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Original article

Sub-millimeter spine position monitoring for stereotactic body radiotherapy using offline digital tomosynthesis

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ABSTRACT

Purpose: Spine stereotactic radiotherapy (SBRT) requires intrafraction motion <1–2 mm. We evaluated the accuracy and precision of digital tomosynthesis (DTS) in combination with triangulation for spine position tracking.

Materials/methods: Single-slice DTS images were generated from kV cone beam CT (CBCT) projection images. They were registered to reference DTS images reconstructed from the planning CT-scan to determine 2D shifts between actual patient position and treatment plan position. 3D spine position was obtained by triangulation of each registration with a previous registration, for every 1° of data. For 7 patients who underwent spine SBRT, the standard deviation (SD) of DTS + triangulation over one entire dataset was evaluated for different DTS angles (2–16°) and triangulation angles (1–46°). For 32 CBCT datasets, acquired before or after treatment of the 7 patients, using 4° DTS and 18° triangulation angle, SDs were determined and average positions were compared to clinically performed CBCT registrations.

Results: Mean SDs were 0.29 ± 0.10 mm for lateral (range 0.1–0.55 mm), 0.14 ± 0.08 for longitudinal (0.05–0.39) and 0.24 ± 0.10 for the vertical direction (0.10–0.57). Lateral and vertical SDs for thoracic spine were higher than for lumbar spine. Differences between clinical CBCT registration and DTS + triangulation were 0.1 ± 0.26, 0.02 ± 0.33 and −0.07 ± 0.21 mm.

Conclusion: The combination of DTS and triangulation allows for monitoring spine position with sub-mm accuracy and precision.

Spine stereotactic body radiotherapy (SBRT) is characterized by the delivery of a few fractions of radiotherapy with high doses per fraction. The most common indication is vertebral metastasis, with tumor in the bony vertebra and possibly extending into the spinal canal. Steep dose gradients from the vertebrae to the spinal cord allow for sparing of the latter [1]. These steep dose gradients make accurate delineation of the cord important [2,3], and a high positioning accuracy is required during treatment to avoid delivering too much dose to the cord. Depending on the margins and dose gradients being used, even relatively short duration shifts of 2–3 mm (mm) during delivery with high dose rate beams can lead to an appreciable dose increment to the spinal cord [4].

Currently, on most conventional treatment platforms, patient setup is done with sub-mm accuracy prior to SBRT delivery, using a CBCT-scan or stereoscopic X-ray imaging. However, often a time gap of 5–10 min occurs between setup imaging and the end of irradiation, during which the position of the patient is not monitored. Surrogate external markers or surface imaging may be used for patient position monitoring, but may not be representative of the spine position. Patient immobilization is also no guarantee for sub-mm stability. Intrafraction position monitoring can be performed by X-ray imaging after delivery of each SBRT radiation (sub)field. An extra stereoscopic planar imaging system with sub-mm accuracy and the ability to directly image the spine, such as ExacTrac (BrainLab, Germany) can be added to a conventional platform. However, its views can be obstructed by certain gantry angle segments, especially if volumetric modulated arc therapy (VMAT) is being used. The CyberKnife (Accuray, USA) differs from conventional platforms and also allows for frequent X-ray positional verification during treatment delivery. Alternative systems that use implanted radiofrequency markers (Calypso System, Varian Medical Systems) have the disadvantage of requiring an invasive procedure. Therefore, the availability of spine monitoring with sub-mm accuracy using a technique that could be deployed at all gantry angles during intensity modulated radiotherapy (IMRT) or VMAT delivery would represent a major advance on conventional platforms and increase the confidence that treatment was delivered as planned.

Spine SBRT is increasingly performed using VMAT [5,6] where the gantry continuously rotates around the patient during dose

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delivery. One advantage of VMAT over static field IMRT is the reduced delivery time, especially with high dose rate flattening filter free (FFF) beams [7]. Typical delivery times can then be ~70 s per arc using 2 arcs for a plan. Some linear accelerators now allow for continuous or frequent kV image acquisition during radiation delivery using an on-board kV-source and imager. Potentially, images acquired during delivery of a VMAT plan could be continuously registered with digitally reconstructed radiographs (DRR) generated in advance. However, unprocessed kV X-ray images generally suffer from overprojection of all structures in the path of the X-ray, which could, for certain gantry angles, prevent accurate registration. Therefore, a technique was chosen that could overcome this problem.

Digital Tomosynthesis (DTS) allows for volumetric reconstruction of 3-dimensional (3D) slices of a patient's anatomy based on kV projection images acquired over short gantry angles [8,9]. The principle of DTS is based on the laminography method described in the 1930s by Ziedses de Plantes [10] and later adapted by Kolitsi [8]. Although DTS can generate 3D slices, it has limited resolution in the slicing direction, which is the direction of the central axis of the arc segment. These reconstructed DTS slices can be registered with sub-mm precision in 3D with a CT-scan. In order to increase the registration accuracy, the DTS slices generated from kV projection images can be registered to a reference DTS that is digitally reconstructed from the planning CT-scan [11–14].

