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ARTICLE

Basic evaluation of the Eu:BaFBr and Ce:CaF_2 hybrid type optical fiber based dosimeter system for correction of quenching effect under carbon ion irradiation

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We fabricated the hybrid type optical fiber based dosimeter system using Eu:BaFBr and Ce:CaF_2 optically stimulated luminescence (OSL) materials in order to correct the quenching effect under high LET particle irradiation. The fabricated dosimeter probe can obtain signals from both OSL materials through one optical fiber. We investigated the probe response by irradiating it with mono-energetic carbon ions and broad-spectrum ones making the spread-out Bragg peak (SOBP). We demonstrated that the SOBP shape can be improved by correction of the quenching effect using the relationship between the luminescence efficiency and the signal intensity ratio of both OSL materials.

Keywords: ***dosimeter; carbon ion radiotherapy; optically stimulated luminescence; optical fiber; quenching phenomena; correction method***

1. Introduction

Carbon ion radiotherapy takes advantage of fine and desired dose distribution compared with other radiotherapies such as X-ray therapy [1]. Although fine dose distribution can attack only a target organ, a miss alignment of an irradiation position might lead significant over-irradiation to surrounding normal tissues. In order to prevent accidental exposure, the dose irradiated to a critical organ should be monitored during a treatment.

As a small-size and on-line dosimeter system, the optical fiber based dosimeter system using an optically stimulated luminescence (OSL) material was proposed and their responses were evaluated [2-5]. We consider applying this type of dosimeter system to therapeutic dose monitoring especially in carbon ion therapies. One of the problems in this type of dosimeter system is the quenching effect under irradiation of a high linear energy transfer (LET) radiation, such as high-energy carbon ions. The quenching effect is the luminescence efficiency reduction under high LET particle irradiation [4,6]. The quenching effect is considered to occur when a part of electrons densely excited by high LET particles cannot find luminescence sites because these sites are already occupied [7]. This means that the quenching effect depends on materials. We, therefore, proposed to correct the quenching effect by using two different OSL materials [5].

Although we can obtain signals from two different OSL materials by using two optical fibers, it is preferable to obtain signals through one optical fiber. In this paper, we propose the hybrid type optical fiber based dosimeter system, which can measure the two different OSL signals from one optical fiber. We fabricated a prototype dosimeter system and evaluate its basic response. We, consequently, demonstrate the quenching effect correction in the spread-out Bragg peak (SOBP) of the carbon ion radiotherapy.

2. Hybrid type optical fiber based dosimeter system

Figure 1 (a) shows the configuration of the hybrid type optical fiber based dosimeter system. We used a quartz optical fiber with 400 µm diameter core. The hybrid type optical fiber based dosimeter probe held two OSL elements on a tip of the optical fiber. Eu:BaFBr and Ce:CaF_2 were adopted as OSL elements. Eu:BaFBr is the one of the most famous OSL materials, which are used as the Imaging Plate [8]. The Eu:BaFBr emits OSL of 420 nm. And the Ce:CaF_2 emits OSL of 340 nm. OSL intensities of Eu:BaFBr and Ce:CaF_2 is relatively high [9]. The transmittance of Ce:CaF_2 is higher than Eu:BaFBr. In order to collect the OSL signal effectively, the Ce:CaF_2 was adhered first and then the powdered Eu:BaFBr was coated on the Ce:CaF_2. The OSL elements adhered by ultraviolet curing resin, which

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has high transmittance in the ultraviolet to visible region. The dosimeter head was coated with a $BaSO_4$ reflection coating and the acrylic based protective coating.

