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FULL PAPER

Effect of secondary particles on image quality of dynamic flat panels in carbon ion scanning beam treatment

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Objective: Real-time markerless tumour tracking using radiographic fluoroscopic imaging is one of the better solutions to improving respiratory-gated radiotherapy. However, particle beams cause secondary particles from patients, which could affect radiographs. Here, we evaluated the quality of radiographs during carbon ion pencil beam scanning (CPBS) irradiation for respiratory gating.

Methods: A water phantom and chest phantom were used. The phantoms were irradiated with CPBS at 290 MeV n⁻¹ from orthogonal directions. Dose rates were 3.4×10^8 , 1.14×10^8 and 3.79×10^7 particles per second. A dynamic flat panel detector (DFPD) was installed on the upstream (DFPD1) or downstream (DFPD2) side of the vertical irradiation port. DFPD images were acquired during CPBS at 15.00, 7.50 and 3.75 frames per second (fps). Charge on the DFPD was cleaned using fast readout

technique every 30 fps. DFPD images were acquired during CPBS with radiographic exposure, and results with and without fast readout technique were compared.

Results: Secondary particles were visualized as spots or streak-like shapes. Capture of secondary particles from the horizontal beam direction was lower with fast readout technique than without it. With regard to beam irradiation direction dependency, CPBS from the horizontal direction resulted in a greater magnitude of secondary particles reaching DFPD2 than reaching DFPD1. When CPBS was delivered from the vertical direction, however, the magnitude of secondary particles on both DFPDs was very similar.

Conclusion: Fast readout technique minimized the effect of secondary particles on DFPD images during CPBS.

Advances in knowledge: This technique may be useful for markerless tumour tracking for respiratory gating.

Research for particle beam treatment has continued for several decades, and several centres now use proton or carbon ion beams in the treatment of cancer.¹ Clinical advantages have been reported elsewhere.^{2–4} While most centres use passive scattering beam irradiation, a few use scanning beam irradiation. Scanning irradiation minimizes excessive dosing around the proximal side of the target but is more sensitive to motion than passive scattering. Most centres therefore restrict its use to sites that show little or no impact from respiratory motion. The Heidelberg Ion Therapy Center, Heidelberg, Germany, which started carbon ion scanning beam liver treatment in 2012, uses an abdominal compression technique to significantly minimize respiratory motion.⁵ By contrast, our treatment centre aims to maximize both patient comfort and treatment accuracy and conducts respiratory-gating treatment under free-breathing conditions without abdominal compression. Scanning beam dose distribution to moving targets has been improved, and the range of treatment sites has accordingly increased.^{6–9}

Several treatment centres delivered treatment beam using a respiratory sensing system, which monitors patient surface motion (=external surrogate), with direct monitoring of tumour position using medical equipment, or is based on correlation models between tumour position and patient surface motion.^{10–12} With the external surrogate system, the treatment beam is on when the respiratory phase is around exhalation (phase-based respiratory gating) but not always the same tumour amplitude. However, human respiratory patterns are not strictly regular but vary in amplitude and period from one cycle to the next.^{13–15} Because tumour position is not always the same within the respective respiratory phases, an irregular respiratory pattern may cause the tumour to move out of the treatment beam. Moreover, the correlation between patient surface and tumour position is not always high.¹⁶ The basic concept of gating treatment is that the beam is on whenever the tumour is positioned within the gating window, as defined in the treatment planning. Our group previously reported that amplitude-based gating with multiple phase-controlled rescanning

improves particle beam scanning dose distribution to a moving target under an irregular respiratory pattern.¹⁷

To solve these problems, radiography fluoroscopic imaging systems have been integrated with the medical linac or particle beam irradiation system to capture tumour position in real time.^{11,18,19} Tumour-tracking-computing accuracy is strongly dependent on the quality of radiographs, particularly in marker-less tumour tracking.²⁰ It is well known that secondary particles such as proton, neutron and prompt γ -ray are induced from patients during particle beam irradiation.²¹ These secondary particles might affect the quality of radiographs and degrade tumour-tracking accuracy.

