SUBSECOND AND SUBMILLIMETER RESOLUTION POSITIONAL VERIFICATION FOR STEREOTACTIC IRRADIATION OF SPINAL LESIONS

Colien Hazelaar, Max Dahele, Hassan Mostafavi, Lineke van der Weide, Ben Slotman, Wilko Verbakel

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Chapter 2

ABSTRACT

Purpose: Spine stereotactic body radiation therapy (SBRT) requires highly accurate positioning. We report our experience with markerless template matching and triangulation of kilovoltage images routinely acquired during spine SBRT, to determine spine position.

Methods and Materials: Kilovoltage images, continuously acquired at 7, 11 or 15 frames/s during volumetric modulated spine SBRT of 18 patients, consisting of 93 fluoroscopy datasets (1 dataset/arc), were analyzed offline. Four patients were immobilized in a head/neck mask, 14 had no immobilization. Two-dimensional (2D) templates were created for each gantry angle from planning computed tomography data and registered to prefiltered kilovoltage images to determine 2D shifts between actual and planned spine position. Registrations were considered valid if the normalized cross correlation score was ≥0.15. Multiple registrations were triangulated to determine 3D position. For each spine position dataset, average positional offset and standard deviation were calculated. To verify the accuracy and precision of the technique, mean positional offset and standard deviation for twenty stationary phantom datasets with different baseline shifts were measured.

Results: For the phantom, average standard deviations were 0.18 mm for left-right (LR), 0.17 mm for superior-inferior (SI), and 0.23 mm for the anterior-posterior (AP) direction. Maximum difference in average detected and applied shift was 0.09 mm. For the 93 clinical datasets, the percentage of valid matched frames was, on average, 90.7% (range: 49.9-96.1%) per dataset. Average standard deviations for all datasets were 0.28, 0.19, and 0.28 mm for LR, SI, and AP, respectively. Spine position offsets were, on average, -0.05 (range: -1.58 to 2.18), -0.04 (range: -3.56 to 0.82), and -0.03 mm (range: -1.16 to 1.51), respectively. Average positional deviation was <1 mm in all directions in 92% of the arcs.

Conclusions: Template matching and triangulation using kilovoltage images acquired during irradiation allows spine position detection with submillimeter accuracy at subsecond intervals. Although the majority of patients were not immobilized, most vertebrae were stable at the sub-mm level during spine SBRT delivery.
INTRODUCTION

In stereotactic body radiation therapy (SBRT), large radiation doses are delivered to the tumor in only a few fractions. Steep dose gradients from the planning target volume (PTV) to nearby organs at risk (OARs), such as the spinal cord, are used and highly accurate positioning is required to reduce the risks associated with excessive OAR irradiation.\textsuperscript{37,38}

Patient setup for spine SBRT on a conventional linear accelerator platform is generally performed using cone beam computed tomography (CBCT) scans with a positional accuracy <1 mm.\textsuperscript{9,39} However, there is often a time gap of several minutes between CBCT acquisition and the start/end of treatment delivery,\textsuperscript{10} during which the spine position is not monitored and may potentially move, despite immobilization.\textsuperscript{25}

Although several techniques have been developed for real-time monitoring of internal targets,\textsuperscript{11-18} they rely either on supplementary hardware, or on implanted markers/transponders requiring an invasive procedure. Some linear accelerators allow kilovoltage image acquisition during radiation delivery using a standard gantry-mounted kilovoltage-source and imager. This permits the development of direct and markerless spine position monitoring techniques using existing hardware. We previously demonstrated the feasibility of offline spine position monitoring using digital tomosynthesis (DTS) applied to kilovoltage projection data of CBCT scans acquired before and after radiation delivery.\textsuperscript{40,41} In this analysis, we report our experience with a markerless spine position monitoring technique based on template matching and triangulation. This technique, which has advantages of being fast and can be performed multiple times per second, performs direct registration of prefiltered kilovoltage projection images and filtered digitally reconstructed radiographs generated from planning CT data.\textsuperscript{42} We evaluated spine stability during spine SBRT, using images acquired during irradiation.

