

Scientific Article

Less Time Is Less Motion: Analysis of Practical Efficiencies Gained With a Modified Workflow Integrating Planar kV Midimaging With CBCT for Spine Stereotactic Body Radiation Therapy



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Abstract

Purpose: Our purpose was to optimize an image guided radiation therapy (IGRT) workflow to achieve practical setup accuracy in spine stereotactic body radiation therapy (SBRT). We assessed the time-saving efficiencies gained from incorporating planar kV midimaging as a surrogate for cone beam computed tomography (CBCT) for intrafraction motion monitoring.

Methods and Materials: We selected 5 thoracic spine SBRT patients treated in 5 fractions and analyzed patient shifts captured by a modified IGRT workflow using planar kV midimaging integrated with CBCT to maintain a tolerance of 1 mm and 1°. We determined the frequency at which kV midimaging captured intrafraction motion as validated on repeat CBCT and assessed the potential time and dosimetric advantages of our modified IGRT workflow.

Results: Patient motion, detected as out-of-tolerance shifts on planar kV midimaging, occurred during 6 of 25 fractions (24%) and were validated on repeat CBCT 100% of the time. Observed intrafraction absolute shifts (mean ± standard deviation) for the 25 fractions were 0.39 ± 0.21 , 0.56 ± 0.22 , and 0.45 ± 0.21 mm for lateral-longitude-vertical translations and $0.38 \pm 0.12^\circ$, $0.32 \pm 0.09^\circ$, and $0.47 \pm 0.14^\circ$ for pitch-roll-yaw rotation, which if uncorrected, could have significantly affected target coverage and increased spinal cord dose. The average times for pretreatment imaging, midtreatment verification, and total treatment time were 8.94, 2.81, and 16.21 minutes. Our modified IGRT workflow reduced the total number of CBCTs required from 120 to 35 (70%) and imaging dose from 126.2 to 43.4 cGy (65.6%) while maintaining high fidelity for our patient population.

Conclusions: Accurate patient positioning was effectively achieved with use of multiple 2-dimensional-3-dimensional kV images and an average of 1 verification CBCT scan per fraction. Integration of planar kV midimaging can effectively reduce treatment time associated with spine SBRT delivery and minimize the potential dosimetric effect of intrafraction motion on target coverage and spinal cord dose.

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Introduction

Spine stereotactic body radiation therapy (SBRT) has become widely adopted as improved oncologic therapies have increased the need to safely deliver high doses of radiation in the setting of spine reirradiation and oligometastatic disease and for patients with radioresistant tumor histology.^{1,2} Evolving techniques in patient immobilization, treatment planning, image guidance, and treatment delivery have further advanced the ability to efficiently and precisely deliver an ablative treatment while minimizing spinal cord dose and the catastrophic risk of radiation-related myelopathy.²⁻⁴ Common SBRT prescription regimens include 18 to 20 Gy in a single fraction, 27 to 30 Gy in 3 fractions, and 30 to 35 Gy in 5 fractions. Hypofractionation in spine SBRT is ultimately restricted by the dose-limiting proximity of nearby critical organs and the image guided radiation therapy (IGRT) workflows that ensure that steep dose gradients between tumor and spinal cord are delivered at the time of treatment as intended.

We previously reported an analysis of spine SBRT positioning accuracy and intrafraction motion using an in-house-developed stereotactic body frame (SBF) on a Varian Novalis Tx integrated with Brainlab ExacTrac system imaging (Brainlab AG, Heimstetten, Germany) (referred to as “BHS” for Brainlab Heimstetten Stereotactic) and a commercial SBF as a benchmark, to maintain a preset threshold of 1 mm/1°. ⁵ More recently, our institution has adopted new methods of patient immobilization and SBRT treatment delivery using a Varian TrueBeam platform with a 6D robotic couch (translational X-Y-Z and rotational pitch-roll-yaw) and equipped with standard kilovoltage (kV) cone beam computed tomography (CBCT), kV 2-dimensional (2D)-3-dimensional (3D), and ExacTrac imaging capabilities. While midimaging (midtreatment imaging, ie, imaging between treatment arcs) with CBCT scans confirms setup accuracy pretreatment, these images and associated couch movements prolong treatment time and may introduce systematic perturbations to patient positioning. Midimaging modalities may additionally expose patients to unnecessary radiation dose or inadvertently increase the risk of spinal cord myelopathy, as this radiation dose is not accounted for in treatment planning or plan evaluation. Although prior studies have analyzed the dosimetric effects of translational and rotational errors in spine SBRT and thus recommended setup translational errors of ≤ 1 mm and rotational errors $\leq 2^\circ$,⁶⁻⁸ to our knowledge, none have analyzed whether incorporating planar kV-imaging with CBCT can maximize delivery efficiency while also maintaining high fidelity to detect intrafraction motion.

The objectives of this study were (1) to validate a practical IGRT workflow for spine SBRT by assessing whether integration of planar kV-imaging to verify initial setup

with CBCT followed by planar kV midimaging could reliably track patient position within our institutional tolerance of 1 mm and 1° and (2) to assess the potential time-saving efficiencies and dosimetric effects of our modified workflow using planar kV midimaging as a surrogate for CBCT between treatment arcs.

Methods and Materials

Simulation, SBRT planning, and treatment machine

The patients were simulated in the supine position with arms abducted above the head, immobilized with either an in-house stereotactic body frame or commercial CIVCO SBRT system.⁵ CT images were acquired on a GE 16-slice scanner (Lightspeed; General Electric Medical System, Waukesha, WI) with a slice thickness of 1.25 mm and 65-cm field of view. Gross tumor volumes and clinical target volumes were contoured with international treatment guidelines using fusion of CT with high-resolution contrast-enhanced magnetic resonance imaging (T1- and T2-weighted).⁹ A 1-mm planning target volume (PTV) symmetrical expansion from clinical target volume contour and 1-mm planning organ at risk volume (PRV) margin from spinal cord were used. All cases were planned with volumetric modulated arc therapy (VMAT) in the Eclipse treatment planning system (Varian Medical Systems) with priorities set to achieve a steep dose gradient between target and spinal cord (Fig 1).

