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Preliminary study of MAGAT polymer gel dosimetry for boron-neutron capture therapy

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Abstract. MAGAT gel dosimeter with boron is irradiated in Heavy Water Neutron Irradiation Facility (HWNIF) of Kyoto University Research Reactor (KUR). The cylindrical gel phantoms are exposed to neutron beams of three different energy spectra (thermal neutron rich, epi-thermal and fast neutron rich and the mixed modes) in air. Preliminary results corresponding to depth-dose responses are obtained as the transverse relaxation rate ($R_2=1/T_2$) from magnetic resonance imaging data. As the results MAGAT gel dosimeter has the higher sensitivity on thermal neutron than on epi-thermal and fast neutron, and the gel with boron showed an enhancement and a change in the depth-R_2 response explicitly. From these results, it is suggested that MAGAT gel dosimeter can be an effective tool in BNCT dosimetry.

1. Introduction

Boron-neutron capture therapy (BNCT) is a promising cancer therapy using the nuclear reaction of ^{10}B with thermal neutron (< 0.5 eV) [1, 2]. ^{10}B is delivered selectively to tumor-cells by boron carriers such as BPA (*p*-boronophenylalanin) and BSH (sodium borocaptate). In the tumor-cell, the boron nucleus captured thermal neutron splits into an alpha particle and a lithium nucleus [$^{10}B(n, \alpha)^{7}Li$]. They are high LET particles and almost entirely deposit their energy in the small area comparable with a single cell. As the result, only tumor-cells can be killed selectively while the damage on normal cells is minimized. So far, nuclear reactors have been mainly used as the neutron source. Recently, accelerator-based neutron source facilities are under development, and it is expected to spread into the clinical use.

However, neutron delivered to tissue reacts with not only ^{10}B but also other nuclei depending on the energy. Fast and epi-thermal neutrons spin off recoil protons due to elastic scattering with hydrogen nuclei [$^{1}H(n, n)^{1}H$]. Thermal neutron leads to the nitrogen capture [$^{14}N(n, p)^{14}C$] and the hydrogen capture [$^{1}H(n, \gamma)^{2}H$]. These secondary radiations result to the background absorbed dose in the normal tissue. Therefore quality assurance and quality control (QA/QC) for BNCT to evaluate each dose contribution from the complicated radioactive components is required.

On the other hand, polymer gel dosimeters have been investigated for the 3D dose measurement of the complex conformal dose distributions in the clinical applications [3-5]. These devices utilize radiation-induced polymerization reactions of vinyl monomer in the gel to preserve information about the radiation dose. The 3D absorbed dose distribution is deduced from the polymer distribution measured by imaging modalities, such as MRI, optical or x-ray CT [6, 7]. Applications of polymer gel dosimeters to neutron irradiation have been investigated by several authors, and the potential as a 3D dosimeter has been suggested [8-12]. Polymer gel dosimeter is also regarded as tissue equivalent to neutron beam because the components are mainly water and a small amount of other chemicals consisting of carbon, nitrogen and oxygen. As a further advantage of the polymer gels, the interaction of neutron with the gels could be controlled by addition of some compounds with neutron-capture-nuclei such as nitrogen or boron. By the variety of elemental composition, each dose component can be distinguished from complex dose due to various primary and secondary radiations. In the previous studies, only Farajollahi *et al* [8] has reported the application of gel with ^{10}B to the dose measurements in boron neutron capture using a size of test tube gel dosimeter exposed to accelerator beam. In this work, the NMR response of MAGAT gel with boron is examined its availability to measure the depth-dose responses in the irradiation of neutron beams with different energy spectra from nuclear reactor.

2. Materials and methods

The composition of MAGAT gels with and without boron is shown in table 1. Boric acid, $B(OH)_3$, containing ^{10}B of 20% naturally was added, and the concentration in the gel is the same order (approximately 50 ppm) as the clinical use. The resulting solution was subdivided by pouring into quartz tall beakers (65 mm diameter and 135 mm length, 400 mL). After allowed to gel at room temperature, all samples were stored in a refrigerator at a fixed temperature (4 °C) for three days.

The neutron irradiations were performed using Heavy Water Neutron Irradiation Facility (HWNIF) of Kyoto University Research Reactor (KUR, power of 1 MW) [13]. The samples were irradiated from the bottom direction through the axis with the field size of almost 50 cm diameter in air at room temperature. As shown in table 2, the three different modes (Mode-1: thermal neutron rich, Mode-2: epi-thermal and fast neutron rich and Mode-3: the mixed modes) of neutron beams made by heavy water spectrum shifter and cadmium thermal-neutron filters were applied to each sample [14]. It is noted that the irradiation time is different in each mode.

MRI measurements were performed using a 1.5 T scanner (Siemens) with a quadrature torso SPEEDER coil. A multiple spin-echo sequence was applied using the following parameters, (TR / TE's / FOV / Slice Thickness / Matrix Size) = (5 s / 20 - 320 ms, 32 echos / 192 x 192 mm^2 / 10 mm / 192 x 192) with a resulting voxel size of 1.0 x 1.0 x 10.0 mm^3. The transverse relaxation rate ($R_2 = 1/T_2$) is determined by fitting equation, $S(TE) = S(0) \exp(-TE/T_2)$, where S(0) and S(TE) are the signal intensities at echo times, 0 and TE, respectively.

