response for an absorbed dose value D in mGy, B is the relative standard deviation at high doses (1.3% for UT-$CaSO_4$:Dy) and A is the absolute standard deviation for the detector zero-dose reading (29 µGy for UT-$CaSO_4$:Dy). The value 1.3% is the mean relative standard deviation obtained from detectors irradiated with 75 mGy. The value 29 µGy is the mean absolute standard deviation obtained from three zero-dose readings of a group of ten detectors. For this case the calibration factor obtained from the 75 mGy irradiations was used. A linearity correction factor obtained from figure 2, curve A, which displays the absorbed dose calibration curve for the detector irradiated with the ^{90}Sr - ^{90}Y source, was applied. The lower detection limit determined was 87 µGy.

The detectors irradiated with the ^{90}Sr - ^{90}Y source presented a linear response from 0.5 mGy (Figure 2, curve A). In the case of ^{204}Tℓ, the linear response behaviour was observed from 1 mGy (Figure 2, curve B), while for ^{147}Pm the detectors presented a linear response from 2 mGy (Figure 2, curve C). No dependence on beta absorbed dose rate, within an uncertainty of 1% (1σ), was found for the UT-$CaSO_4$:Dy TL response. The detectors presented optical fading (Table 1). In the most unfavourable case (90°) the observed angular dependence in relation to a frontal irradiation were 70, 75 and 73% respectively for ^{90}Sr - ^{90}Y, ^{204}Tℓ and ^{147}Pm beta rays.

The energy dependence of the detector TL response per unit beta absorbed dose in air is shown in figure 3, curve A. It can be observed that the detector underestimates by 60% the beta absorbed dose in air for a ^{147}Pm irradiation.

This causes a greater lower detection limit approximately equal to 139 μGy for low-energy beta radiation. For beta absorbed dose values below 2 mGy (^{147}Pm irradiation) the UT-$CaSO_4$:Dy TL response is not linear (Figure 2, curve C). Therefore the calibration curve 2C must be used if the detector is intended to be utilized for the assessment of such low doses.

Table 2 presents the transmission factors obtained for different thicknesses of tissue-equivalent material for UT-$CaSO_4$:Dy. These results showed an agreement of better than 10% with those reported by Murthy and Böhm$^{(7)}$ for the same sources. The results can not be directly compared because the experimental conditions were different.

5. PROPOSAL OF A DOSEMETER

For practical purposes, the ICRP$^{(4)}$ recommends that the skin dose due to beta radiation should be determined at a depth of 7 mg.cm^{-2}. It is therefore necessary to calibrate the dosemeter for beta absorbed dose values at this depth. The beta absorbed dose at a depth of 7 mg.cm^{-2} tissue-equivalent material can be determined from the beta absorbed dose to air, in air, using conversion factors equal to 1.111, 1.139 and 1.15 respectively for ^{90}Sr - ^{90}Y, ^{204}Tℓ and ^{147}Pm sources, and transmission factors respectively equal to 1.068, 0.955 and 0.20 for the same sources$^{(17,18)}$. The TL response (R_t) of the UT-$CaSO_4$:Dy dosemeters irradiated under different thicknesses (t) of tissue-equivalent material can be computed, for a certain beta mean energy value, using the transmission factors (T_t) obtained for the detector beneath different layers of tissue-equivalent material (Table 2). Thus,

$$R_t = R_0 . T_t$$

where R_0 is the TL response of the dosemeters irradiated without a tissue-equivalent layer for the beta mean energy considered.

The TL response beneath an absorber thickness t (R_t) per unit absorbed dose to tissue at a depth of 7 mg.cm^{-2} (D_7) is

$$F = R_t / D_7 .$$

The resulting energy dependence curves for different absorber thicknesses are shown in Figure 3, curves b (1-6). It can be obserbed that for a tissue-equivalent material layer of 3.4 mg.cm^{-2}, the UT-$CaSO_4$:Dy TL response per unit absorbed dose to tissue at a 7 mg.cm^{-2} depth presents an energy independence of better than 12% in the beta radiation mean energy range in question.