Patients were treated on a Varian TrueBeam linear accelerator, equipped with kV 2D-3D and CBCT on-board imaging and a robotic couch with 6° of freedom capable of incremental translational and rotational adjustments of 0.1 mm and 0.1° in treatment mode. In addition, the Varian TrueBeam is equipped with a Brainlab ExacTrac system of 2 floor-mounted kV-energy x-ray units with 2 room-mounted amorphous silicon detectors and an infrared tracking system. The ExacTrac coordinate system is calibrated to treatment isocenter with the 2 x-ray units aligned to project through the isocenter of the treatment machine and providing oblique views of the patient's bony anatomy.

Image guidance workflow

Our modified IGRT workflow for spine SBRT is as follows (Fig 2). After initial setup using skin tattoos and with an orthogonal pair of kV images (usually anteroposterior and lateral) matched to digitally reconstructed radiographs, a region of interest is set on day 1 at the treatment console to encompass the relevant bony anatomy around the target PTV, which is imported from the planning

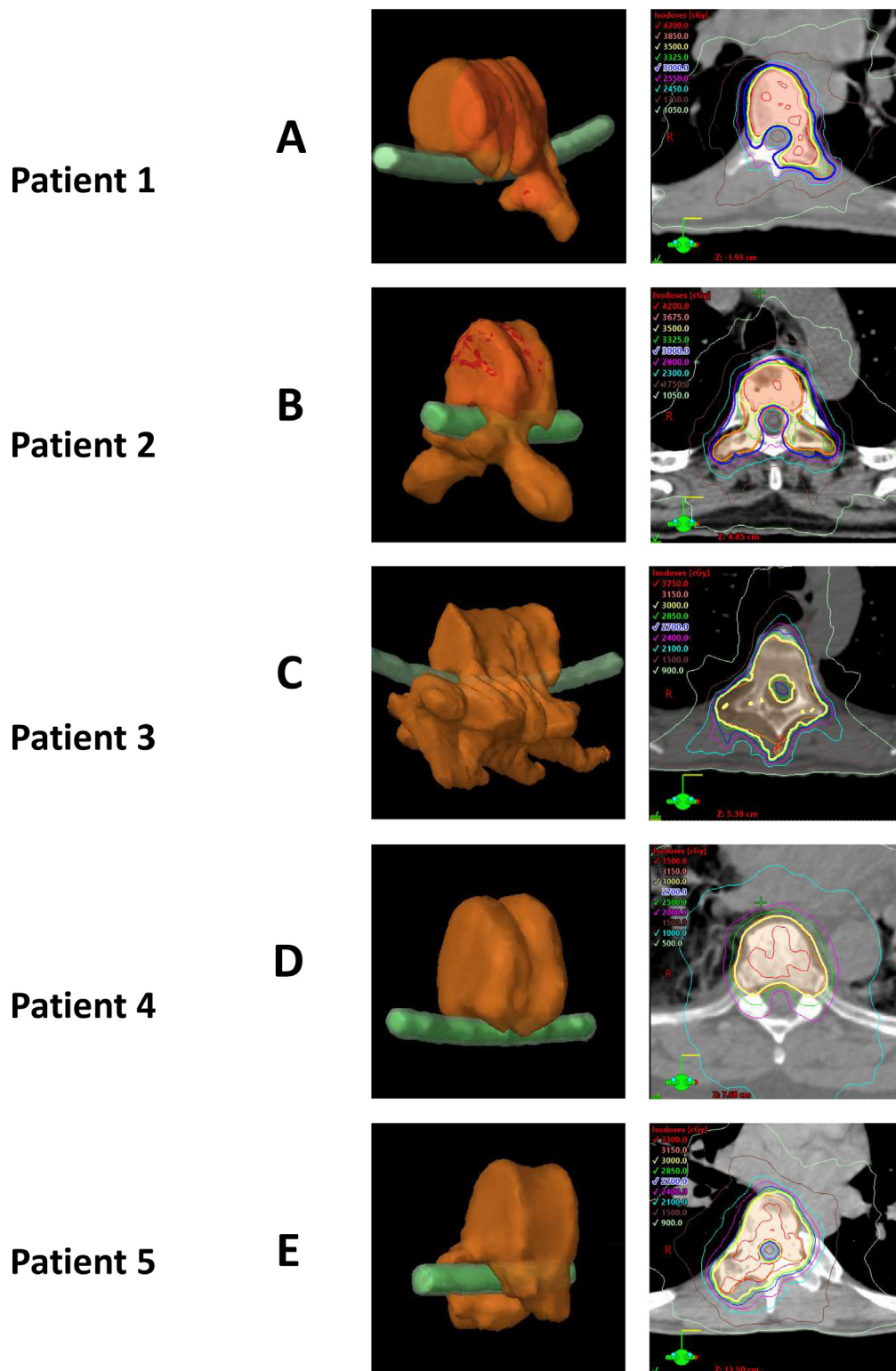


Figure 1 T-Spine stereotactic body radiation therapy cases planned with Volumetric Modulated Arc Therapy in Eclipse with priorities set to achieve a steep dose gradient between target and spinal cord. (A) Patient 1 target volume delineated as the 2 vertebral bodies and ipsilateral transverse process. (B) Patient 2 target volume delineated as the single vertebral body and ipsilateral transverse process. (C) Patient 3 target volume delineated as circumferential spanning 2 vertebra bodies due to bilateral pedicle invasion. (D) Patient 4 target volume delineated as single vertebra body. (E) Patient 5 target volume delineated as circumferential spanning single vertebra body due to bilateral pedicle invasion.

