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Quenching Effect in an Optical Fiber Type Small Size Dosimeter Irradiated with 290 MeV · u^{-1} Carbon Ions

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ABSTRACT

Background: We are developing a small size dosimeter for dose estimation in particle therapies. The developed dosimeter is an optical fiber based dosimeter mounting an radiation induced luminescence material, such as an OSL or a scintillator, at a tip. These materials generally suffer from the quenching effect under high LET particle irradiation.

Materials and Methods: We fabricated two types of the small size dosimeters. They used an OSL material Eu:BaFBr and a BGO scintillator. Carbon ions were irradiated into the fabricated dosimeters at Heavy Ion Medical Accelerator in Chiba (HIMAC). The small size dosimeters were set behind the water equivalent acrylic phantom. Bragg peak was observed by changing the phantom thickness. An ion chamber was also placed near the small size dosimeters as a reference.

Results and Discussion: Eu:BaFBr and BGO dosimeters showed a Bragg peak at the same thickness as the ion chamber. Under high LET particle irradiation, the response of the luminescence-based small size dosimeters deteriorated compared with that of the ion chamber due to the quenching effect. We confirmed the luminescence efficiency of Eu:BaFBr and BGO decrease with the LET. The reduction coefficient of luminescence efficiency was different between the BGO and the Eu:BaFBr. The LET can be determined from the luminescence ratio between Eu:BaFBr and BGO, and the dosimeter response can be corrected.

Conclusion: We evaluated the LET dependence of the luminescence efficiency of the BGO and Eu:BaFBr as the quenching effect. We propose and discuss the correction of the quenching effect using the signal intensity ratio of the both materials. Although the correction precision is not sufficient, feasibility of the proposed correction method is proved through basic experiments.

Keywords: Dosimeter, Optically stimulated luminescence, Optical fiber probe, Radiotherapy

Original Research

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Introduction

Irradiation technology of radiotherapies has been evolving rapidly. Especially heavy ion therapy can form fine dose distribution and irradiate only a target organ [1]. Although fine dose distribution can reduce undesired irradiation into normal organs, misalignment of an irradiation position may cause significant accidental exposure and/or deficiency of the irradiation dose into a tumor. In order to assure a planned treatment, dose estimation procedures is quite important. At the present, the irradiation dose distribution is cautiously planned and estimated with treatment planning software. In addition, the planned irradiation is assured based on phantom measurements as routine works. However, in order to effectively and accurately estimate the dose in fine irradiation conditions, small dosimeters are preferred to be inserted into an affected region in a patient body to monitor the dose on-line.

Ion chamber, metal oxide semiconductor field effect transistor (MOS-FET) and scintillator were widely used as a dosimeter. However, the size of ion chamber is a few mm at least so too large to insert into a body. Although the MOSFET is enough small, the sensitivity is not so high [2]. In addition, for these dosimeters, bias voltage should be applied to a dosimeter probe so it is undesired in safety. Scintillators mounted on a tip of an optical fiber can be made small and need no bias voltage on a dosimeter probe [3-5]. However, a small size scintillation detector with an optical fiber suffers from interference of luminescence in an optical fiber itself due to Cherenkov radiation and weak scintillation.

We are developing a small size dosimeter consisting of an optical fiber and radiation induced luminescence materials. As mentioned above, since an optical fiber itself shows prompt luminescence when irradiated with radiations, it is undesired to acquire signals during irradiation in terms of signal-to-noise ratio. In order to solve this problem, we chose an optically stimulated luminescence (OSL) element as a luminescence material [6]. An OSL element can accumulate radiation irradiation information. In an accumulation process, information carriers, such as electrons and holes, excited by radiations are partially trapped in the OSL element. By irradiating the element with stimulation light, trapped carriers are relaxed and the element emits OSL proportional to irradiated dose. The OSL signal, therefore, can be a measure of irradiated dose [7]. The OSL signal can increase by increasing accumulation time so that the OSL element can show significant signal intensity even if a quite small element is used. In addition, since the OSL signals can also be readout in the intervals of pulse irradiation, the OSL dosimeter can show excellent performance in terms of the signal-to-noise ratio. The small OSL dosimeter using an optical fiber shows good linearity to the irradiated dose and the lower limit of detectable dose was evaluated to be 0.9 mGy [8].