Here, as part of the efforts to evaluate the image quality of radiographs during carbon ion pencil beam scanning (CPBS) irradiation with respiratory gating, we evaluated the impact of secondary particles on the quality of dynamic flat panel detector (DFPD) images during CPBS irradiation.

METHODS AND MATERIALS

Radiography fluoroscopic imaging system

We previously developed a paired radiography imaging system for the respiratory-gating system in particle beam therapy. This system provides continuous acquisition with or without an implanted fiducial marker using two oblique radiography fluoroscopic units.¹⁹ The respiratory-gating system consists of a pair of DFPDs, X-ray tubes and acquisition controller.

The imaging device is an indirect type of DFPD (PaxScan 3030+; Varian® Medical Systems, Palo Alto, CA) with an imaging area size of 296×296 mm, pixel size of $388 \mu\text{m}$ (2×2 binning mode using the original pixel size of $194 \mu\text{m}$ for fluoroscopic mode) and an amorphous silicon receptor. The distance from the room isocentre (ISO) and source–image receptor distance is 1690 and 2390 mm, respectively, allowing acquisition of an image size of approximately 210×210 mm at the room ISO. Image acquisition frame rate is <30 frames per second (fps). An antiscatter grid is not used because of reducing radiation dose to the patient. Dynamic range of DFPD is 14 bits. DFPD1 and DFPD2 are installed on the right and left sides of the vertical irradiation port at 35° and 325° , respectively, and the X-ray tubes are installed under the floor (Figure 1a).

Data acquisition

Data acquisition parameters are tabulated in Table 1.

Data acquisition sequence

DFPD images were acquired at 15, 7.5 and 3.75 fps, which are 66.7, 133.3 and 266.7 ms, respectively. Owing to limitations of the accuracy of the time clock (≥ 0.1 ms), we set the minimum time clock at 34.0 ms. Image acquisition rate was then set to 68 ms ($=15$ fps), 136 ms ($=7.5$ fps) and 272 ms ($=3.75$ fps).

An example image acquisition sequence at 15 fps is shown in Figure 2a. Image sequence pattern was processed with an internal clock, which was set to 68.0 ms in the 15 fps image acquisition mode. DFPD charge process was started a few milliseconds after the internal clock. Since the time interval between radiographic exposure and the DFPD readout process should be small to minimize the time lag between respiratory motion and image acquisition, radiographic exposure of 4 ms was set at 6.5 ms before output of the internal clock. Image data stored in DFPD internal memory were transferred to the workstation after the DFPD readout process.

This image acquisition sequence had a 75% DFPD charge time within each frame rate even though radiographic exposure time was short. When X-ray and carbon ion beam were irradiated during treatment, the DFPD charge process collected both primary and scattered photons from the X-ray tube and secondary particles by the irradiating carbon ion beam, which could have affected DFPD image quality. To minimize the degradation of image quality owing to secondary particles, the internal clock interval was set to 34 ms ($=30$ fps) in the respective frame rate (fast readout) (Figure 2b). By doing this, DFPD charge time was shortened to approximately 34 ms, and the magnitude of secondary particles collected on the DFPD was reduced.

Image acquisition

We used a water phantom and a chest phantom to quantify secondary particles and image quality, respectively, under conditions, that closely reflected clinical conditions.

The water phantom was a water-filled acrylic cylinder of 240-mm diameter and 250-mm height. It was placed on the

Figure 1. Experimental set-up for (a) 240-mm-diameter water and (b) chest phantoms. A dynamic flat panel detector (DFPD) was installed on the upstream (DFPD1) or downstream (DFPD2) side of the vertical irradiation port. deg, degree.