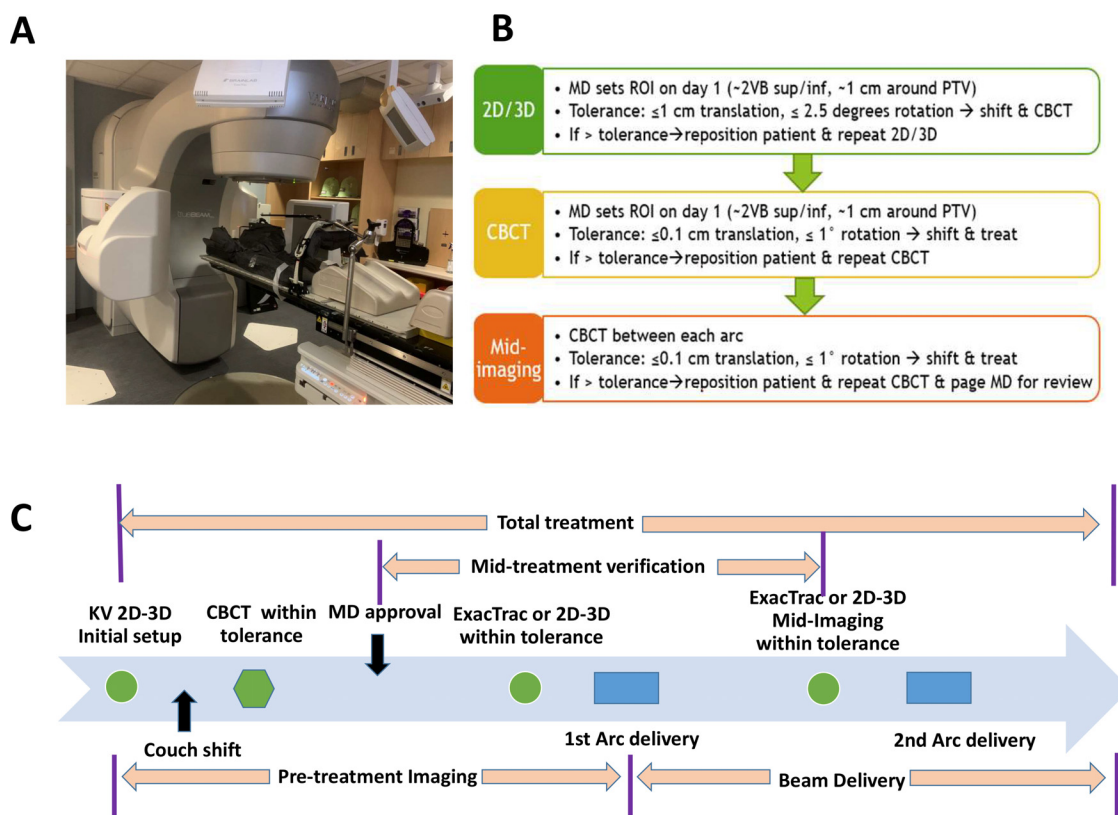


Figure 2 T-Spine stereotactic body radiation therapy (SBRT) treatment setup and our modified image guided radiation therapy (IGRT) workflow. (A) Varian TrueBeam platform with kV 2-dimensional (2D)-3-dimensional (3D), ExacTrac, and kV cone beam computed tomography (CBCT) imaging technique. (B) Imaging steps and action levels for spine SBRT treatment. A unique region of interest (ROI) is defined on day 1 by the therapists at the treatment console for initial setup with both 2D-3D and CBCT imaging. The ROI is confirmed by the IGRT medical doctor (MD) to extend 1 to 2 vertebral bodies superior and inferiorly and approximately 1 cm around the planning target volume (PTV) imported from the planning system, per our departmental guidelines, and this must be approved to be within 1 mm and 1° tolerance before treatment is delivered. (C) Pretreatment imaging (initial setup to beam on), midtreatment verification (CBCT to midimaging), and total treatment (initial setup to end of treatment) time in workflow.

system. An automated 2D/3D kV-kV match (orthogonal pair to planning CT) is then performed (Varian advanced imaging package), and rotational and translational shifts will be applied via the robotic couch. A 3D kV-CBCT scan and an automated 3D/3D match of the CBCT with the planning CT is then performed, and 6° of freedom shifts are applied after physician review of alignment using an region of interest set on day 1 at the treatment console to extend 1 to 2 vertebral bodies superiorly and inferiorly and 1 cm around the target PTV. If any of the rotational or translational shifts exceed a preset threshold of 1 mm and 1° , the CBCT and automated 3D/3D match will be repeated until the shifts/rotations are within this tolerance. The final approved shifts and rotations were applied with the robotic couch. CBCT imaging position is then verified with either ExacTrac or 2D/3D kV-kV imaging to ensure stable patient positioning within 1 mm in translation and 1° in rotation before radiation beam delivery. For midtreatment imaging, the ExacTrac or 2D-3D kV images are acquired and fused before delivery of

subsequent arcs to confirm patient positioning remains within tolerance throughout treatment. In cases where ExacTrac or kV 2D-3D imaging is out of tolerance, a repeat CBCT is performed to verify whether recorded shifts reflected actual patient motion. If ExacTrac or 2D-3D kV imaging was a poor surrogate for CBCT, midtreatment imaging is performed with CBCT alone to verify patient position. CBCT is considered the gold standard due to the ability to verify target position using 3D bony anatomy.

Patients and data analysis

Five thoracic spine SBRT patients, prescribed 30 Gy in 5 fractions, were evaluated with respect to the observed shifts captured by planar kV midimaging and the number of CBCT and kV 2D-3D images required with our modified IGRT workflow in comparison to a CBCT-only workflow to confirm the patient was within tolerance for safe

treatment. The time associated with pretreatment imaging, midtreatment verification, and total treatment delivery was recorded. Instances where planar kV midimaging detected a shift exceeding our institutional tolerance of 1 mm and 1° were further analyzed with respect to patient shifts detected on repeat CBCT imaging. Translations (vertical, longitude, lateral) and rotations (yaw, roll, and pitch) recorded with ExacTrac midimaging were reproduced in the treatment planning system by rigidly transforming the planning CT image set using MIM Maestro (MIM Software, Inc) for each patient for each fraction of treatment (Fig E1). The dosimetric effect of these shifts was analyzed and evaluated in terms of PTV coverage receiving 100% of the prescription dose (PTV V100) and maximum dose to the spinal cord plus a 1-mm margin (cord + 1 mm D_{max}), by recalculating the plans using the original VMAT beam geometry, multileaf collimator (MLC) motion, and monitor units (MUs) on the shifted and rotated CT scans (Fig E2).