METHODS AND MATERIALS

Phantom experiments

To assess the precision and accuracy of the positional verification software, fluoroscopy datasets of an anthropomorphic pelvic phantom with spine structures (BrainLab AG, Feldkirchen, Germany), acquired during RapidArc (Varian Medical Systems Inc., Palo Alto, CA) spine SBRT delivery, were analyzed. Images were acquired with the phantom positioned in the isocenter (after CBCT-CT registration) and with 0.5-, 1-, and 2-mm offsets for each of the three individual directions (left-right [LR], superior-inferior [SI], and anterior-posterior.
[AP]), while keeping the other two coordinates at 0. These experiments were performed twice (during separate experiments), resulting in 20 datasets. Fluoroscopy images were acquired at 7 frames per second (fps), 100 kV, and 10 mA.

**Patient data**

For 18 patients treated with spine SBRT, excluding patients with metal fixation of the vertebrae, a total of 103 fluoroscopy datasets (where 1 fluoroscopy dataset represents 1 full or partial arc) were routinely acquired during RapidArc volumetric modulated arc therapy (VMAT) delivery, using a TrueBeam platform (version 2.0; Varian). Patients were treated between June 2014 and June 2015 in 3 or 5 fractions to a total prescription dose ranging from 21 to 35 Gy, typically using 2 arcs/fraction and 10 MV flattening filter free (FFF) beams with a maximum dose rate of 2400 MU/min and maximum gantry speed of 6°/s. Patients with lesions at or below the 4th thoracic vertebra (cervicothoracic junction) were positioned using a simple shoulder/arm/head support (Posirest; Civco Medical Solutions, Coralville, IA) and foam knee support (Civco), lying on a thin mattress with arms either supported above the head or alongside the body, depending on what was manageable and comfortable. For more cranial targets, patients were immobilized in a thermoplastic head and neck mask, with arms alongside the body. Setup was performed prior to radiation delivery and between arcs, using 6D CBCT (1.5- or 2.0-mm slice thickness)-planning CT (1.0- or 1.25-mm slice thickness) registration based on spine bony anatomy. The positional waveform of a marker block located on the patient’s body was routinely monitored in 3 dimensions using a real-time position management system (Varian) to help detect major movement of the patient during CBCT acquisition and radiation delivery. Kilovoltage images acquired during treatment delivery were analyzed offline using nonclinical software in order to verify spine stability during MV irradiation.

Kilovoltage datasets that did not contain the complete arc due to, for example, technical issues were excluded from the current analysis (n = 10). The remaining 93 fluoroscopy datasets were acquired at 7 fps (n = 75), 11 fps (n = 14), and 15 fps (n = 4). Kilovoltage projection images, with an effective pixel size of 0.259 × 0.259 mm² at the isocenter, were acquired using, on average ± SD, 96 ± 7 kV (range: 85-113 kV) and 10.2 ± 1.2 mA (range: 7.7-13.3 mA) and captured using iTools Capture (Varian). In the version of the TrueBeam software being used, the fluoroscopy kV and mA values had to be increased to the desired values during the first few seconds of image acquisition. As the image quality of these initial images was poor, projection images acquired at <80 kV were removed from each dataset (on average ± SD, 20 ± 34 images), leaving, on average ± SD, 473 ± 121 projection images (range: 238-898) per dataset.
For the offline analysis, we verified the position of the involved vertebra or the most central vertebra when more than one was treated. These vertebrae were delineated in their entirety on the planning CT scan. In one patient, the most central vertebra was largely destroyed by tumor and therefore the adjacent caudal vertebra was delineated.

**Markerless positional verification of the spine**

Nonclinical software for template generation, template matching, and triangulation (template-based tracking and sequential stereo; Varian) was used to verify 3-dimensional (3D) spine position. Figure 1 shows the general procedure for positional verification of the spine. 2D reference templates of the planning CT were created for every degree of gantry rotation in the form of band-pass-filtered digitally reconstructed radiographs. The band-pass filter was implemented by a kernel resulting from the subtraction of a high-pass Gaussian-shaped kernel ($\sigma = 1.6$ mm) from a low-pass Gaussian-shaped kernel ($\sigma = 0.4$ mm). The 360 templates consisted of the contoured vertebra with 4-mm isotropic margins. Kilovoltage projection images were prefiltered by applying the same band-pass filter. For each kilovoltage image, the template associated with the gantry angle closest to the projection image was selected. To find the best match between the template and kilovoltage image, the normalized cross correlation of all possible 2D template locations within a specified search region on the kilovoltage image was calculated as a measure of similarity. This search region consisted of the template size plus 5-mm search margin. For each kilovoltage image, this resulted in a match score (a value between 0 and 1), which is the highest template matching normalized cross correlation value found within the search region. It is necessary to declare matches as valid or not, as the best match may not necessarily be valid. Invalidity can occur in cases where the image quality is too poor to visualize the spine due to insufficient transmission of x-rays. To classify the match as valid, the match score had to exceed a threshold of 0.15, which was determined experimentally using the available datasets. If declared valid, the resulting match is the 2D spine position in rotating imaging axis coordinates. If declared invalid, the match is rejected and the image is not used for positional verification.

