COMPARISON OF EXPERIMENTAL AND SIMULATED RESPONSES OF TL AND OSL DOSIMETERS IN POLY-ENERGETIC AND MULTI-DIRECTIONAL PHOTON RADIATION FIELDS

by

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The aim of this paper is to examine the energy and angular responses of thermoluminescent (LiF:Mg,Ti and LiF:Mg,Cu,P) and optically stimulated luminescent (Al_2O_3:C) dosimeters with experimental measurements and Monte Carlo simulations. Nine radiation qualities, with mean energies ranging from 33 keV to 1.25 MeV, and five angles of incidence, between 0° and 80°, were used to conduct this analysis. The IEC 62387:2020 international radiation protection standard was used as the dosimeter response measure of quality. The experimental and simulated data exhibit that the dosimeter responses meet the standard's criteria, with certain exceptions on lower energies.

Key words: angular response, energy response, Monte Carlo simulation, optically stimulated luminescence, personal dosimetry, photon radiation, thermoluminescence

INTRODUCTION

Passive personal dosimeters are included in the regulatory control of occupationally exposed personnel. Dosimeters are used for the estimation of the user's effective dose by measuring either the personal dose equivalent or the ambient dose equivalent. Aside from the most commonly used thermoluminescent dosimeters (TLD), optically stimulated luminescent dosimeters (OSLD) are increasingly adopted [1-4]. In previous research, for the purpose of assessing the performance and compliance of these types of dosimeters with international radiation protection standards, they have been irradiated in a wide range of photon energies and angles of incidence [5]. These fields can often be found in various ionizing radiation applications (industry and medicine, including diagnostic radiology and radiotherapy), while different angles of incidence were used to realistically represent real-time workplace radiation exposure conditions. The focus of contemporary research is mostly related to the performance of passive dosimetry systems in low-energy radiation fields, where numerous radiation protection instruments exhibit either a pronounced over-or under-response or even the inability to perform remotely accurate dosimetric measurements [2, 6]. These effects have been reported in specific applications of ionizing radiation, such as diagnostic radiology, and low-energy radioisotope brachytherapy [6, 7]. In this research two types of TL detectors were used – LiF:Mg,Ti and LiF:Mg,Cu,P, along with one type of OSL detectors – Al_2O_3:C. Monte Carlo simulations represented a method of validation of the previous experimental results. Similar research evaluated the performance of TL detector materials by using experimental measurements along with Monte Carlo simulations [8-10].

This paper aims to compare and validate the beforementioned experimental results with Monte Carlo simulations and to analyze if the simulated energy and angular responses of the tested dosimeters fulfill the requirements of the international radiation protection standard IEC 62387:2020 [11]. These dosimeter characteristics represent crucial considerations for their use in various fields where radiation monitoring is required, including industrial, medical, military, and environmental applications.

MATERIALS AND METHODS

The TL dosimeters

The TLD used in the experimental procedures have consisted of a slider and a filtered holder, pro-

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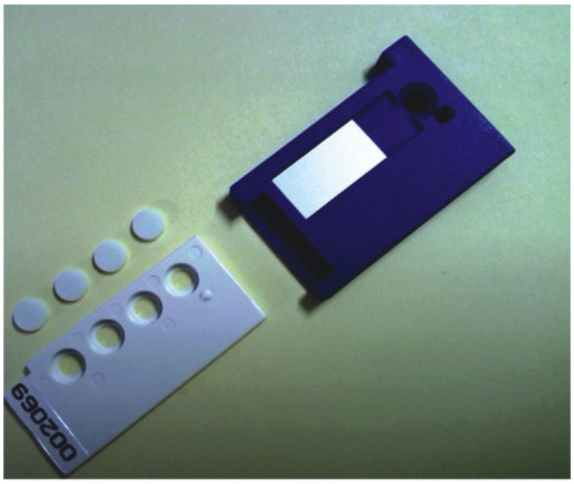

Figure 1. The TLD components: detector elements, a slider, and a filtered holder

duced by Mirion Technologies [12], with either MTS-N (LiF:Mg,Ti) or MCP-N (LiF:Mg,Cu,P) detectors, manufactured by TLD Poland [13, 14]. Although the case itself can hold up to four crystals, fig. 1, only two are needed for the calculation of the personal dose equivalent $H_p(10)$, which is determined as the average dose value of the two crystals under the 0.5 mm aluminum filters [15]. This is the rationale why the plastic filter and the unfiltered slots were left empty during the experimental procedures. After irradiations, the TLD were read with a RE2000 reader, also produced by Mirion Technologies [12]. For further reference, TLD with MTS-N or MCP-N detectors will be denominated as MTS-N or MCP-N dosimeters, respectively.

