Estimation of thermal neutron flux with thermoluminescent dosimeter

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Abstract: The thermal neutron flux estimation in the BNCT is important, due to its high capture reaction probability with boron compounds. The gold foil activation analysis is widely used method to estimate thermal neutron flux. However, this method needs additional instruments such as a high purity germanium detector, a liquid nitrogen cooling system and lead shielding blocks. In this study, we propose thermoluminescent detectors to evaluate thermal neutron flux with less complicated and labor intensive than the conventional method. The ^{252}Cf source was used to calibrate the TLD-600 and TLD-700 with cadmium sheets. The amount of incident thermal neutrons is validated aided by Monte Carlo simulations. The TLDs were placed with the 3 different shielding, i.e. without shield, one side shielded and both sides shielded. The gamma induced signals were corrected by subtracting TLD-700 signals from TLD-600 signals. Then the different shielding configuration enables to evaluate thermal neutron induced signals from them. The irradiation was repeated 3 times with the same condition. The estimation of incident thermal neutron flux to the TLDs was aided by Monte Carlo simulations. The calibration factor (TLD signals to thermal neutron flux) was evaluated by dividing corrected TLD signals by the thermal neutron flux.

1. Introduction

The Boron Neutron Capture Therapy (BNCT) is binary radiation treatment modality. It delivers radiation damage to the tumor cell selectively using ^{10}B compound and neutron beam. The ^{10}B nuclei which have high thermal neutron capture cross-section, release α particle and ^{7}Li ion in ^{10}B(n, α)^{7}Li reaction. These products have high linear energy transfer characteristics and their ranges are around single cell diameter (~10 μm) in the tissue. The BNCT can selectively treat the tumor cell with the targeted boron drug delivery [1, 2]. Therefore, measuring thermal neutron flux should be done in air or in phantom configuration is important to optimize therapeutic effect at the treatment planning procedure.

The measurement of thermal neutron flux in the neutron and gamma mixed radiation fields is commonly done with gold foil activation method. However, this method requires additional instruments such as a High Purity Germanium (HPGe) detectors, liquid nitrogen cooling system and lead shielding blocks. In this study, we propose thermoluminescent dosimeters (TLD) to avoid the complexities of the foil activation method. To separate the neutron and gamma induced signals of TLDs in the mixed radiation fields, we used pairs of TLD-600 and TLD-700 and cadmium sheets. The cadmium sheets were used to estimate the thermal neutron induced signals from total neutron induced signals.

The primary object of this study is to develop the method to estimate the thermal neutron flux with TLDs. The TLDs were irradiated with ^{252}Cf source and the thermal neutron flux calibration factor aided by Monte Carlo simulations was established.

2. Materials and Methods

2.1 Experimental work

The 21 TLD-600 and 21 TLD-700 (Harshaw, USA) chips were prepared for this study. Its diameter was 4.5 mm and the thickness was 0.6 mm. The TLDs used in this study are lithium fluoride based materials (LiF:Mg,Ti). TLD-600 was enriched by ^{6}Li (95.6%) whereas TLD-700 was enriched by ^{7}Li(99.99%) [3]. Due to the difference in neutron cross-section of ^{6}Li and ^{7}Li, TLD-600 is sensitive to neutrons and TLD-700 is insensitive to neutrons [4]. The TLDs were annealed with an electric furnace at 400°C for 1 hour followed by 100°C for 2 hours to eliminate the residual signals before the irradiation.

The measurement was repeated 3 times with the same configuration of TLDs. The TLDs were positioned at 3 different cadmium shielding methods as shown in figure 1. At the position A, bare TLDs were placed. The TLDs at the position B were shielded by both sides and only front side was shielded at the position C. The thickness of cadmium sheets used in this study was 1 mm. Due to the high neutron cross-section of the cadmium, a 1-mm-thick cadmium sheet absorbs most of the neutrons below about 0.5 eV while passes the other energy range.

The readout of TLDs was done by using Harshaw TLD reader (Model 3500). The TLDs were linearly heated from 50 °C to 300 °C at 10 °C/sec. The acquisition time was 33.3 seconds.