In order to correct the quenching effect, the OSL signals of Eu:BaFBr and Ce:CaF_2 should be read out separately. **Figure 1 (b)** shows the schematic diagram of the hybrid OSL signal readout system. The OSL of Eu:BaFBr and the OSL of Ce:CaF_2 are most efficiently emitted by the red light and the green light stimulation, respectively. The red and green laser diodes were used as stimulation light sources for Eu:BaFBr and Ce:CaF_2, respectively. These laser beams were combined by a 532 nm dichroic mirror, and introduced into an optical fiber thorough an achromatic lens. The laser intensities of red and green lasers were 12 mW and 15 mW at the tip of the optical fiber, respectively. The OSL signals of the Eu:BaFBr and the Ce:CaF_2 can be divide by using difference in the OSL emission wavelength. The OSL photons passing through the optical fiber were collimated into a parallel beam by the achromatic lens. The collimated beam enters to two dichroic mirrors. The 340 nm dichroic mirror (Thorlabs, M254H45) reflects photons with the wavelength from 298 to 370 nm. However, photons with the wavelength from 400 to 690 nm can transmit it. This dichroic mirror reflects only the OSL of Ce:CaF_2, and transmit one of Eu:BaFBr. The 420 nm dichroic mirror (Thorlabs, DMLP490) reflects and transmits photons with the wavelength from 380 to 475 nm and from 510 to 800 nm, respectively. The second dichroic mirror reflects only the OSL of Eu:BaFBr. Both dichroic mirrors transmit the stimulation lights. The divided OSL signals were detected by photo multiplier tubes (PMTs). Since the dichroic mirror cannot perfectly separate photons with the designed wavelength, the residual photons are removed by the bandpass filters mounted in front of the PMTs. In addition, in order to avoid contamination between two different OSL signals, the read-out timings were also separated. **Figure 2** shows examples of signals obtained from PMT1 and PMT2. PMT1 and PMT2 measured the OSL signals from Eu:BaFBr and Ce:CaF_2, respectively. The Eu:BaFBr emits the OSL when irradiated by both of the red and green lasers. The Ce:CaF_2 emits the OSL only when irradiated by the green laser. The OSL signal intensity of the Eu:BaFBr

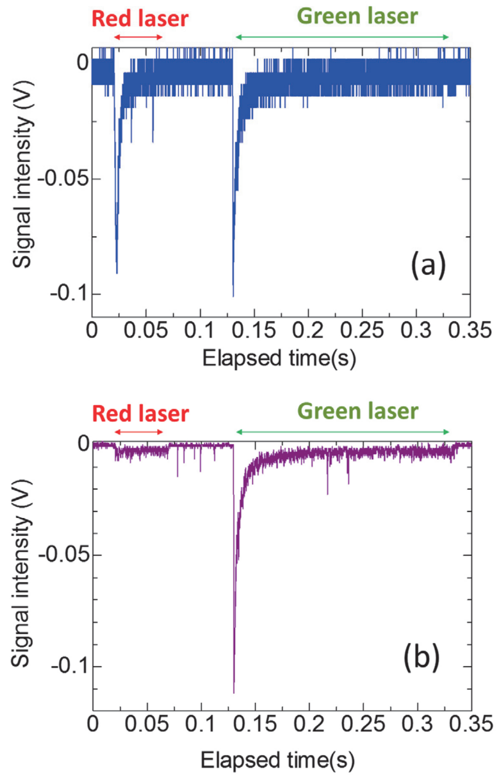

Figure 2. Examples of the OSL signal obtained from (a) PMT1 for the Eu:BaFBr OSL signals and (b) PMT2 for the Ce:CaF_2 signals.

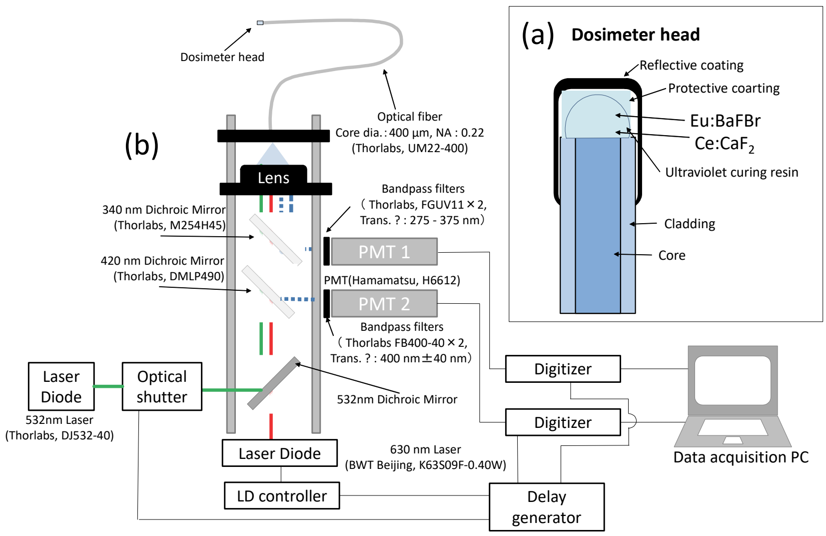

Figure 1. (a) Hybrid type optical fiber based dosimeter probe. The Ce:CaF_2 was adhered first and then the powdered Eu:BaFBr was coated on the Ce:CaF_2. (b) Schematic diagram of the hybrid OSL signal read out system. The OSL and the stimulation light were divided by the dichroic mirrors. PMT1 and PMT2 measure the OSL signal emitted from Ce:CaF_2 and Eu:BaFBr, respectively. The timing of stimulation and reading out was controlled by the data acquisition PC.

was determined by summing up signals stimulated by the red and green lasers. On the other hand, the $Ce:CaF_2$ signal intensity was determined by integrating signals only for the green laser.

