Estimation of shifts of therapeutic carbon-ion beams owing to cavities in a polyethylene target by measuring prompt X-ray images

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We evaluated an estimation ability of shifts of therapeutic carbon-ion beams owing to cavities in a polyethylene target by measuring prompt X-rays emitted from beam trajectories. Carbon-12 beams having the energy of 241.5 MeV u−1 were irradiated on a polyethylene target. The target had a square-prism-shaped cavity in it. The thickness of the cavity was changed from 3.0 to 0.0 cm with 0.3 cm steps. For each setup of the cavity, 7.5 × 1019 carbon ions were irradiated. A pinhole-type X-ray camera was placed beside the target and utilized to acquire the beam images. The beam trajectory and a gap on the trajectory clearly appeared in the acquired images. The actual beam shifts well coincided with the estimated beam shifts from the acquired images. The maximum fluctuation of the estimated shifts was approximately 0.2 cm. It was confirmed that the internal cavity can be imaged and the range can be accurately evaluated. © 2020 The Japan Society of Applied Physics

1. Introduction

Because of its pinpoint-irradiation ability owing to the dose concentration property, particle-beam therapies have been established as radiation treatment with less damage to normal tissues and becoming increasingly widespread. Normally, the dose distributions of the therapeutic particle beams are calculated using computed tomography imaging data acquired before irradiating the beams to a patient. However, if the irradiated beams shift due to anatomical changes in the patient’s body, there is a risk of irradiating high doses to normal tissues. In order to detect such mis-irradiations promptly, monitoring methods of particle beams based on measuring secondary radiations generated by the particle beams are being energetically studied. The first proposed method is based on measuring the distribution of positron-emitting nuclei by detecting the annihilation gamma rays from positron emitters1–17). Recently, other methods based on measuring prompt gamma rays have been studied18,19) to overcome metabolic washout.6,10,17,20–22)

Some of these methods utilize imaging devices with mechanical collimations,23–36) or electronic collimations,37–48) and other methods utilize time-of-flight information49–54) or spectroscopic information.55–59)

Recently, a new method based on measuring prompt X-rays, which mainly consist of secondary electron bremsstrahlung (SEB), was proposed60–69). This method imaged beam trajectories of proton60,65) and carbon-ion beams66,69) in water targets successfully. It was shown that the method was able to analyze about 2 cm or less range shifts caused by change in incident energy. Although it is already known that the range can be evaluated, it is unknown whether the internal structure of the irradiation targets can be imaged. Changes in the dose distribution that occur in actual treatment are often caused by changes in the patient’s anatomy, such as changes in cavities in a body. Therefore, an analysis method for estimating beam shifts in the body caused by cavities formed in the body unexpectedly is required. In addition, the estimation capability of 2 cm is not enough. More precise estimation is required.

In this work, we evaluated an estimation ability of shifts of therapeutic carbon-ion beams owing to cavities in a polyethylene target by measuring prompt X-ray images. Experimental study for measuring prompt X-ray images using an X-ray camera and its results are summarized in Sects. 2 and 3.1, respectively. In Sect. 3.2, we newly propose an analysis method named “accumulation analysis” to estimate the beam shifts from the acquired prompt X-ray images. In Sect. 3.3, the experimental result is compared with a Monte Carlo simulation study. We also simulate a smaller cavity size to check the dependence of the cavity size.

2. Methods

Beam irradiation experiments were performed at the Hyogo Ion Beam Medical Center (HIBMC). A diagram and a photo of the experimental setup were shown in Figs. 1 and 2(a), respectively. Carbon-12 beams having the energy of 241.5 MeV u−1 were irradiated on a polyethylene target. The beam axis was perpendicular to a horizontal plane and irradiated from the upside of the target. The shape of the beam-intensity distribution along the transaxial direction was a Gaussian one having a diameter (FWHM) of 1.88 cm. The beam axis was set to include the mass center of the target.

The target consisted of high-density (0.96 g cm−3) polyethylene plates stacked on a table. The depth of the Bragg peak in the polyethylene was 11.6 cm, which was calculated by using the Particle and Heavy Ion Transport code System (PHITS) version 3.17.70) The outer dimension of each plate was 10.0 cm × 10.0 cm × 0.3 cm. We prepared two types of plates: one was “perforated plate”, which had a square-shaped (5.0 cm × 5.0 cm) central hole, as shown in Fig. 2(b); and the other was “normal plate”, which had no holes. The outer
dimension of the target was $10.0 \text{ cm} \times 10.0 \text{ cm} \times 23.4 \text{ cm}$. The target had a square-prism-shaped cavity in it. The cavity was made by sandwiching a cavity layer made of perforated plates between two layers made of normal plates. The top surface of the cavity layer was placed at 4.5 cm below the top surface of the target. The thickness of the cavity layer was changed from 3.0 to 0.0 cm with 0.3 cm steps by exchanging the lowest plate of the cavity layer with a normal plate. For each setup of the cavity layers, $7.5 \times 10^{10}$ carbon ions were irradiated on the target. Each irradiation time was 60 s.

