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Response of LiF:Mg,Cu,P TL Detector Simulated with Geant4

(Tindak Balas Pengesan TL LiF:Mg,Cu,P yang Disimulasi Menggunakan Geant4)

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ABSTRACT

The Geant4 simulation code was developed to study the $H_p(10)$ *energy response of the LiF:Mg,Cu,P (TLD-100H). Initial study chose the simulation conditions similar to the work reported by Obryk et al. in year 2011, in which a TLD-100H chip without filter was used. The work went further to simulate the* $H_p(10)$ *results obtained experimentally at SSDL Malaysia. The experiment used a TLD-100H chip embedded in a TLD card and the card was enclosed in a badge complete with PTFE filter. Irradiation with eleven photon energies in the range of 24-1250 keV was applied. The simulation code therefore took into accounts the details of the badge (the materials type and the dimensions of the chip, the card, the badge and the filters) and the set-up of the experiment (the source distance and the energies). In comparison with Obryk's work, the simulation code yielded the mean deviation of 0.59%. For the experimental work, the simulated* $H_p(10)$ *curves obtained were quite similar and comparable and a mean deviation of 13.96% was obtained. As both 0.59% and 13.96% deviations are within the acceptable limit of ±25%, it was concluded that a satisfactory level of accuracy has been achieved by the developed simulation code and the selection materials and physics processes that have been adapted in the code were correct. Sources of uncertainty that has contributed to this deviation are discussed.*

Keywords: Energy response; Geant4; $H_p(10)$*; LiF:Mg,Cu,P; TLD-100H*

ABSTRAK

Kod simulasi Geant4 dibangunkan untuk mengkaji tindak balas tenaga $H_p(10)$ *LiF:Mg,Cu,P (TLD-100H). Kajian awal memilih keadaan simulasi yang sama dengan kertas yang dilaporkan oleh Obryk et al. pada tahun 2011, dengan satu cip TLD-100H tanpa penuras telah digunakan. Penyelidikan ini diteruskan untuk mensimulasi keputusan* $H_p(10)$ *yang diperoleh secara eksperimen di SSDL Malaysia. Eksperimen menggunakan cip TLD-100H dimasukkan ke dalam kad TLD dan kad ini disimpan dalam satu lencana lengkap dengan penuras PTFE. Penyinaran dengan sebelas tenaga foton dalam julat 24-1250 keV digunakan. Kod simulasi telah mengambil kira perincian lencana (jenis bahan dan dimensi cip, kad, lencana dan penuras) serta susunan eksperimen (jarak sumber dan tenaga). Berbanding dengan kerja Obryk, kod simulasi memberikan purata sisihan 0.59%. Untuk kerja eksperimen, lengkok* $H_p(10)$ *yang disimulasi didapati hampir sama dan boleh dibandingkan, dan purata sisihan 13.96% diperoleh. Kerana kedua-dua sisihan 0.59% dan 13.96% termasuk dalam had penerimaan ±25%, disimpulkan bahawa satu aras ketepatan yang memuaskan telah dicapai oleh kod simulasi yang dibangunkan dan pemilihan bahan dan proses fizik yang diambil dalam kod ini adalah betul. Sumber ketidakpastian yang menyumbang kepada sisihan ini dibincangkan.*

Kata kunci: Geant4; $H_p(10)$*; LiF:Mg,Cu,P; respons tenaga; TLD-100H*

INTRODUCTION

Three commercial names for LiF TL dosimeter doped with Mg, Cu, P have been reported. They are MCP-N (Carinou et al. 2008; Obryk et al. 2011), TLD-100H (Carinou et al. 2008) and GR200A (González et al. 2007). SSDL Malaysia is using the TLD-100H equipped with a card of TLD-0110H. There are two chips (or elements) on this card and these chips are meant to yield the personal dose equivalents of $H_p(10)$ and $H_p(0.07)$. For individual monitoring of the penetrating external ionising radiation, $H_p(10)$ is more often used. $H_p(10)$ is now considered as the internationally recommended operational quantity for the purpose of radiation protection (Hranitzky & Stadtmann 2007). It was no surprise that on the recent Fukushima nuclear plant damage, $H_p(10)$ has been used to measure the individual dose rate (Yoshida et al. 2012). This study focuses on the $H_p(10)$ personal dose equivalent of the TLD-100H.