3. Experimental setup

We irradiated the fabricated hybrid dosimeter probe with high-energy therapeutic carbon ions at the Heavy Ion Medical Accelerator in Chiba (HIMAC). Water equivalent acrylic phantoms with various thicknesses were placed in front of the dosimeter probe. We can change the equivalent water depth at the probe position by changing the total phantom thickness. A farmer-type ion chamber (PTW23343, Markus Ion Chamber) was also mounted near the fabricated probe as a reference. These experimental configurations were the same as the previous works [4,5].

The fabricated probe was irradiated by the carbon ion pulses with the duration and the cycle period of 1.9 s and 3.3 s, respectively. In order to avoid scintillation and prompt luminescence from the optical fiber and other probe components, the OSL signals were read out after the end of the carbon ion pulse. The red laser irradiation was made for 50 ms from 100 ms after the end of the carbon ion pulse. The green laser irradiation started at 40 ms after the end of the red laser pulse. The green laser pulse duration was 200 ms. We measured with a small size dosimeter using only Eu:BaFBr or $Ce:CaF_2$ in this system. In this laser irradiation timing, the OSL signal contamination can efficiently be eliminated.

First, we irradiated the fabricated probe through the phantom with 290 MeV/u mono-energetic carbon ions and measured a Bragg peak by changing the phantom thickness. In practical cases, since a target organ has a certain volume, the Bragg peak should be spread out. In order to make the SOBP, carbon ions with broad energy distribution are created by the ridge filters. We also evaluated the probe response for the broad-spectrum carbon ions making the SOBP.

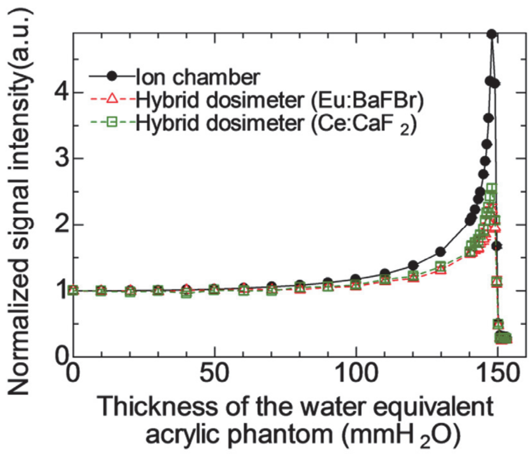

Figure 3. Dosimeter signal intensities at various phantom thicknesses when irradiated with the mono-energetic 290 MeV/u carbon ions. These intensities were normalized at the 0mm thickness.

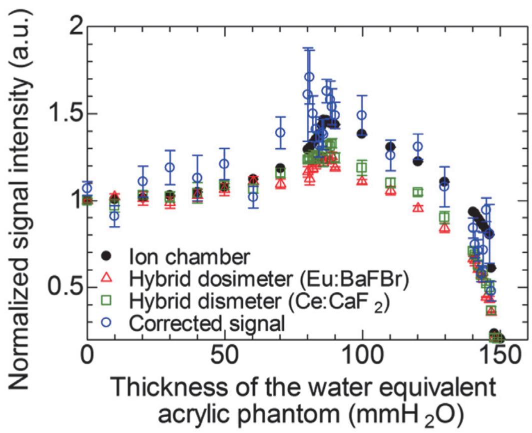

Figure 4. Dosimeter signal intensities at various phantom thicknesses when irradiated with the broad-spectrum carbon ions. These intensities were normalized at the 0mm thickness. The corrected results were also plotted.

4. Results and discussion

Figure 3 shows the dosimeter signal intensities at various phantom thicknesses when irradiated with the mono-energetic 290 MeV/u carbon ions. The dosimeter signal intensities were normalized at the phantom surface corresponding to the 0 mm thickness. The measurements were made three times at each phantom thickness to determine the standard deviation of the signal intensity. The hybrid dosimeter probe and the ion chamber showed the Bragg peak at the water-equivalent phantom thickness of 147.92 mm. In the response of the hybrid OSL dosimeters, the quenching effect was observed near the Bragg peak, where the LET of the carbon ions is quite high.

