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Luminescence imaging of water during irradiation of X-ray photons lower energy than Cerenkov- light threshold

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ABSTRACT

Luminescence imaging of water using X-ray photon irradiation at energy lower than maximum energy of ~200 keV is thought to be impossible because the secondary electrons produced in this energy range do not emit Cerenkov- light. Contrary to this consensus assumption, we show that the luminescence imaging of water can be achieved by X-ray irradiation at energy lower than 120 keV. We placed water phantoms on a table with a conventional X-ray imaging system, and luminescence images of these phantoms were measured with a high-sensitivity, cooled charge coupled device (CCD) camera during X-ray photon irradiation at energy below 120 keV. We also carried out such imaging of an acrylic block and plastic scintillator. The luminescence images of water phantoms taken during X-ray photon irradiation clearly showed X-ray photon distribution. The intensity of the X-ray photon images of the phantom increased almost proportionally to the number of X-ray irradiations. Lower-energy X-ray photon irradiation showed lower-intensity luminescence at the deeper parts of the phantom due to the higher X-ray absorption in the water phantom. Furthermore, lower-intensity luminescence also appeared at the deeper parts of the acrylic phantom due to its higher density than water. The intensity of the luminescence for water was 0.005% of that for plastic scintillator. Luminescence imaging of water during X-ray photon irradiation at energy lower than 120 keV was possible. This luminescence imaging method is promising for dose estimation in X-ray imaging systems.

1. Introduction

Recently, Cerenkov-light imaging has been employed for dose estimation in water phantoms using X-ray photons produced by a high-energy linear accelerator [1–4]. In these works of Cerenkov-light imaging, X-ray photons of more than several MeV were irradiated to the phantoms, and high-sensitivity charge coupled device (CCD) cameras were used for the imaging. The optical signals from the water phantoms were attributed to the Cerenkov-light emitted by secondary electrons. However, if such optical luminescence were due to Cerenkov-light, it would be impossible to image the luminescence distribution for X-ray photons lower than maximum energy of ~200 keV, since Cerenkov-light is not emitted by the secondary electrons produced with X-ray photons in that energy range.

Recently, we successfully imaged the proton-beam distribution in a water phantom during proton irradiation using a CCD camera [5]. Also we successfully imaged the alpha particle distribution in water using a CCD camera [6]. The luminescence was not thought to be from the Cerenkov-light emitted by the produced electrons but from the radicals produced in water by the irradiation of the proton beam or alpha particles. If this conjecture is true, it may be possible to image the distribution of X-ray photons at energy lower than ~200 keV, an energy level at which Cerenkov-light is not produced. There are some reports on luminescence detection by electron beam irradiation to water lower than the Cerenkov-light threshold [7], there is no report on the luminescence images of water during irradiating X-ray below Cerenkov-light threshold (~260-keV). The luminescence imaging of water during irradiation of X-ray lower energy than Cerenkov-light threshold would be a new dose distribution evaluation method for X-ray imaging or X-ray computer tomography (X-CT) systems.

For this purpose, we tried using a CCD camera to image a water phantom during X-ray photon irradiation at energy lower than 120 keV. We also conducted additional experiments to demonstrate the possibility of luminescence imaging with low-energy X-ray and its potential for use in dose estimation for X-ray photons lower energy than Cerenkov-light threshold.

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2. Methods

2.1. A Experimental setup for luminescence imaging

Fig. 1(A) is a schematic drawing of the experimental setup for luminescence imaging during low-energy X-ray photon irradiation to a water phantom. We placed the phantom on a table alongside a conventional X-ray imaging system (Toshiba KXO – 1000, with X-ray tube of DRX-2425HD). A magnified schematic drawing of the X-ray beam area is shown in Fig. 1(B). The X-ray from the tube was reduced the size by the collimator and irradiated to the water contained in the phantom.

A cooled CCD camera operating at $-10\,°C$ (BITRAN BS-40L, Japan) with a C-mount F-0.95 lens (Schneider) was set ~40 cm from the phantom surface. The cooled CCD camera used was monochrome type, the pixel size of 772×580 with 16 bit depth. The sensitivity of the CCD camera was highest for 500-nm light and was lower than 60% of the peak sensitivity below 400 nm.

A photo taken during imaging experiments is shown in Fig. 1 (C). When conducting the luminescence imaging experiments, the phantom and the CCD camera were covered with a black curtain to minimize the detection of background light by the CCD camera.

