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Stability and linearity of luminescence imaging of water during irradiation of proton-beams and X-ray photons lower energy than the Cerenkov light threshold

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A R T I C L E I N F O

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A B S T R A C T

Luminescence of water during irradiations of proton-beams or X-ray photons lower energy than the Cerenkov-light threshold is promising for range estimation or the distribution measurements of beams. However it is not yet obvious whether the intensities and distributions are stable with the water conditions such as temperature or addition of solvable materials. It remains also unclear whether the luminescence of water linearly increases with the irradiated proton or X-ray energies. Consequently we measured the luminescence of water during irradiations of proton-beam or X-ray photons lower energy than the Cerenkov-light threshold with different water conditions and energies to evaluate the stability and linearity of luminescence of water. We placed a water phantom set with a proton therapy or X-ray system, luminescence images of water with different conditions and energies were measured with a high-sensitivity cooled charge coupled device (CCD) camera during proton or X-ray irradiations to the water phantom. In the stability measurements, imaging was made for different temperatures of water and addition of inorganic and organic materials to water. In the linearity measurements for the proton, we irradiated with four different energies below Cerenkov light threshold. In the linearity measurements for the X-ray, we irradiated X-ray with different supplied voltages. We evaluated the depth profiles for the luminescence images and evaluated the light intensities and distributions. The results showed that the luminescence of water was quite stable with the water conditions. There were no significant changes of intensities and distributions with the different temperatures. Results from the linearity experiments showed that the luminescence of water linearly increased with their energies. We confirmed that luminescence of water is stable with conditions of water. We also confirmed that the luminescence of water linearly increased with their energies.

1. Introduction

We previously reported that luminescence is emitted during X-ray irradiations of water phantoms even at a lower energy than the Cerenkov-light threshold and imaging of X-ray beam distribution was possible using a charge coupled device (CCD) camera [1]. The luminescence was not Cerenkov-light emitted by the electrons because the maximum X-ray energy used for the measurements was 120 keV, which is far below the Cerenkov-light thresholds. We also obtained luminescence images of water during irradiations of proton [2], carbon-ion [3] and alpha particles [4] at lower energy than the Cerenkov-light threshold.

Cerenkov-light is a well-known phenomenon, and imaging has already been tried for dose estimation using X-rays from high-energy linear accelerators [5–12]. In these works on Cerenkov-light imaging, X-rays over several MeV, which is much higher than the Cerenkov-light threshold, were irradiated to water phantoms, and high-sensitivity CCD cameras were used for the imaging. In the Cerenkov-light imaging, the intensity is reported to be stable with conditions such as temperature or impurity of solution [13].

The luminescence of water at lower energy than the Cerenkov-light threshold is quite a different phenomenon from Cerenkov-light because it is observed below Cerenkov-light threshold. Thus it remains unclear whether the intensity of the luminescence of water at a lower energy

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than the Cerenkov-light threshold is stable with water conditions. We already checked the luminescence intensity and distribution were not changed between pure-water and tap-water [2]. However it is not yet clear whether the luminescence of water is affected by other conditions such as temperature, addition of inorganic and organic materials.

Also it remains unclear whether the luminescence of water linearly increases with the irradiated proton or X-ray energies. The intensity of the Cerenkov light as a function of the radiation energy is not linear that is a drawback of the Cerenkov light imaging when it is applied for the dose estimation [9]. Cerenkov light has the energy threshold level (~260 keV in water), and the light intensity rapidly increases above the threshold as the electron energy increases and almost saturates more than ~1000 keV [13]. If the luminescence of water lower energy than the Cerenkov-light threshold linearly increases with energy, unlike Cerenkov light, it would be an advantage and the phenomenon will have a potential to be used for dose estimation. For these purposes, we measured and evaluated the luminescence intensity of water during proton and X-ray irradiations with different water conditions and energies.

2. Methods

2.1. Experimental setup for luminescence imaging for stability measurements

2.1.1. Luminescence imaging of proton-beam for stability measurements

Fig. 1 shows a schematic drawing of the experimental setup for the luminescence imaging during proton irradiation. We placed one of the phantoms containing different conditions of water on a table of the spot scanning proton therapy system (Hitachi Corporation). A cooled CCD camera (BITRAN BU-56-DUV, Japan) with a C-mount F-1.4 lens (Computar, Japan) was set ~40 cm from the phantom surface. The cooled CCD camera used was monochrome type and the sensitivity of the CCD camera was from ~200 to ~800 nm.

We used a water container made of acrylic resin plates with outer dimensions of 20 cm (horizontal) × 20 cm (vertical) × 10 cm (depth), and the plates were 5-mm-thick. In the phantom, water with different conditions was filled ~2 cm from the top of the phantom.