An ideal dosimeter that can yield a flat energy response (Izewska & Rajan 2003) is most sought after. The measured dose equal to the delivered dose at any energy is the characteristics of this ideal dosimeter. From the many reported works of TLD-100H, it is obvious however the flat energy response is only achieved at higher energy (i.e. >500 keV). For lower energy (<500 keV) this has yet to be materialised. For this reasons, extensive simulation studies (Guimarães et al. 2007; Hranitzky et al. 2006; Moralles et al. 2005; Olko et al. 1999), on the TLD-100H have been carried-out by many researchers in the search of this flat response for the lower energy region.

The present work reports a preliminary study on the simulation of the $H_p(10)$ energy response of the TLD-100H. It is by the use of the Geant4 simulation code. The first stage of the work simulated the energy response of the TLD-100H chip without filter, based on the work reported by Obryk et al. (2011). The second stage of the work simulated the experimentally obtained energy response of the TLD-100H badge, based on the work obtained at the SSDL Malaysia laboratory.

Eakins et al. (2008) has reported that in a simulation work, a deviation of ±25% between the measured and simulated response is acceptable. The purpose of the first stage was to evaluate the accuracy of the developed simulation code based on the simplified model. Once this accuracy has been achieved, the work moved on to the second stage, where the simulation code was extended to suit the close-to-reality model. The long-term aim of the work is to simulate a model of a TLD-100H which can exhibit a flat response at the lower energy regions.

MATERIALS AND METHODS

THE SIMULATION SYSTEM

The present simulation system consists of Geant4 toolkit and a High Performance Computing (HPC) Grid. The Geant4 toolkit version 9.4.p02 released on 24 June 2012 was utilised in this work. Written in C++ programming language, this toolkit provides the necessary tools to simulate the passage of particles through matters (Agostinelli et al. 2003; Allison et al. 2006). The HPC is self-built hardware with a network of six 3.4 GHz i-7 Quad Core CPUs with 8 GB RAM each and the Geant4 toolkit was installed in it. This simulation system is capable of executing a maximum value of 2×10^{12} events. It was from this simulation system that the simulation code was developed and executed.

The present simulation code deals with photons (of energy 16 to1250 keV) as the primary radiation and electrons (produced after photons interact with materials) as the secondary particles. Therefore fundamental particles of interest in this work were photons and electrons. The Geant4 physics processes were selected to govern the interaction of these particles with materials. For photons, they are: G4PhotoElectricEffect, G4ComptonScattering and G4GammaConversion, and for electrons: G4eIonisation, G4eMultipleScattering, G4eBremsstrahlung and G4eplusAnnihilation. A threshold value for secondary particle production which is defined as range cut was fixed to 0.05 mm throughout the geometry.

SIMULATION BASED ON A PUBLISHED WORK

In this first stage of work, the simulation was based on the Obryk's experimental work (Obryk et al. 2011). The developed code used a simplified geometry to get the energy response from a single TLD chip without filter. The input of the code were: a TLD circular chip with 4.5 mm diameter and 0.9 mm thickness; water phantom of 30×30×15 cm^3; chip positioned on the front surface (centre point) of a water phantom; twelve photon energies, i.e. ten from the x-ray source (16, 20, 24, 33, 48, 65, 83, 100, 118, 164, and 208 keV) and two from radionuclides (energy 662 and 1250 keV); irradiation direction is normal to the phantom surface (90^o angle), (f) 2.5 m and 2 m, respectively, for the distance of x-ray machine and the radionuclides to the TLD; and air is the medium between the photon sources and the TLD.

The simplified geometry is shown in Figure 1. To represent the $H_p(10)$ value evaluated in Obryk's work, two absorbed dose scoring volumes were simulated. These were labelled as D_{TLD} (TLD on the water phantom surface) and $D_w(10)$ (10 μm slice of water at 10 mm deep in the phantom). These scoring volumes were surrounded by air. Obryk's work however did not provide the value of the two parameters that were needed for the code, namely the number of primary photon and the field size. To get these parameters value, the present work did an optimisation work, in which the parameter value that will yield a statistical uncertainty below 5% will be selected. In selecting the primary photon numbers, the field size was fixed to 30×30 cm^2 and a range of 2×10^7 to 2×10^{12} were tested. Satisfactory number of photon obtained was 2×10^9. Using these 2×10^9 photons, the optimisation work to get a satisfactory field size among 4.5×4.5 cm^2 to 30×30 cm^2 was done. Results yielded a field size of 30×30 cm^2. These optimised values 2×10^9 primary photon with field size 30×30 cm^2 were fed-in in the simulation code.