We used three types of phantoms: a transparent liquid container, an acrylic block and a plastic scintillator block. The liquid container was made of acrylic resin plates with outer dimensions of 10 cm (horizontal)x10 cm (vertical)x10 cm (depth), and the plates were 5 mm thick. In the container, pure water was filled up to 1 cm from the top of the container. The acrylic block was made

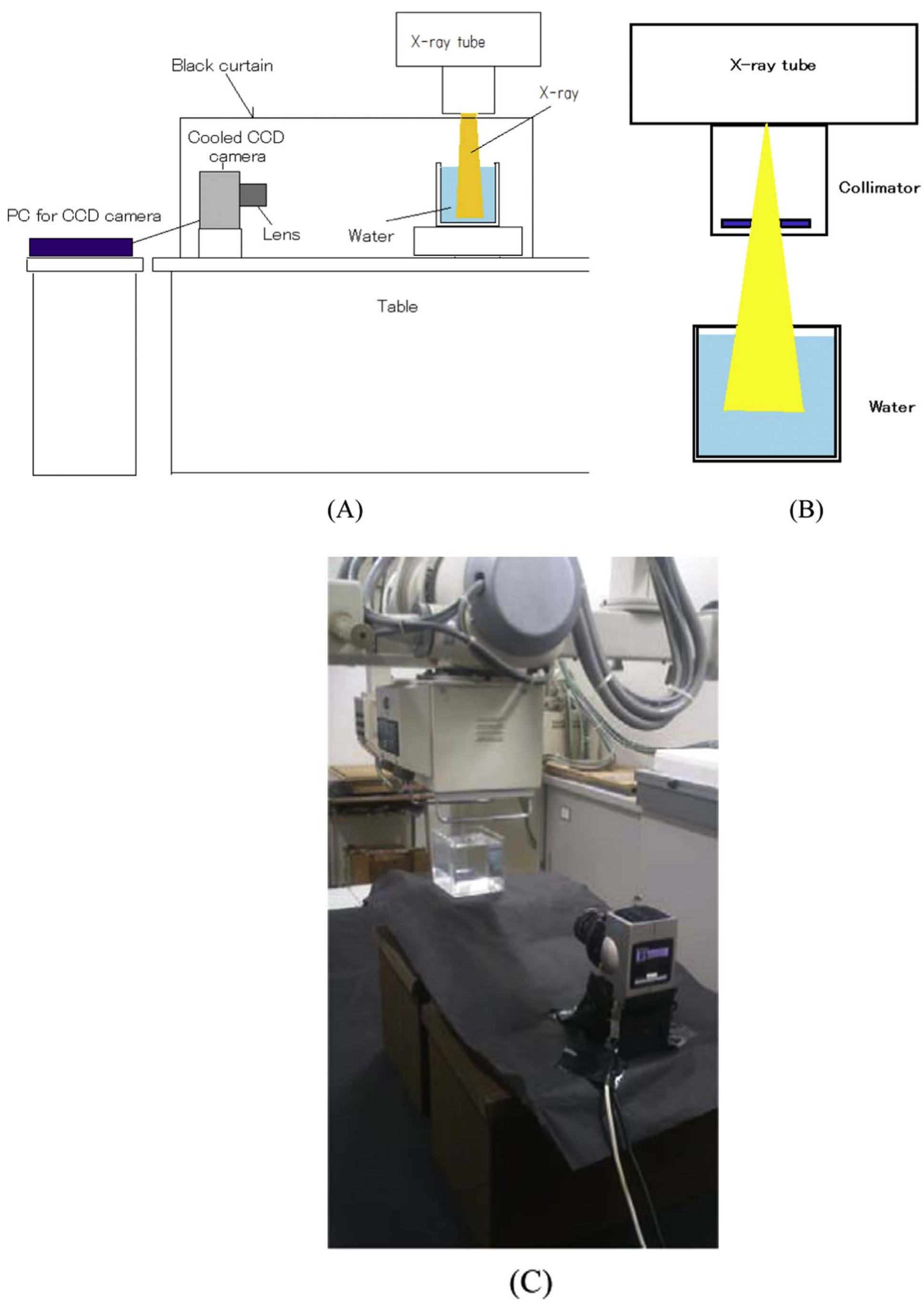

Fig. 1. Experimental setup for luminescence imaging during X-ray photon irradiation: schematic drawing of experiment (A), magnified schematic of X-ray tube area (B), and photo during experiment without light shield (C).