Since heavy ion radiotherapies can make quite fine dose distribution by using pencil beam scanning irradiation technique, urethra dose in prostate irradiation can be reduced [9]. In order to apply the developed small dosimeter to heavy ion radiotherapies, the dosimeter response to heavy ions should be evaluated. Since heavy ions, such as carbon ions, have quite high linear energy transfer (LET), the quenching effect, which is luminescence efficiency reduction under high LET particle irradiation, should be considered. Under high LET particle irradiation, density of excited carriers, such as electrons and holes, along its track is quite high. In OSL elements, excited carriers move in conduction band and fall into trap centers. Since the trap centers are fully filled with excited carriers near a track of heavy ions, the number of trapped carriers, which is proportional to the OSL intensity, tends to saturate [10, 11]. The quenching effect in scintillators is also caused by similar mechanism, in which the emission centers are fully filled instead of the trap centers. The density of the trap or emission centers and mobility of the carriers depends on materials. Therefore, the quenching effect can also depend on materials [12]. This discrepancy can be an index of degree of the quenching effect. In this paper, we discuss the quenching effect of radiation induced luminescence materials used in small size dosimeters under irradiation of therapeutic 290 $MeV \cdot u^{-1}$ carbon ions. We, additionally, discuss feasibility of a correction method of the quenching effect using discrepancy in luminescence efficiencies between different materials.

Materials and Methods

1. Details of small size dosimeter using OSL and scintillation elements

We fabricated two types of small size optical fiber dosimeter systems based on radiation induced luminescence materials as shown in Figure 1. One of them uses a Eu:BaFBr OSL element and other one uses a bismuth germanate ($Bi_4Ge_3O_{12}$: BGO) scintillator as radiation induced luminescence materials. A Eu:BaFBr OSL dosimeter system consists of quartz optical fibers (core dia.: 400 μm, numerical aperture: 0.22), a dosimeter probe using an OSL element, a red (630 nm) laser diode for a stimulation light source K63S09F-0.40W (BWT Beijing LTD., Beijing, China), a photomultiplier tube (PMT) H6612 (Hamamatsu, Shizuoka, Japan), a timing control unit, a signal processing unit and a personal computer to control the whole system and to acquire data. The dosimeter head is coated with acrylic paint, and outer diameter is about 1 mm. We select a Eu:BaFBr, which is used as an imaging plate material and emits OSL of 400 nm wavelength with red light stimulation, as an OSL element. Eu:BaFBr powder is adhered with ultraviolet curing resin on a tip of the optical fiber. Another end of the fiber is split into two ways through an optical fiber coupler. The branching ratio of the fiber coupler is 9:1. One terminal with 10% branching ratio is connected to a red laser diode. Another terminal with 90% branching is connected to the PMT. In order to avoid red laser reflection light, the band-pass filter FB400-40 (Thorlabs Inc., Newton, NJ) is mounted in front of the photocathode of the PMT. The center wavelength and bandwidth of transmission of the band-pass filter is 400 and 10 nm, respectively, which matches the OSL wavelength of Eu:BaFBr. The laser diode is operated in pulse mode with the duration of 50 ms. For the current laser power, the pulse duration of 50 ms is sufficient to fully readout all trapped carriers in the OSL element. The OSL signals are recorded through the digitizer into the PC. The recorded signals are analyzed in the control PC.

A BGO scintillator system consists of a dosimeter probe, an optical fiber, a photomultiplier tube and a data acquisition. Since a BGO scintillator has no hygroscopicity and relatively high light yields, it is easy to fabricate an optical fiber type dosimeter [13]. A BGO dosimeter probe is fabricated in the similar way as the OSL dosimeter system. BGO powder is also adhered on a tip of an optical fiber and another end of the fiber is directly connected to the PMT H12400 (Hamamatsu, Shizuoka, Japan).