An X-ray camera was utilized to measure the SEB images. The camera was named “YAP camera-S”. Details of the camera will be explained in another paper. The camera consists of a tungsten-alloy radiation shield and a 0.5 mm thick, $2.0 \text{ cm} \times 2.0 \text{ cm}$ Ce-doped YAlO$_3$ [YAP(Ce)] plate optically coupled to a 2.5 cm square high quantum efficiency cross-wire anode-type position sensitive photomultiplier tube (PS-PMT) (R8900-100-C12, Hamamatsu Photonics, Japan). The energy window of the camera was 30–60 keV. The radiation shield had a wide-angle ($\sim 55^\circ$) pinhole collimator on the front face of it. The diameter of the pinhole was 1.5 mm. The distance between the pinhole and the YAP(Ce) plate was approximately 3.0 cm. Calculated position signals from the PS-PMT was utilized to produce a 0.45 mm pixel-size $44 \times 44$ matrix image. The area of the field of view of the camera at the beam position was $29.04 \text{ cm} \times 29.04 \text{ cm}$. To measure the SEB images, the camera was placed at the distance of approximately 44 cm apart from the beam axis. The height of the camera was set to locate the pinhole at 13.5 cm from the table. A left-hand system of Cartesian coordinates was defined. The height of the origin of the system was set at the same height of pinhole. The $y$-axis was set to coincide with the beam axis and the direction of the $y$-axis was set to point up. The $z$-axis was set to include the center of the pinhole. The direction of the $z$-axis was set to point to the pinhole.

3. Results

3.1. Resultant images and projection images

Acquired images are shown in Fig. 3. The beam trajectory and a gap on the trajectory in the targets clearly appeared for the image of 3 cm cavity. As the thickness of the cavity layer...
decreases, the end position of the trajectory seems to move up correctly and the gap on the trajectory seems to decrease correctly.

In Fig. 4, projections of the images in Fig. 3 onto the y-axis were summarized. As already pointed out in the previous paragraph, the end position appears to shift to the right.
Fig. 4. (Color online) Projections of the acquired images in Fig. 3 on the y-axis. The black dashed lines represent the injection surfaces of the targets. The green dashed lines represent the lower and upper edges of the cavity layers. The solid red lines represent the Bragg-peak positions calculated by using PHITS. The horizontal axis represents the y-coordinate.
To estimate the beam shifts, we propose an analysis method named "accumulation analysis". Supposing that each projection $f(y)$ onto the $y$-axis in Fig. 4 is expressed by the sum of SEB component $f_{\text{SEB}}(y)$ and background (BG) component $f_{\text{BG}}$, the SEB component is expressed as follows:

$$f_{\text{SEB}}(y) = f(y) - f_{\text{BG}},$$

where the BG component is assumed to be independent on $y$. Here we estimated $f_{\text{BG}}$ by using the counts in the leftmost bins in Fig. 4. We define accumulation $A(y)$ as follows:

$$A(y) = \int_{y_{\text{min}}}^{y_{\text{max}}} f_{\text{SEB}}(y') dy' / \int_{y_{\text{min}}}^{y_{\text{max}}} f_{\text{SEB}}(y') dy',$$

where $y_{\text{min}}$ and $y_{\text{max}}$ are the minimum and maximum of the horizontal axis of the histograms in Fig. 4. Figure 5 represents the calculation results of accumulation $A(y)$ for all the cavities by using the experimental results in Fig. 4. The accumulation takes values from 0 to 1 and is monotonically decreasing functions.