The TL signal was converted in the unit of electric charges by integrating the glow curves from channels 72 to 200. The thermal neutron induced TL signal was separated by using the combination of TLD-600, TLD-700 and cadmium sheets with their different interaction probabilities of neutrons and gamma rays.

The neutron emission rate of ^{252}Cf source in this study was calibrated by the Korea Research Institute of Standards and Science (KRISS) which is the National Metrology Institute (NMI). The calibrated neutron emission rate was 3.711×10^{7} s^{-1} (at 2019.11.01) and it was corrected depending on the irradiation date. The TLDs were irradiated to deliver 1 mSv to them. The additional 15-cm-thick D_2O moderator was used to make thermal neutrons delivered to TLDs. The TLDs are placed on the water phantom which is 50 cm apart from the center of the ^{252}Cf source (figure. 2 (a)).

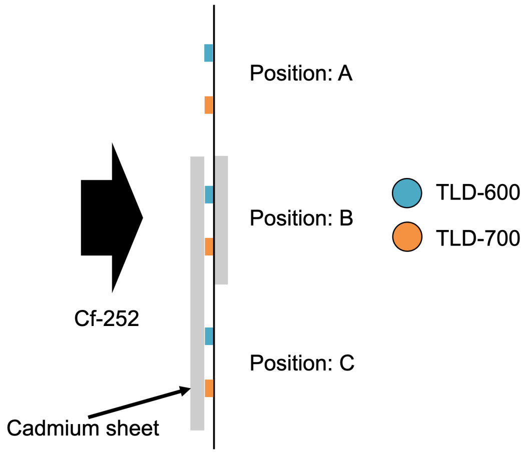

Figure 1. The side view of TLDs of this study.

2.2 Monte Carlo simulation

The irradiation room was modeled using the MCNP6 (Monte Carlo N-Particle) code (figure. 2 (b)) to calculate the number of incident thermal neutrons to TLDs [5]. The MCNP6 was developed by the Los Alamos National Laboratory (USA) and widely used in the radiation related research areas.

The neutron energy spectrums were calculated at three TLD positions using F4 tally in the MCNP6. The fluence to dose conversion factors from ICRU report [6] were applied to calculate the neutron dose rate. To validate the MC simulation of this study, the calculated neutron dose rate and measured neutron dose rate by the neutron probe (LB 6411, Berthold Technologies) were compared.

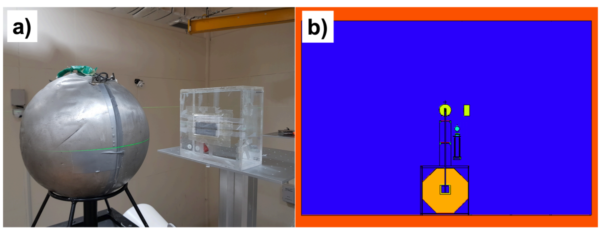

Figure 2. The TLD irradiation setup (a), The modeled geometry of irradiation room by MCNP6.

3. Results and discussion

3.1 Monte Carlo simulation

The calculated neutron ambient dose rate was 7.28 μSv/min at the TLD position which is 50 cm apart from the ^{252}Cf center. However, the neutron probe placed at the 57 cm apart from the source due to the dimensional limitation of the stand. To compensate the different distance between them, the inverse-square law was adopted to correlate the data at 57 cm to 50 cm. Then, the measured value by the neutron probe was converted from 5.63 μSv/min (distance from the source: 57 cm) to 7.32 μSv/min (distance from the source: 50 cm) which has fair agreement with the calculated value.

The neutron energy spectrums at three TLD positions were shown in figure. 3. The neutrons below 0.5 eV at position B and C absorbed by the cadmium sheet, while the neutrons in the other energy ranges passed without interactions. The amount of thermal neutrons at position B were 90% of the position A. The position C showed that only 10% of neutrons passed. By the position B data most of the thermal neutrons were came from the ceiling and wall scattered portion.