For short DTS angles (e.g., <10°), the reconstruction results in DTS slices of insufficient resolution in the third dimension to acquire sub-mm precision in that direction from such registration. Information on this third dimension can be obtained by triangulating at least two 2D DTS registration results separated by a small angle [15]. Previous work has demonstrated the use of the combination of DTS and triangulation for continuous registration for determining the spine position of an anthropomorphic phantom with a precision <0.3 mm for 1 standard deviation [13].

The goal of this study was to determine whether the combination of DTS and triangulation of X-ray projection images is capable of monitoring patient spine position with sub-mm accuracy and precision during treatment. To do this, we applied the technique to X-ray projection images from CBCT-scans acquired during previous spine SBRT treatments.

Materials and methods

From 7 patients treated with spine SBRT, kV projection data from 32 CBCT scans acquired pre or post radiation delivery on the TrueBeam platform (Varian Medical Systems, Palo Alto, USA), were used for this retrospective study. All patients were treated without external immobilization. They were positioned supine on a thin mattress with arm and knee support [16]. Three patients (11 CBCTs) had thoracic spine treatments and 4 patients (21 CBCTs) lumbar spine. Projection data were acquired in the "pelvic spotlight" mode (125 kV, 80–110 mA). Five CBCT scans were acquired over 360° while the other 27 comprised only 200° of projection data, all with 0.55° between projection images. The rotation time of the CBCT was one revolution per minute. CBCT scans acquired before radiation delivery were used for initial patient setup on the spine, and therefore the acquisition position could deviate by up to several mm from the planned position whereas the post delivery CBCT generally only deviated by the intrafraction motion and motion during CBCT acquisition.

Non-clinical research software for DTS (DTS Toolkit, Varian Medical Systems) was used to generate a single slice (2D) DTS image using kV projection images acquired over a segment of previous gantry angles, the DTS angle (α_{DTS}). The DTS image was centered in the isocenter, and was parallel to the central kV projection image used for the DTS. DTS images were generated for every degree of gantry rotation [13,15]. The resolution of the DTS images was 0.5×0.5 mm^2. Using the same software, for each gantry angle, the online (projection based) DTS image was registered using a rectangular region of interest around the planning isocenter of typically 6×6 cm^2, to a corresponding 2D reference DTS image, which was digitally reconstructed from the planning CT-scan. The planning isocenter was typically in the vertebra to be treated. The software uses normalized cross-correlation [17] to find the relative 2D position of the reference image that results in the best overlap between it and the online image. This relative position is used to determine the transverse offset between the expected position of the anatomy and the actual position.

For every degree of gantry rotation, "Sequential Stereo" non-clinical software (Varian Medical Systems) was used for triangulation of the last DTS registration with one DTS registration obtained at angle α_{Trian} earlier. Assuming that the patients were immobile during kV image acquisition, the standard deviation (SD) over the registration results of each complete dataset, thus for all gantry angles, would represent the precision of a single DTS + triangulation. If the patient moved during CBCT acquisition then the SD would also include the positional uncertainty due to motion.

Analogous with our phantom study [13], for one dataset per patient, the precision was evaluated for a range of DTS-angles of 2–20° with a fixed triangulation angle of 22°, and for a range of triangulation angles of 2–45° with a fixed DTS angle of 4°. Based on these results, standard settings of 4° and 18° were used for α_{DTS} and α_{Trian}, respectively, for further analyses.

As a measure of the accuracy, for each dataset, the mean result over all gantry angles of DTS + triangulation was compared to the clinically applied CBCT registration. The clinical CBCT registration was done automatically, but occasionally tweaked by the treating technologists. As a measure of precision the SD was determined for each of the 32 datasets over all registration results.

Results

The SD for the *y* (longitudinal) direction was almost independent of both DTS and triangulation angle (Fig. 1). SD for *x* (lateral) and/or *z* (vertical) as a function of α_{DTS} varied for the patients. For three patients, it decreased with increasing α_{DTS}, up to α_{DTS} = 4–10°, while for other patients, SD remained unchanged or increased after $\alpha_{DTS} > 4°$. As the shortest α_{DTS} is preferred in order to reduce latency, $\alpha_{DTS} = 4°$ was therefore selected for all further investigations. For all patients, the SD for *x* and *z* decreased with increasing triangulation angle (Fig. 1). As a result of this, and considering the increased latency of the registration results when α_{Trian} is increased, $\alpha_{DTS} = 4°$ and $\alpha_{Trian} = 18°$ were chosen for subsequent analysis of all 32 CBCT datasets.

For 4 out of 32 CBCT scans, comparison with the clinical CBCT registration could not be performed, as the CBCT reconstructions were not available. This was due to software problems at the accelerator when trying to save them. The maximum clinical shifts of the 28 remaining CBCT registrations were 3.2, 3.1 and 7.1 mm for *x*, *y* and *z*, respectively. Clinical registrations of CBCT with planning-CT were compared with the mean of all DTS + triangulation positions based on kV projection data from the same CBCT scans. Differences were always smaller than 1 mm. The mean position differences (±SDs) between the average DTS + triangulation result and the CBCT-CT registration over the 28 data sets, which is a measure of accuracy, were -0.04 ± 0.27, 0.02 ± 0.30 and 0.24 ± 0.36 mm, for *x*, *y* and *z*, respectively. The mean difference for the *z*-direction deviated from 0 mm, which was caused by the 7th patient that had on average a difference from CBCT registration in the *z*-direction of 0.72 mm. This patient was treated on one

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