Figure 4 shows the dosimeter signal intensities at various phantom thicknesses when irradiated with the broad-spectrum carbon ions. The normalization and the determination of the standard deviation were made with the same procedures as the mono-energetic carbon ion measurements. Although a rough SOBP shape was shown for all dosimeters, the quenching effect in the OSL signals were clearly observed at a high LET region.

Luminescence efficiency is defined as the ratio of the measured OSL signals and the ion chamber signals, which is considered to be the real dose. The luminescence efficiencies decrease with the LET owing to the quenching effect according to the Birks formula,

$$\varepsilon_L(x) = A\frac{1}{\left\{1 + kB\frac{dE(x)}{dx}\right\}} \tag{1}$$

where $\varepsilon_L(x)$; the normalized luminescence efficiency at the phantom thickness of x, A; a normalization factor, kB; the quenching factor of a luminescence material, and $dE(x)/dx$; the LET of charged particles at the thickness of *x* [5,10]. By modifying the ratio of the normalized luminescence efficiency of two different OSL materials, we can determine the normalized luminescence efficiency from the ratio of the signal intensity.

$$\begin{aligned}\varepsilon_\alpha &= A_\alpha \frac{A_\beta / A_\alpha \, \varepsilon_\alpha / \varepsilon_\beta - k_\beta B_\beta / k_\alpha B_\alpha}{1 - k_\beta B_\beta / k_\alpha B_\alpha} \\ &= C_0 + C_1 \frac{\varepsilon_\alpha}{\varepsilon_\beta}\end{aligned} \tag{2}$$

where subscripts α and β represent the OSL materials, *ε*, *A* and *kB* are same as the Eq. (1), and C_0 and C_1 are constants. Since the ratio of the normalized luminescence efficiency is proportional to the ratio of the normalized signal intensity, the normalized luminescence efficiency is proportional to the ratio of the normalized signal intensity. **Figure 5** shows the relationship between the ratio of the normalized signal intensity and the normalized luminescence efficiency of Ce:CaF_2 when irradiated with the mono-energetic 290 MeV/u and the broad-spectrum carbon ions. Both cases have roughly linear relationship. Fragment particles, however, were generated from the nuclear spallation reaction of carbon ions in SOBP. These particles that have different charge and mass from carbon ions may distorted the relationship of Figure 5. We corrected the signal intensities in the broad-spectrum case by using the relationship of Eq. (2) for the mono-energetic case. The corrected SOBP is also plotted in Figure 4. Although the fluctuation of the corrected signals is larger than that of the uncorrected ones, the corrected results are improved in terms of the quenching effect. In order to improve the fluctuation, the photon collection efficiency of the OSL signals should be improved to make the measurement accuracy high.

5. Conclusions

We fabricated the hybrid type optical fiber based dosimeter system using Eu;BaFBr and Ce:CaF_2. This system can obtain the OSL signals of both materials through one optical fiber. This means that the fabricated dosimeter probe is easy to insert into a human body. The fabricated dosimeter was irradiated with the 290 MeV/u mono-energetic and the broad-spectrum carbon ions for response evaluation. Both OSL materials showed the quenching effect under high LET particle irradiation. The luminescence efficiency can be determined from the ratio of the signal intensities of both OSL materials. We demonstrated that the SOBP shape was improved by using the relationship between the luminescence efficiency and the ratio of the signal intensities, which was determined when irradiated with the mono-energetic carbon ions.

As a future work, we will improve the light collection efficiency of the whole system to increase the signal level or to improve the signal level fluctuation.

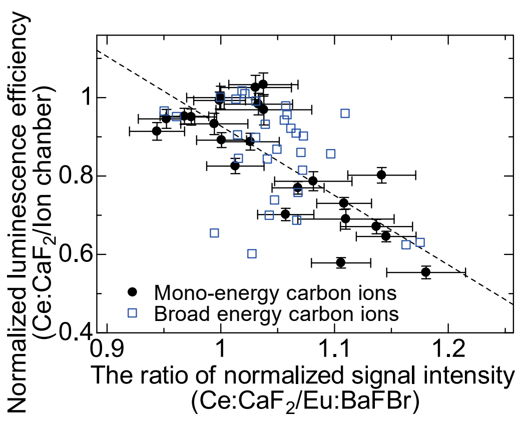

Figure 5. Relationship between the ratio of the normalized signal intensity and the normalized luminescence efficiency when irradiated with mono-energetic and the broad-spectrum carbon ions. The broken line is the linear fitting result to the data of the mono-energetic carbon ion irradiation.

Acknowledgement

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