Each registration was triangulated with multiple previous registrations in order to determine the 3D position of the spine in the LR, SI, and AP directions. This offline analysis was performed as if the images were analyzed in real-time during treatment by only using prior images for triangulation. Minimum and maximum stereo separation angles were set at 14° and 72°, respectively. The minimum angle is close to the earlier DTS triangulation angles of 12° and 18°, and the maximum was based on initial phantom experiments in which 10 different maximum angles ranging from 18° to 120° were tested.
For each spine position dataset, the average spine offset (compared to the planning CT) and standard deviations over all gantry angles were calculated. For stationary phantom measurements, the standard deviation of a dataset represents the precision of the template matching including triangulation. For patient data, the standard deviation also included the positional deviation due to actual spine motion. For datasets that showed an average positional deviation of ≥1 mm, the pre- and post-treatment CBCT scans were analyzed.

**Dose measurements**

To estimate the additional radiation dose to the patient, the dose from kilovoltage imaging was measured in the center and periphery of a 32 cm diameter cylindrical polystyrene phantom, using an RTI CT Dose Profiler and RTI Piranha (RTI Electronics AB, Mölndal, Sweden). Fluoroscopic images were acquired for a full arc at 7 fps, 100 kV, 10 mA, using a titanium filter and collimation of 12 × 7 cm. In addition, the dose of a CBCT scan was measured (spotlight mode; full fan, 125 kV, 750 mAs).
Spine position during SBRT delivery

Table 1. Average positional offsets for a phantom.

<table>
<thead>
<tr>
<th>LR-SI-AP displacement (mm)</th>
<th>Mean measurement ± SD 1</th>
<th>Mean measurement ± SD 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LR (mm)</td>
<td>SI (mm)</td>
</tr>
<tr>
<td>0-0-0</td>
<td>0.00 ± 0.17</td>
<td>0.00 ± 0.17</td>
</tr>
<tr>
<td>0.5-0-0</td>
<td>0.51 ± 0.17</td>
<td>-0.03 ± 0.17</td>
</tr>
<tr>
<td>1-0-0</td>
<td>1.00 ± 0.19</td>
<td>-0.05 ± 0.16</td>
</tr>
<tr>
<td>2-0-0</td>
<td>2.04 ± 0.17</td>
<td>-0.06 ± 0.16</td>
</tr>
<tr>
<td>0-0.5-0</td>
<td>0.02 ± 0.21</td>
<td>0.52 ± 0.17</td>
</tr>
<tr>
<td>0-1-0</td>
<td>0.01 ± 0.20</td>
<td>1.00 ± 0.16</td>
</tr>
<tr>
<td>0-2-0</td>
<td>0.02 ± 0.21</td>
<td>2.02 ± 0.16</td>
</tr>
<tr>
<td>0-0-0.5</td>
<td>0.01 ± 0.18</td>
<td>0.00 ± 0.17</td>
</tr>
<tr>
<td>0-0-1</td>
<td>-0.01 ± 0.17</td>
<td>0.00 ± 0.17</td>
</tr>
<tr>
<td>0-0-2</td>
<td>0.00 ± 0.18</td>
<td>0.00 ± 0.18</td>
</tr>
</tbody>
</table>

Data show average detected positional offsets ± SD for a phantom positioned with different baseline shifts in the left-right (LR), superior-inferior (SI), and anterior-posterior (AP) directions. Average detected offsets were corrected for setup inaccuracies with the average detected offsets of (0,0,0) measurements.

RESULTS

Phantom experiments

The average detected offsets for the LR, SI, and AP directions for the phantom positioned in the isocenter were -0.09, 0.12, and -0.02 mm for measurement 1 and 0.10, 0.17, and -0.06 mm for measurement 2, respectively. The other detected offsets were corrected for setup inaccuracies with these initial offsets, after which the maximum difference in average detected and applied offset was 0.09 mm (table 1). Average standard deviations for the 20 measurements were 0.18, 0.17, and 0.23 mm for LR, SI, and AP, respectively.

