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Technical notes

# Estimation of the optical errors on the luminescence imaging of water for proton beam

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A B S T R A C T

Although luminescence imaging of water during proton-beam irradiation can be applied to range estimation, the height of the Bragg peak of the luminescence image was smaller than that measured with an ionization chamber. We hypothesized that the reasons of the difference were attributed to the optical phenomena; parallax errors of the optical system and the reflection of the luminescence from the water phantom. We estimated the errors cause by these optical phenomena affecting the luminescence image of water. To estimate the parallax error on the luminescence images, we measured the luminescence images during proton-beam irradiation using a cooled charge-coupled camera by changing the heights of the optical axis of the camera from those of the Bragg peak. When the heights of the optical axis matched to the depths of the Bragg peak, the Bragg peak heights in the depth profiles were the highest. The reflection of the luminescence of water with a black wall phantom was slightly smaller than that with a transparent phantom and changed the shapes of the depth profiles. We conclude that the parallax error significantly affects the heights of the Bragg peak and the reflection of the phantom affects the shapes of depth profiles of the luminescence images of water.

## 1. Introduction

A quality assurance (QA) for proton therapy is commonly conducted by the use of ionization chambers in water or water equivalent phantoms. Since ionization chambers are thought to measure the precise doses, they are routinely used to measure dose distribution. However, to measure the depth profiles of the proton beams, ionization chambers need to move in a water phantom and the procedure takes a long measurement time. To measure two or three dimensional dose distributions of proton beam, it takes more time with ionization chambers. Three-dimensional dose distributions can be obtained by using grids of ionization chambers and gel dosimeters but these dosimeters have their disadvantages and they are not routinely used to measure dose distributions for QA [1]. Other possible methods to measure the dose distribution of the proton beam are the prompt gammas photon and annihilation radiation imaging [2–15]. However the measured profiles with these methods are different from those measured with ionization chambers because the produced radionuclide distribution in water is different from doses. Optical imaging using a liquid scintillator was also tried for dose evaluation but the method has a quenching effect of the scintillation light in Bragg peak region [16–18].

Recently, we have successfully imaged a luminescence of water during proton-beam irradiation using a cooled charge-coupled device (CCD) camera [19]. The measured luminescence images showed clear Bragg peak and the depth profile showed almost the same ranges of the proton beam as those measured by the ionization chamber. However, the depth profiles estimated from the luminescence images were different from those measured by the ionization chamber; the Bragg peak heights were smaller than those of the ionization chamber. We hypothesized that difference was caused by optical phenomena; parallax errors of the CCD camera and reflection of the luminescence by the water phantom. If the difference is removed, the luminescence of water could be used for the dose measurements. For this purpose, we estimated the errors caused by these optical phenomena affecting the luminescence images of water.

## 2. Materials and methods

### 2.1. Measurements setup for luminescence imaging

Fig. 1 shows the experimental setup for the luminescence imaging during proton-beam irradiation. A phantom of transparent container was filled with tap water up to 2 cm from the top of the phantom. The

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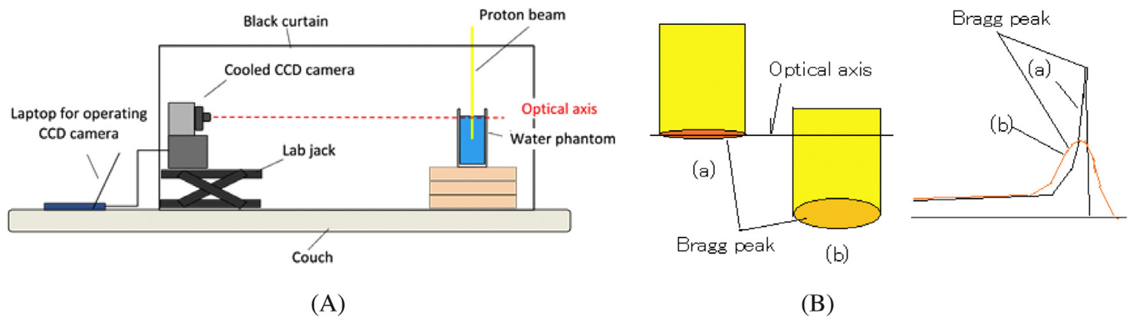


**Fig. 1.** Experimental setup for luminescence imaging of water during proton-beam irradiations (A) and schematic drawing of parallax error in Bragg peak (B).