The CCD camera and water phantom were set in a black box and proton-beam was irradiated from the top of the water phantom to the center of the phantom. During irradiation of proton beam, luminescence imaging was conducted by the CCD camera from the side of the phantom. Since the entrance of the black box where the proton-beam was irradiated was made of black paper, the attenuation or scatter of the proton-beam was negligible.

For each measurement, the CCD camera was exposed for 3 min. During the exposure period, proton-beam of 100 MeV was irradiated to water in the phantom with different conditions for 1 min with dose of 180 MU. The energy of 100 MeV protons was lower than Cerenkov-light threshold for protons as well as the secondary electrons produced by protons [14].

2.1.2. Luminescence imaging of X-ray photon for stability measurements

Fig. 2 show a schematic drawing of the experimental setup for the luminescence imaging during low-energy X-ray photon irradiation to a water phantom. We placed one of the phantom containing various conditions of water on a table of a conventional X-ray imaging system (Toshiba KXO−1000, with X-ray tube of DRX-2425HD). The X-ray from the tube was reduced the size by the collimator and irradiated to the water in the phantom.

The same cooled CCD camera (BITRAN BU-56-DUV, Japan) used for proton experiments was used with a C-mount F-0.95 lens (Schneider) set ~40 cm from the phantom surface. Brighter lens (low F number) was selected because the luminescence was small for the low energy X-ray [1]. The size of the phantom was 15 cm (horizontal) × 15 cm (vertical) × 10 cm (depth), and the plates were 5 mm thick. This smaller phantom than that used for proton experiments was used because the

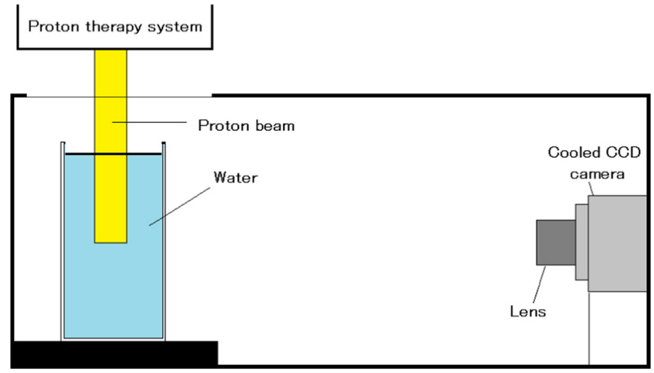

Fig. 1. Schematic drawings of experimental setups of luminescence imaging for stability measurements during proton irradiations.

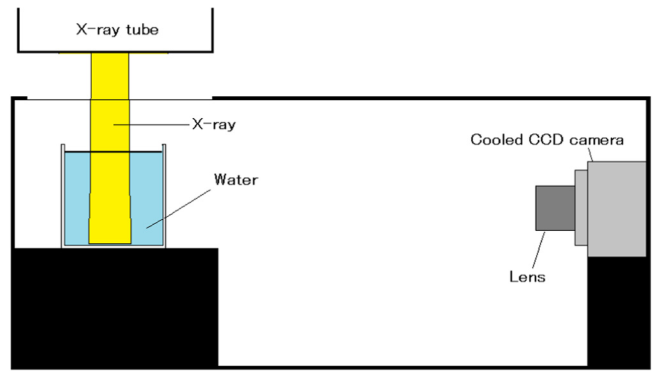

Fig. 2. Schematic drawings of experimental setups of stability measurements for luminescence imaging during X-ray irradiations.

maximum angle of the lens used was smaller than that used for proton experiments. In the container, water with various conditions was filled with ~2 cm from the top of the phantom.

The CCD camera and water phantom were set in a block box and X-ray photons was irradiated from the top of the water phantom to the center of the phantom. During irradiation of X-ray, luminescence imaging was conducted by the CCD camera from the side of the phantom.

For each measurement, the luminescence imaging was conducted by the CCD camera with exposure time for 3 min. During the exposure time of the CCD camera, X-ray photons was irradiated to one of the water phantoms of with different conditions with maximum energy of 120 keV, 200 mA, 0.5 s repeated 6 times with ~30 s intervals.

2.1.3. Imaging of water phantom with different temperatures for stability measurements

For the measurements of the stability of the luminescence of water, we conducted the imaging of water phantom with different temperatures. If the intensity of luminescence of water has high dependency on the temperature, it may be a problem when we use the method for the dose estimation. The temperature of water was increased by a water heater and imaging of the luminescence was made during the temperature of water decreased. We conducted imaging of water phantom with different temperatures of 20 °C, 40 °C, and 60 °C. Luminescence of water measurements were conducted for proton and X-ray photons.

2.1.4. Imaging of water with different concentrations of organic and inorganic materials for stability measurements

The purpose of the measurements was to check whether the luminescence of water changed with addition of organic and inorganic materials to water. Relatively high concentrations of organic and inorganic