2. Experimental setup

The fabricated small size dosimeter was irradiated with carbon ions at Heavy Ion Medical Accelerator in Chiba (HIMAC). Figure 2 shows timing chart of HIMAC carbon ion beam pulses and data acquisition of the dosimeter system. Cycle period and carbon ion pulse width of the HIMAC are 3.3 seconds and about 1 second, respectively. The delay from an accelerator trigger signal to the signal readout timing was controlled. The readout of the Eu:BaFBr OSL dosimeter was set at intervals between carbon ion pulses. The signal readout time for the OSL dosimeter was set to be 50 ms. This means that the OSL dosimeter signals can be readout during the intervals between each carbon ion pulse. On the other hand, BGO scintillator signals were acquired during irradiation. The optical fiber also slightly shows luminescence during irradiation. In order to subtract this component, the re-

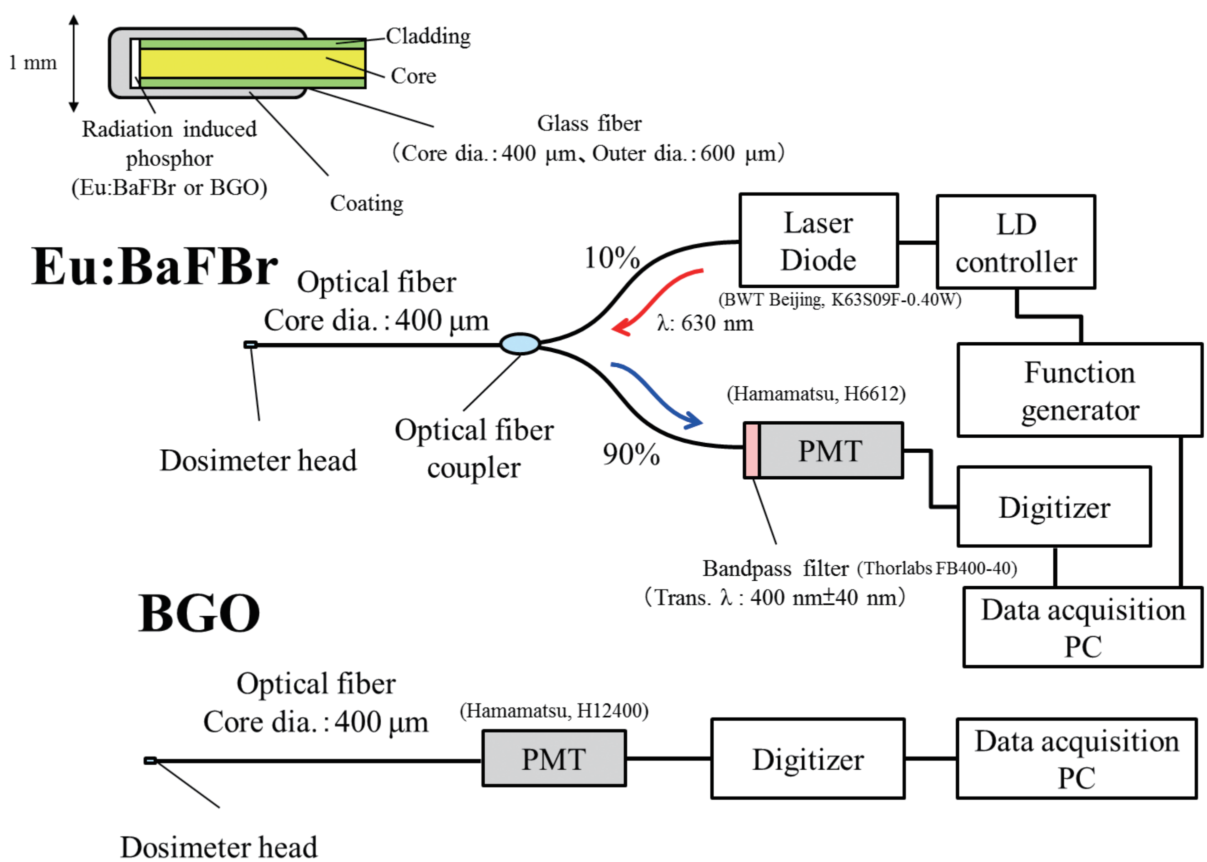

Fig. 1. Schematics of an optical fiber type small size dosimeter systems. A Eu:BaFBr OSL dosimeter system consists of a dosimeter head, optical fiber based light transmission lines, a laser diode as a stimulable light source, a photomultiplier tube and a data acquisition system. A BGO scintillator system consist of a dosimeter head, an optical fiber, a photomultiplier tube and a data acquisition.

