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SHORT COMMUNICATION

Real-time image-processing algorithm for markerless tumour tracking using X-ray fluoroscopic imaging

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Objective: To ensure accuracy in respiratory-gating treatment, X-ray fluoroscopic imaging is used to detect tumour position in real time. Detection accuracy is strongly dependent on image quality, particularly positional differences between the patient and treatment couch. We developed a new algorithm to improve the quality of images obtained in X-ray fluoroscopic imaging and report the preliminary results.

Methods: Two oblique X-ray fluoroscopic images were acquired using a dynamic flat panel detector (DFPD) for two patients with lung cancer. The weighting factor was applied to the DFPD image in respective columns, because most anatomical structures, as well as the treatment couch and port cover edge, were aligned in the superior-inferior direction when the patient lay on the treatment couch. The weighting factors for the respective columns were varied until the standard deviation of the pixel values within the image region was minimized. Once

the weighting factors were calculated, the quality of the DFPD image was improved by applying the factors to multiframe images.

Results: Applying the image-processing algorithm produced substantial improvement in the quality of images, and the image contrast was increased. The treatment couch and irradiation port edge, which were not related to a patient's position, were removed. The average image-processing time was 1.1ms, showing that this fast image processing can be applied to real-time tumour-tracking systems.

Conclusion: These findings indicate that this image-processing algorithm improves the image quality in patients with lung cancer and successfully removes objects not related to the patient.

Advances in knowledge: Our image-processing algorithm might be useful in improving gated-treatment accuracy.

The image guidance technique quantifies intra-/interfractional changes in anatomical structures of the patient and is a key factor in improving treatment accuracy. A number of techniques have been introduced and several have been integrated for clinical use in both photon beam and particle beam therapy.^{1,2} A number of treatment centres now use the respiratory-gated strategy for thoracic and abdominal treatment, and generally use external gating for respiratory monitoring. External gating is generally performed using tagging points with reflective artificial markers on the patient's abdomen. However, normal irregularity in respiratory patterns might result in inconsistencies between the external respiratory signal and internal target movement (e.g. phase shift/drift),³ which in the worst case might cause the treatment beam to miss the tumour if applied using only the external respiratory signal.

To solve this problem, photon beam and particle beam treatment centres have installed X-ray fluoroscopic

systems for the direct capture of tumour positions in real time.⁴⁻⁶ The use of an implanted fiducial marker strongly facilitates the detection of tumour positions, but is somewhat invasive owing to the risk of pneumothorax on insertion,⁷ and cannot be used in all patients owing to patient condition. Tumour position tracking without a marker has therefore been introduced.^{6,8} This technique is dependent on good quality images for calculating normalized cross-correlation. Although X-ray fluoroscopic imaging involves significantly less X-ray radiation exposure than does treatment beam, radiological protection nevertheless requires that this exposure be minimized. As an additional safety issue, while the position of the patient is adjusted according to treatment planning, the relationship between the patient position and treatment couch can differ among consecutive treatment fractions. Since markerless tumour-tracking systems operate within the current image and output a treatment gate signal to the treatment beam delivery system before the next frame, they require

Figure 1. The geometry of the X-ray imaging system: (a) front view and (b) lower view. The red circle and blue dotted lines show the position of the room isocentre and the irradiation port cover edge, respectively. DFPD, dynamic flat panel detector.

a short image-processing time. By contrast, the trade-off between complex image processing, such as processing utilizing neural networks, and image quality is well known.

To solve these problems, we developed an image-processing algorithm to improve the image quality of X-ray fluoroscopic images. Here, we report the preliminary results of two patients with lung cancer.

Figure 2. Image-processing procedures for (a) the pre-calculation of the weighting factor and (b) application to respective images. (c) Multiplying the respective weighting factor (w) to image matrix along the y-axis. The x- and y-axes are the lateral and superior-inferior directions, respectively. DFPD, dynamic flat panel detector; Im , original image; Im' , new image; SD, standard deviation.

Figure 3. (a) Original radiographs [dynamic flat panel detector 1 (DFPD1) and DFPD2] of Patient 1. Yellow arrows show the tumour position. Blue and red arrows show the treatment couch and irradiation port cover edge, respectively. (b) Image-processed radiographs (DFPD1 and DFPD2). (c) Weighting factors for DFPD1 and DFPD2. Blue and red arrows show the irradiation cover edge and treatment couch positions, respectively.