The OSL dosimeters

Landauer's InLight OSLD [16], inherently contain four Al_2O_3:C detector elements under various filters (aluminum, copper, plastic, and unfiltered), fig. 2. Since the dosimeters were invariably irradiated at 1 mSv, the low dose function was automatically selected on the microStar reader for better photomultiplier tube sensitivity during readouts, as doses equal to or above 100 mSv are classified as high [16]. Counts from all four detector elements are used for the calculation of the personal dose equivalent value. An algorithm can accommodate a range of photon energies from 20 keV to over 1.3 MeV without prior irradiation field knowledge by using smooth correction factor curves based on individual detector count ratios [17]. The microStar reader is also manufactured by Landauer [16].

Irradiation time

A secondary standard spherical cavity ionization chamber and electrometer system measured the reference air kerma rate values of the used radiation qualities, which were previously established in reference to

Figure 2. The OSLD components: a slider containing detector elements, and a filtered holder

ISO 4037-1 [18]. Narrow-energy spectrum or N-series radiation qualities represented reference X-ray fields, while radioisotopes ^{137}Cs (S-Cs) and ^{60}Co (S-Co) represented reference gamma radiation fields. The irradiation time needed to deliver the predefined personal dose equivalent value was calculated with the following

$$\tau(E,\theta) \quad \frac{H_p(10)}{\dot{H}_p(10)} \quad \frac{H_p(10)}{Q(E) N_k(E) h_k(E,\theta)} \qquad (1)$$

where $Q(E)$ represents the ionization chamber and electrometer system collected charge, $N_k(E)$ the calibration coefficient of the ionization chamber, and $h_k(E,\theta)$ the air kerma to personal dose equivalent conversion coefficient [19]. Quantities E and θ symbolize photon energy and photon beam angle of incidence, respectively.

Energy response experimental measurements

In the interest of examining the dosimeters' energy responses, a wide photon energy range was used, which covers mean energies from 33 keV to 1,25 MeV, tab. 1. A sum of 60 dosimeters (20 MTS-N, 20 MCP-N, and 20 InLight) was irradiated per radiation quality to obtain results with low statistical fluctuations. The dosimeters were positioned equidistantly on an ISO water slab phantom, which imitates a human torso and can accommodate up to 20 dosimeters per irradiation. The point of the test was 2 m from the radiation source and the delivered personal dose equivalent H_p (10) value was 1 mSv, regardless of the reference air kerma rate. The dosimeters' energy responses were calculated by dividing the measured $H_p(10)$ value of a

Table 1. Radiation qualities used in the experimental measurements, along with their respective mean photon energies [18]

Radiation quality	Mean photon energy [keV]
N-40	33.3
N-60	47.9
N-80	65.2
N-100	83.3
N-120	100
N-150	118
N-200	165
S-Cs	662
S-Co	1250

Table 2. The IEC 62387:2020 performance requirements for the relative response due to mean photon radiation energy and angle of incidence [11]

Mean photon energy E [keV]	Angle of incidence θ [°]	Relative energy response r
80 E 1250	0 θ 60	0.71 r 1.67

given radiation quality with the reference S-Cs value. The IEC 62387:2020 performance requirements for H_p (10) dosimeters are presented in tab. 2. It is important to point out that three out of nine used radiation qualities fall below the standard's lower mean photon radiation energy bound of 80 keV. The reason behind using these radiation qualities in the analysis is to examine how the dosimeters perform on lower photon energies and if they fulfill the standard criteria in this unprescribed range.

