Measurement of spatial fluence distribution of neutrons and gamma rays using MAGAT-type gel detector doped with LiCl for BNCT at Kyoto University Reactor

Kenichi Tanaka¹, Tsuyoshi Kajimoto¹, Aruma Mitsuyasu¹, Yuto Ito¹, Shin-ichiro Hayashi², Yoshinori Sakura³, Hiroki Tanaka³, Takushi Takata³, Gerard Bengua⁴ and Satoru Endo¹
¹Graduate School of Engineering, Hiroshima University, Higashi-Hiroshima, Japan.
²Faculty of Health Sciences, Hiroshima International University, Higashi-Hiroshima, Japan.
³Institute for Integrated Radiation and Nuclear Science, Kyoto University, Kumatori, Japan.
⁴Auckland City Hospital, Auckland, New Zealand.
Email:tanakake@hiroshima-u.ac.jp

Abstract. The spatial distributions of neutrons and gamma rays in the epithermal mode of the Kyoto University Reactor were measured using a MAGAT-type polymer gel detector doped with LiCl at ⁶Li concentrations of 0, 10, 100 ppm. Reasonable distributions for thermal neutrons and gamma rays were obtained for 0 and 100ppm.

1. Introduction
In boron neutron capture therapy (BNCT), the quality assurance (QA) of an irradiation field can be performed by monitoring the spatial beam component distributions in a phantom. Ideally, the beam components are measured separately, e.g., thermal neutrons (<0.5eV), epithermal neutrons (0.5eV-10keV), fast neutrons (>10keV), and gamma rays. The QA regime, however, needs to be easily implemented as a routine verification method. A good candidate detector for spatial distribution measurements are a gel detector [1] which have been used in three-dimensional dose distribution measurement for photons and heavy ion irradiations [2]. In a related study, we have demonstrated that gel detectors can separately measure the relative fluence of the components of a BNCT neutron field [3]. We found from Monte Carlo calculations that the MAGAT-type polymer gel detector doped with ⁶Li at concentrations of 0 (for fast neutron component), 10 and 100 ppm are potentially usable for thermal and fast neutrons, and gamma ray measurements. The present paper describes an experimental demonstration of these measurements using the gel detectors.

2. Materials and methods
The beam components of a BNCT irradiation field can be measured separately by increasing the sensitivity of the gel detector to the fast neutron component via recoil protons produced in the gel detector and increasing the sensitivity of the detector to the thermal neutron component via the secondary particles from the ⁶Li(n,α)³H reaction. The gamma ray component of the beam deposits its energy mainly...
via secondary electrons. It will therefore be possible to detect the enhanced components with the gel detector.

We previously proposed [3] potential combinations of the gel detector compositions for converters used in the standard epithermal neutron irradiation mode at the Kyoto University Reactor Heavy Water Neutron Irradiation Facility (KUR-HWNIF) which is currently used for BNCT treatments [4]. Simulations by using the Monte Carlo code PHITS ver. 2.82 [5] showed that the MAGAT-type polymer gel detector doped with $^6$Li at concentrations of 0, 10 and 100 ppm were viable for the measurement of thermal and fast neutrons, and gamma rays. In the study, the MAGAT-type polymer gel detector was assumed to be made up of methacrylic acid, gelatin and an oxygen scavenger (tetrais-hydroxymethylphosphonium chloride, THPC). Its elemental composition was H:10.5 wt%, C:9.5 wt%, N:1.4 wt%, O:77.7 wt%, P:0.4 wt%, Cl:0.5 wt%.

In the experiments for the present study, the MAGAT-type gel detector was infused with LiCl, where the naturally abundant isotope $^6$Li was used. The $^6$Li concentrations were set at 0, 10 and 100 ppm. The dimension of the gel detector was $60 \times 60 \times 60 \text{ mm}^3$. The gel detector was encased in a box made of 5 mm thick acrylic acid resin. The box was set inside a $200 \times 200 \times 200 \text{ mm}^3$ acrylic acid resin phantom, to simulate a human head in a brain tumor treatment. During the irradiation, the box was placed in contact with the collimator aperture of the KUR-HWNIF. The irradiation was performed with the standard epithermal neutron irradiation mode at 1 MW delivered for 40 minutes. The aperture of the collimator was $120 \times 120 \text{ mm}^2$. The central axes of the phantom, gel detector, and collimator aperture were aligned. The nominal value of the flux at the center of the collimator aperture was $7.07 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$, $1.33 \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$ and $1.38 \times 10^7 \text{ cm}^{-2}\text{s}^{-1}$ for thermal, epithermal and fast neutrons, respectively. The gamma ray flux was $1.25 \times 10^7 \text{ cm}^{-2}\text{s}^{-1}$. After the irradiation, the transverse relaxation rate was measured as the signal intensity ($S_i$) in the unit ‘$s^{-1}$’ of the gel detector, by using a 0.3T MRI scanner (AIRIS II comfort, Hitachi Medical Corp.) with a standard head coil. Here, $i$ indicates the $^6$Li concentration in the gel detector wherein 1, 2 and 3 denote 0, 10, and 100 ppm, respectively.