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sponse only of the optical fiber was also acquired. Figure 3 shows examples of signal waveforms obtained from an Eu:BaFBr OSL element and BGO scintillator. The signals were digitally integrated in the control PC during the period shown in Figure 3. The time integrated signal intensities were applied as the dosimeter output.

The energy of carbon ions was 290 MeV·u^{-1}. Carbon ion beams had a circular shape with a diameter of 10 cm. The fabricated dosimeters and an ion chamber PTW23343 (PTW, Freiburg, Germany), which was used as a reference dosimeter, were simultaneously set near the center of the beam. Figure 4 shows the experimental arrangement. The water equivalent acrylic phantoms, which are called as to "binary filter", were placed at upstream of the dosimeter set position. The total thickness of the phantoms can be changed to imitate changing the depth of the dosimeter set position from a

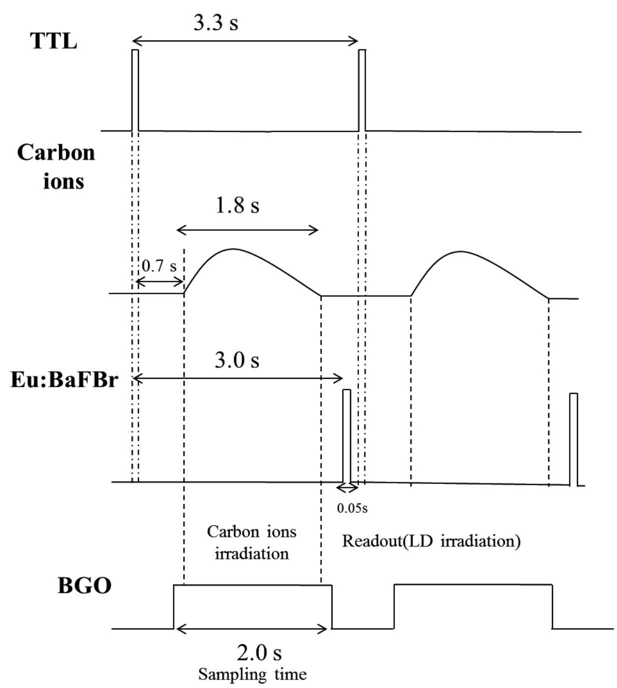

Fig. 2. Timing chart of data acquisition of the dosimeter system and carbon ion beam pulses of HIMAC. The signal readout time for the OSL dosimeter was set to be 50 ms.