Angular response experimental measurements

In order to simultaneously cover wide energy and angular range during the angular response experimental measurements, three radiation qualities (N-40, N-150, and S-Cs) and five angles of incidence (0°, 20°, 40°, 60°, and 80°) were used. A total of 12 dosimeters (4 MTS-N, 4 MCP-N, and 4 InLight) were irradiated per angle of incidence and per radiation quality. The dosimeters were mounted on an ISO water slab phantom, which was previously positioned on a rotating wheel. The point of the test was 2 m from the radiation source. To ensure that the set distance was constant throughout the experimental procedure, the dosimeters were aligned with the wheel's vertical axis of rotation, fig. 3. Additionally, the irradiation times were individually calculated with eq. (1), so the delivered personal dose equivalent H_p (10) value was exactly 1 mSv for every radiation quality and angle of incidence. The dosimeters' angular responses were determined by dividing the measured H_p (10) value of given radiation quality and angle of incidence with the reference S-Cs value at 0°. According to the IEC

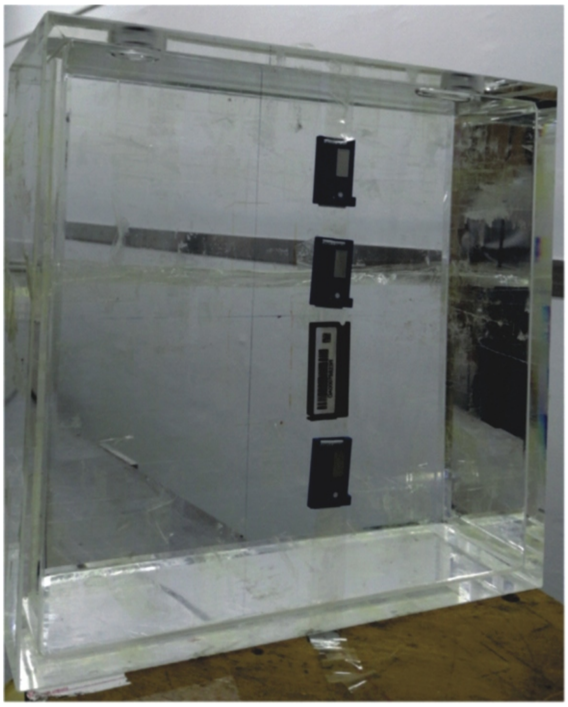

Figure 3. Angular response experimental measurements setup – four dosimeters mounted on a phantom placed on a rotating wheel

62387:2020 criteria, the incident angle rated range covers the extent from 0° to 60°. Equivalently to the case of the energy response experimental measurements, an additional angle of incidence was used to test how the dosimeters perform on large angles of incidence and if they fulfill the standard's criteria in the unprescribed range. Additionally, it is important to point out that the dosimeters' response is symmetrical, as presented in recent research of OSLD performance testing [20].

Monte Carlo Simulations

The simulations of the experimental measurements were performed with Monte Carlo code MCNPX [21]. The simulated geometry included a photon source, an ISO water slab phantom, and TL and OSL dosimeters. The phantom was modeled as a rectangular prism made of PMMA walls filled with water. The thickness of the front wall was 0.25 cm, while the other walls were 1 cm thick. An additional 3 mm PMMA layer was introduced in front of the dosimeters to account for the secondary charged particle equilibrium in high-energy S-Cs and S-Co radiation fields [18].

The simulated TLD model is represented in fig. 4. The model consists of two cylindrical tablets 4.5 mm in diameter and 0.9 mm thick. The tablets are covered by two 0.5 mm thick aluminum filters (one in front and one behind the tablets). On the other hand, the simulated OSLD model contained four cylindrical tablets 5 mm in diameter and 0.3 mm thick. Each of the four tablets has different filtration (aluminum, copper,

Figure 4. The simulated TLD model

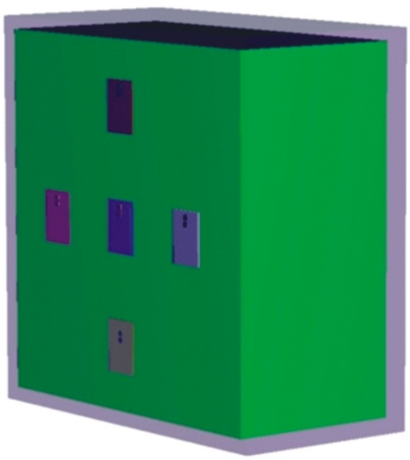

Figure 5. The simulated TLD on the phantom

plastic, or unfiltered), as specified by the manufacturer [17]. The OSLD tablets are also filtered from both sides, as in the case with TLD. Figure 5 depicts the simulated TLD on the phantom.

