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Low-energy X-ray Angular Response of Optically Stimulated Luminescent Dosimeters

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

***Abstract*—Following the requirements of radiation protection international standards, passive dosimetry systems are type tested, which includes the angular dependence. As it represents one of the most important dosimeter characteristics, the angular dependence of commercially available optically stimulated luminescent dosimeters has been examined in this paper. The empirically determined air kerma to the personal dose equivalent conversion coefficients decrease as the angle of incidence increases. It was anticipated that the dosimeter response would show a similar behavior. This expectation has been confirmed for all the used angles of incidence and energies of the primary X-ray beam, except for the 80° angle of incidence and the 33 keV and 48 keV mean photon energies, where an increase in the angular response has been observed.**

***Index Terms*—angular dependence; low-energy X-ray photons; OSL dosimeters**

I. Introduction

Optically stimulated luminescent dosimeters (OSLDs) represent a standard passive dosimetry system used for personal dosimetry and environmental monitoring of ionizing radiation. Thus, it is important to perform type testing of these dosimeters in laboratory conditions in standard photon radiation fields, so their performance in real-life uses can be properly examined. In medical applications (e.g. medical imaging), omnidirectional scattered radiation has a great impact on the measured values of operational dosimetric quantities, such as the personal dose equivalent. Various medical applications employ low-energy X-ray radiation fields, which is why in this paper the angular dependence of OSLDs was determined for X-ray photons up to the energy of 100 keV.

The personal dose equivalent $H_p(10)$ is used for the approximation of the effective dose of external exposure in personal radiation monitoring. It is defined for the ICRU tissue at the depth of 10 mm in the human body under the position where the dosimeter is worn by the user. $H_p(10)$ is defined for strongly penetrating radiation, which includes X-rays [1]. The values of this operational dosimetric quantity vary from one person to another since they are position and orientation dependent.

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II. Materials and Methods

OSLDs represent passive accumulating dosimeters of ionizing radiation. When exposed to ionizing radiation, electron-hole pairs are created and trapped in the pre-existing defects within the crystal lattice. Illumination triggers the OSL process, resulting in electron-hole recombinations, which are followed by the emission of photons. The photon intensity is a function of the absorbed dose in the material. A photomultiplier tube converts these photons into an electrical signal. The stimulation photons and the emitted photons have different wavelengths, and only a small amount of the generated charge is needed for the dose information (i.e. the OSLDs can be read multiple times) [2].

In the experimental part of this paper, InLight OSLDs, manufactured by Landauer [3], were examined. They contain four Al_2O_3:C powder crystals under different filters (open window, plastic, copper and aluminum). All of the crystals are needed for the dose information and their sensitivity is provided by the manufacturer. The dosimeters are read using a microStar reader (also manufactured by Landauer), which has 38 green light-emitting diodes operating in the continuous-wave mode [3].

The angular dependence of the OSLDs has been determined for four narrow-beam X-ray radiation qualities (N-series), established according to international standards [4]. These radiation qualities are defined by their photon spectrum, or in practice, by their maximum X-ray tube voltage (maximum photon energy), and half-value layer (mean photon energy) [5]. The used radiation qualities were N-40, N-60, N-80 and N-100, with mean photon energies of 33 keV, 48 keV, 65 keV and 83 keV, respectively. The range of angles of incidence was from 0° to 80°, with an increment of 20°. The personal dose equivalent value that was delivered to the dosimeters was 1 mSv.

The dosimeter angular dependence is expressed as the ratio of the value measured by the dosimeter at a given angle of incidence and the reference value at 0°. The personal dose equivalent rate was calculated by converting the air kerma rate value (measured by the secondary standard ionization chamber), with the h_k conversion coefficients. These coefficients display an energy and angular dependence [6].

The angular dependence of the air kerma to the personal dose equivalent conversion coefficients (h_k) for the previously mentioned radiation qualities is shown in Table I.

TABLE I
THE ANGULAR DEPENDENCE OF THE AIR KERMA TO THE PERSONAL DOSE EQUIVALENT CONVERSION COEFFICIENTS FOR THE N-40, N-60, N-80 AND N-100 RADIATION QUALITIES [6].

h_k	Angle of incidence	0°	20°	40°	60°	80°
Radiation quality	N-40	1.17	1.15	1.06	0.85	0.32
	N-60	1.65	1.62	1.52	1.27	0.60
	N-80	1.88	1.86	1.76	1.50	0.80
	N-100	1.88	1.86	1.76	1.53	0.86

The OSLDs were mounted on an ISO water slab phantom (shown on Fig. 1), which was placed on a rotating wheel. The dosimeters were aligned with the wheel's vertical axis of rotation, in order to keep the distance of 2 m between the dosimeters and the focal point of the X-ray tube unchanged during the irradiations. For each angle of incidence and each radiation quality, a sample of five OSLDs was irradiated.