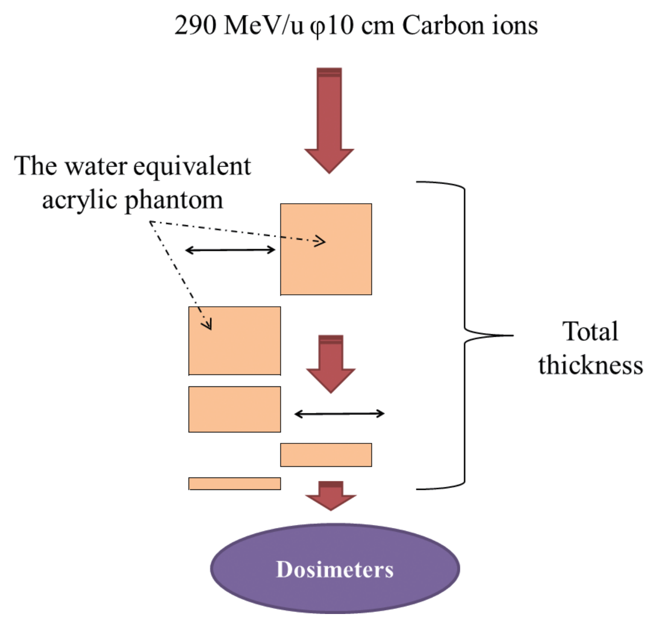

Fig. 4. Experimental arrangement of Bragg curve measurements. The fabricated small size dosimeters and the standard ion chamber were set behind the water equivalent acrylic phantom with various thickness and irradiated by a carbon ion beam with 290 MeV·u^{-1} and 10 cm diameter.

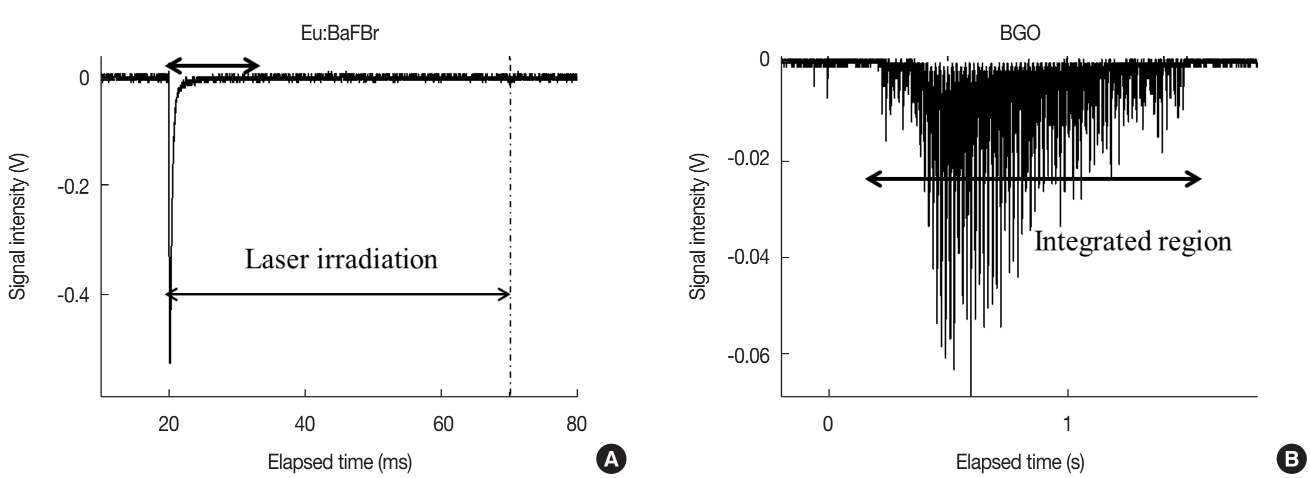

Fig. 3. Signal time profiles obtained from (A) Eu:BaFBr OSL dosimeter and (B) BGO scintillator. The signal integrated regions are also indicated in the figures.