The tablets themselves were either made of LiF or Al_2O_3:C, whose composition was taken from [22]. Initially, the MTS-N and MCP-N dosimeters were simulated separately, but since their chemical structure barely differs, their simulated responses were practically identical. This represents the reason these two TL materials were simulated only as LiF.

The simulated photons were emitted from a point source. The distance between the source and the center of the frontal phantom surface was 200 cm. The entire frontal surface of the phantom was covered by the simulated cone beam. The N-series radiation qualities were approximated as monoenergetic sources, whose photon energy values were equal to the ISO 4037-1 mean energies [18]. The S-Cs radiation quality had a discrete energy value of 662 keV, while the S-Co quality had discrete energies of 1.17 MeV and 1.33 MeV.

As presented in fig. 5, a total of five dosimeters were placed on the phantom for the energy response simulations. On the other hand, only the three central dosimeters were used in the case of the angular response simulations, since the source was successively repositioned, as depicted in fig. 6. The distance between the source and the center of the phantom's frontal surface was constant.

The number of simulated photons was 25 million, which ensured a low relative error for all tallies. The F6 tally was used for the dosimeter-measured absorbed dose calculations, which calculated the energy deposition averaged over a cell in $MeVg^{-1}$. The calculated per particle energy deposition was converted to $H_p(10)$ value in [Sv] by using the relevant conversion coefficients [23]. To determine the absolute dosemeter response, the simulation of reference air-kerma measurement was necessary. That being the case, an additional F6 tally was positioned 1 cm in front of the frontal phantom surface center. The absolute response eq. (2) was determined as the quotient of the reference personal dose equivalent value and the average value measured by the dosimeters [24].

$$R(E, \ ) \quad \frac{K_{\mathrm{air}}(E)\; h_k(E, \ )}{H_{\mathrm{p}}(10)(E, \ )} \tag{2}$$

Additionally, the relative dosimeter responses were determined by normalizing the absolute response values, determined at certain energies and angles of incidence, to the reference absolute response determined for the S-Cs radiation quality at the 0° angle of incidence.