Table 1. Experimental parameters

Item	Parameters	Value
X-ray tube	Exposure rate (pulse per second)	15, 7.5, 3.75
	Tube voltage (kVp)	80
	Tube current (mA)	80
	Exposure time (ms)	4
Dynamic flat panel detector	Image acquisition (fps)	15, 7.5, 3.75
	Fast readout	On, off
Carbon ion beam	Dose rate (particles per second)	3.4×10^8 (high); 1.14×10^8 (middle); 3.79×10^7 (low)
	Beam direction (degree)	0 (vertical), 90 (horizontal)

fps, frames per second.

treatment couch with its centre set to the room ISO (Figure 1a). Image acquisition was performed at 15, 7.5 and 3.75 fps with and without the fast readout. CPBS was irradiated with 290 MeV n^{-1} at a single spot. Dose rate was 3.4×10^8 (high dose rate), 1.14×10^8 (middle dose rate) and 3.79×10^7 particles per

second (pps) (low dose rate). CPBS was irradiated from 0° or 90° , with 0° defined as the 12 o'clock position and increasing in a clockwise manner (standard International Electrotechnical Commission gantry angle notation).²² Details of the CPBS irradiation system are described elsewhere.²³ DFPD images were

Figure 2. Image acquisition sequences for 15 frames per second (a) without and (b) with fast readout. These sequences were synchronized with the internal clock. DFPD, dynamic flat panel detector.

acquired during carbon ion beam irradiation (carbon ion image) not radiographic exposure. Offset image was acquired to allow the capture of background pixel value without both radiographic and carbon ion beam irradiations.

With regard to the chest phantom (thoracic phantom; Kyoto Kagaku Co., Ltd, Kyoto, Japan), the centre of the phantom, the xiphoid process, was set to the room ISO in the lateral and craniocaudal directions (Figure 1b). Cine image acquisition was carried out at 15, 7.5 and 3.75 fps with and without the fast readout. First, we obtained DFPD images without radiographic exposure (offset image) for 20 s, and then obtained images with radiographic exposure (radiograph) for 20 s. Radiographic exposure conditions were tube voltage of 80 kV, tube current of 80 mA and exposure time per frame of 4 ms. Radiographic exposure was performed from two directions at the same time. Finally, we acquired DFPD images with radiography during carbon ion beam irradiation. Carbon ion beam dose rate was 3.4×10^8 pps (high dose rate) with 290 MeV n^{-1} only.

Data analysis

DFPD images were transferred to the workstation for data analysis. For the water phantom study, we subtracted the offset image from that with CPBS irradiation to produce an offset image. For the chest phantom study, we calculated the difference in pixel value (Δ pixel value) by subtracting pixel values in the DFPD images acquired during CPBS irradiation from those acquired by radiographic irradiation only. A square region of interest (ROI) (40×40 mm) was established on the centre of the DFPD images. Mean pixel values and standard deviation were calculated within the ROI.

RESULTS

Water phantom study

Since image quality could be strongly affected by both image acquisition rate and dose rate, the effect of secondary particles was emphasized by acquiring DFPD images at 3.75 fps with a high dose rate ($=3.4 \times 10^8$ pps) (Figure 3). The secondary particles were visualized as spots or streak-like shapes on the DFPD image. Fast-readout technique reduced the capture of secondary particles (mean pixel value = 3.0 ± 0.4 for DFPD1, 11.8 ± 0.5 for DFPD2) from the horizontal beam direction compared with that without fast readout (mean pixel value = 25.4 ± 1.9 for DFPD1, 101.2 ± 2.8 for DFPD2).