This procedure is general and may be applied to different detectors, in order to select a suitable absorber thickness which could improve the energy dependence of their TL response per unit abosrbed dose to tissue at a depth of 7 mg.cm^{-2}.

A dosemeter is proposed consisting of two UT-$CaSO_4$:Dy detectors. One detector is placed under a layer of 3.4 mg.cm^{-2} tissue-equivalent material and is used to assess the skin dose at a depth of 7 mg.cm^{-2} with an energy independence of better than 12%. It is necessary to use an opaque material, aluminised Mylar for instance, since the detector presents optical fading. The other detector is placed under a 10mm Lucite layer (made opaque) and is used to evaluate the high-energy gamma radiation contribution after a proper calibration.

6. CONCLUSIONS

Ultra-thin $CaSO_4$:Dy TL detectors show some interesting characteristics for skin beta dose assessment. Their TL response has good reproducibility, although the use of a special planchet is necessary in order to avoid triboluminescent effects. They have a good lower detection limit (87 μGy). Since the detectors showed optical fading, they must be used with a cover of opaque tissue-equivalent material. Under a layer of 3.4 $mg.cm^{-2}$ tissue-equivalent material the detector can be used to determine the skin beta dose at a depth of 7 $mg.cm^{-2}$ with an uncertainty, due to its energy dependence, of better than 12%. It is necessary to emphasise that the usefulness of the proposed beta dosemeter is potential. Tests under routine conditions are necessary to prove the good performance of such a dosemeter.

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Table 1: Optical fading of UT-$CaSO_4$:Dy detectors

RADIANT EXPOSURE x 10^2 ($J.m^{-2}$)	OPTICAL FADING (%)
2.6	3.6
7.4	11.5
15.5	26.1
24.8	48.7

Table 2: Transmission factors for beta radiation sources using UT-$CaSO_4$:Dy detectors

TISSUE THICKNESS		SOURCE		
(mm)	($mg.cm^{-2}$)	^{147}Pm	$^{204}T\ell$	^{90}Sr - ^{90}Y
0	0	1.000	1.000	1.000
0.01	1	0.820	0.988	1.008
0.02	2	0.670	0.973	1.014
0.04	4	0.435	0.948	1.022
0.05	5	0.345	0.933	1.028
0.07	7		0.908	1.034
0.10	10		0.868	1.044
0.20	20		0.740	1.072
0.50	50			1.100
1.00	100			1.083
2.00	200			0.872
3.00	300			0.702