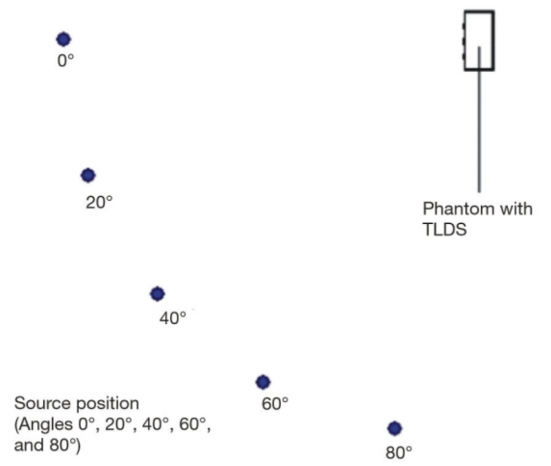

Figure 6. Angular response simulation spatial configuration

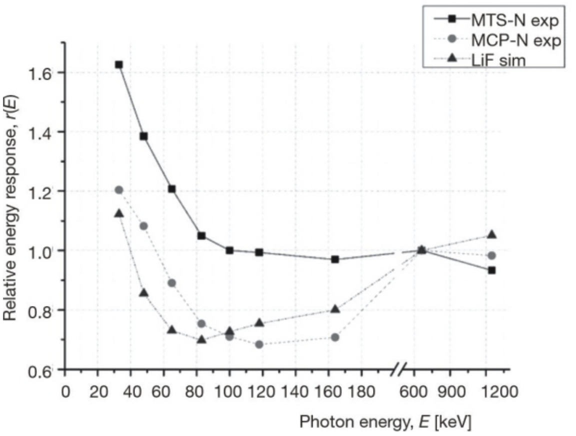

Figure 7. The TLD experimental and simulated relative energy responses

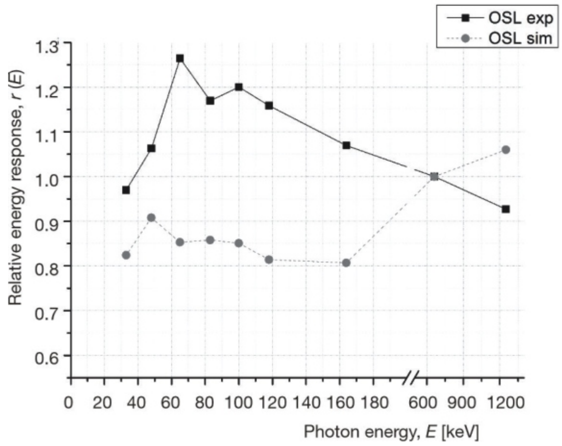

Figure 8. Thee OSLD experimental and simulated relative

RESULTS AND DISCUSSION

Energy response

The comparative experimental and simulated relative energy response results for the MTS-N and MCP-N dosimeters are presented in fig. 7. The simulated LiF-based TLD display a similar energy response trend in comparison to the experimental results. In the case of the MCP-N dosimeters, the simulated results deviate from the experimental data less than 10 %, except in the case of the N-60 and N-80 radiation qualities (approximately 22 % and 16 %, respectively). Even though the MTS-N experimental and simulated data have similar trends, a pronounced overresponse in the lower energy range is not visible in the simulated results. A possible explanation for this difference may be the approximated monoenergetic X-ray beams used in the simulations, instead of the complete X-ray spectra. As photons with energies higher than the mean energy of a given radiation quality are not present in the simulations, they cannot be absorbed by the tablets, which would certainly contribute to the absorbed dose of the dosimeters. Additionally, standard conversion coefficients may not be applicable for air-kerma to personal dose equivalent conversions, as the scattered radiation is partially accounted for.

Considering the IEC 62387:2020 criteria, the MTS-N dosimeters have performed in line with the requirements in the mandatory energy range (80 keV-1.25 MeV). Furthermore, the MTS-N dosimeters would also fulfill the standard's criteria in the unprescribed range below 80 keV. Since the experimental MCP-N and simulated LiF results are quite similar, they only fall slightly outside the standard's requirements in the case of the N-150 and N-100 radiation quality, respectively. Correspondingly, both results would meet the standard's criteria in the unprescribed range down to 33 keV.

The comparative experimental and simulated relative energy response results for the InLight dosimeters are presented in fig. 8. The simulated OSLD data displays a significant under-response in comparison to the experimental results for all the X-ray radiation qualities. The differences range from approximately 14 % (N-40) to 41 % (N-80). As before, this discrepancy could be explained due to the use of monoenergetic X-ray beams in the simulations, which leads to different low-energy photon interactions, especially absorption. Another factor to account for is that OSL dosimeters have predefined crystal sensitivities, which change over time during usage. Since there is no way to recalculate these characteristics, they can have a significant effect on the experimental results. This is a major shortcoming of these commercially used OSL dosimeters.

Regarding the IEC 62387:2020 criteria, both the experimental and simulated OSLD responses meet the criterium in the 80 keV-1..25 MeV mandatory energy range. Additionally, both results would perform in line with the standard's criteria in the unprescribed range down to 33 keV.

Angular response

The comparative experimental and simulated relative angular response results for the MTS-N, MCP-N, and InLight dosimeters are presented in figs. 9-11.

Looking at the LiF-based TL dosimeters, the simulated and experimental results for the S-Cs radiation quality are analogous for all the five angles of incidence fig. 9(a). The simulated results minimally deviate from the experimental data. The largest differences for the MTS-N and MCP-N dosimeters are for the 80° angle of incidence (8.51 % and 5.68 %, respectively). The significant under-response present at the 80° angle of incidence both in the simulated and experimental data is the result of a substantial part of the incident radiation being absorbed outside of the dosimeter crystals. Regarding the IEC 62387:2020 criteria, in the mandatory angle range (0°-60°), both the experimental and simulated