IGRT imaging dose measurement

Planar kV imaging dose for machine-specific anatomic protocols of head medium (kVp = 85, mAs = 5) and pelvis large (kVp = 85, mAs = 15) were measured using the MagicMax (Ion Beam Applications, Inc, Walloon Brabant, Belgium) multidetector X-ray (XR) sensor placed on couch top at a source to surface distance of 100 cm at the detector surface. The kV blades are set to 5 cm for a field size of 10×10 cm² with the kV source at gantry 0 (International Electrotechnical Commission coordinate system) and no kV source filter attached. Our institutional CT dose index (CTDI) Quality Assurance (QA) assessment were performed on 4 Varian TrueBeam LINACs. The clinical head and pelvis protocol CTDI were measured with the American College of Radiology (ACR) head and torso phantoms at isocentric setup with 10-cm pencil ion chamber PC-4P (Capintec, Inc, Florham Park, NJ) and Innovision electrometer (model 35040; Fluke Biomedical, Corp., Cleveland, OH), under the protocols of high-quality head (kVp = 100, mAs = 150, gantry degrees = 200) and standard pelvis (kVp = 125, mAs = 1080, gantry degrees = 360), respectively. ACR CTDI head or body phantom was placed at a source to chamber distance of 100 cm at the central chamber position at each measurement. The set of measurements was taken along the central axis of the phantom and at each of the off-axis periphery positions on the ACR phantoms. The weighted CTDI was calculated based on the values given.¹⁰

$$CTDI_{100} = \frac{1}{L} \int_{-50mm}^{50mm} D(z) dz \quad (1)$$

Where, $\int_{-50mm}^{50mm} D(z) dz$ represents with dose measurement with 10-cm standard pencil chamber, and L is the

measurement width.

$$CTDI_w = \frac{1}{3} \cdot CTDI_{100}\{1\} + \frac{2}{3} \cdot \left[\frac{1}{4} \cdot \sum_{i=2}^5 CTDI\{i\} \right] \quad (2)$$

$$CTDI_w^n = \frac{100 \cdot CTDI_w}{mAs} \quad (3)$$

The set of measurements was taken along the central axis of the phantom (i = 1) and at each of the off-axis periphery positions on the ACR head and torso phantoms (i = 2...5). The weighted CTDI_w was calculated by Eq (2). The normalized weighted CTDI_w was calculated by Eq (3). All patients were imaged using a thorax CBCT protocol. The imaging dose value was similar to the dose value from head CBCT protocol per American Association of Physicists in Medicine (AAPM) TG-180¹¹ and was estimated by using the CTDI_w provided by Varian. The relative imaging dose associated with our modified IGRT workflow in comparison to a CBCT-only workflow was calculated based on the estimation given previously.

Results

Five thoracic spine SBRT patients treated to a similar anatomic location with a prescription of 30 Gy in 5 fractions for metastatic disease were selected for systematic review. Target volumes were delineated as per international consensus guidelines and target volumes ranged from a single vertebral body (Patient (PT) 4), the vertebral body and ipsilateral transverse process (PT 1), the vertebral body and bilateral transverse process (PT 2), and 2 patients with circumferential target volumes due to bilateral pedicle invasion (PT 3 and PT 5) (Fig 1).⁹ Patient 3 had a circumferential target volume spanning 2 vertebral body levels due to 2 levels of metastatic tumor involvement (Fig 1).

The translational and rotational shifts observed per patient over each day of treatment and captured by planar kV midimaging with our modified IGRT workflow are displayed in Figure 3. The absolute mean and standard deviation (SD) are summarized in Table E1. Patient 1 remained within our institutional tolerance on midimaging over the entire course of their treatment (Fig 4) (mean ± SD: lat 0.22 ± 0.21 mm, long 0.42 ± 0.33 mm, vert 0.22 ± 0.23 mm, pitch 0.39 ± 0.22°, roll 0.31 ± 0.37°, yaw 0.34 ± 0.23°). Patient 2 was within tolerance on days 1 through 4; however, they had translational shifts of -0.2, -0.5, +1.5 mm (vertical, longitudinal, and lateral) and rotations of -1.0°, 0.1°, and 0.5° (yaw, roll, and pitch) on day 5 that exceeded tolerance, which prompted 2 repeat CBCT scans to confirm position before proceeding with further treatment (Fig. 3 and 4A,B) (mean ± SD: lat 0.68 ± 0.51 mm, long 0.36 ± 0.26 mm, vert 0.36 ± 0.18 mm, pitch 0.40 ± 0.23°, roll 0.22 ± 0.19°, yaw 0.49 ± 0.38°).