Upon execution, the code yielded the D_{TLD} and $D_w(10)$ values. The $H_p(10)$ response can be obtained from (Othman et al. 2010),

$$H_p(10) = \frac{D_{TLD}}{D_w(10)}. \quad (1)$$

The relative energy response R (relative to Cs-137 662 keV) can be obtained from,

$$R = \frac{\left(\frac{D_{TLD}}{D_w(10)}\right)_E}{\left(\frac{D_{TLD}}{D_w(10)}\right)_{662\,keV}}. \quad (2)$$

SIMULATION BASED ON THE PRESENT EXPERIMENTAL WORK

The target for the experimental work now was a TLD-badge. The badge consists of TLD-100H chip, a TLD-card and filters, which dimensions are shown in Figure 2. The TLD-100H chip is fixed in an aluminium card covered by PTFE wrapping. Each card consists of four chips which are labelled as elements 1, 2, 3 and 4. In this study, only the elements 2 were analysed as it acts as the $H_p(10)$ detectors. The shape and the filter material of the element 2 are shown in Figure 3.

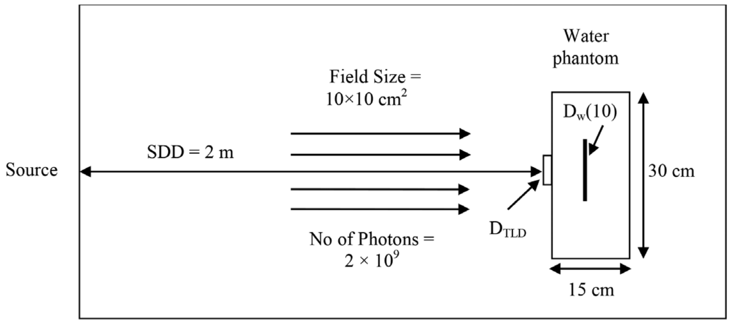

FIGURE 1. Simplified geometry of the simulation

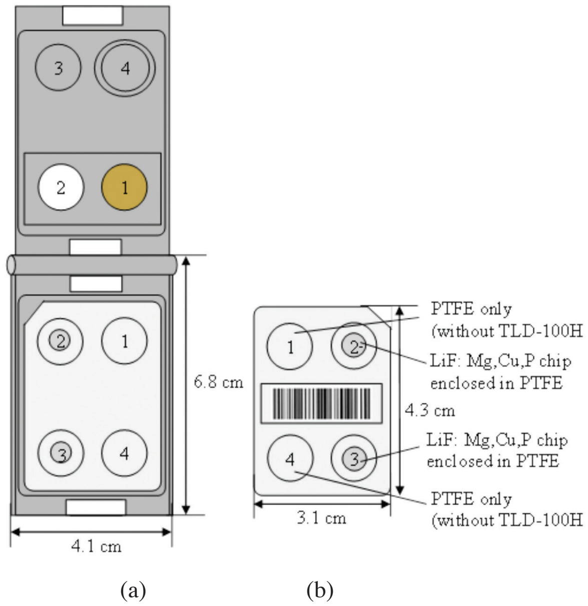

FIGURE 2. Schematic diagram of TLD-100H: (a) TLD card inside a badge, (b) TLD chip inside a card, with number of element

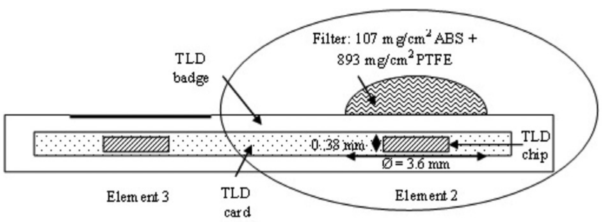

FIGURE 3. The side view cross section of TLD-100H. The circled part shows the element 2