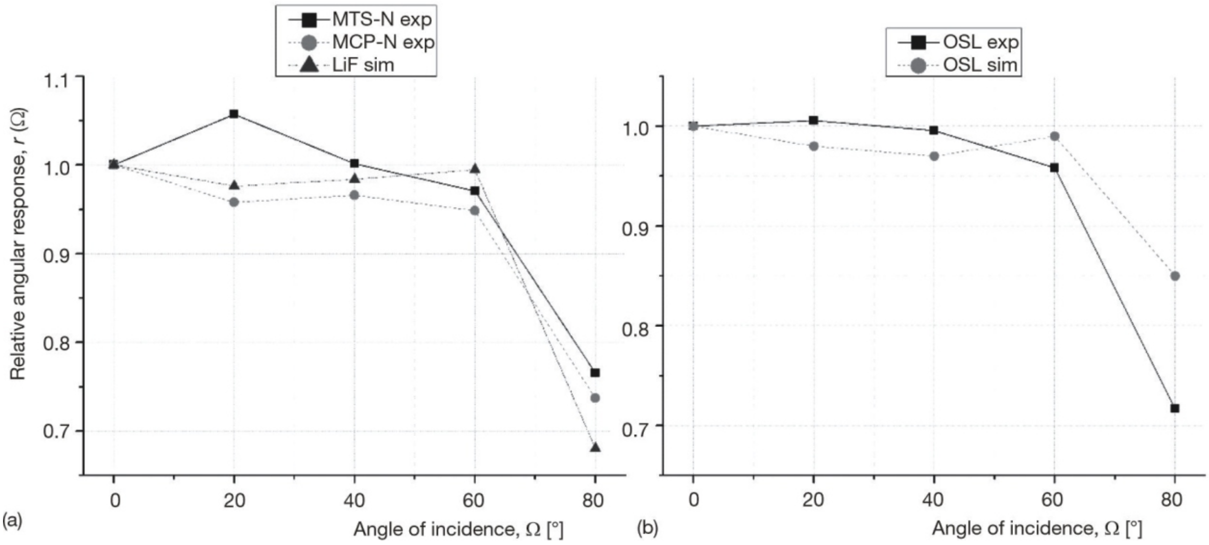

Figure 9. (a) TLD and (b) OSLD experimental and simulated relative angular responses for the S-Cs radiation quality

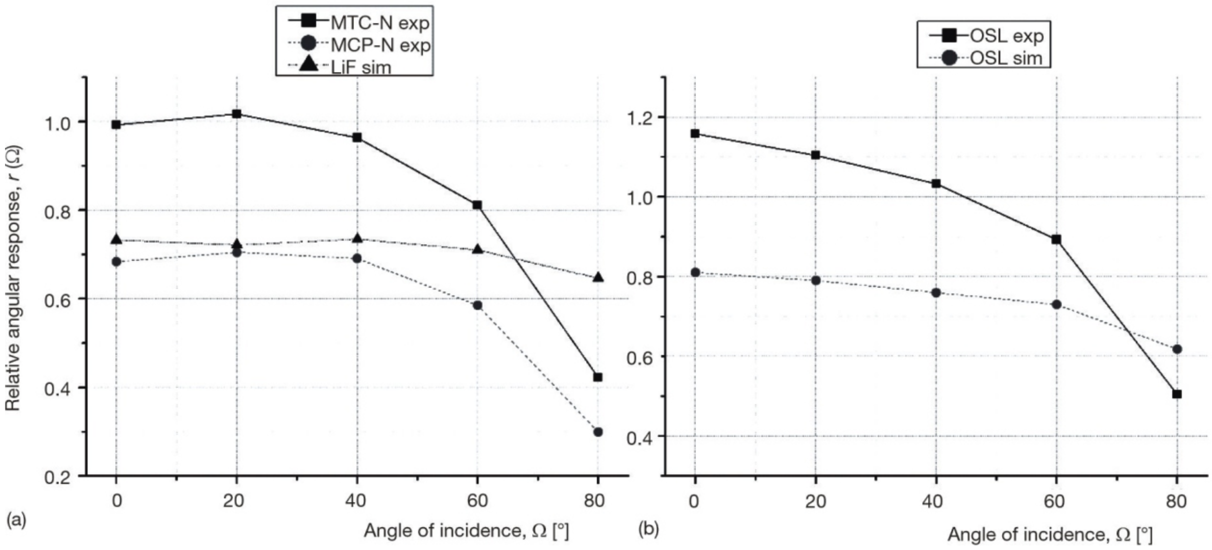

Figure 10. (a) TLD and (b) OSLD experimental and simulated relative angular responses for the N-150 radiation quality

data were performed in line with the standard's requirements. As for the unprescribed 80° angle of incidence, only the simulated relative response of 0.68 slightly falls outside the standard's criteria.

Considering the OSLD, the experimental and simulated results are comparable fig. 9(b). Taking the IEC 62387:2020 criteria into account, both the experimental and simulated data fulfill its requirements in the mandatory angle range. Additionally, both results would meet the standard's criteria for the unprescribed 80° angle of incidence.