METHODS AND MATERIALS

Image acquisition

Two oblique X-ray fluoroscopic units [dynamic flat panel detectors (DFPDs)] were installed in the treatment room for respiratory-gated particle beam treatment with or without an implanted fiducial marker (Figure 1a). The DFPDs (PaxScan® 3030+; Varian Medical Systems, Palo Alto, CA) have an imaging area size of 296×296 mm, a pixel size of $388 \mu\text{m}$ (2×2 binning mode using the original pixel size of $194 \mu\text{m}$ for fluoroscopic mode), a matrix size of 768×768

pixels and an amorphous silicon receptor. The distance from the room isocentre (marked with a red circle in Figure 1a) to X-ray source and the source–image receptor to X-ray source were 1690 and 2390 mm, respectively, meaning that an image size of approximately 209×209 mm could be acquired at the room isocentre. Image acquisition frame rate was <30 frames per second (fps). An antiscatter grid was not used. Owing to the design of the vertical irradiation port cover, the port cover edges (blue dotted lines in Figure 1b) caused image artefacts in DFPD images.

Figure 4. Image histograms for the original and processed image for (a) dynamic flat panel detector 1 (DFPD 1) and (b) DFPD2 (Patient 1).

Two patients, aged 79 and 78 years, with lung tumours were randomly selected from among patients undergoing X-ray fluoroscopic imaging and carbon-ion beam therapy at our institute (National Institute of Radiological Sciences, Chiba, Japan). The tumour was located in the right lower lobe in Patient 1 and the right middle lobe in Patient 2. The patients gave informed consent before their participation in the study, which was approved by the institutional review board of our institute. DFPD images were acquired at 15 fps under free breathing conditions. Acquisition conditions were a tube voltage of 80 kV, a tube current of 40 mA and an exposure time of 4 ms.

Image-processing algorithm

Our image-processing protocol is a two-step procedure that consists of pre-calculating the weighting factors and applying the factors to images (details are described in Steps 1–2 and Step 3, and Figure 2). Our approach is similar to the look-up table (LUT) technique: once the LUT is calculated, obtaining the processed image is rapid, and recalculation for every new image is not required. Nevertheless, calculation times to determine weighting factors and their application to all image matrices [total number of 589,824 pixels = 768 pixels (height) $\times$ 768 pixels (width) per image] can be prolonged. Furthermore, the anatomical structures of most patients, such as the spine and lung, as well as the treatment couch and port cover edge, are oriented along the superior–inferior axis when the patient lies down on the treatment couch. Moreover, image pixel values within and external to the patient markedly differ, and most of these regions are classified along the superior–inferior axes. We therefore calculated the weighting factor along the y axes only, which resulted in the calculation of a total of 768 weighting factors in this study.

DFPD images for the pre-calculating process should be acquired before the treatment beam is turned on. To ensure the greatest possible minimization of X-ray radiation exposure in visualizing the anatomical structures of a patient, a recursive filter was utilized using eight frames to reduce the magnitude of image

noise. The resulting weighting factor was less affected by pixel value fluctuations due to image noise.

- Step 1 (initialization). Initial weighting factors were set at 1 [$w(x) = 1$, $k = 1, \dots$, number of columns].
- Step 2 (pre-calculation of weighting factor). The weighting factor at the k th column (x axis) was searched by the optimum design problem method as follows (Figure 2a). The objective function (F) is the standard deviation (n), the index n is the number of iterations of the image after the n th iteration, which was the original image (Im) multiplied by the weighting function (w) as follows:

$$F = SD(n)$$

The goal of the procedure was to minimize the objective function, and as a result, we obtained $w(k)$. To minimize the number of iteration processes, we used the Brent method, which minimizes the objective function by exact line search optimization.⁹ These processes were repeated until the weighting factors for all columns were optimized. Then, the optimized weighting factor was multiplied by the original image to calculate the new image (Im').

- Step 3 (application of the factor to images). Once the weighting factor was calculated, the quality of the DFPD images was improved by applying the weighting factor to the respective DFPD images (Figure 2b,c).

Since both the position of the patient and the position of the treatment couch during treatment generally remained unchanged from complete patient setup until the patient left the treatment room, the weighting factor can be optimized for individual patients and treatment couch positions and should accordingly be recalculated when these positions are changed.