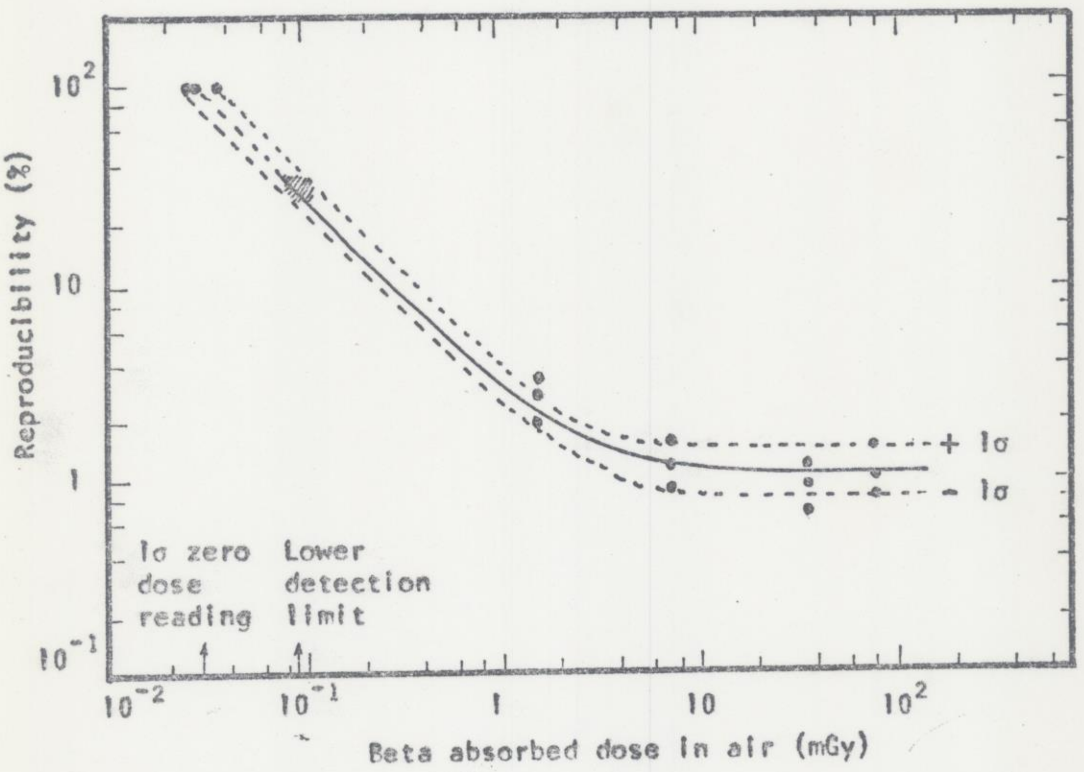

Figure 1 - Reproducibility curve of UT-$CaSO_4$:Dy

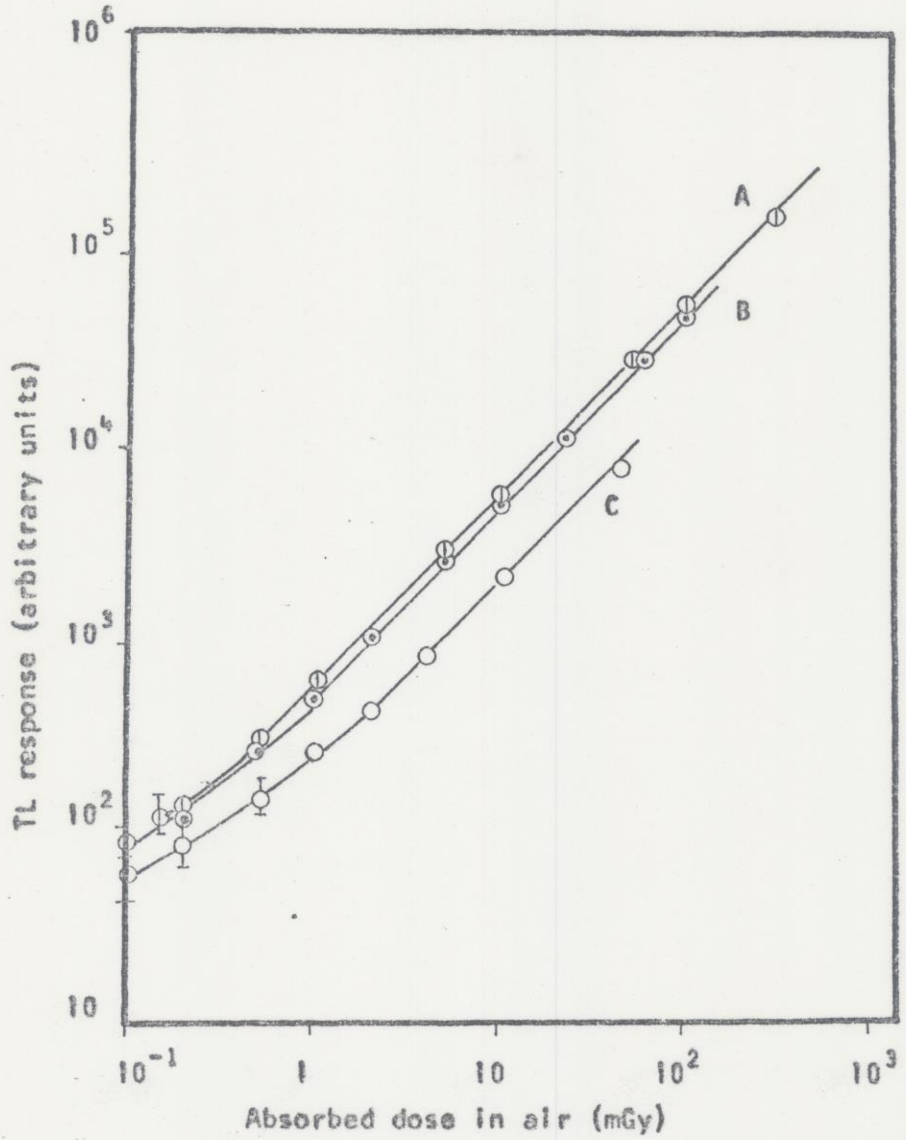

Figure 2 - TL response as a function of absorbed dose in air for ^{90}Sr - ^{90}Y (A), ^{204}Tℓ (B) and ^{147}Pm (C) radiation fields

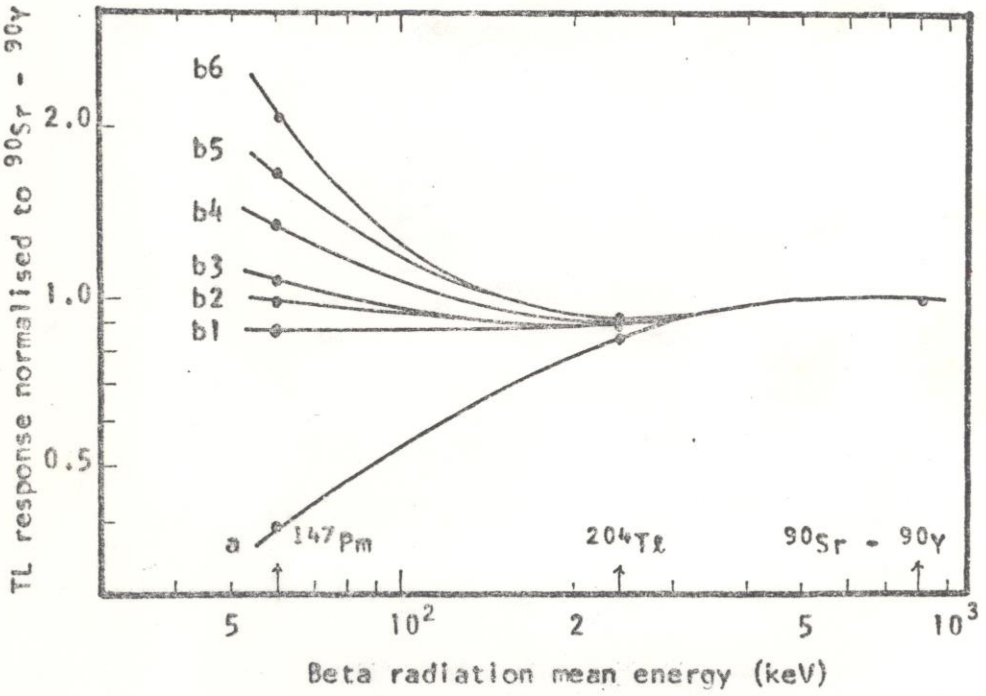

Figure 3 - Energy dependence of UT-$CaSO_4$:Dy response per unit absorbed dose. Curves: a, in air; b, at a depth of 7 $mg.cm^{-2}$ to soft tissue with the following thicknesses of tissue-equivalent material overlying the detector: b1, 4 $mg.cm^{-2}$; b2, 3.4 $mg.cm^{-2}$; b3, 3 $mg.cm^{-2}$; b4, 2 $mg.cm^{-2}$; b5 1 $mg.cm^{-2}$; b6, 0 $mg.cm^{-2}$