In the case of the N-150 radiation quality, both the experimental and simulated TLD data display a similar trend fig. 10(a). Disregarding slight, statistically insignificant increases, a relative response decrease is observed with the increase of the angle of incidence. As with the previously mentioned S-Cs quality, the most significant under-response is present at the 80° angle of incidence. Regarding the IEC 62387:2020 criteria, the MTS-N dosimeters and the simulated LiF data met the standard criteria for the mandatory angle range (0°-60°), while the MCP-N dosimeters did not, due to the under-response also present in the energy dependence tests at 0°.

The OSLD exhibit an analogous behavior as the TLDs for the N-150 radiation quality. Their under-response increases with the increase of the angle of incidence fig. 10(b). The largest deviation from the experimental and simulated data is 46.28 % for the 20° angle of incidence. Still, both the experimental and simulated data fall inside the requirements of the IEC 62387:2020 standard in the 0°-60° angle of incidence range.

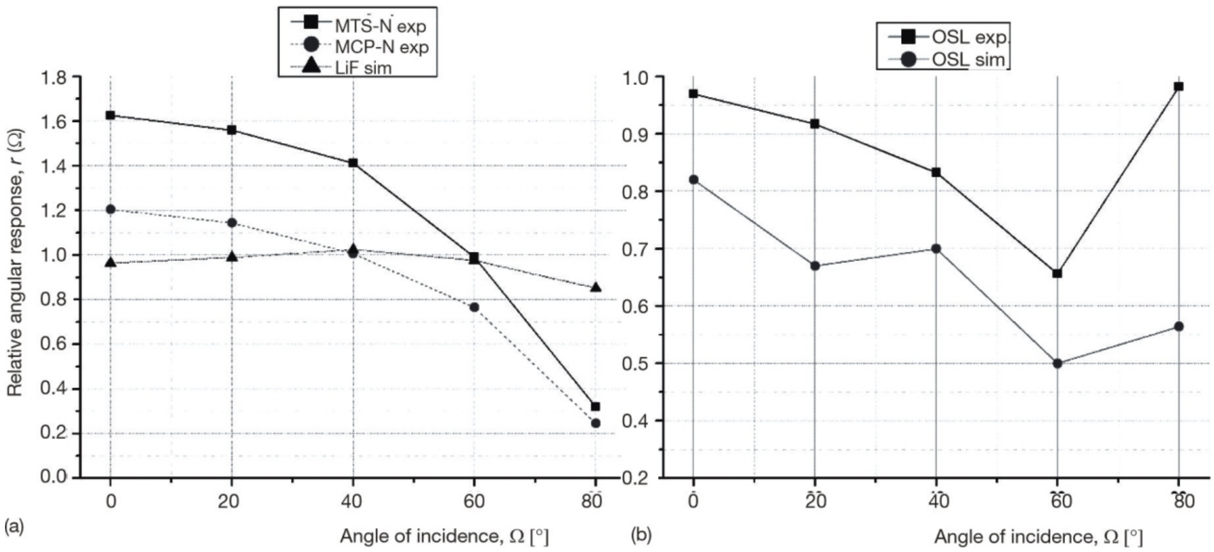

Figure 11. (a) TLD and b) OSLD experimental and simulated relative angular responses for the N-40 radiation quality

Regarding the N-40 radiation quality, the experimental and simulated TLD data exhibit a similar trend as in the case of the previous radiation qualities – a response reduction with the increase of the angle of incidence fig. 11(a). Similarly, the maximum under-response is present at the 80° angle of incidence. Even though the N-40 radiation quality falls below the mean photon energy bounds of the IEC 62387:2020 standard, the TLD experimental and simulated data would still fall inside its criteria for the mandatory 0°-60° angle of incidence range.

The OSLD experimental and simulated data also display a similar trend for the N-40 radiation quality fig. 11(b). However, their minimal response values are at the 60° angle of incidence, as an increase of response is noticeable at 80°. A possible explanation for this result, which falls outside the bounds of the IEC 62387:2020 standard both in terms of energy and angle of incidence, could be that the low-energy photons are still absorbed by the tablets under plastic and without any filtration, while photons striking copper and aluminum filters are being scattered due to a high angle of incidence and absorbed in the beforementioned tablets. In the case of the unprescribed N-40 radiation quality, the experimental and simulated OSLD data would not fulfill the IEC 62387:2020 criteria for the mandatory angle range due to the under-response present at the 60° angle of incidence.

