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Lung cancer radiotherapy

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 $\leq$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.

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) [1,2]. 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 [3,4]. 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 off-line analysis [5]. However, this technique is currently not available for on-line use. The feasibility of acquiring a CBCT scan during VMAT delivery has been described before [6–10] 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 $\geq$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

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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]. Each kV fluoroscopy dataset represents the 1st (full or partial) arc of a treatment fraction and was routinely acquired during RapidArc delivery on a TrueBeam™ (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-CBCTs) 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-CBCTs [11]. The reconstructed fluoro-CBCTs 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 mm^2), 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

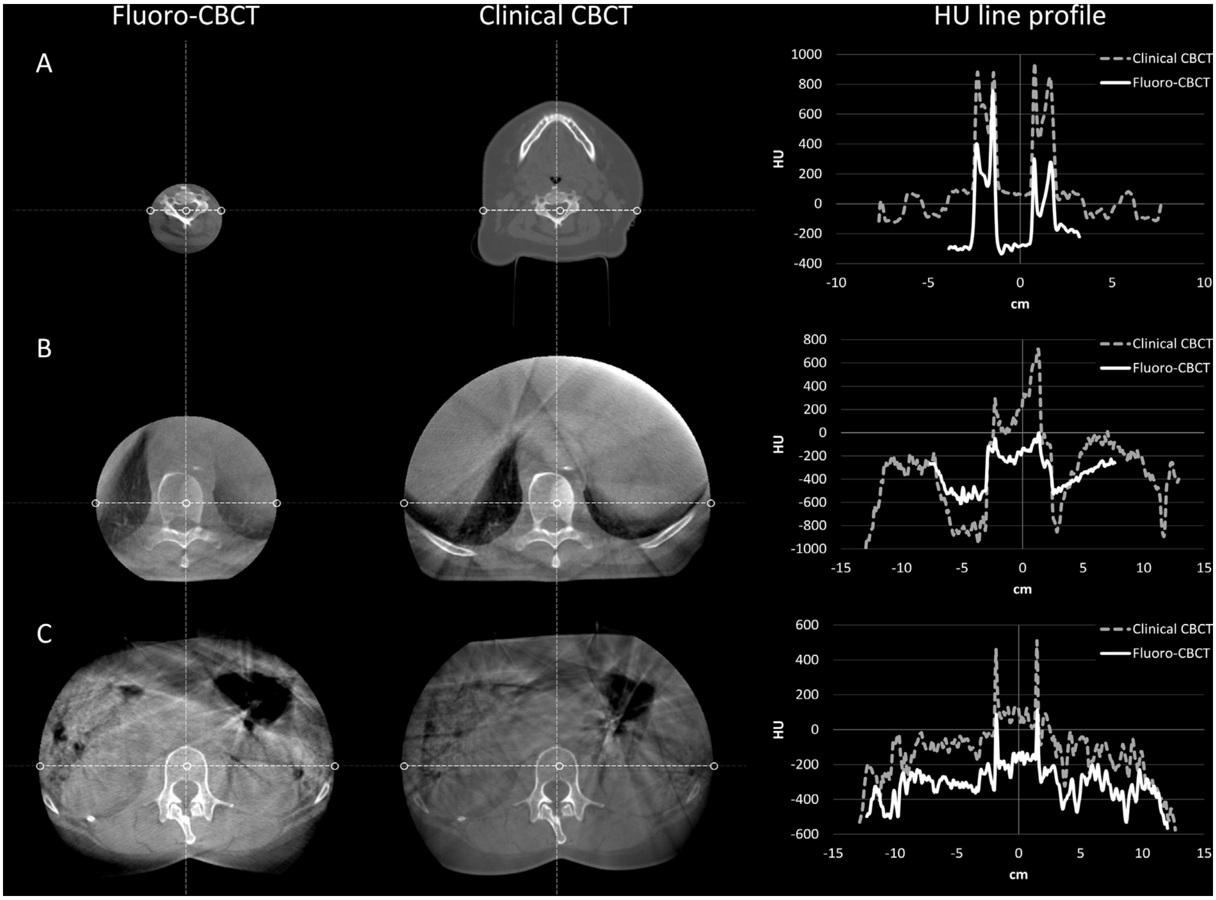

Fig. 1. Example images of a CBCT slice of an (A) cervical, (B) thoracic, and (C) lumbar vertebra, for both the CBCT reconstructed from fluoroscopic images acquired during radiation delivery (left column) and clinical CBCT (middle column), together with the Hounsfield unit line profiles measured at the level of the horizontal lines on the images.