The experimental set-up that was used to get energy response from TLD-100H was almost similar to Figure 1. The exact diagram of the set-up was described elsewhere (Priharti et al. 2013, 2012). During the irradiation, four TLD badges were positioned at the front surface (centre point) of the water phantom and two TLD were used as background control (not being irradiated). The dose delivered to TLD, $H_p(10)_{del}$ was fixed to 1 mSv. Nine photon energies from ISO narrow-spectrum X-ray (energy 24, 32, 47, 65, 84, 102, 121, 171 and 218 keV) and two from radionuclides (energy 662 and 1250 keV) were used. The irradiation direction is normal to the phantom surface (90° angle) and the distance of x-ray machine and the radionuclides to the TLD was 2 m. When the irradiation was completed, the TL glow curve signals of the TLD were measured by a Harshaw hot-gas TLD reader model 6600 (using a fast routine readout procedure). Pre-heating process was carried out for 13.33 s at 260°C continued by post-annealing process at 260°C for 10 s. Evaluated TL signals was detected as the measured dose, $H_p(10)_{meas}$. The irradiation and reading processes were carried-out at SSDL Malaysia. The ratio of the measured dose to the delivered dose normalised to 662 keV is then defined as,

$$R = \frac{\left(\frac{H_p(10)_{meas}}{H_p(10)_{del}}\right)_E}{\left(\frac{H_p(10)_{meas}}{H_p(10)_{del}}\right)_{662\,keV}}. \quad (3)$$

As mentioned earlier this second stage of the work was to simulate the experimentally obtained energy response. The input for the simulation can be divided into two parts: the details of the TLD badge; and the details of the set-up (Priharti et al. 2013, 2012). Figures 2 and 3 describe the information needed for the input in part (i), they are: TLD circular chip with 3.6 mm diameter and 0.38 mm thickness; TLD rectangular card with dimension 4.1×3.1×0.2 cm³; TLD rectangular badge with dimension 6.85×4.11×0.68 cm³; TLD filter with thick dome made by 107 mg/cm² ABS + 893 mg/cm² PTFE. For the part (ii) input of the set-up, they are: water phantom of 30×30×15 cm³; TLD badge positioned on the front surface (centre point) of a water phantom; eleven monoenergetic photon energies, i.e. nine from the X-ray source (24, 32, 47, 65, 84, 102, 121, 171 and 218 keV) and two from radionuclides (energy 662 and 1250 keV); irradiation direction normal to the phantom surface (90° angle); 2 m for the distance of x-ray machine and the radionuclides to the TLD; and air as the medium between the photon sources and the TLD.

Figure 4 shows the simulated geometry of element 2 (of TLD-100H, shown in Figure 3) when the TLD configuration was fed-in as the input in the simulation code. This figure was produced by the Geant4 code. The technique used to get the simulated energy response from this experiment

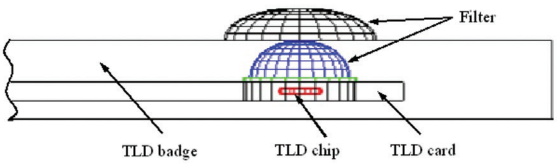

FIGURE 4. The simulated geometry of the cross section of TLD-100H (element 2) produced by Geant4 code

was similar to the technique used before. Two absorbed dose scoring volumes D_{TLD} and $D_w(10)$ described in (1) were used again to yield the $H_p(10)$. Also (2), was re-used to calculate of relative $H_p(10)$ response R. Note that (2) in the simulation is equivalent to (3) in the experiment. For the number of primary photon and the field size, optimisation work for this experimental condition yielded satisfactory values (to comply a statistical uncertainty below 5%) of 2×10^9 and 10×10 cm^2, respectively.

RESULTS AND DISCUSSION

Figure 5 shows the results of the first stage of the work. It can be seen that the simulated relative $H_p(10)$ responses are located very close to the Obryk's measured data. If the measured data (Obryk's data) were taken as the standard, the deviations as the function of the energy can be summarized as follows: 0% (662 keV), ±5% (20, 24, 65 and 208, 250 keV), 10% (16, 33, 48, 83, 100 and 164 keV), ±15% (118 keV) and ±20% (1250 keV). From these values, it was found that the mean deviation for all energies was 0.59%. As this deviation is less than 1% and within the benchmark criterion of ±25% (Eakins et al. 2008), it can be concluded that the Gean4 code that was developed to simulate the energy response is accurate.

It is interesting to note here that from all the 14 deviation values (for 14 photon energies), 10 values gave positive sign (i.e. simulated $H_p(10)$ > measured $H_p(10)$) and 4 gave the negative sign. As the deviations tend to have more positive signs, it looks as if there is a systematic error in the simulated results. Student's t was calculated to check whether there is evidence that the simulated results are systematically higher than the Obryk's results. Based on n=14, the mean (μ), the standard deviation () and the standard error (SE) in the mean of the deviations were found to be μ= 0.59, = 7.26, SE= 1.94 (all in terms of percentage values) (Samat & Evans 1992; Samat et al. 2009). For 13 degrees of freedom and a significant level of 5%, Student's t is 1.77 (Lind et al. 2008). Since 1.77×1.94 is greater than 0.59, there is no evidence, at the 5% significant level, that the simulated results are systematically higher than the measured results.