3. Results and discussion

Figure 1 shows the depth-R_2 profiles obtained from our polymer gel dosimeters exposed to neutron beams of the different energy spectrum modes. In the thermal neutron mode (Mode-1), both profiles of the gels with and without boron show monotonically decreasing with depth after the peak near the surface. It seems that the decrease for the gels with boron corresponds to decreasing of thermal neutron in tissue and the peak shifts to near the surface significantly due to the reaction with boron. In the epi-thermal and fast neutron mode (Mode-2), broad peaks are observed at deeper position, around from 20 to 25 mm of depth. It is suggested that the R_2 profile for the gel with boron corresponds to the distribution of the thermal neutron due to the moderation of epi-thermal neutron. But for the gels without boron, it seems that the decreases correspond to decreasing of gamma ray. As same as the profiles in Mode-1, the peak shift due to boron was also observed. The depth profiles of the mixed mode (Mode-3, not shown) were similar to that of Mode-1. It is suggested that the contributions of epi-thermal and fast neutrons are small compared to that of thermal neutron. These results indicate both MAGAT gel dosimeters with and without boron have the effective sensitivity on the thermal neutron rather than on fast neutron.

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Table 1. The composition of MAGAT type gel prepared in this study. (Boric acid of 25mM approximately corresponds to 50 ppm of ^{10}B.)

Chemical	Concentration
Water	87 wt%
Gelatin	8 wt%
Methacrylic acid	5 wt%
Boric acid	0 and 25 mM
Tetrakis(hydroxymethyl)phosphonium chloride (THPC)	5 mM

Table 2. The dose rates composition (Gy/h) in the different irradiation modes (Mode1-3). Thermal, epi-thermal and fast neutron energies are less than 0.5 eV, from 0.5 eV to 10 keV, and more than 10keV, respectively.

Mode	Fast	Epi	Th	Gamma	Total	Irr. Time (min.)
1	0.05	0.00	0.20	0.20	0.44	15
2	0.33	0.04	0.00	0.12	0.50	30
3	0.33	0.05	0.48	0.66	1.52	5

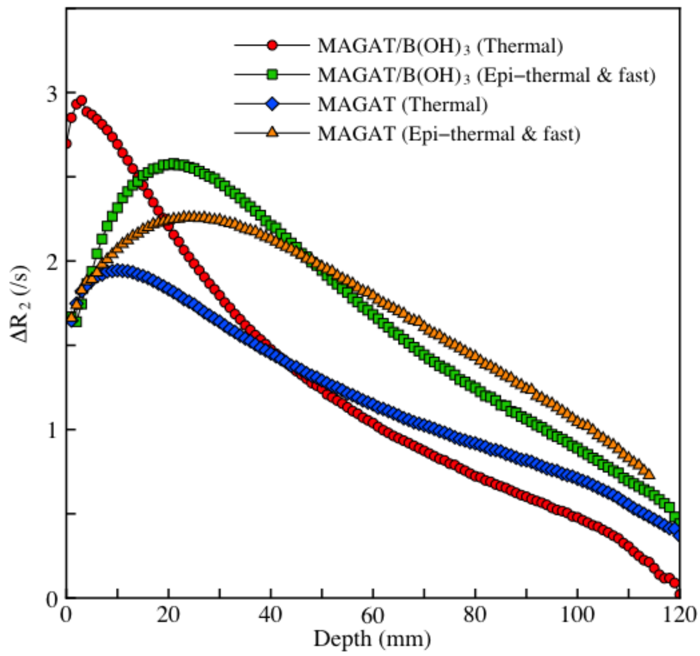

Figure 1. The depth from phantom surface vsΔR_2 [$=R_2 - R_{2,bg}$] responses in different energy spectra of MAGAT gel dosimeters with and without boron.

The thermal neutron reacts with nitrogen and hydrogen nuclei in polymer gel and produces proton [$^{14}N(n, p)^{14}C$] and prompt gamma ray [$^{1}H(n, \gamma)^{2}H$] from their nuclei as the secondary radiations. In this experiments, R_2 response of gel dosimeter without boron will mainly be due to them while the influence of boron-neutron capture [$^{10}B(n, \alpha)^{7}Li$] was obviously observed in the gel with boron. From these results the estimation of the dose distribution in the gel dosimeter with heterogeneous distribution of boron might be possible by using a gel-in-gel such as a gel container [15]. Moreover by adding some compounds containing neutron-capture-nuclei and by varying the concentrations, each dose component might be distinguished. The comparison with simulations is also needed in the next step.

4. Conclusion

In this work, we have examined the depth-R_2 responses of MAGAT polymer gel dosimeter with and without boron on neutron beams with different energy spectra. In the results, it was shown that the gel dosimeter with boron had the effective sensitivity on thermal neutron. The studies on the fundamental characteristics, the effect of additive compounds with neutron-capture-nuclei and the comparison with Monte Carlo simulations and other dosimeters are under way.

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