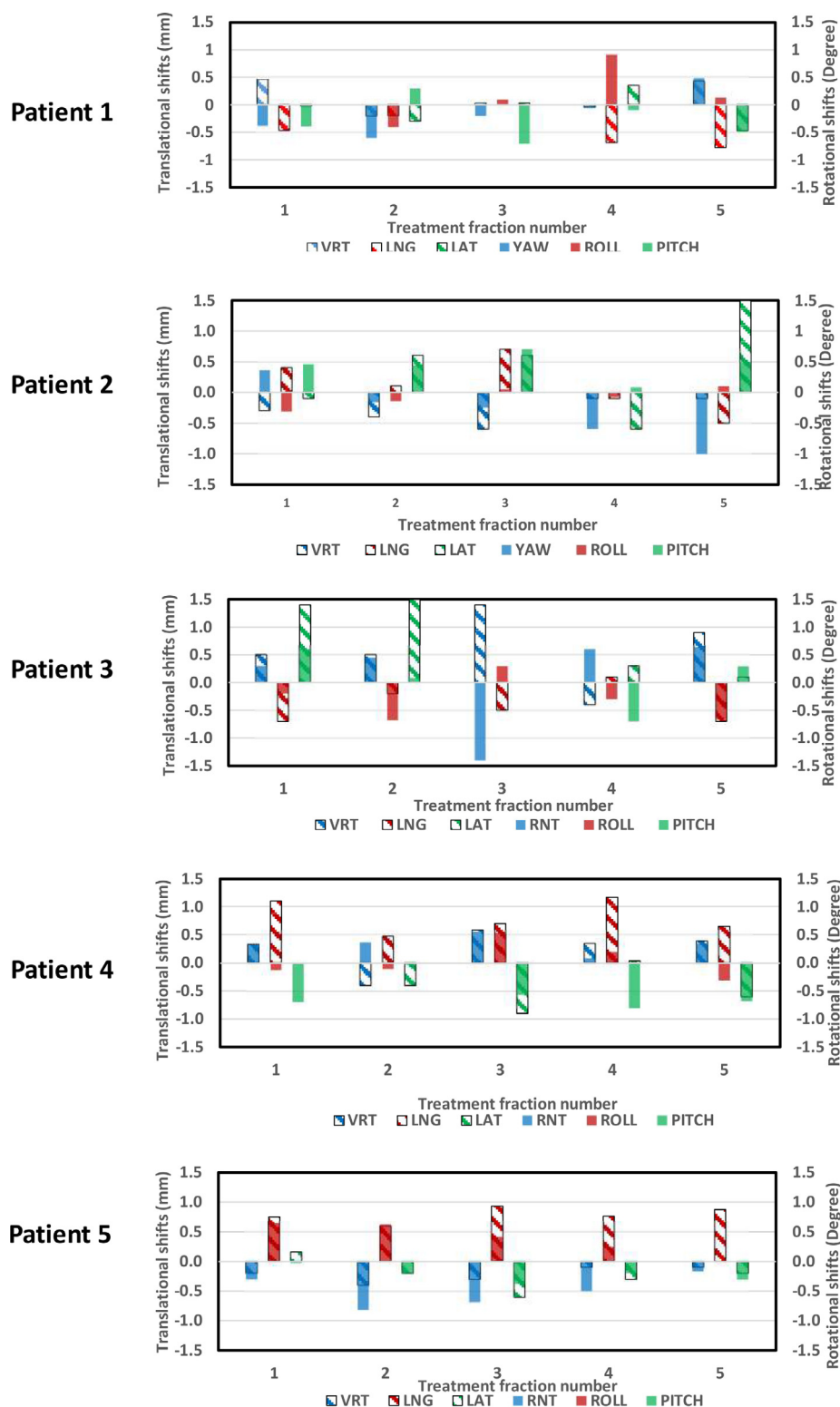


Figure 3 Patient shifts in X-Y-Z directions and in pitch-roll-yaw directions observed in midimaging on each treatment day for each patient for a total of 5 days. (A) Patient 1 shifts. (B) Patient 2 shifts. (C) Patient 3 shifts. (D) Patient 4 shifts. (E) Patient 5 shifts. *Abbreviations:* LAT = lateral; LNG = longitudinal; RNT = rotation; VRT = vertical.

Patient 3 exceeded tolerance on the translational shifts acquired from midimaging on days 1 through 3, which required an additional CBCT (Fig. 3 and 4A,B) but had

all shifts within tolerance on days 4 and 5 (Fig 3) (mean \pm SD: lat 0.66 ± 0.73 mm, long 0.44 ± 0.28 mm, vert 0.74 ± 0.42 mm, pitch $0.33 \pm 0.31^\circ$, roll $0.43 \pm 0.23^\circ$, yaw

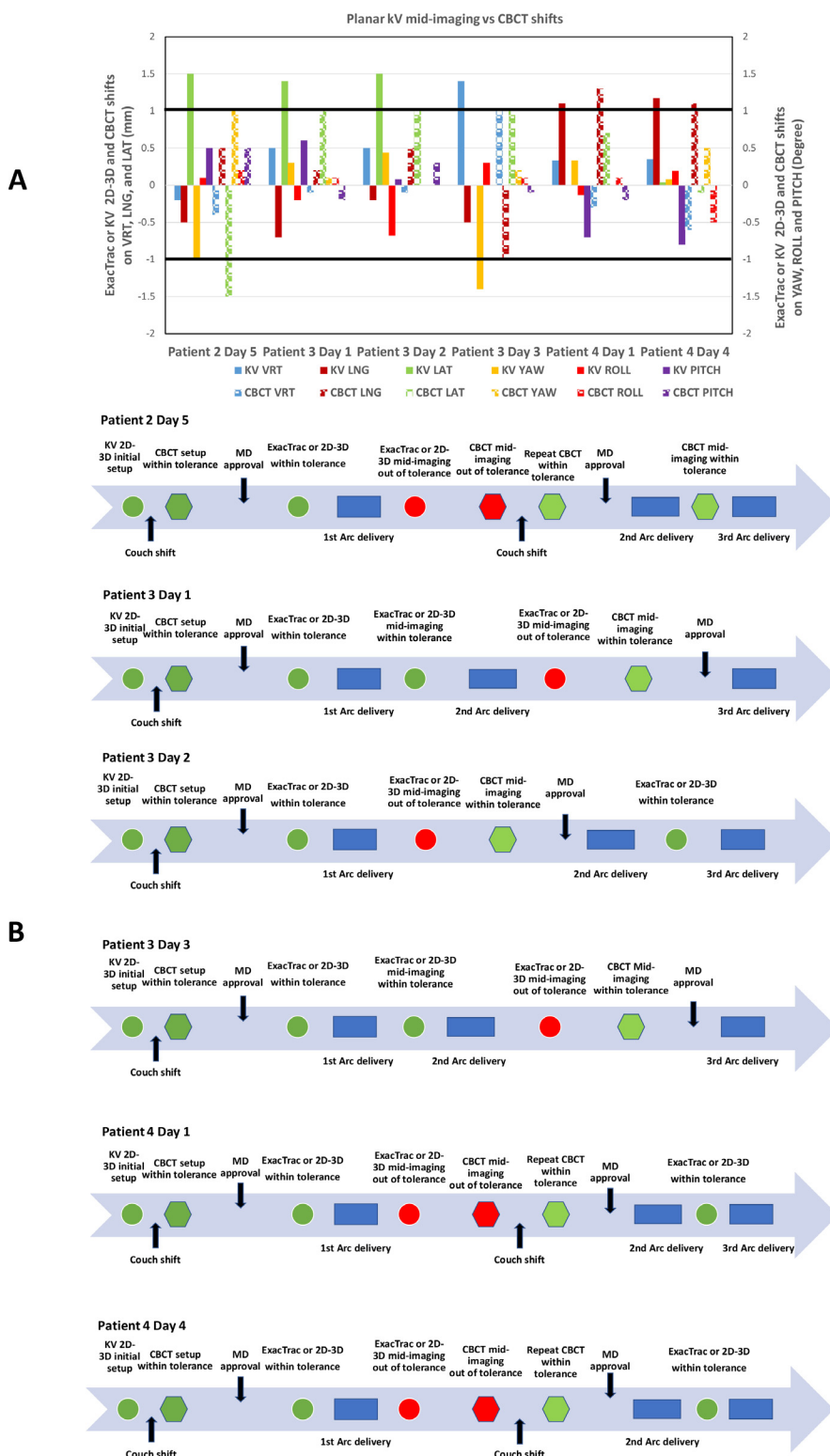


Figure 4 (A) Out-of-tolerance shifts captured on planar kV midimaging and subsequent repeat cone beam computed tomography (CBCT). A shift was out-of-tolerance if >1 mm or $>1^\circ$. (B) Timeline of pretreatment verification, midtreatment imaging for patients with out-of-tolerance shifts with kV 2-dimensional (2D)-3-dimensional (3D), ExacTrac, or CBCT imaging. Medical doctor approval of CBCT alignment within tolerance was required before starting treatment delivery or before resuming treatment after an out-of-tolerance shift. *Abbreviations:* LAT = lateral; LNG = longitudinal; MD = medical doctor; VRT = vertical.

