VERIFYING TUMOR POSITION DURING STEREOTACTIC BODY RADIATION THERAPY DELIVERY USING (LIMITED-ARC) CONE BEAM COMPUTED TOMOGRAPHY IMAGING

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**ABSTRACT**

**Background and purpose:** Proof of tumor position during stereotactic body radiotherapy (SBRT) delivery is desirable. We investigated if cone-beam CT (CBCT) scans reconstructed from (collimated) fluoroscopic kV images acquired during irradiation could show the dominant tumor position.

**Materials and methods:** Full-arc CBCT scans were reconstructed using FDK filtered back projection from 38 kV fluoroscopy datasets (16 patients) continuously acquired during volumetric modulated spine SBRT. CBCT-CT match values were compared to the average spine offset values found using template matching + triangulation of the individual kV images. Multiple limited-arc CBCTs were reconstructed from fluoroscopic images acquired during lung SBRT of an anthropomorphic thorax phantom using 20°-180° arc lengths and for 3 breath-hold lung SBRT patients.

**Results:** Differences between 3D CBCT-CT match results and average spine offsets found using template matching + triangulation were 0.1 ± 0.1 mm for all directions (range: 0.0-0.5 mm). For limited-arc CBCTs of the thorax phantom, the automatic 3D CBCT-CT match results for arc lengths of 80-180° were ≤1 mm. 20° CBCT reconstruction still allowed for positional verification in 2D.

**Conclusions:** (Limited-arc) CBCT reconstructions of kV images acquired during irradiation can identify the dominant position of the tumor during treatment delivery.
INTRODUCTION

High precision treatments, like stereotactic body radiotherapy (SBRT), require accurate positioning to correctly irradiate the target and reduce the risk of excessive dose to nearby organs-at-risk (OARs)\textsuperscript{37,38}. Robust positional verification during irradiation itself is, therefore, desirable.

SBRT is often delivered using 2 volumetric modulated arc therapy (VMAT) arcs per fraction. Patient setup is performed prior to the first arc and occasionally between arcs, using cone-beam computed tomography (CBCT) scans\textsuperscript{10,26}. In general, no proof of the target position is available during actual irradiation. Furthermore, the time lag between scan acquisition prior to or between arcs and start of treatment increases the uncertainty. In spine SBRT, the position of the bony spine, typically well visualized on kilovoltage (kV) images, can be used to monitor the target and infer the spinal cord position. We have previously demonstrated sub-second and sub-millimeter resolution spine position verification using markerless template matching + triangulation of fluoroscopic kV images acquired during spine VMAT delivery in a retrospective offline analysis\textsuperscript{58}. However, this technique is currently not available for online use. The feasibility of acquiring a CBCT scan during VMAT delivery has been described before\textsuperscript{59–63} but this too is not yet available in routine practice. Such CBCT scans would allow for volumetric matching to the planning CT (with up to 6 degrees of freedom) and improved visualization of (soft tissue) target changes and OARs. They may also eliminate the need for a scan between arcs, increasing efficiency.

For patients with primary or metastatic tumors treated with breath-hold lung SBRT, there are additional considerations. Standard CBCTs require ≥180° gantry rotation, giving rise to two problems. Firstly, multiple breath-holds are often needed before such a CBCT can be reconstructed and inter-breath-hold variations may result in blurring of the tumor. Secondly, short, partial treatment arcs are frequently used during these treatments. Therefore, limited-arc single breath-hold CBCT is desirable for positional verification.

In this study, we reconstruct CBCT scans from fluoroscopic kV images acquired during spine SBRT treatments and match them to the planning CT. We use tools with identical algorithms to those that are commercially available, to show that clinical implementation is realistic. We contrast the results with the average spine position deviations found using template matching + triangulation of the individual kV projection images. We also investigate limited-arc CBCTs (≥20°) for verification of tumor position during breath-hold lung SBRT.
MATERIALS AND METHODS