Patient data and spine position verification

Characteristics of the 18 patients are shown in table 2. In total, the positions of 2 cervical (16 datasets), 8 thoracic (38 datasets), and 8 lumbar (39 datasets) vertebrae were verified. Duration of the arcs were, on average ± SD, 59.9 ± 5.8 s (range: 34.0–79.7 s). The percentage of frames for which the match was classified as valid (hereafter referred to as matched frames) was, on average, 90.7% (range: 49.9%-96.1%) per dataset, which corresponds to 431 ± 123 frames. As the minimum stereo separation angle for triangulation was set to 14°, no results were obtained for at least the first 14° of all datasets. Frames with invalid matches (i.e., match score <0.15) were mainly lateral images, acquired from thoracic or lumbar targets in patients with their arms alongside the body. Figure 2 illustrates this by showing the patient diameter, match scores and spine position data for a sample patient.
### Table 2. Patient characteristics.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex</th>
<th>Age</th>
<th>Location</th>
<th>Arms up/down</th>
<th>LR body diameter (cm)</th>
<th>No. of involved vertebrae</th>
<th>Mask</th>
<th>PTV volume (cm³)</th>
<th>Dose prescription (fractions x Gy)</th>
<th>No. of arcs</th>
<th>MU/arc</th>
<th>No. of datasets</th>
<th>Tracking volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>42</td>
<td>Cervical</td>
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<td>1</td>
<td>5.0</td>
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<td>2</td>
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<td>6</td>
<td>9.3</td>
</tr>
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<td>5.5</td>
<td>165.3</td>
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<td>10</td>
<td>23.0</td>
</tr>
<tr>
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<td>33.9</td>
<td>no</td>
<td>2</td>
<td>70.8</td>
<td>3 × 10</td>
<td>2</td>
<td>2037/1958</td>
<td>6</td>
<td>41.1</td>
</tr>
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<td>1</td>
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<td>2</td>
<td>2175/2528</td>
<td>1</td>
<td>24.6</td>
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<tr>
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<td>F</td>
<td>67</td>
<td>Thoracic</td>
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<td>no</td>
<td>1</td>
<td>18.4</td>
<td>3 × 10</td>
<td>2</td>
<td>1886/2070</td>
<td>3</td>
<td>59.9</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>57</td>
<td>Thoracic</td>
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<td>29.1</td>
<td>no</td>
<td>1</td>
<td>44.9</td>
<td>3 × 10</td>
<td>2</td>
<td>2210/2201</td>
<td>2</td>
<td>37.6</td>
</tr>
<tr>
<td>7</td>
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<td>yes</td>
<td>1</td>
<td>9.0</td>
<td>3 × 10</td>
<td>2</td>
<td>1714/1800</td>
<td>6</td>
<td>30.7</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>73</td>
<td>Thoracic</td>
<td>down</td>
<td>46.6</td>
<td>yes</td>
<td>1</td>
<td>47.3</td>
<td>3 × 10</td>
<td>2</td>
<td>1919/1850</td>
<td>3</td>
<td>30.1</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>68</td>
<td>Thoracic</td>
<td>up</td>
<td>34.2</td>
<td>no</td>
<td>3.5</td>
<td>254.5</td>
<td>5 × 7</td>
<td>4</td>
<td>846/854/896/940</td>
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<td>43.3</td>
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<td>2575/1687</td>
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<td>F</td>
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<td>Lumbar</td>
<td>up</td>
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<td>35.0</td>
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<td>1740/1886</td>
<td>3</td>
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<td>no</td>
<td>1</td>
<td>66.4</td>
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<td>1</td>
<td>13.4</td>
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<td>225.6</td>
<td>5 × 7</td>
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<td>6</td>
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<td>no</td>
<td>3</td>
<td>241.3</td>
<td>5 × 7</td>
<td>2</td>
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<td>8</td>
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<td>50.0</td>
<td>3 × 10</td>
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<td>3058/2338</td>
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<td>50.2</td>
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<td>18</td>
<td>M</td>
<td>78</td>
<td>Lumbar</td>
<td>up</td>
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<td>1</td>
<td>130.1</td>
<td>3 × 10</td>
<td>2</td>
<td>1940/1983</td>
<td>4</td>
<td>83.5</td>
</tr>
</tbody>
</table>

**Abbreviations:** F = female; LR = left-right body diameter measured through isocenter; M = male; MU = monitor units; PTV = planning target volume.