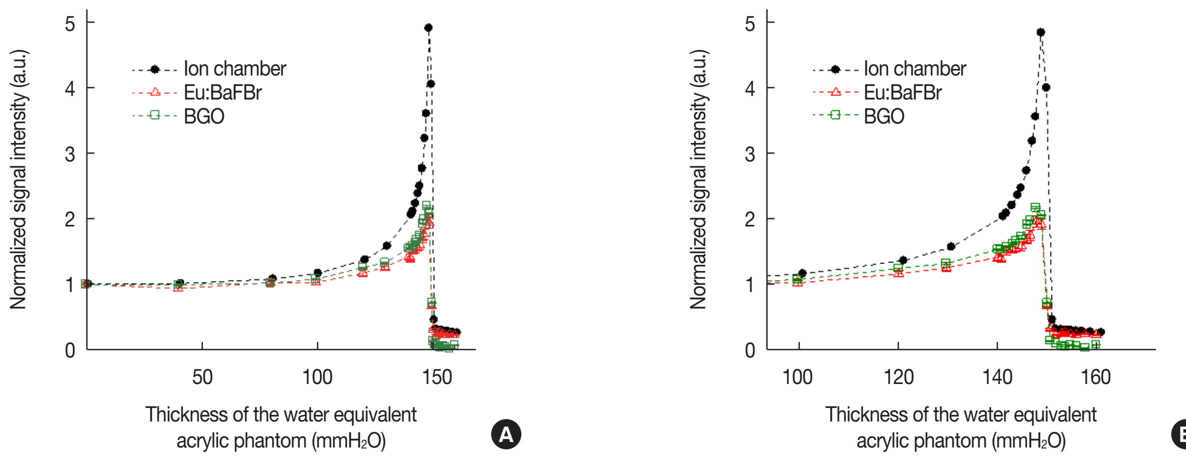

Fig. 5. (A) Phantom thickness dependence of signal intensities obtained from the fabricated small size dosimeters when irradiated with 290 MeV·u-1 mono-energy carbon ions. (B) Extension of the phantom thickness dependence. The dose measured with the standard ion chamber is also plotted. Signal intensities are normalized at zero thickness.

patient body surface. In these experiments, we imitate measuring the dose distribution in a patient with the dosimeters.

Results and Discussion

Figure 5 shows the phantom thickness dependence of signal intensities obtained from the fabricated small size dosimeters when irradiated with 290 MeV·u-1 mono-energy carbon ions. The actual dose distribution measured with the reference ion chamber is also plotted. The signal intensities are normalized at the zero thickness corresponding to a patient surface. The depth of the Bragg peak measured with the fabricated dosimeters is consistent with that measured with the reference ion chamber. However the quenching phenomena, which is reduction of the luminescence efficiency, were also confirmed near the Bragg peak. To compare the quenching effects between Eu:BaFBr and BGO, the luminescence efficiency, which is defined as the ratio of the luminescence intensity to the actual dose measured with the ion chamber, was evaluated at each phantom thickness. The LET at each phantom thickness can be determined with Monte Carlo calculations. Since fragment ions are produced under carbon ion irradiation, the LET at each phantom thickness is not unique and has a broad energy spectrum. The LET is averaged at each phantom thickness by weighting it with the dose. Figure 6 shows the relationship between LET and the luminescence efficiency of Eu:BaFBr and BGO. Clear correlations between the luminescence efficiency and LET can be confirmed. The luminescence efficiency of Eu:BaFBr is more strongly decreased than that of BGO.

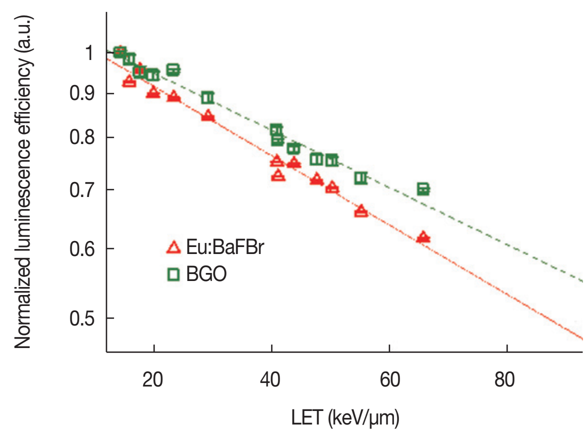

Fig. 6. Relationship between LET and luminescence efficiency of Eu:BaFBr and BGO.