Patient data: spine
In total 38 clinical fluoroscopy datasets of 16 patients treated with spine SBRT were retrospectively analyzed. Patient treatment procedure and positional verification results obtained using template matching + triangulation were reported previously (the spine showed little movement during treatment)\(^5^8\). Each kV fluoroscopy dataset represents the 1\(^{st}\) (full or partial) arc of a treatment fraction and was routinely acquired during RapidArc delivery on a TrueBeam\(^{TM}\) (v2.0, Varian Medical Systems, Palo Alto, USA). Patients were treated with a prescription dose of 6–10 Gy per fraction, using 10 MV flattening filter free (FFF) beams with a maximum dose rate of 2400 MU/min and maximum gantry speed of 6°/s. The kV projection images, with an effective pixel size (at isocenter) of 0.259 × 0.259 mm\(^2\), were acquired at 7 frames per second (fps) \((n = 30)\), 11 fps \((n = 5)\), or 15 fps \((n = 3)\), using on average 98 kV (86-110 kV), 45 mA (34-52 mA), and 28 ms (15-37 ms), with a field size ranging from 10.5 × 9 cm\(^2\) to 26.6 × 20 cm\(^2\) (full field). The datasets consisted of on average ± SD 485 ± 138 images (238-870) and were extracted from the treatment unit using iTools Capture (Varian Medical Systems).

Full-arc CBCT reconstruction: spine
Non-clinical iTools Reconstruction software (v2.7.36.0, Varian Medical Systems), which contains the same CBCT reconstruction procedure as the clinical software, was used to reconstruct CBCTs (fluoro-CBTCs) from the fluoroscopic images acquired during irradiation. As the software was not configured with an energy spectrum for all possible kV values, a value of 100 kV (modified in the image data) was used for all fluoroscopy datasets. Air Norm data were derived according to the parameters used for fluoroscopy acquisition, i.e. 100 kV, 45 mA, 32 ms, without filters. For reconstruction, a standard “spotlight” mode template was modified to suit our data, i.e. full 360° trajectory, full fan, no filters, and 100 kV. In addition, as the norm chamber values of the projection images were very low compared to typical CBCT projection image norm chamber values, these were modified for all images (to 400,000). The Feldkamp-Davis-Kress (FDK) filtered back projection algorithm was used to reconstruct fluoro-CBTCs \(^{64}\). The reconstructed fluoro-CBTCs were matched to the planning CT (1.0 or 1.25 mm slice thickness) in a research environment of Offline Review (Varian Medical Systems). This software uses certain information from the DICOM header to recognize the scan type, which is not available in the headers of the fluoro-CBCT scans. Therefore, the headers of the fluoro-CBCT slices were replaced by those of the corresponding slices of the clinical CBCT that was acquired immediately after the treatment arc (couch position during fluoroscopy and CBCT acquisition was equal). In order to do this replacement correctly, the fluoro-CBCT had to be reconstructed in the same manner as the clinical CBCT, i.e. using the
same slice thickness (1.5, 2.0, or 2.5 mm), pixel spacing (0.511 × 0.511 mm²), and volume sizes. An automated 3D CBCT–planning CT match was performed and, consistent with our standard clinical approach, manually adjusted if necessary, e.g. in case of deformation of the vertebra. For validation purposes, the resulting match was compared to the average spine offset found using template matching + triangulation.

**Template matching + triangulation: spine**

This technique has been described previously 58. In short, 2D templates containing the involved vertebra were generated from planning CT data for every degree of gantry rotation in the form of filtered digitally reconstructed radiographs. To find the best match between the template (associated with the gantry angle closest to the projection image) and pre-filtered kV image, the normalized cross-correlation was calculated as a measure of similarity, resulting in the 2D spine position in rotating imaging axis coordinates. To determine the 3D position of the spine, each registration was triangulated with multiple previous registrations. The average spine offset compared to the planning CT was calculated by averaging the positions of all images within the dataset.