(1) Tracking volume = involved vertebra or the most central vertebra when more than 1 vertebra was treated. This volume may be larger than the PTV volume due to the fact that the vertebra used for matching consists of the entire vertebra whereas the PTV volume may consist of just the vertebral body or an extension of the visible tumor.

(2) Spinal cord lesion.
Figure 2. Illustrative dataset (patient 8, dataset 1). (A) Representative kilovoltage images (part within the search region and including the vertebral contour) and patient diameter measured through the isocenter for each gantry angle. (B) Corresponding match scores with indication of the threshold of 0.15. (C) Spine position data.

Figure 3 shows the matched frame percentage and average positional offset with standard deviation per dataset. For some patients, differences in image kilovoltage values were associated with substantial variation in matched frame percentage (e.g., patient 16, dataset 1 [91 kV] and dataset 3 [107 kV]).

The mean standard deviation for all datasets was 0.28 (range: 0.15–0.82), 0.19 (range: 0.09–0.31) and 0.28 mm (range: 0.14–0.63) for LR, SI, and AP, respectively. Spine position offsets were, on average, –0.05 (range: −1.58 to 2.18), –0.04 (range: −3.56 to 0.82), and −0.03 mm (range: −1.16 to 1.51) for LR, SI, and AP, respectively.
Figure 3. For each dataset and per patient (A) valid matched frame percentage and (B) average positional offset with standard deviation over all gantry angles.
Spine position during SBRT delivery

An average spine offset ≥1 mm in one or more directions was found in 7 datasets, distributed over 5 patients (4, 2, and 3 times in LR, SI, and AP directions, respectively). An average offset of ≥2 mm was found in 2 datasets. Most of the ≥1 mm offset occurred before start of treatment. In 3 of 7 cases, improvements to the CBCT-CT registration prior to irradiation could have reduced the offset to <1 mm from the intended position. The other offsets occurred at some point between CBCT acquisition and start of treatment, which was for these 4 cases, on average ± SD, 5.2 ± 2.3 min (range: 2.5-7.1). For all 7 datasets, the ≥1 mm offset was detected by post-treatment CBCT-CT match.

From the 120,198 combined LR, SI, and AP positional offset components (i.e., 3 components per matched frame), 72.9% deviated by <0.5 mm from the planned position, 94.0% by <1 mm, 98.6% by <1.5 mm, and 99.3% by <2 mm. The percentages of frames with ≤1 mm deviation in the LR, SI, and AP directions were 89.7%, 97.1%, and 95.2%, respectively (figure 4).

**Dose measurements**

For fluoroscopic images, doses of 4.7 and 6.6 mGy were measured in the center and periphery of the phantom, respectively. For the CBCT scan, these were 14.2 and 27.2 mGy, respectively.

![Figure 4. Total number (%) of valid matched frames with a positional offset of >0.5, >1, >1.5, >2, >2.5, and >3 mm.](image-url)
DISCUSSION

This analysis shows that spine stability during spine SBRT delivery can be monitored with sub-mm precision in 3 dimensions and subsecond resolution by automated template matching and triangulation of kilovoltage images continuously acquired during irradiation. This research addresses a limitation of SBRT on conventional linear accelerators, which typically do not permit direct, marker-free positional verification during the most important period, i.e. irradiation itself. The software and workflow (figure 1) are suitable for integration into existing treatment systems, and the analysis is fast enough to provide online positional verification in near real time (the combination of template matching and triangulation was performed within 0.1 s per image).

In addition to providing frequent positional data to the user, an online version of the software could be used to interrupt the treatment when excessive positional displacement is detected, to allow patient repositioning. The interruption could be done automatically, with a manual over-ride option. The positional displacement and time thresholds should be user-adjustable to allow them to take into account institution- and patient-specific parameters, such as acceptable organ-at-risk doses, planned dose distribution/dose gradients, and margins applied to OARs and target, as well as the precision of the positional verification technique. In our clinic, a 2-mm margin is typically used for the spinal cord planning-at-risk volume, and a slightly higher maximum planning-at-risk volume dose is considered acceptable compared to the actual OAR. Using this, treatment could, for example, be interrupted if the detected motion exceeds 1 mm for >5 s. Other possibilities, including automatic couch correction or MLC-based correction of the position of the dose distribution, also merit investigation.

