Comparison of the Energy and Angular Responses of Thermoluminescent and Electronic Personal Dosimeters

Filip Haralambos Apostolakopoulos, Nikola Kržanović, Luka Perazić, Miloš Živanović, Koviljka Stanković

***Abstract*—Determination of the response of thermoluminescent and electronic personal dosimeters as a function of photon energy and angle of incidence has a crucial impact on their application in poly-energetic multidirectional photon radiation fields. In the experimental part of this paper, in order to determine the energy dependence of the dosimeter responses, the dosimeters were mounted on an ISO slab phantom, irradiated in X and gamma ray fields, defined in the IAEA SRS 16, within the energy range of 33 keV - 1,25 MeV. Tested dosimeters have not shown an adequate response in the low photon energies relative to their Cs-137 responses, while in the middle and high energy photon ranges they performed well and have shown a deviation relative to their Cs-137 responses up to ±20%. In order to determine the angular dependence of the dosimeters the N-200 narrow beam radiation quality has been used. The angles of incidence for which the dosimeters were tested range from 0° to 80°, with an increment of 20°. Most of the dosimeters have behaved as expected, except for certain dosimeters due to their significant increase in response caused by the influence of the scattered radiation.**

***Index Terms*—personal dosimeter, energy, angle, response, X-ray field, gamma ray field.**

I. INTRODUCTION

The estimation of exposure levels is measured with personal dosimeters. The personal dose equivalent Hp(10) is used for approximation of the effective dose of external exposure. The personal dose equivalent Hp(*d*) is a quantity defined for the ICRU (International Commission on Radiation Units and Measurements) tissue at the depth of *d* in the human body under the position where the dosimeter is worn by the user, and it represents an operational quantity for personal monitoring [1,2]. The ICRU tissue is a material with a density of 1 g/cm^3 and is consisted of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen. This material is an adequate approximation of the human tissue [1]. The measurement unit for the personal dose equivalent is Sievert (Sv). The depth *d* is expressed in millimeters. The ICRU recommends a depth of 10 mm for strongly penetrating radiation (personal dose equivalent Hp(10)), while for weakly penetrating radiation the recommended depth for the skin is 0.07 mm, and 3 mm for the eye lens (personal dose equivalent Hp(0.07) and Hp(3), respectively) [1,2].

The personal dose equivalent is defined for the human body, meaning that personal dosimeters cannot be calibrated in real-life conditions, which is why appropriate phantoms are used as a substitution for the human body during the calibration (slab, pillar or rod phantoms) [3,4].

The measured values of the personal dose equivalent take into consideration attenuation and scattering of the incident photon beams but they differ from one person to another and are position dependent. In anisotropic fields the values of the personal dose equivalent depend on the orientation of the person wearing the dosimeter in the radiation field.

Since thermoluminescent dosimeters are considered reliable and are widely used in the field of personal dosimetry, the aim of this paper was to compare the energy and angular responses of electronic personal dosimeters to those of thermoluminescent dosimeters.

II. CHARACTERISTICS OF THERMOLUMINESCENT AND ELECTRONIC PERSONAL DOSIMETERS

Thermoluminescent dosimeters (TLDs) are passive accumulating dosimeters of ionizing radiation. While passing through the thermoluminescent material radiation particles produce electron-hole pairs. The generated charge is trapped on discrete energy levels in the forbidden energy zone of the semiconductor crystal (the traps are formed due to existence of impurities in the crystal structure). The number of trapped electron-hole pairs is proportional to the number of pairs generated inside the crystal. By heating up the crystal after exposing it to ionizing radiation (and charge accumulation in the traps), the recombination of electron-hole pairs is induced. This process is followed by the emission of photons from the visible spectrum of electromagnetic radiation. The photomultiplier tube converts emitted photons into electrical pulses, whose intensity is proportional to the absorbed dose [5,6].

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Electronic personal dosimeters (EPDs) are active dosimeters which directly display the absorbed dose information or the absorbed dose rate information. By exposing EPDs to ionizing radiation, charge pairs are generated in their active volume (electron-ion pairs in the fill gas mixture of the Geiger-Müller tube or electron-hole pairs in the space charge region of the semiconductor), which are collected using the applied voltage. The electrical field accumulates the generated charge on the electrodes of the radiation detectors. The number of collected charge pairs represents the electrical signal of EPDs, which is proportional to the absorbed dose [7,8].