**Limited-arc CBCT reconstruction: lung**

Fluoroscopic images were acquired of a static 3D printed anthropomorphic thorax phantom that contains soft tissue (silicone), bony structures (printed in gypsum), airways, and lungs consisting of blood vessels and tumors (printed in nylon). The images were acquired for a partial arc (imaging source angle: -31° to -269°, in which 0° is an image acquired in the anterior–posterior direction) during SBRT irradiation of a printed lung tumor (10 MV FFF beams, 11 Gy/fraction, 2 arcs/fraction) at 7 fps, using a titanium filter, 100 kV, 45 mA, and 32 ms per image. In order to determine which arc length is required to obtain sufficient image quality for reliable CBCT–CT matching, multiple limited-arc fluoro-CBCTs (with 1.5 mm slice thickness) were reconstructed, using a similar FDK algorithm as for spine and decreasing arc lengths from 180° down to 20° in steps of 20°. Different arc orientations were tested by repeating this for imaging source angles between -31° to -211° and -89° to -269°.

To determine the effect of a moving tumor on the CBCT reconstruction, e.g., to mimic what might happen when a patient cannot maintain a stable breath hold, phantom measurements were performed, in which the treatment couch was automatically moved during MV delivery and kV image acquisition using the Developer Mode on the TrueBeam. Two 120° (gantry angle from 59° to -61°) arcs were programmed, one in which the couch moved during the second half of the arc and one in which the couch moved during the last quarter of the arc, both using a gradual displacement of 8 mm in the longitudinal and 4 mm in the vertical direction.
To demonstrate that limited-arc fluoro-CBCT reconstruction can be transferred from a phantom to the clinical scenario, fluorescent images routinely acquired during irradiation of three patients (2× arc length of 103°, 1× 79°) treated with breath-hold lung SBRT were reconstructed into fluoro-CBCT scans (with 2.5 mm slice thickness) to show the tumor position during SBRT delivery.

RESULTS

Full-arc CBCT: spine
Fluoro-CBCT scans were reconstructed of 2 cervical (8 datasets), 7 thoracic (14 datasets), and 7 lumbar (16 datasets) vertebrae, using an arc length (average ± SD) of 343° ± 31° (195°–358°). The left-right body diameter measured through the isocenter was 12.5–46.6 cm. The CBCTs were reconstructed with a slice thickness of 1.5 mm (n = 20), 2 mm (n = 11), or 2.5 mm (n = 7).

Figure 1. Example images of a CBCT slice of an (A) cervical, (B) thoracic, and (C) lumbar vertebra, for both the CBCT reconstructed from fluorescent images acquired during radiation delivery (left column) and clinical CBCT (middle column), together with the Hounsfield unit line profiles measured at the level of the horizontal lines on the images.
Figure 1 shows representative CBCT slices of a cervical, thoracic, and lumbar vertebra, for both the fluoro-CBCT and the clinical CBCT, as well as representative Hounsfield unit (HU) line profiles of these images. It demonstrates that concurrent MV delivery did result in errors in HU values (by up to >700 HU), that varied in magnitude between different tissues and patients. However, despite the loss of contrast, the visual image quality of the spine is not affected. 3D matching of the fluoro-CBCTs to the planning CT revealed mean positional offsets of –0.1 ± 0.8 mm (–1.5–2.2) for the left-right, –0.1 ± 0.4 mm (–1.3–0.7) for the superior-inferior, and –0.1 ± 0.5 mm (–1.1–1.3 mm) for the anterior-posterior direction. Comparison of these match results to the average spine offsets found using template matching + triangulation showed mean differences of 0.1 ± 0.1 mm for all directions (0.0–0.5 mm). Figure 2 shows the fluoro-CBCT–CT match results together with the average template matching + triangulation results for the individual datasets. Although slice thickness may affect image resolution and noise, no relation was found between the thickness and differences in match results between CBCT–CT matching and template matching + triangulation. In addition, a larger left-right body diameter did not result in poorer match results.