Along the beam axis, the mass of the target per unit area from $y$ to $y_{\text{max}}$ and $A(y)$ correspond one-to-one. Therefore, we define estimated beam shift $s$ at $y$ as follows:

$$s_{\text{c}}(y) = y - A_{\text{c}}^{-1}(A_{\text{c}}(y)),$$

where $s_{\text{c}}$ and $A_{\text{c}}^{-1}$ are the estimated beam shift and inverse function of the accumulation for the setup with cavity $c$ and $A_{\text{c}}$ is the accumulation for the one without cavity. Figure 6(a) represents the estimated beam shifts at $y = 0$. Except that the estimated shifts are approximately 0.2 cm shorter than the actual thicknesses of the cavity layers, the estimated shifts coincide with the actual shifts very well and the maximum fluctuation of the estimated shifts is small (approximately 0.2 cm). Figure 6(b) represents the same plot as Fig. 6(a) except that the measuring time was reduced to 10 s, corresponding to $1.25 \times 10^{10}$ carbon-ion injections. The estimated shifts coincide with the actual shifts well although the maximum fluctuation of the estimated shifts increased to approximately 0.5 cm.

### 3.3. Comparison with Monte Carlo simulation

The experimental result was compared with a Monte Carlo simulation study. Monte Carlo simulations were performed on a supercomputer system "ICE X": a large-scale Linux cluster system at the Japan Atomic Energy Agency (JAEE). The simulation code used was PHITS version 3.20. The simulations were basically the same as was used for our previous study, where the whole image was separated into two partial components of SEB and BG. In the present study, only the SEB component was calculated and used because the background component has flat distribution and does not reflect the beam shapes. The X-ray camera was simulated by placing a sheet of YAP in a tungsten radiation shield. A three-dimensional view of the simulation setup is shown in Fig. 7.

We simulated the same target and beam geometries as in the experiment. In addition, we simulated smaller cavities (1.0 cm $\times$ 1.0 cm) and smaller diameter of beams (0.376 cm) to check the dependence on the size of the cavities. The number of the carbon-ion injections for each simulation was $7.5 \times 10^{10}$.

Accumulations and estimated shifts at $y = 0$ by using the simulation results are shown in Figs. 8 and 9, respectively. In both the figures, (a) and (b) represent the results for the simulation setups with the same cavity size as the experimental and with the smaller cavities, respectively. The accumulations in Fig. 8 shows the same trends as the experimental ones in Fig. 5. The maximum fluctuations of the estimated shifts in Figs. 9(a) and 9(b) are approximately...
0.3 and 0.4 cm, respectively. For both the cavity sizes, the estimated shifts coincide with the actual shifts well although the maximum fluctuations of the estimated shifts are slightly larger than the experimental one.

4. Discussion

The estimated beam shift can be expressed as a function of depth position $y$. Therefore, by using this method, it is possible to estimate the beam shift at any $y$ even if there are multiple cavities in the beam trajectories or more complicated cases where the target density changes continuously.

The number of injected carbon ions used to acquire the graph in Fig. 6(b) is approximately 16 times larger than that used in clinical treatment. This result indicates that the beam shift can be estimated with an error of approximately 0.5 cm even for the clinical beams by increasing the detection sensitivity of the camera by approximately 16 times. The error can be reduced by further enhancing the detection sensitivity.

In the case of prompt gamma imaging and in-beam positron emission tomography, the 2 mm [8,9,11,12] and sub-mm [8,11,12] precisions of beam shift detection have been reported, respectively. In the present study, we found that the beam shifts can be estimated in the precision of approximately 0.2–0.4 cm in the case of ion injection of $7.5 \times 10^{10}$. Therefore, by increasing the detection sensitivity, it is possible to achieve the same level of precision as the other two methods.

This method can be applied even if the distance between the beam and the camera is changed because the change of the distance affects only the magnification of the camera and the number of X-rays incident on the camera. However, if the distance becomes too short, a fragmented beam of protons and helium ions originating in the vicinity of the beam axis will enter the camera, which will cause the BG component to be much larger than the SEB component, and the image of the beam trajectory will not be acquired by the camera.
In this work, experiments and analyses were performed on carbon-ion beams, and the same method could be applicable to proton beams. These will be performed for proton beams in a future study. In addition, in order to investigate whether this method can be used clinically or not, it is necessary to perform experiments using human phantoms for actual clinical treatments in the future.

5. Conclusion
We found that beam shifts owing to unexpected cavities in the target can be estimated from the acquired prompt X-ray images using accumulation analysis. Except that the estimated shifts are approximately 0.2 cm shorter than the actual thicknesses of the cavity layers, the estimated shifts coincide with the actual shifts very well and the maximum fluctuation of the estimated shifts is small (approximately 0.2–0.4 cm). Even if the number of injections is reduced to $1.25 \times 10^{10}$, the maximum fluctuation is kept to approximately 0.5 cm. In summary, it was confirmed that the internal cavity can be imaged using this method, and that the range can be accurately evaluated even if the range is extended by the cavity.

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