$0.68 \pm 0.43^\circ$). Patient 3 had relatively larger observed shifts introduced from the first 3 days of treatment. Patient 4 exceeded tolerance on days 1 and 4, prompting 2 repeat CBCT scans those days (Fig. 3 and 4A,B) (mean \pm SD: lat 0.39 ± 0.38 mm, long 0.82 ± 0.30 mm, vert 0.40 ± 0.11 mm, pitch $0.56 \pm 0.31^\circ$, roll $0.25 \pm 0.17^\circ$, yaw $0.33 \pm 0.17^\circ$). Patient 5 was within tolerance throughout their treatment (Fig. 3) (mean \pm SD: lat 0.29 ± 0.18 mm, long 0.78 ± 0.13 mm, vert 0.22 ± 0.13 mm, pitch $0.22 \pm 0.13^\circ$, roll $0.39 \pm 0.27^\circ$, yaw $0.50 \pm 0.27^\circ$). The average of these shifts for the selected 5 patients in total 25 fractions based on midimaging were 0.45 ± 0.21 , 0.56 ± 0.22 , and 0.39 ± 0.21 mm for lateral-longitude-vertical translations and $0.38 \pm 0.12^\circ$, $0.32 \pm 0.09^\circ$, and $0.47 \pm 0.14^\circ$ for pitch-roll-yaw rotations, respectively (Table E1).

Over the 25 fractions delivered, there were 6 instances of out-of-tolerance shifts detected with planar kV midimaging, representing an overall frequency of 24%, distributed variably across our patient population (PT2 day 5, PT3 day 1, PT3 day 2, PT3 day 3, PT4 day 1, PT4 day 4) (Fig. 3). We analyzed each of these events with respect to the observed shifts detected on kV midimaging relative to shifts detected on subsequent repeat CBCT (Fig. 4A). Patient 2 had a lateral shift on kV midimaging day 5, and repeat CBCT showed another out-of-tolerance lateral shift (Fig. 4A), which prompted a couch shift and second repeat CBCT to confirm that the patient was within tolerance before treatment proceeded (Fig. 4B). CBCT was used for subsequent midimaging before the third arc delivery (Fig. 4B). Patient 3 was out of tolerance with a lateral shift on kV midimaging on days 1 and 2 and with a vertical shift and yaw rotation on kV midimaging on day 3 (Fig. 4A). Repeat CBCT for patient 3 on days 1 and 2 confirmed patient was within tolerance of 1-mm vertical shift and treatment proceeded (Fig. 4A,B). Repeat CBCT for patient 3 on day 3 was taken to confirm the patient was within tolerance before the third arc delivery (Fig. 4A, B). For patient 4, planar kV midimaging showed an out-of-tolerance roll on days 1 and 4, which was also confirmed on repeat CBCT (Fig. 4A). This prompted a couch shift and a second CBCT to confirm that the patient was within tolerance before the second arc delivery on both days (Fig. 4B). Among these 6 instances where out-of-tolerance shifts were detected on planar imaging, repeat CBCT confirmed the out-of-tolerance translational or rotational shift in 3 of 7 cases, or for 2 of 3 patients. Among these 6 instances, where both out-of-tolerance kV and repeat CBCT imaging were captured, there were 32 of 36 records where translations and rotations were confirmed to be within tolerance with both imaging modalities (89%), if we consider all parameters independent and each day of treatment among the same individual independent of each other.

For all other instances ($n = 19$, 76% of fractions), planar kV midimaging verified that the patient was within tolerance and further CBCT scans were not needed

between treatment arcs. With planar kV imaging incorporated as a surrogate for CBCT midimaging, the number of CBCT images needed for treatment was reduced from 120 to 35, or 76% (Table 1). Repeat CBCT scans were only required on days where kV planar midimaging captured an out-of-tolerance shift (Table 1).

To calculate the potential dosimetric effect of patient movement on spinal cord dose and PTV coverage, we applied the observed intrafractional patient shifts to the original plan (Fig E1) and recalculated cord + 1 mm D_{\max} and PTV V100 (Fig E2). The effect of shifts on target coverage and spinal cord dose varied per patient and per day, depending on the magnitude of the shift and proximity of PTV to spinal cord (Fig E2). The maximum increase in potential spinal cord dose was for patient 1 on day 3 with the dose of 391.6 cGy maximum (7.8% Rx) for 1 fraction. The Wilcoxon signed rank test was used to assess difference in PTV V100 and cord + 1 mm D_{\max} within the patient cohort. There was a significant difference between the PTV V100 originally planned and PTV V100 with patient shifts ($P = .03$). The significant difference was also observed between cord + 1 mm D_{\max} originally planned and cord + 1 mm D_{\max} with patient shifts ($P = .06$).

We measured the imaging dose associated with kV and CBCT imaging (Table E2) with head and pelvic protocols to capture the range of potential exposure, with the highest dose associated with pelvic protocol imaging due to the increased number of x-rays required. For the thorax CBCT protocols used for our patient population, the average kV dose and the CTDI_w of CBCT were estimated to be in similar ranges of head protocol, or 0.034 and 1.8 cGy, respectively. The total imaging dose from our modified IGRT workflow was 43.4 cGy in comparison to 126.2 cGy, representing a reduction of 65.6% through integration of planar kV midimaging.