**Limited-arc CBCT: lung**

Figure 3 shows example images of limited-arc fluoro-CBCTs of the anthropomorphic thorax phantom with arc lengths of 180°, 100°, 80°, 40°, and 20° in transversal, frontal and sagittal planes (120° is shown in figure 4). An arc length of at least 80° was found to be desirable for sub-millimeter accuracy CBCT–CT matching. For arc lengths <80°, larger distortions were found in transversal and frontal planes. However, depending on the arc orientation, i.e. if mainly lateral or AP/PA images are used for reconstruction, images in the sagittal or frontal plane could still give a reliable representation of tumor position in two directions, even for the 20° arc. Figure 4 shows example images of 120° limited arc-CBCT scans of the moving phantom. Although both movements resulted in more blurring of the tumor, the movement during 30° did not result in different match results. The amount of blurring caused by the motion during 60° made it impossible to perform a reliable CBCT–CT match, however, the image could still be used to determine if the tumor was within the planning target volume (PTV). Figure 5 illustrates limited-arc fluoro-CBCTs of tumors treated with breath-hold SBRT, as well as the clinical CBCT scans acquired after the treatment arc, showing that the image quality is good enough to determine if the tumor was within the PTV during treatment.
Figure 2. CBCT-CT match results (circles) and average template matching + triangulation results (crosses) for each spine dataset and per patient in the left-right (LR), superior-inferior (SI), and anterior-posterior (AP) directions.
Figure 3. Example images of limited-arc fluoro-CBCTs of a thorax phantom with arc lengths of 180° (imaging source angle: -31° to -211°), 100° (-31° to -131°), 80° (-31° to -111°), 40° (-31° to -71°), and 20° (-31° to -51°) in the transversal, frontal and sagittal planes.
**DISCUSSION**

We demonstrated the feasibility of reconstructing full and limited-arc fluoro-CBCTs from planar (sometimes collimated) fluoroscopic kV images acquired during spine and breath-hold lung SBRT irradiation. This verifies the dominant position of the tumor during actual treatment delivery. The spine CBCT-planning CT match showed a high level of agreement with the average template matching + triangulation results for spine position using the same kV imaging data. This provides independent verification of the fluoro-CBCT match accuracy. In addition, we have shown that limited-arc fluoro-CBCTs with sufficient image quality for matching can be obtained with standard reconstruction techniques, which might be especially relevant for patients treated in breath-hold. For breath-hold lung SBRT, variations in tumor position typically occur in the superior-inferior direction due to inter-

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**Figure 4.** Example images of 120° limited-arc fluoro-CBCTs of a stationary and moving thorax phantom (imaging source angle: -31° to -150°) in the transversal, frontal and sagittal planes. Movements are during the last 30° and 60° of the arc, both using a gradual displacement of 8 mm in the longitudinal and 4 mm in the vertical direction. As the whole phantom was moved, the entire CBCT is more blurred. The contours indicate the GTV.
**Figure 5.** Example images of limited-arc fluoro-CBCT scans and clinical CBCT scans of three patients treated with breath-hold lung SBRT in the transversal, frontal and sagittal planes. The contours indicate the PTV. Imaging source angles are -100° to -203° for patient 1, 89° to 10° for patient 2, and -165° to -268° for patient 3.
breath-hold differences. Therefore, the ability to verify whether the tumor was inside the PTV during each breath-hold or arc is valuable. As the tumor position may be difficult to see on single kV images, limited-arc (e.g. 20°) CBCT reconstructions could be used to determine the superior-inferior tumor position, even when no reliable 3D match can be performed. Potential clinical applications of these findings extend to other clinical scenarios and are not limited to high dose/fraction treatments.

Although continuous positional information would allow transient, larger displacements to be identified and if necessary corrected, a CBCT scan during irradiation would represent a substantial improvement on what is currently available. Furthermore, the ability to reconstruct and store CBCTs in the treatment database means that fluoro-CBCTs should be relatively straightforward to implement since they use currently available clinical software and hardware. Compared to the current generation template matching + triangulation technique, which gives 3D translational information, CBCTs have the benefit of providing 6D positional information, for both target and OARs. Besides this, when multiple arcs are used, a CBCT during irradiation may eliminate the need for a scan between the arcs, increasing treatment efficiency. Other benefits of a CBCT during irradiation are that the dose distribution can be assessed on the actual treatment anatomy, and it provides a benchmark to which other developments for real-time positional verification techniques could be compared.