Since the quenching effect is inevitable in the solid phosphor, the response of the small size p based on luminescence should be corrected to derive accurate dose. The luminescence efficiency depends on the LET as described above. The fabricated dosimeters have a difference in the LET dependence of the luminescence efficiency. We, therefore, propose the correction of the quenching effect using the discrepancy of the luminescence efficiency of Eu:BaFBr and BGO. Figure 7 shows the relationship between LET and the ratio of normalized signal intensities of Eu:BaFBr and BGO. The signal intensity ratio depends on LET. This means that the LET at a dosimeter setting position can be estimated with the signal intensity ratio between the both dosimeters. We can, therefore, correct the signal intensity by dividing by the luminescence efficiency determined with the estimated LET. Figure 8 shows the phantom thickness dependence of the

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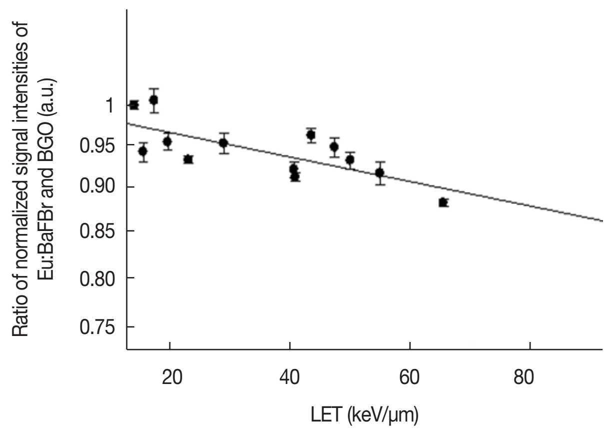

Fig. 7. Relationship between LET and the ratio of normalized signal intensities of Eu:BaFBr and BGO.

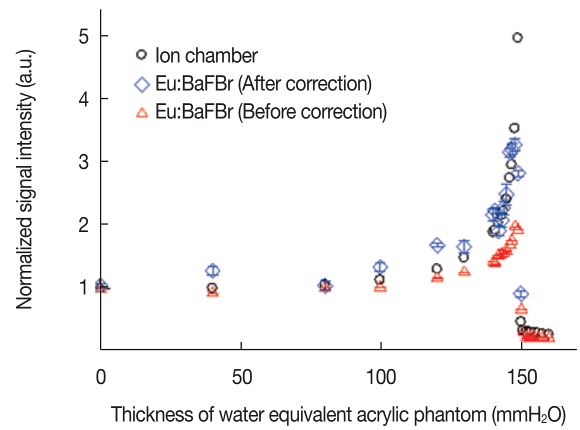

Fig. 8. Phantom thickness dependence of the corrected signal intensity of Eu:BaFBr when irradiated with 290 MeV·u^{-1} mono-energy carbon ions.

corrected signal intensity of Eu:BaFBr when irradiated with 290 MeV·u^{-1} mono-energy carbon ions. Although the corrected signal intensity slightly shows a discrepancy with the actual dose near the top of the Bragg peak, it is excellently improved compared with the results before correction. The discrepancy near the top of the Bragg peak is considered to be because the luminescence efficiency depends not only on the averaged LET but ion mass, charge and so on. In addition, since the LET change near the top of the Bragg peak is quite large, the uncertainty of the correction is also large. In order to improve precision of the correction, a discrepancy in the luminescence efficiency between different materials is desired to be large. Selection of optimum combination of phosphors will be a future work.

Conclusion

We fabricated the small size optical fiber type dosimeter system using Eu:BaFBr OSL element and BGO scintillator. We evaluated the LET dependence of the luminescence efficiency of the both materials as the quenching effect. A discrepancy in the LET dependence of the luminesce efficiency between the both is confirmed. We propose the correction of the quenching effect using the signal intensity ratio of the both materials, which is a discrepancy of the luminescence efficiencies. Although the correction precision is not sufficient, feasibility of the proposed correction method is confirmed through basic experiments. As future works, we will select the optimum combination of radiation induced luminescence materials through experimental comparisons of the luminescence properties.

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