Finally, the treatment setup and delivery time for each patient was analyzed based on average time over 5 days for pretreatment imaging (initial setup to beam on), mid-treatment verification (CBCT to midimaging), and total treatment time (initial setup to end of treatment) (Fig 2C, Table 2). Patient 1 had the shortest overall treatment time with pretreatment imaging (7.97 ± 1.30 min), midimaging (2.85 ± 0.68 min), and total treatment (11.36 ± 1.66 min) to deliver a 2 arc VMAT plan. All patient shifts captured on midimaging were within tolerance of 1 mm and 1° over the entire treatment course and as such minimal CBCT imaging was needed as per our modified IGRT workflow. Patient 3 had the longest times needed for mid-treatment verification (3.53 ± 1.78 min) and total treatment time (20.20 ± 3.76 min) due to the translational or rotational shifts exceeding tolerance on the first 3 days and repeated CBCT during midtreatment verification to deliver a 3 arc plan. Patients 4 and 5 had relatively longer times on pretreatment imaging (10.69 ± 4.93 min and 9.49 ± 4.00 min, respectively) compared with the other 3 patients, potentially due to differences with use of

Table 1 Summary and comparison of CBCT numbers and total imaging dose for 5 patients

Day 1 CBCT#	Day 2 CBCT no.	Day 3 CBCT no.	Day 4 CBCT no.	Day 5 CBCT no.	Total CBCT no.	Total ExacTrac or kV 2D-3D # in treatment	Total imaging dose from CBCT and kVs (our workflow) (cGy)*	Minimum total CBCT nos. in CBCT- only workflow†	Minimum CBCT imaging dose (CBCT-only workflow) (cGy)
PT 1 1	1	1	1	1	5	15	6.3	20	21.0
PT 2 1	1	1	1	4	8	19	9.7	25	26.3
PT 3 2	2	2	1	1	8	20	9.8	25	26.3
PT 4 3	1	1	3	1	9	20	10.9	25	26.3
PT 5 1	1	1	1	1	5	20	6.7	25	26.3

Abbreviations: 2D-3D = 2-dimensional–3-dimensional; CBCT = cone beam computed tomography; CTDI = computed tomography dose index. PT = patient
* We estimated that the imaging dose from 1 kV pair is equal to 0.035 cGy x 2 = 0.07 cGy from our imaging dose measurement and the imaging dose from CBCT by taking the ratio of CTDIs from thorax protocol and pelvis protocol as 4 cGy x 0.47 mGy/1.8 mGy = 1.05 cGy.
† Minimum total CBCT#s in CBCT-only workflow means the total number of CBCTs required to deliver treatment over 5 days for each patient if CBCT imaging is the only modality used for patient initial setup and midimaging verification. The number is the minimum because it assumes the patient has no out-of-tolerance shifts and no need to take any additional CBCT during the midimaging process.

Table 2 The average treatment time for 5 patients in total 25 fractions recorded

	Pretreatment* Ave time (mins) between initial setup imaging and beam on	Midtreatment* Ave time (mins) between CBCT and midimaging	Total treatment* Ave time (mins) between initial setup and end of treatment	Immobilization device and arc number	Ave CBCT number in each fraction
PT 1	7.97 ± 1.30	2.85 ± 0.68	11.36 ± 1.66	CIVCO 2	1.0
PT 2	7.56 ± 2.00	3.20 ± 1.31	16.94 ± 6.43	CIVCO 3	2.0
PT 3	8.99 ± 2.14	3.53 ± 1.78	20.20 ± 3.76	CIVCO 3	1.8
PT 4	10.69 ± 4.93	2.55 ± 1.02	17.97 ± 6.54	BHS 3	1.8
PT 5	9.49 ± 4.00	2.74 ± 0.97	14.6 ± 4.43	BHS 3	1.4
Total ave	8.94 ± 1.25	2.81 ± 0.59	16.21 ± 3.38		

Abbreviations: BHS = Brainlab, Heimstetten, Germany Stereotactic Body Frame; CBCT = cone beam computed tomography; CIVCO = CIVCO Body Pro-Lok ONE™ Stereotactic Body Frame; PT = patient.
* Pretreatment imaging was time from initial setup to beam on. Midtreatment verification was time from CBCT medical doctor approval to planar kV midimaging. Total treatment was time from initial setup imaging to end of treatment.

immobilization devices (in-house BHS board vs CIVCO prolock). Across all 5 patients, the average time for pretreatment imaging, midtreatment verification, and total treatment time was 8.94 ± 1.25 , 2.81 ± 0.59 , and 16.21 ± 3.38 minutes, respectively.

Discussion

This study demonstrates the potential benefits of a practical workflow that integrates planar kV midimaging as a surrogate for CBCT for spine SBRT intrafraction motion monitoring to maintain a tolerance of 1 mm and 1° . Our modified IGRT workflow efficiently captured out-of-tolerance shifts on kV midimaging that were validated with repeat CBCT such that additional imaging was used only when clinically indicated. In 3 of 6 instances (PT 2 day 5, PT 4 day 1 and day 4), repeat CBCT showed further out-of-tolerance shifts that warranted a couch shift and an additional confirmatory CBCT scan before further treatment delivery. For patient 3, planar kV midimaging showed out-of-tolerance shifts on days 1, 2, and 3 that were within tolerance on repeat CBCT such that treatment proceeded without applying further shifts. Patient 3 remained within tolerance on days 4 and 5 and thus may have been prone to movement initially in his course of treatment. Our modified IGRT workflow was able to reduce the number of CBCT images by 70%, reducing both the imaging time and imaging dose associated with spine SBRT delivery. By requiring medical doctor approval only on occasions where further verification was needed after an out-of-tolerance shift (Fig 4B), our modified workflow also reduced time related to obtaining further physician review. We had a 24% frequency of out-of-tolerance shifts captured with kV midimaging, and for the remaining 76% of fractions, planar kV midimaging was sufficient to verify that the patient remained within tolerance.

Though prior studies have proposed adopting patient-specific imaging frequency based on residual motion observed with more frequent imaging during the first fraction,⁶ in our study, observed out-of-tolerance shifts were unpredictable and could occur early, at the end, or throughout a patient's course of treatment. The magnitude of translations and rotations captured by midimaging varied per patient per day, illustrating the need for daily intrafractional IGRT.

Dose gradients of 10% per millimeter on 6 MV photon beam penumbra region are required in spine SBRT to deliver high doses to the tumor while respecting the spinal cord tolerance. A small setup error or motion during treatment can lead to significant target undercoverage or overdose to the spinal cord, resulting in either a local control failure or radiation-related myelopathy. Prior studies have reported that a 2-mm translational error in any direction can lead to >5% tumor coverage loss and >25% maximum dose increases to the organs at risk.⁷ The

observed shifts in this study had the potential to result in target undercoverage of up to 4.9% and a maximum increase in dose to the spinal cord of 391 cGy, highlighting the critical importance of intrafraction monitoring and the importance of a PRV margin on spinal cord. The increase in dose was also directly related to the steep dose gradient between the tumor and spinal cord, which is frequently the most critical and dose-limiting structure interface of spine SBRT treatment.