Regarding dependency on beam irradiation direction, CPBS irradiation from the horizontal direction caused a larger magnitude of secondary particles (mainly charged fragments) reaching DFPD2 (mean pixel value = 101.2 ± 2.8 without fast readout) than DFPD1 (mean pixel value = 25.4 ± 1.9 without fast readout) (Figure 3a), because the prompt γ -ray emission was isotropic, but secondary particles go in a forward rather than backward direction. However, when CPBS was irradiated from the vertical direction, the magnitude of the secondary particles in DFPD1 (mean pixel value = 24.3 ± 11.4 without fast readout) and DFPD2 (mean pixel value = 21.6 ± 2.4 without fast readout) was very similar (Figure 3b). Similar tendencies were observed with other image acquisition frame rates and dose rates. The results for all image acquisition and dose rates in the horizontal and vertical directions are summarized in Figure 4.

Regarding DFPD frame rate dependency, the pixel value was decreased with increasing frame rate without fast readout

Figure 3. Dynamic flat panel detector (DFPD) images during carbon ion pencil beam scanning (CPBS) irradiation with and without fast readout. DFPD image was acquired at 3.75 frames per second. CPBS direction was (a) horizontal (90°) and (b) vertical (0°). Image size is cropped in the region of 384×384 pixels. Dose rate was set to high ($=3.4 \times 10^8$ particles per second).

because DFPD charge time was shortened. Pixel value ratios against 15 fps averaged for all data acquisitions (DFPD1 and DFPD2, all dose rates and beam directions) without fast readout were 1.8 ± 1.0 for 7.5 fps and 3.3 ± 1.4 for 3.75 fps. These results were very similar to those for a DFPD frame rate of 15 fps against 7.5 fps of 2 and against 3.75 fps of 4. Since charge time with fast readout in the respective DFPD acquisition frame rates was the same as that at 30 fps, pixel values at 15 fps without fast readout were almost twice as large as those with fast readout.

With regard to dose rate dependency, pixel values increased with increasing dose rate (Figure 4). Since ratios of the high dose

rate against middle and low dose rates were 3 ($=3.4 \times 10^8$ pps/ 1.14×10^8 pps) and 9 ($=3.4 \times 10^8$ pps/ 3.79×10^7 pps), respectively, the respective pixel value ratios with fast readout were approximately 3 and 9.

Chest phantom study

For the horizontal beam direction, we showed a DFPD image acquired at the acquisition rate of 3.75 fps with high dose rate to emphasize the effect of secondary particles (Figure 5). Image quality of DFPD obtained during carbon ion beam irradiation without fast readout (second column in Figure 5) was degraded compared with that obtained by X-ray beam only (Δ pixel

Figure 4. Pixel values averaged in the region of interest (ROI) with and without fast readout. Bars show standard deviation. Dose rates were (a) high [$=3.4 \times 10^8$ particles per second (pps)], (b) middle ($=1.14 \times 10^8$ pps) and (c) low ($=3.79 \times 10^7$ pps) from the horizontal beam direction, and (d) high, (e) middle and (f) low from the vertical beam direction. DFPD, dynamic flat panel detector; fps, frames per second.

value = 31.5 ± 1.8 for DFPD1 and 181.9 ± 2.6 for DFPD2) (the first column in Figure 5). In particular, anatomical structure was unclear in DFPD2. The results for the chest phantom showed almost the same tendency as those for the water phantom; Δ pixel values were decreased with increased frame rate without fast readout because the DFPD charge time was shortened [e.g. Δ pixel value (DFPD2) = 181.9 ± 2.6 , 89.6 ± 2.0 and 41.4 ± 1.4 for the frame rate of 3.75, 7.50 and 15.00 fps, respectively] (Figure 6a).

However, image quality was improved when fast readout was applied (the third column in Figure 5), and the difference in pixel values with fast readout was very similar for all image acquisition frame rates (Δ pixel value = 3.1 ± 0.5 for DFPD1 and 21.0 ± 0.8 for DFPD2).

With regard to the vertical beam direction, Δ pixel values for the respective frame rates were smaller than for the horizontal beam irradiation; however, the results showed similar tendencies to those for the horizontal beam irradiation. We have not shown the DFPD images here; however, the Δ pixel values with fast readout maximize <10 for the respective frame rates, and therefore, the DFPD image quality was similar to that for the horizontal beam direction.