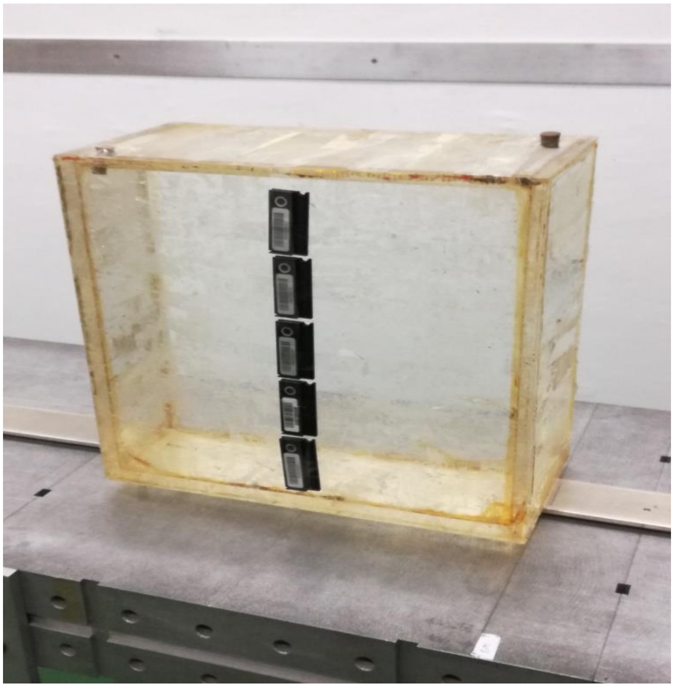

Fig. 1. Five InLight OSLDs mounted on an ISO water slab phantom.

Equation (1) from the Student's t-distribution was used for the measurement uncertainty calculations (with the confidence level of 95%), due to the small sample size:

$$U = t \frac{s}{\sqrt{n}}, \tag{1}$$

where t represents the t-parameter of the Student's distribution, s is the standard deviation of the sample, and n represents the sample size [7].

III. RESULTS AND DISCUSSION

The angular dependence of the InLight OSLDs was tested for low-energy X-ray radiation qualities, established according to international standards [4]. For each radiation quality, the reference values for the angular response were the 0° angle of incidence values.

At the angle of incidence of 20°, for all the tested radiation qualities, the dosimeter under-response was below 12% (maximum -11.08% for the N-80 radiation quality), while for the 40° angle of incidence, the dosimeter under-response was below 25% (maximum -24.20% for the N-80 radiation quality). At the angle of incidence of 60°, the measured $H_p(10)$ values have significantly dropped and the dosimeter under-response has increased for every radiation quality (maximum -44.70% also for the N-80 radiation quality). At the angle of incidence of 80°, the measured $H_p(10)$ values have continued to decline for the N-80 and N-100 radiation qualities (maximum -50.57% deviation from the respective reference 0° value for the N-100 radiation quality). On the contrary, for the N-40 and N-60 radiation qualities, the InLight dosimeters have exhibited an increase in response relative to the respective 60°, and even to the respective 40° values. The only over-response in reference to the respective 0° value, was observed for the N-40 radiation quality at the 80° angle of incidence (measured at just +1.30%).

The measured $H_p(10)$ values for the used radiation qualities and angles of incidence are given in Table II, while the deviations from the respective reference values at 0° are listed in Table III.

TABLE II
THE MEASURED $H_P(10)$ VALUES FOR THE N-40, N-60, N-80 AND N-100 RADIATION QUALITIES AND THE 0°, 20°, 40°, 60° AND 80° ANGLES OF INCIDENCE.

$H_p(10)$ [mSv]	Angle of incidence	0°	20°	40°	60°	80°
Radiation quality	N-40	1.002	0.947	0.860	0.678	1.015
	N-60	1.098	1.055	0.866	0.706	0.915
	N-80	1.306	1.162	0.990	0.722	0.712
	N-100	1.208	1.192	1.125	0.816	0.597

TABLE III
THE DEVIATIONS FROM THE RESPECTIVE REFERENCE VALUES AT 0° FOR THE N-40, N-60, N-80 AND N-100 RADIATION QUALITIES AT THE 20°, 40°, 60° AND 80° ANGLES OF INCIDENCE.

Deviation [%]	Angle of incidence	20°	40°	60°	80°
Radiation quality	N-40	-5.43	-14.19	-32.32	+1.30
	N-60	-3.94	-21.09	-35.67	-16.63
	N-80	-11.08	-24.20	-44.70	-45.51
	N-100	-1.29	-6.89	-32.45	-50.57

The measured $H_p(10)$ values for the mentioned radiation qualities and angles of incidence are graphically represented in Fig. 2, while the deviations from the respective reference values at 0°, along with the corresponding measurement uncertainties are shown in Fig. 3.