CONCLUSIONS

Due to the frequent use of passive dosimetry systems in both individual and ambient monitoring, it is of the utmost importance to investigate their characteristics. Extensive performance testing of passive thermoluminescent and optically stimulated luminescent dosimetry systems has been conducted, by examining their responses in realistic poly-energetic and multi-directional photon radiation fields and comparing the results with the requirements of the IEC 62387:2020 international standard. The used X-ray and gamma-ray radiation fields were defined by the ISO 4037-1, while the Monte Carlo simulations were used to validate the experimental data.

Regarding the relative energy response of the tested dosimeters, the experimental MTS-N, experimental InLight, and simulated OSLD data meet the mandatory criteria of the IEC 62387:2020 standard, while the experimental MCP-N and simulated LiF do not in the case of the N-150 and N-100 radiation quality, respectively, due to an existing under-response.

In the case of the relative angular response of the tested dosimeters, the experimental MTS-N and simulated LiF data fall inside the mandatory requirements of the IEC 62387:2020 standard for the S-Cs, N-150, and N-40 radiation qualities. The MCP-N experimental results do not meet the mandatory requirements only for the N-150 radiation quality due to an under-response also present in the energy response measurements. Finally, the experimental InLight and simulated OSLD data fulfill the mandatory criteria for the S-Cs and N-150 radiation qualities but fail to do so due to an under-response for the N-40 radiation quality.

In general, the experimental and simulated data display similar energy and angle of incidence dependence trends, meaning that the simulation successfully validated previous experimental measurements. Notable discrepancies between the simulated and experimental data may be attributed to the fact that the simulated X-ray beams were monoenergetic, whose energies correspond to the mean photon energies of the realistic spectra.

The data discrepancies are more pronounced in the cases where the joint effects of influential quantities are present (*i. e.*, low energy photon spectra and large angles of incidence). The validation of the experimental tests with Monte Carlo simulations could be used as a basis for further examination of the dosimeter performance while being exposed to non-standard radiation fields, whose properties could relate to realistic fields in an improved manner. A possibility for further dosimeter testing would be the addition of linearity influence along with the energy dependence, or the influence on environmental characteristics on the dosimeter performance such as ambient temperature and relative humidity air density parameters.

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AUTHORS' CONTRIBUTIONS

The manuscript was written by F. H. S. Apostolakopoulos and N. Lj. Kržanović. The Figures were prepared by N. Lj. Kržanović. The experimental measurement setup was conceived and prepared by F. H. S. Apostolakopoulos, K. Dj. Stanković and L. S. Perazić. The experimental measurements were performed by F. H. S. Apostolakopoulos and N. Lj. Kržanović. The Monte Carlo results were simulated by P. M. Božović. All authors analyzed and discussed the results and reviewed the manuscript.

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КОМПАРАЦИЈА ЕКСПЕРИМЕНТАЛНИХ И СИМУЛИРАНИХ ОДЗИВА ТЛ И ОСЛ ДОЗИМЕТАРА У ПОЛИЕНЕРГЕТСКИМ И МУЛТИДИРЕКЦИОНИМ ФОТОНСКИМ ПОЉИМА ЗРАЧЕЊА

Циљ овог рада је испитивање енергетских и угаоних одзива термолуминисцентних (LiF:Mg,Ti и LiF:Mg,Cu,P) и оптички стимулисаних луминисцентних (Al_2O_3:C) дозиметара експерименталним мерењима и Монте Карло симулацијама. Девет квалитета зрачења, са распоном средњих енергија од 33 keV до 1.25 MeV, и пет инцидентних углова, између 0° и 80°, коришћено је за спровођење ове анализе. Међународни стандард из заштите од зрачиеа IEC 62387:2020 коришћен је као мера квалитета одзива дозиметара. Експериментални и симулирани подаци показују да одзиви дозиметара испуњавају критеријуме стандарда, са одређеним изузецима на нижим енергијама.

Кључне речи: угаони одзив, енергетски одзив, Монте Карло симулација, оптички стимулисана луминисценција, лична дозиметрија, фотонско зрачење, термолуминисценција