The fluence $\Phi_j$ in the unit ‘$\text{cm}^{-2}$’ of each beam component was determined using the following model:

$$D = \begin{pmatrix} S_1 k_1 \\ S_2 k_2 \\ S_3 k_3 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \end{pmatrix} = A \cdot \Phi \quad (1)$$

$$\Phi = A^{-1} \cdot D \quad (2)$$

where $k_i$ denotes the conversion factor from the signal intensity to the absorbed dose in the unit ‘Gy s’, where $a_{ij}$ denotes the sensitivity of the $i$th gel detector for the component $j$ and where $j$ corresponds to the beam components, i.e., 1 for gamma-rays, 2 for thermal neutrons and 3 for fast neutrons. The sensitivity is the signal intensity per unit of the beam fluence in the unit ‘Gy cm$^{-2}$’. The value $D=S_k$, corresponds to the absorbed dose.

The sensitivity $a_{ij}$ was estimated using the PHITS simulation of the irradiation condition at KUR-HWNIF. Assuming that the signal intensity is proportional to the energy deposition, the ratio of the energy deposition to the beam component fluence at the gel detector regions of $5 \times 5 \times 5 \text{ mm}^3$ along the central axis was computed and assigned as a representative of $a_{ij}$. The conversion factor $k_i$ from the signal intensity to the absorbed dose was measured for the irradiation with $^{60}$Co gamma rays at the Graduate School of Advanced Science and Engineering, Hiroshima University [6].

As a reference, the fluence of thermal neutrons and gamma rays was measured with gold wire activation combined with $^{nat}$Cd covers, and thermoluminescence dosimeter (TLD), respectively. For the TLD measurements, the dose was assumed to be proportional to the fluence. The gold wire and TLDs were placed on the central axis of the gel detector and their irradiations were performed separately from the irradiation to the gel detectors.
3. Results and discussion

The sensitivity of the gel detector, $a_{ij}$, was calculated with the PHITS code and is shown in figure 1. The depth shown is the distance from the surface of the gel detector set inside the box made of 5 mm thick acrylic acid resin. The relative contributions of the beam components to the total of the energy depositions in the gel detectors are shown in figure 2. The uncertainties in figures 1 and 2 were estimated by considering only statistical uncertainty by the PHITS simulation. The sensitivities in figure 1 were used for the fluence estimation with the equation (2).

Figure 1. Sensitivity (the ratio of energy deposition to the beam component fluence) of the gel detector with $^6$Li at (a) 0 ppm, (b) 10 ppm, and (c) 100 ppm.

Figure 2. Contribution of beam component to energy deposition in the gel detector with $^6$Li at (a) 0 ppm, (b) 10 ppm, and (c) 100 ppm.

The raw signal intensity of the gel detector is shown in figure 3 (a). The plotted value and error bar shown are the average and standard deviation of the signal intensity in the region of $5 \times 5 \times 5$ mm$^3$ along the central axis of the gel detector. The background signal intensity, without the irradiation, was 6.3, 6.1, and 5.1 s$^{-1}$ for the gel detector with LiCl at $^6$Li concentrations of 0, 10, and 100 ppm, respectively. As a result of the irradiation with the $^{60}$Co gamma rays, the signal intensity dependence on the absorbed dose is 7.2, 7.5, and 7.1 s$^{-1}$Gy$^{-1}$, at $^6$Li concentrations of 0, 10, and 100 ppm, respectively. These values were treated as the dose-response of the gel detectors.

The data in figure 3 (a) was corrected so that all the gel detectors would have the same dose-response as the gel detector without $^6$Li, and the background signal intensity was subtracted. The corrected result is shown in figure 3 (b). The data at the depths of 2.5 and 57.5 mm, which are within the regions 0 to 5 mm away from the wall of the acrylic acid resin box, were omitted from further analysis since the oxygen penetrating the wall reduced the polymerization and thus the signal intensity.
4. Conclusion
A trial to measure the spatial distribution of the neutrons, depending on their energy, and gamma rays separately was carried out by using the MAGAT-type gel detector infused with LiCl. Potential usability of the gel detector was shown for two components, i.e., thermal neutrons and gamma rays, for which the plausible fluence distributions was obtained. This suggests the potential usability of polymer gel detector in spatial measurement of fluence in BNCT beam.
5. Acknowledgments
This work was supported by JSPS KAKENHI Grant Numbers JP26293281. This work has been carried out in part under the visiting Researcher’s Program of the Institute for Integrated Radiation and Nuclear Science, Kyoto University. The authors express their sincere appreciation to Mr. Yuto Murakami and Mr. Yuto Ito in Hiroshima University, and the Innovation Plaza in Hiroshima University (especially to Mr. Seisuke Noguchi), Japan for their support in the investigations.

6. References
[1] Khajeali A, Farajollahi AR, Kasesaz Y et al 2015 Appl. Rad. Isot. 105 72-81
[2] De Deene Y and Vandecasteele J 2013 J. Phys. Conference Series 444 012015
[3] Tanaka K, Sakurai Y, Hayashi S et al 2017 Appl. Rad. Isot. 127 253-259
[4] Sakurai Y and Kobayashi T 2000 Nucl. Instr. Meth. A453 569-596
[5] Sato T, Niita N, Matsuda N et al 2013 J. Nucl., Sci. Technol. 50 913-923
[6] Murakata A, Endo S, Kojima Y et al 2010 J. Radiat. Res. 51 198-203