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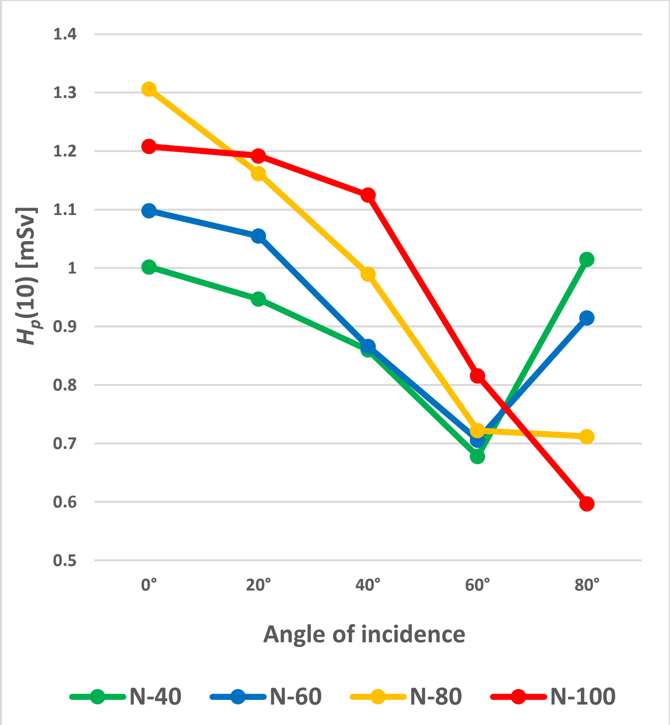

Fig. 2. The measured $H_p(10)$ values for the N-40, N-60, N-80 and N-100 radiation qualities at the 0°, 20°, 40°, 60° and 80° angles of incidence.

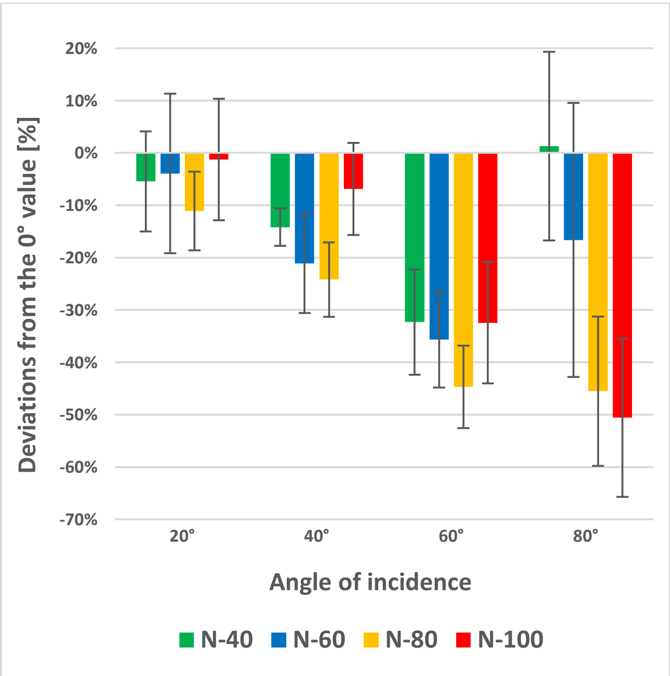

Fig. 3. The deviations from the respective reference values at 0° for the N-40, N-60, N-80 and N-100 radiation qualities at the 20°, 40°, 60° and 80° angles of incidence, along with the corresponding measurement uncertainties.

The cause of the large measurement uncertainties, which can be clearly observed on Fig. 3, lies in the fact that the Al_2O_3:C crystal sensitivity cannot be calibrated, but instead is provided by the manufacturer. During use, the crystal sensitivity changes over time, which has a direct impact on the dosimeter's reading, and can lead to large measurement uncertainties.

IV. Conclusion

Landauer's InLight OSLDs, examined in this paper, have demonstrated an angular dependence for all the used radiation qualities. At the angles of incidence of 20° and 40°, the largest deviations from the respective reference values at 0° were -11.08% and -24.2%, respectively. At the 60° angle of incidence, an expected decline in the dosimeter response was observed. At the 80° angle of incidence, for the N-80 and N-100 radiation qualities, the dosimeter under-response had increased (reaching a maximum of -45.51% and -50.57%, respectively). On the other hand, at the same angle of incidence, for the N-60 radiation quality, the InLight dosimeters displayed an increase in response (-16.63% from -35.67%), while for the N-40 radiation quality, even a slight over-response of +1.30% was observed.

For the N-40, N-60, N-80 and N-100 radiation qualities at the 20°, 40°, 60° and 80° angles of incidence, the InLight dosimeters have always displayed an expected under-response in reference to the respective 0° $H_p(10)$ values (except in the case of the N-40 radiation quality and the angle of incidence of 80°). One of the causes for the expected dosimeter under-response lies in the angular dependence of the air kerma to the personal dose equivalent conversion coefficients h_k.

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