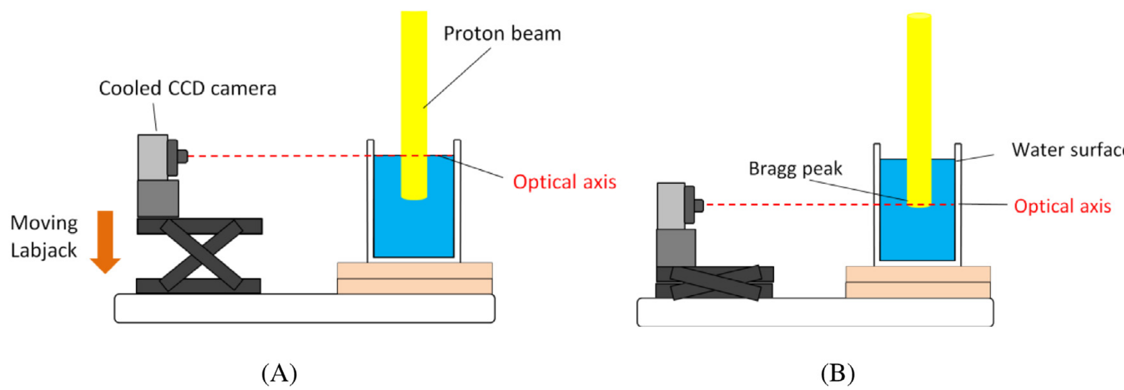


**Fig. 2.** Schematic drawings of set-up of luminescence imaging with different heights of optical axis; matched to water surface (A) and to Bragg peak (B).

water phantom was placed on a couch in the spot scanning treatment room (Hitachi, Japan). The phantom was made of acrylic resin plates with outer dimensions of 20 cm (horizontal) × 20 cm (vertical) × 10 cm (depth) and each plate was 5 mm thick. The measurement was performed at the spot scanning room of the Nagoya Proton Therapy Center [20]. A cooled CCD camera (BITRAN BS-40L, Japan) operating at 3 °C was set on the lab jack. We used C-mount F-1.4 lens (Computar, Japan) whose F values was 1.4 and focal length was 8 mm. The camera and lab jack were set ~40 cm from the phantom surface. To shut off the background light in the room, the phantom and the CCD camera were covered with a black curtain.

The acquired image size of the CCD camera was $772 \times 580$. Since we expected the pixel size of the images will affect the height and sharpness of Bragg peak, we measured higher resolution images to estimate the parallax errors. We also measured an optical photo of the phantom and a blank image (image without irradiating proton beam). The former was used to measure the absolute size of the phantom, while the latter was used to correct the background offset and the non-uniformity of the CCD camera for the measurement.

Fig. 1(B) shows the schematic drawing of the parallax error of the luminescence images. When the Bragg peak position is on the optical axis of the lens, the image of the Bragg peak has thin shape in vertical direction as shown in (a) in Fig. 1(B). Meanwhile when the Bragg peak position is lower position of the optical axis, the image of the Bragg peak has wider in vertical direction and the intensity is lower as shown in (b) in Fig. 1(B). Therefore the estimated depth profile for (a) has sharp and high peak while that for (b) is broad and low as shown in right part in Fig. 1(B).

### 2.2. Estimation of the parallax errors

The parallax error is an optical phenomenon where the subject near the camera is formed to more peripheral part in the image and the subject far from the camera is formed to its central part in the image although the distance from the center to the subject is the same. To evaluate the effect of the parallax errors on the depth profiles of the luminescence images of water, we measured the images by changing the heights of the optical axis of the camera from those of the Bragg peak by moving the lab jack vertical direction as shown in Fig. 2(A) and (B). The luminescence images were measured for the 10 positions for 72. 5 MeV protons and 7 positions for 100.2 MeV protons as listed in Table 1. In Table 1, plus means that the optical axis position was located lower than the Bragg peak and minus means that optical axis position was located higher than the Bragg peak.

**Table 1**
Distance from the optical axis to Bragg peak of measured luminescence images.

| Proton energy (MeV) | Distance from optical axis to Bragg peak (mm) |
|---|---|
| 72.5 MeV | −40, −20, −10, −5, −2.5, 0, +2.5, +5 +10, +20 |
| 100.2 MeV | −73.5, −40, −20, −10, −5, −2.5, 0 |

We irradiated proton beams to the water phantom and measured the luminescence image of water at each position using the CCD camera for three minutes. We irradiated proton beam to the center of the water phantom with a fixed dose of 300 monitor units (MU). Irradiated proton energies were 72.5 MeV and 100.2 MeV. The width of 72.5 MeV proton beam was about 32 mm FWHM and that of 100.2 MeV proton beam was 23 mm FWHM. The depths of these Bragg peak are measured to be 40.0 mm and 73.5 mm from the water surface by the measurements with a Bragg peak ionization chamber (PTW Model 34070, Germany) for 72.5 MeV and 100.2 MeV protons, respectively.

### 2.3. Estimation of reflection of luminescence from water phantom

With a phantom made of transparent acrylic plates, the measured luminescence images might be included the reflected luminescence from the backside of the phantom. Therefore, we measured the luminescence images using a transparent phantom and a black wall phantom and