III. THE EXPERIMENT

In the experimental procedure the passive MTS-N TLDs (Mirion Technologies) which contain LiF:Mg,Ti crystals have been used along with 4 different kinds of EPDs for comparison: a GPD 100+ (Graetz), a RAD 60 S (Rados), an EPDMk2 (Thermo Fisher Scientific) and a PM1610B (Polimaster). The GPD 100+ and the PM1610B contain a Geiger-Müller (GM) tube, while the RAD 60 S and the EPDMk2 contain a silicon semiconductor diode detector.

A water slab phantom of polymethyl-methacrylate (PMMA) walls has been used. PMMA is a material with a density of 1,19 g/cm^2 and the structural composition is 8,05% hydrogen, 59,99% carbon and 31,96% oxygen [4].

A spherical ionization chamber has been used to measure the values of air kerma rates of Co-60 and Cs-137 gamma radiation sources, and of the N-40, N-60, N-100, N-200 and N-300 narrow X-ray beam qualities [9].

The measurements of the air kerma rates have been repeated 10 times for each radiation quality for the duration of 1 minute. Along with the spherical ionization chamber (which is a secondary standard), a Unidos electrometer and monitoring chamber have been used. The monitoring chamber was used to ensure that corrections have been made to account for the voltage and current fluctuations of the X-ray tube. The personal dose equivalent rate is related to the air kerma rate by the following equation:

$$\dot{H}p(10) = \dot{K}_{air} h_k \qquad (1)$$

where h_k is a conversion factor from the air kerma rate to the personal dose equivalent rate [4].

All of the dosimeters were placed on an ISO water slab phantom (dimensions: 300 mm × 300 mm × 150 mm) at a 2 m distance from the X-ray tube. Based on the conducted measurements, the personal dose equivalent rate was 150 μSv/min. The dosimeters were irradiated for 2 minutes, meaning that the expected value of the personal dose equivalent was 300 μSv. Five units of TLDs have been irradiated for every used radiation quality (Fig. 1). Before the experiment, zero dose values of the TLDs have been read-out. The EPDs were irradiated separately for every radiation quality (as shown on Fig. 2).


Fig. 1. Five MTS-N TLDs placed on a ISO water slab phantom prior to the irradiation.


Fig. 2. A PM1610B EPD placed on the ISO water slab phantom prior to the irradiation.

The dosimeter response R is the ratio of the personal dose equivalent measured with the dosimeters (M) and the reference values of the personal dose equivalent measured with the spherical ionization chamber [4]:

$$R = \frac{M}{Hp(10)}. \qquad (2)$$

The energy responses of the dosimeters were determined for the following photon fields: N-40, N-60, N-100, N-200, N-300, Cs-137 and Co-60, while the angular responses were determined for the N-200 radiation quality at the following angles of incidence: 0°, 20°, 40°, 60° and 80°. The mean energies and the conversion factors are displayed in Table I.

TABLE I
THE MEAN ENERGIES OF THE USED PHOTON FIELDS AND THEIR AIR KERMA TO PERSONAL DOSE EQUIVALENT CONVERSION FACTORS [9].

Photon fields	Mean energy [keV]	Conversion factor [Sv/Gy]
N-40	33	1.17
N-60	48	1.65
N-100	83	1.88
N-200	164	1.57
N-300	208	1.42
Cs-137	662	1.21
Co-60	1250	1.15

IV. THE RESULTS

The used dosimeters were irradiated in 5 different narrow beam radiation qualities (N-40, N-60, N-100, N-200 and N-300), and two gamma ray fields (Cs-137 and Co-60), defined in [4]. The values of personal dose equivalents are directly measured by the EPDs, while the TLDs were read-out using the RE 2000 reader (Mirion Technologies). The measured values of the TLDs were averaged for each used radiation quality. Cs-137 was used as a reference photon field.

The measured results are displayed in Table II and they are graphically represented in Fig. 3. The deviations of the energy responses relative to the Cs-137 response are given in Fig. 4.

TABLE II
ENERGY RESPONSES R OF THE TLDS AND EPDS FOR THE N-40, N-60, N-100, N-200, N-300, CS-137 AND CO-60 PHOTON FIELDS, RELATIVE TO THEIR CS-137 RESPONSE.