Figure 6 shows the results of the second stage of the work. The two curves are located quite close to each other which show a good agreement was achieved between the simulated value and the experimental result. Upon calculating the deviation (where the experimental results were taken as the standard), the mean deviation yielded a value of 13.96%. This showed that the Geant4 simulated energy response simulated yielded satisfactory results as this deviation is within the acceptable ±25% limit.

The experimental results obtained in this study are in good agreement with another published results (Kadir et al. 2013; Luo & Rotunda 2006). It can be seen from Figure 6 that the phenomena of under-response and over-response were exhibited by both the simulated values and experimental results. This under and over-responses were due to the different interaction processes of the incoming photon (of different energy) with the TLD-100H, such as photoelectric and compton effects. This will consequently cause different energy deposition to the detector, by both the direct photon and the indirect secondary electron. For low energy photons (20 - 50 keV), the photoelectric effect is dominant, in which almost the entire energy of photon is converted into the energy of photoelectron. When the photon energy increases the secondary electron energy also increases and this has affected the over-response to occur (Olko 2006; Olko et al. 1999, 1993). In the figure, the maximum over-response for experimental and simulation results are 16% at 32 keV and 50% at 24 keV, respectively.

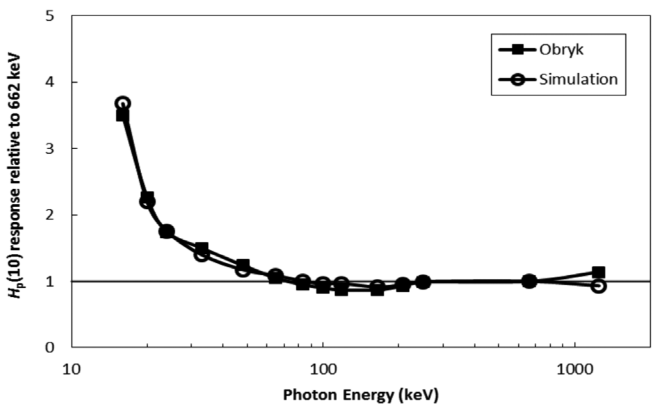

FIGURE 5. Simulated relative $H_p(10)$ response of TLD-100H compared with published experimental data (Obryk et al. 2011)

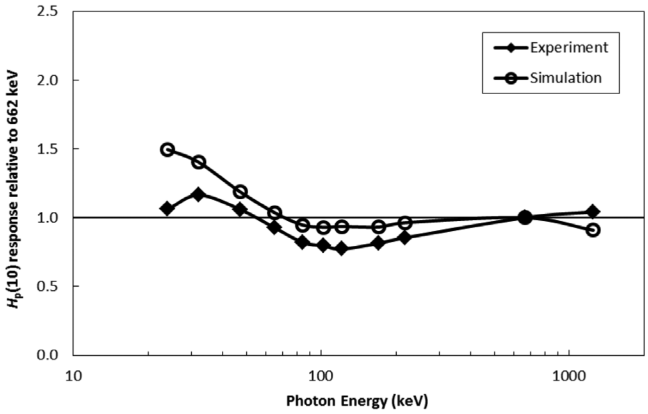

FIGURE 6. Simulated relative $H_p(10)$ response of TLD-100H compared with present work experimental data

For photon energy 50 - 120 keV, the photoelectric effect is gradually replaced by Compton scattering, thus the secondary electron spectra gradually change. This has caused the under-response to occur (Olko 2002). In the figure, the maximum under-response for experimental and simulation results are 23% at 121 keV and 9% at 1250 keV, respectively.

CONCLUSION

Two stages of simulation work to get the LiF:Mg,Cu,P detector response have been carried out in this study. The purpose was to verify the accuracy of relative $H_p(10)$ response obtained from the simulation in comparison with experimental work. It was found that the deviations of both stages were 0.59% and 13.96%, respectively. These deviations are within the acceptable limit of ±25%, so it was concluded that a satisfactory level of accuracy has been achieved by the developed simulation code and the selection materials and physics processes that have been adapted in the code were correct.

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