Markerless lung tumor motion monitoring using kV projection images would be preferable during treatment. However, this has proven to be technically challenging due to limited visibility of the lung tumors on such images, especially for small, low density, or centrally located tumors. We showed that limited-arc reconstructions can provide information on the dominant tumor position for centrally located (figure 5, Pt 1) or small tumors (figure 5, Pt 2), although limited information on motion will be provided (figure 4). It is expected that limited-arc CBCT reconstruction will be easier to implement clinically than a tumor motion monitoring technique where the results may depend on several user-selected parameters.

Instead of using standard reconstruction techniques for limited-arc CBCTs, other techniques have been proposed that may improve image quality, but these are often more complex to implement. For example, Wertz et al. propose combining kV and MV images. As the kV and MV imager are perpendicular to each other, simultaneous kV and MV imaging over 90° will result in images over 180° that can be used for CBCT reconstruction. However, as the multi-leaf collimator is moving through the MV beam when using VMAT, possibly blocking part of the target, it may be challenging to use this technique during irradiation, even though some studies report CBCT reconstruction using MV portal imaging during VMAT. Other techniques include using different reconstruction algorithms, prior
information, and deformation models for reconstructing 4D CBCT scans \(^{72-75}\). Previously, digital tomosynthesis (DTS) has been described, and this is an alternative to limited-arc CBCT \(^{40,76,77}\). However, preliminary visual comparison of DTS and CBCT images using 20°-80° arcs revealed that CBCT did not result in worse tumor and OAR visibility compared to 20°-80° DTS.

We acknowledge some limitations of this study. These include the fact that we did not optimize image quality and did not look at MV scatter correction techniques, nor did we quantitatively analyze image quality for different fluoro-CBCTs \(^{62,63,78-80}\). We identified that the fluoro-CBCT Hounsfield Units were not correct. Contributing factors may include MV scatter, incorrect norm chamber values, and adjustments to the kV values. The exact reason for the extremely low norm chamber values observed with concurrent MV delivery is currently unknown and under investigation at the manufacturer. As MV scatter results in a higher signal level in the kV imager, which is interpreted as lower attenuation of the object, the HU values are generally lower for fluoro-CBCT scans compared to clinical CBCT scans. For positional verification, contrast differences are more important than the correct HU values. However, to allow for dose calculation, in addition to compensation for incorrect HU values, compensation for the limited field of view would be required \(^{81-83}\). Potential workarounds include using deformable image registration to deform the planning CT so that dose can be calculated on the CT. As we used Offline Review for the CBCT-CT registration, we needed to replace the headers of the fluoro-CBCT with those of the clinical CBCT. However, only minor adaptations would be needed to make this imaging workflow suitable for clinical use. For example, the lack of energy spectrum for all possible kV values could be avoided by using standard kV values, and the use of clinical software would eliminate the need for replacement of DICOM headers. In the current paper, we have focused on the target volume, with spine and lung lesions as clinical cases. Further work will be needed to define the visibility and verification of different target areas and OARs, and the influence of different arc lengths and orientations on the observed distortions.

Although integrated magnetic resonance imaging (MRI) scanners and treatment delivery units are marketed or in development \(^{84,85}\), these are currently expensive, only available in selected centers, and do not represent a technology that will be available to most or many patients in the near future \(^{86}\). There is, therefore, a need to continue improving current CBCT-guided platforms. In addition, invasively implanted fiducial markers are available. These can be inserted into or next to the tumor and then imaged during irradiation, but they are associated with additional risks, costs, and the requirement for expertise, that limit their use. Furthermore, even when markers are implanted in or near to the tumor, this does not provide information about the position of OARs.
In conclusion, we have obtained CBCT reconstructions of planar kV images acquired during VMAT irradiation using standard reconstruction techniques. The spine position on the reconstructed fluoro-CBCT showed good similarity with the average position obtained from the individual projection images, providing support for the methodology and outcomes in this analysis. For partial arc treatments, limited-arc fluoro-CBCTs can be reconstructed with sufficient image quality for matching in multiple, or at least one imaging plane, depending on the available arc length. As standard imaging and reconstruction techniques are used, it is anticipated that this capability could be implemented clinically with few modifications to current treatment platforms.

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