Dosimeter	Energy response R, relative to the Cs-137 response with mean photon energies [keV]						
	33	48	83	164	208	662	1250
MTS-N	1.59	1.36	1.07	1.02	1.03	1	0.92
EPDMk2	0.97	0.85	1.08	1.20	1.25	1	0.91
RAD 60-S	0.05	0.85	1.40	1.18	1.20	1	0.99
GPD 100+	0.12	0.34	0.77	0.94	0.92	1	1.12
PM1610B	0.75	1.22	1.19	0.99	0.82	1	1.19

The best performing EPDs were the EPDMk2 and the PM1610B because in the used energy range they have not shown a deviation from the Cs-137 response larger than 24.9% and 25.2%, respectively. The RAD 60-S and the GPD 100+ have shown very low energy responses in low energy ranges, with deviations relative to the Cs-137 response of 94.6% and 88.4%, respectively. In the medium and high energy ranges their responses had a deviation of 19.6% and 22.5%, respectively. The TLDs have shown an increased response for low photon energies (up to 60 keV) relative to the Cs-137 response, while at photon energies higher than 60 keV, the TLDs had the closest relative response to the reference Cs-137 value. According to the experimental results it can be stated that all of the EPDs and TLDs had good energy responses for photon energies higher than 100 keV with deviations relative to Cs-137 response in the range of ±20%.

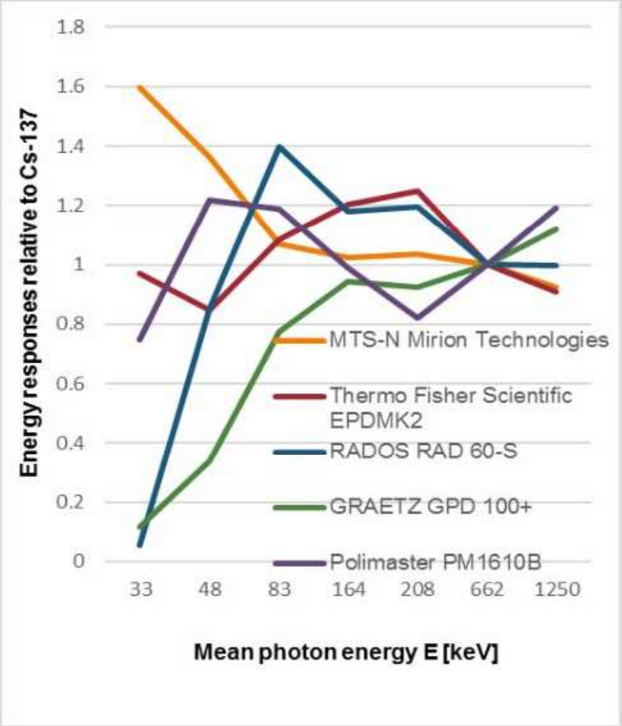

Fig. 3. The energy responses R of the dosimeters used in the experiment relative to their Cs-137 response.

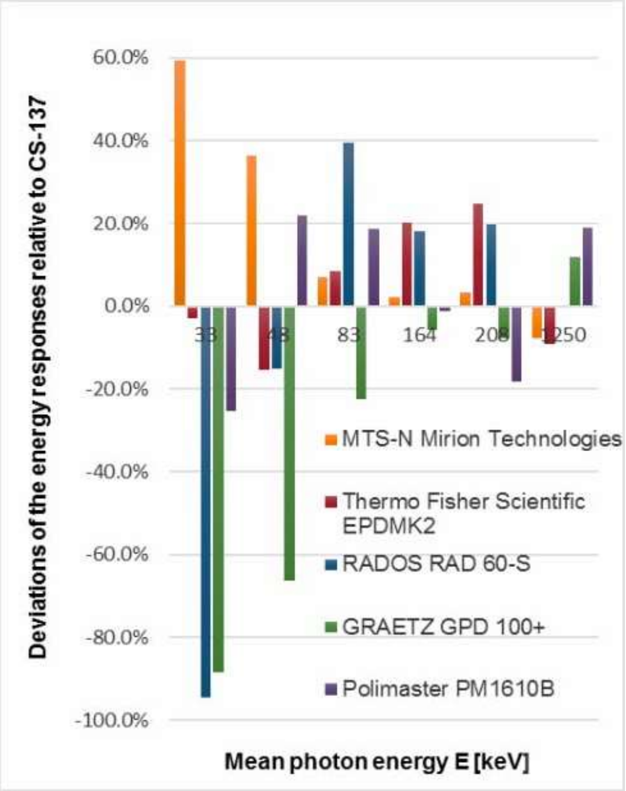

Fig. 4. The deviations of the energy responses R of the dosimeters used in the experiment relative to their Cs-137 response.