With regard to image-processing speed, recent high-performance central processing units possess multiple integrated processing units that allow multiple add operations per clock cycle. We used a specific application-programming interface (“OpenMP” and

Figure 5. (a) Original radiographs [dynamic flat panel detector 1 (DFPD1) and DFPD2] of Patient 2. Yellow arrows show the tumour position. Blue and red arrows show treatment couch and irradiation port cover edge, respectively. (b) Processed image radiographs (DFPD1 and DFPD2). (c) Weighting factors for DFPD1 and DFPD2. Blue and red arrows show the irradiation cover edge and treatment couch positions, respectively.

“multithreaded computations”) to accelerate image processing. Calculation of weighting factors and applying the weighting factor took less than 10 s and a few milliseconds for both the DFPD1 and DFPD2 images, respectively.

RESULTS AND DISCUSSION

DFPD lung images for Patient 1 without image processing are shown in Figure 3a. Tumour positions are marked using yellow arrows. In the DFPD2 image, the left edge of the tumour overlaps

the treatment couch (red arrow), hampering recognition. The high pixel value vertical line marked with blue arrows is the irradiation port cover edge (Figure 3c). The lung region shows high-contrast resolution compared with the mediastinum region due to the low lung density, hindering adjustment of the window level/width to simultaneously display all regions in the image clearly. Application of image processing to the original DFPD images produced a marked improvement in image quality, and the image contrast was increased over all regions of the image

(Figure 3b). Both the mediastinum and lung regions in the processed DFPD images were clearly visualized but not in the original images. The treatment couch and irradiation port edge regions were corrected to allow anatomical structures to be displayed clearly, and the tumour edge was clearly observed in the DFPD2 image.

Weighting factors for each x position that were used to generate the image processing are shown in Figure 3c. The weighting factor showed a continuous curve. However, the weighting factor was decreased at around row 220 in the DFPD1 image and row 550 in the DFPD2 image to correct for the irradiated port cover region (blue arrow in Figure 3c). Since the DFPD2 image included the treatment couch and port cover edge, the weighting factor sharply increased at around row 480 (red arrow in Figure 3c).

Quantitative results were obtained from image histograms with or without image processing (Figure 4). Images with processing were distributed across a narrower range of pixel values than were the original images. For the DFPD2 image, the distribution around the pixel value of 6000 was owing to the air region outside the patient.

For the second case (Patient 2), the tumour was located close to the treatment couch and the port cover edge in the original DFPD1 image (Figure 5a). Processed images showed improved image quality and clear minimization of the treatment couch and port cover edge regions (Figure 5b). Large pixel value differences were because of the inclusion of air and the patient's superior and inferior regions, which resulted in dark band-like regions because processing was performed along the column direction only (white arrow in Figure 5b). Weighting factors for these images were lower than those for Patient 1 because this patient had a thicker chest wall (Figure 5c).

Image-processing time for both the DFPD1 and DFPD2 images averaged for five measurements was 1.1 ms, showing that this fast image processing can be applied to real-time markerless tumour tracking systems.

Because it is unnecessary to conduct patient setup positional verification in real time, our algorithm can be extended across a single-frame image. Automatic two–three-dimensional registration systems for patient setup are now commercially available.¹⁰ Positional differences between the patient and treatment couch also affect patient setup accuracy, suggesting that our image-processing algorithm might also be useful in improving positional accuracy.

One limitation of this study warrants mention. Although the application of our image-processing algorithm improved patient image quality, a small remnant of artefacts remained because the treatment couch was deflected by the patient's weight, and because errors in installing the imager and/or port cover meant that the irradiation port cover edge was not completely parallel along the DFPD imager column direction. One approach to removing the port cover artefact is to pre-calculate the magnitude of the installation error (rotation error is sufficient) and to rotate the DFPD images to compensate for the installation error before pre-calculation of the weighting factor and the application to respective images. Regarding treatment couch deflection, recent couches allow for correction of this error, and the use of this function should realign the treatment couch sufficiently parallel to the column direction to avoid these artefacts. Evaluation of our image-processing algorithm using patient data showed a marked improvement in image quality, and the clinical benefit was obvious, although small artefacts remained. We therefore consider that this simple image-processing strategy is a suitable approach to real-time image processing.

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