Our institutional spine SBRT protocol of using ExacTrac and kV-CBCT imaging to maintain a tolerance of 1 mm and 1° with an average total treatment of 16.21 ± 3.38 minutes commonly related to pretreatment imaging and verification (8.94 ± 1.25 minutes). Midimaging with ExacTrac reduced the overall time needed to confirm setup position (2.81 ± 0.59 minutes) and consistently captured when patients were out of tolerance.

Evolving methods of patient immobilization and IGRT technology directly affect the setup uncertainties typically accounted for with PTV or PRV margin expansions on target volumes and organs at risk. These expansions must be assessed in the context of what is technologically and clinically feasible to achieve. In this study, all patients were treated on a Varian TrueBeam platform incorporating a 6D robotic couch equipped with kV CBCT and kV 2D-3D and ExacTrac imaging capability. A prior analysis of an in-house SBF combined with ExacTrac imaging demonstrated the combination was highly effective in achieving setup accuracy and intrafraction stability, on par with that of mask-based cranial radiosurgery.⁵ At that time, a 3-mm PRV margin was typically applied to the spinal cord and SBRT was performed with a Novalis platform. Since then, we have adopted a CIVCO SBRT system for patient immobilization compatible for use with magnetic resonance simulation to acquire T1- and T2-weighted spinal cord and tumor imaging in treatment position and a Varian TrueBeam platform for SBRT treatment delivery. Our IGRT workflow has also evolved to rely on CBCT 3D matches as a pretreatment gold standard with ExacTrac or 2D-3D kV/kV as a verification for pretreatment imaging and midtreatment imaging verification.

As IGRT reduces setup uncertainty, each clinic has its own protocols (technique, sequence, and frequency), depending on the imaging device availability, delivery platform, tumor site, target delineation, and its own institutional experience in setup variation with custom patient immobilization.¹²⁻¹⁹ The potential imaging dose from IGRT is usually not considered in treatment plan evaluation due to the relatively minimal contribution of dose to the treatment target. However, during an imaging procedure, large portions of the body are potentially irradiated, including radiosensitive structures such as the lung, breast, thyroid, and reproductive organs with high risk of induction of secondary malignancy. Bone structures also receive higher doses than other tissue at kV energies due to increased photoelectric absorption.¹⁰ In spine SBRT,

intrafractional imaging with multiple kV CBCT scans introduces the additional radiation dose to the peripheral tissues, bone, and spinal cord, with implications particularly for pediatric patients or those at high risk of myelopathy in the setting of reirradiation. With the reported effective doses of between 8 and 46 mSv per CBCT, leading to an increased risk of a patient developing a secondary malignancy, the risks associated with the concomitant imaging should be balanced against the benefits.²⁰ Recent studies have examined how incorporating volume-of-interest imaging could help reduce the field size and improve image quality associated with intrafraction motion monitoring for SBRT.^{21,22} In our workflow, CBCT, as part of pretreatment verification and to verify when kV midimaging was out of tolerance, was necessary, with a primary aim to reduce the number of CBCT scans needed to the minimum number for safe treatment.

Correlating the CBCT imaging dose reference based on Rando phantom measurement and Monte Carlo simulation in the literature, the imaging dose to the spinal cord in our clinic was estimated as 3 to 4 cGy with the pelvis protocol CBCT scan.^{11,23,24} The kV ExacTrac or kV 2D-3D imaging is one-tenth of the dose from 3D kV-CBCT. One fraction of the spine SBRT treatment will typically have 1 kV-2D-3D pair to initially setup the patient, 1 kV-CBCT 3D scan for the treating physician to review and approve, another kV-2D-3D pair as the verification before first arc, and 1 kV-2D-3D midimaging pair between the sequential arcs, which would represent a total imaging dose of 3.4 to 4.4 cGy per fraction. Compared with an imaging workflow using only CBCT imaging, the total imaging dose to the spinal cord from 1 fraction of a 3 arc VMAT treatment is estimated as 12 to 16 cGy per fraction and 60~80 cGy over a 5-fraction course. Furthermore, kV ExacTrac or kV 2D-3D takes 2 orthogonal 2D kV images with the advantage of fast image acquisition. The x-ray sources mounted on the floor from kV ExacTrac enable the imaging acquisition from any couch angle, while the kV 2D-3D or kV-CBCT images have to be acquired at couch 0°. Midimaging with ExacTrac at gantry 0° or kV 2D-3D is a faster surrogate to confirm patient position than repeat CBCT, allowing for faster treatments and reduced exposure to radiation. In addition to prolonging treatment time, kV-CBCT for midtreatment verification may also introduce additional perturbations to patient position from couch movements required for image acquisition.

Rational PTV and PRV margins should incorporate an analysis of intrafraction motion captured with existing technologies for patient immobilization and midimaging workflow because these factors all affect setup uncertainty and create practical tradeoffs between imaging to confirm patient position and the additional risk of increased motion due to prolonging treatment time. The imaging workflow that we have adopted prioritizes kV-2D-3D over kV-CBCT if it is sufficient for achieving practical

setup accuracy and significantly reduces the number of CBCT scans required for spine SBRT delivery within our institutional tolerance. Through reducing the overall treatment time associated with repeated CBCT imaging, patients undergoing spine SBRT are less likely to have motion related to discomfort and thus the potential catastrophic risk of radiation myelopathy is reduced.

Conclusions

In this study, we assessed the robustness of a modified IGRT workflow incorporating planar kV midimaging as a surrogate for CBCT in spine SBRT. Our current patient positioning accuracy, effectively achieved with the use of multiple 2D-3D kV images and 1 verification CBCT per fraction was able to maintain our institutional tolerance of 1 mm and 1° with high fidelity and reduce the time and imaging dose associated with intrafraction motion monitoring. Given the catastrophic risks of radiation-related myelopathy, our workflow offers a practical mechanism to balance safety and efficiency using modern SBRT techniques.

Supplementary materials

Supplementary material associated with this article can be found in the online version at [doi:10.1016/j.adro.2022.100961](https://doi.org/10.1016/j.adro.2022.100961).

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