DISCUSSION

We evaluated the quality of DFPD images during CPBS irradiation. Secondary particles degraded the quality of DFPD images, particularly from the horizontal beam direction. However, the image quality was improved with fast-readout technique, and patient anatomical structures could be clearly visualized.

In this study, we analysed DFPD image quality during CPBS irradiation. However, passive scattering irradiation has not yet been evaluated. Beam field size in passive scattering irradiation is larger than in scanning irradiation, and expensive patient accessories (compensating bolus, patient collimator, disposal immobilization devices etc.) are necessary to fit the particle beam to the target shape in three dimensions. However, the stopping of particle beams by these accessories produces γ -ray, neutron and other particles. The magnitude of these particles may be larger than for those in scanning beam irradiation, resulting in a greater degradation of DFPD image quality than with scanning beam irradiation. Moreover, we did not evaluate proton beam irradiation in this study. Since approximately 36-fold more protons than carbon ions are required to produce an equivalent biological dose, the magnitude of prompt γ -ray by proton beam irradiation is likely to be larger than by carbon ion irradiation.

Our treatment machine irradiates CPBS with a markedly high dose rate. We therefore set a dose rate of 3.4×10^8 pps to reflect clinical treatment. This high rate is not continued during treatment but is varied according to the prescribed treatment beam to the target. A high dose rate and fast scanning speed reduce the treatment time, improving patient comfort. Moreover, a short treatment time minimizes variation in respiratory pattern during treatment, which is important given that the patient respiratory pattern is not always reproducible.¹³

With regard to radiographic radiation dose to the patient, a number of factors can extend radiographic exposure time, including target size, respiratory cycle, duty cycle of the gating

Figure 5. Chest phantom images acquired by radiography only and/or during carbon ion pencil beam scanning (CPBS) irradiation with and without fast readout. CPBS direction was horizontal (90°). Image size is 384×384 pixels. Image acquisition rate was 3.75 frames per second. Dose rate was high ($=3.4 \times 10^8$ particles per second). DFPD, dynamic flat panel detector.

Figure 6. Difference in pixel values [Δ pixel value; obtained by subtracting pixel values of dynamic flat panel detector (DFPD) acquired by radiography during carbon ion beam irradiation from those acquired by radiography only] averaged in the region of interest (ROI) with and without fast readout in the (a) horizontal and (b) vertical beam directions. Dose rate was high ($=3.4 \times 10^8$ particles per second). fps, frames per second.

window, treatment beam dose rate and DFPD image acquisition frame rate, among others. Estimated treatment time for lung and liver treatment using our irradiation machine with a 30% gating window ranges from a few to less than 10 min (planning target volume for liver treatment is relative large). To minimize the magnitude of radiographic radiation exposure, we integrated the frame rate modulation function to our respiratory-gating system. DFPD images are acquired at a high frame rate when tumours move around the gating window region and at low frame rate when they are away from the gating window region. Another approach is respiratory prediction, which supports tumour positional detection at a low image acquisition frame rate.^{24,25} However, as we showed in the present study, image acquisition at a low frame rate degrades DFPD image quality. Although we did not evaluate real-time tumour-tracking accuracy in this study, degradation of image quality can impact this function also. Applying fast readout technique is thus useful in

both minimizing radiation exposure and preserving tumour tracking accuracy. However, it is hard to detect tumour motion from secondary particle image because of its blurred distribution. Therefore, radiography fluoroscopic tumour tracking is currently a better choice to direct monitoring of tumour position.

In conclusion, this study quantified the quality of DFPD images during CPBS irradiation and compared DFPD image quality with and without fast-readout technique. Fast readout minimized the effect of secondary particles on DFPD images during particle beam irradiation. This technique might thus be useful for markerless tumour tracking in respiratory gating.

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