The average standard deviations found in this analysis were below 0.3 mm for each direction, demonstrating that the spine of most patients (most of whom were not immobilized) was stable at the sub-mm level during treatment. In accordance with other published results 48–53, in 8% of the datasets, an average positional offset of ≥1 mm was found (≥2 mm in 2 patients). Analysis of CBCT data suggested that some patients moved between CBCT acquisition and start of treatment and highlighted the fact that CBCT-CT matching is susceptible to interobserver variation. This emphasizes the need for fast positional verification options just prior to or at the beginning of treatment delivery and robust automated matching systems. These observations may be especially relevant for treatments where a single large dose is delivered (e.g., spine treatments of ≥20 Gy). It is entirely possible that, because most patients lie still for most of the time, the number of clinically relevant positional deviations will be small. However, because we cannot yet predict which patients will move, when, and by how much, highly selective/individualized imaging strategies during spine SBRT are
Spine position during SBRT delivery

Currently unreliable. Because positional deviation during irradiation may result in clinically relevant differences between planned and delivered dose, both for very fast and also for longer duration treatments, imaging during beam-on could help to both minimize the risks of damage to normal tissues and verify that the designated target has been irradiated as planned. Additional positional verification could therefore increase user, and perhaps also patient, confidence in their treatments. In addition, the imaging technique described here is not only applicable to stereotactic spine treatments but could also be used during high-precision irradiation at other locations, assuming that the spine is a suitable surrogate for stability. Further work is needed to develop similar imaging solutions for other anatomical locations.

Although this positional verification technique delivers an extra radiation dose to the patient, this was measured at <50% of the CBCT dose. Using this technique for real-time positional verification could eliminate the need for a routine CBCT scan between arcs. For some patients, this could actually result in an overall reduction in imaging radiation dose (and shorten the overall treatment time) compared to the current clinical practice, at the same time as the user is provided with near real-time information.

The average standard deviations given in this paper reflect the combination of the precision of the whole kilovoltage fluoroscopy positional verification system and intrafraction spine motion. Standard deviations for the stationary pelvic phantom data (0.18 for LR, 0.17 for SI, and 0.23 mm for AP) indicate sub-mm precision of the system and confirm the fact that the applied offsets were detected with high accuracy. We previously reported standard deviations of ≤0.15 mm for kilovoltage DTS of a phantom during MV radiation using 6 MV FFF and 2400 monitor units (MU)/min, suggesting only minor differences in precision between the current technique and DTS.

The precision of the positional verification system is influenced by the image quality, which is affected by kilovoltage image acquisition parameters, MV treatment beam parameters and, most importantly, patient-related factors, such as patient diameter, bone density and location of the vertebra. As patient diameter is usually largest from left to right, especially when the patient has the arms positioned alongside the body, images acquired laterally are more subject to noise than, for example, AP images, resulting in more likelihood of a match rejection.

Standard deviations for the SI direction were smaller than those for the LR and AP directions, as the SI direction is fully determined by template matching and not by triangulation. Triangulation has the limitation that positional changes occurring in the latency period between the registrations used for triangulation may not be detected correctly. In addition,
for a small triangulation angle, a small uncertainty caused by template matching can lead
to an amplification of the uncertainty in the “depth” direction, that is, the direction of the
mid-axis of the 2 images used for triangulation \(^{41}\). Using a minimum stereo separation angle
of 14° and a gantry speed of 6°/s, motion in the depth direction is detected immediately,
although the correct position is detected with a latency of 2.4 s, once the patient has
stopped moving.

We acknowledge some limitations of this analysis. The analysis has not yet been performed
in real time during patient treatment, and the image quality has not been optimized for
individual patients. We expect that the image quality can be improved by further optimizing
factors like kilovoltage, milliamperage, and frame rate \(^{54-56}\). In addition, dynamic adjustment
of kV and mA at specific gantry angles where the patient diameter increases, might further
improve the results. Because this positional verification technique is associated with an
imaging radiation dose, the use of portal images from the MV treatment beam for positional
verification also merits further evaluation \(^{57}\).

**CONCLUSIONS**

Template matching and triangulation using kilovoltage images acquired during MV FFF
VMAT delivery allows detection of spine position with sub-mm accuracy at subsecond
intervals, without the need for supplementary hardware or implanted markers.

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