In the second part of the experiment the dosimeters were irradiated in the narrow beam N-200 X-ray radiation quality at 5 different angles of incidence: 0°, 20°, 40°, 60° and 80° [10]. The EPDs were irradiated separately. Groups of 5 TLDs were used for each incident angle and the measured values were averaged for each group. The angular responses are given in Table III, while Fig. 5 represents a graphical representation of the deviations of the angular responses, relative to the reference value measured at 0°.

TABLE III
THE ANGULAR RESPONSES R OF THE TLDS AND EPDS FOR THE N-200 RADIATION QUALITY, RELATIVE TO THEIR RESPONSE AT 0°.

Dosimeter	The angular response R for the N-200 radiation quality, relative to the response at 0°				
	0°	20°	40°	60°	80°
MTS-N	1	1.03	1.02	0.99	0.89
EPDMk2	1	0.99	1.02	1.09	1.57
RAD 60-S	1	0.99	0.99	1.01	0.81
GPD 100+	1	0.99	0.91	0.85	1.30
PM1610B	1	0.99	0.96	0.90	0.96

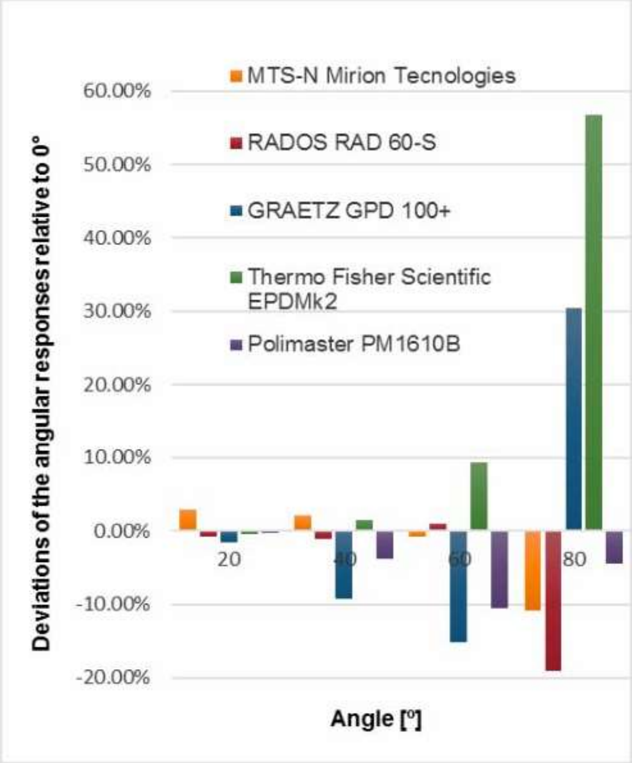

Fig. 5. The deviations of the angular responses R of the dosimeters used in the experiment relative to their response at 0°.

It was expected that the angular response values of the TLDs and EPDs would decrease with the increase of the angle. This is due to the decrease of the geometric cross-sections for the interaction of photons with the active volume of the detectors. The MTS-N, PM1610B and RAD 60-S dosimeters have behaved as expected, while the GPD 100+ and the EPDMk2 have shown a noticeable increase in their responses. This increase of the angular response of the GPD 100+ and the EPDMk2 can be accredited to the increased influence of the scattered radiation in the water slab phantom.

V. CONCLUSION

Given by the experimental results of the energy and angular responses of the TLDs and EPDs, it can be concluded that in real-life conditions (in poly-energetic, multidirectional photon fields), the MTS-N (Mirion Technologies) and the PM1610B (Polimaster) dosimeters are the most accurate. The RAD 60-S (Rados) dosimeter had a good angular response, but it has shown low response values compared to the reference Cs-137 response at low photon energies (N-40 radiation quality). The EPDMk2 (Thermo Fisher Scientific) and GPD 100+ (Graetz) dosimeters have shown significantly increased response values at the angle of incidence of 80°, whereby the GPD 100+ has shown a low energy response at low photon energies, compared to its Cs-137 response. The EPDMk2 has shown satisfactory results even in low energy X-ray fields. Determination of the angular and energy responses of personal dosimeters for X and γ photon fields is of great significance for their practical application, in areas of personal dosimetry and radiation protection.

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