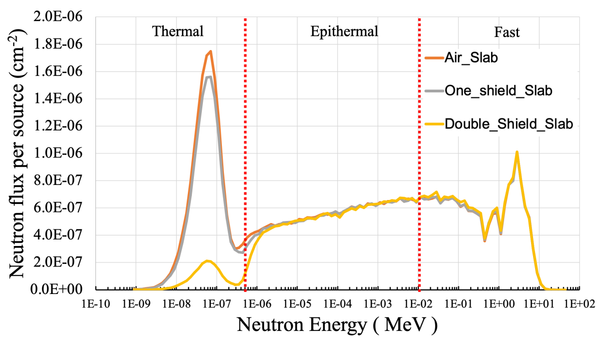

Figure 3. The neutron energy spectrum for each TLD positions calculated by MCNP6.

3.2 TLD reading

The averaged glow curves of TLD 600 and TLD 700 at three positions are shown in figure. 4. The peak at the lower channels is stem from the readout procedure without the preheat time. The ROI (region of interest) was selected from 76 to 200 channels to eliminate noisy signal in the lower channels (1~75 channels).

Table 1 showed the integrated signals in the ROI. The neutron induced TL signals were separated by subtraction between TLD-600 and TLD-700 signals. Then the values at position A and B were used to obtain thermal neutron induced TLD signals. Three measurement data showed errors around 10%. Then, thermal neutron flux that calculated by MCNP6 were divided by the thermal neutron induced TLD signals. The evaluated calibration factor (TLD signals to thermal neutron flux) was 1.99×10^6 $cm^{-2}nC^{-1}$.

Unit: nC

Label	#1	#2	#3
A (air)	25.78 ± 2.29	27.52 ± 3.25	26.93 ± 2.89
B (both sides shielded	7.44 ± 0.56	6.99 ± 0.36	7.52 ± 0.36
Thermal neutron induced signal	18.34 ± 2.35	20.53 ± 3.26	19.41 ± 2.91

Table 1. The TLD counts in the unit of nC.

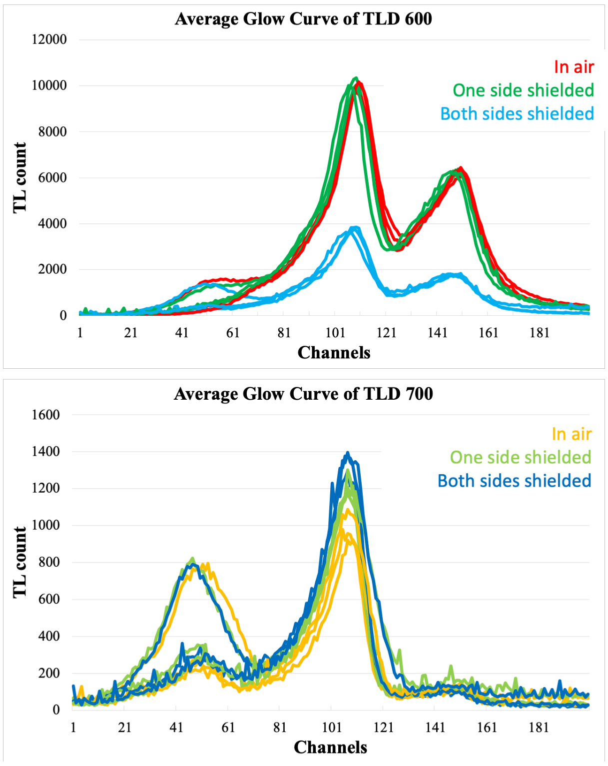

Figure 4. The averaged glow curves of TLD-600 and TLD-700 at three positions.

4. Conclusions

In this study, TLD-600, TLD-700 and cadmium sheets were used to evaluate the calibration factor with MC aided results. The established method enables to estimate thermal neutron flux without complex instruments used in the conventional method. The errors from three repetitive measurement were around 10%.

For the further study, the uncertainty analysis about the other features such as the errors of reader system (including a high voltage supplier, photomuliplier tube and heating system) and experimental setup errors. Also, the further measurement with the other neutron sources should be done to validate the calibration factor from this study.

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