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Clinical Evaluation of positioning verification using digital tomosynthesis (DTS) based on bony anatomy and soft tissues for prostate image-guided radiation therapy (IGRT)

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Abstract

Purpose—To evaluate on-board digital tomosynthesis (DTS) for patient positioning in comparison with 2D-radiographs and 3D-CBCT.

Methods and Materials—A total of 92 image sessions from 9 prostate cancer patients were analyzed. An on-board image set was registered to a corresponding reference image set. Four pairs of image sets were used; DRR vs. on-board orthogonal paired radiograph for the 2D method, coronal-reference-DTS (RDTS) vs. on-board coronal-DTS for the coronal-DTS method, sagittal-RDTS vs. on-board sagittal-DTS for the sagittal-DTS method, and planning CT vs. CBCT for the CBCT method. Registration results were compared.

Results—The systematic errors in all methods were less than 1 mm/1°. When registering bony anatomy, the mean vector differences were 0.21±0.11 cm between 2D and CBCT, 0.11±0.08 cm between CBCT and coronal-DTS, and 0.14±0.07 cm between CBCT and sagittal-DTS. The correlation of CBCT to DTS was stronger (coefficients=0.92–0.95) than the correlation between 2D and CBCT or DTS (coefficients=0.81–0.83). When registering soft tissue, the mean vector differences were 0.18±0.11 cm between CBCT and coronal-DTS and 0.29±0.17 cm between CBCT and sagittal-DTS. The correlation coefficients of CBCT to sagittal-DTS and to coronal-DTS were 0.84 and 0.92, respectively.

Conclusions—DTS could provide equivalent results to CBCT when bony anatomy is used as landmarks for prostate IGRT. For soft tissue-based positioning verification, coronal-DTS produced equivalent results to CBCT and sagittal-DTS alone was insufficient. DTS could allow comparable soft tissue-based target localization with faster scanning time and less imaging dose compared to CBCT.

Keywords

Digital tomosynthesis; Image-guided radiotherapy; Prostate IGRT; Positioning verification; Cone-beam computed tomography

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INTRODUCTION

In prostate intensity-modulated radiation therapy (IMRT), the conformal dose is delivered to the target while sparing critical structures as optimized in planning. IMRT involves high dose gradients and tight margins, increasing the importance of daily verification of patient positioning. Orthogonal megavoltage (MV) image pairs have historically been used for positioning verification (1,2). The 2D imaging technique is quick to implement, but can leave unresolved setup errors, because information is lost when the 2D imaging technique projects multi-layered anatomy onto a single radiographic image plane. The recent development of MV and kilovoltage (kV) in-room imaging systems now provides the additional capability of 3D online image guidance for radiation treatment (3–7). By rotating the kV or MV source and detector around a patient, on-board cone-beam computed tomography (CBCT) images may be acquired. Registration of the CBCT to the planning CT provides accurate on-line 3D patient positioning verification (7). The current CBCT systems, however, involve higher imaging dose and longer imaging time caused by full gantry rotation. Limited-angle digital tomosynthesis (DTS) can be reconstructed from 2D cone-beam X-ray projection data utilizing the same on-board imaging (OBI) system (8). Stacks of coronal- or sagittal-DTS images can be obtained by centering an acquisition about the anterior-posterior (AP) or later projection, respectively. Individual DTS slices exhibit high spatial resolution in the viewing-plane (i.e. the reconstruction plane), but the effective DTS slice thickness (i.e. the resolution in the plane-to-plane dimension) is limited by the narrow scan angle (9,10). DTS images provide improved visibility in the viewing-plane of both soft tissues and bony anatomy compared to 2D radiographs by resolving overlaying anatomy into planes, yet the technique, reduces imaging dose to the patient and scanning time compared to 3D CBCT (8,11). The purpose of this study is to evaluate the performance of DTS in positioning accuracy, particularly, for prostate treatment. The results of positioning verification using DTS are compared to the results using 2D radiographs and 3D CBCT. Positioning verification based on matching of bony anatomy and matching of soft tissues are analyzed.

METHODS and MATERIALS

Patient data

This study includes 9 prostate cancer patients who received IMRT treatment and were enrolled in an IRB approved clinical IGRT protocol (12). Each patient underwent positioning verification using orthogonal 2D kV radiographs followed by CBCT acquisition at least once a week. A total of 92 on-board imaging data sets were acquired for 9 patients (range of 8–12 scans per patient, with a mean of 10 scans).

On-board image sets

Patients were initially positioned by aligning the room lasers and the cross hair from the linear accelerator with respect to the skin marks. Anterior and right-lateral kV radiographs with the OBI system (Varian Medical Systems, Palo Alto, CA) were acquired and used as an on-board image set for 2D positioning verification. Standard radiographic techniques for prostate cancer patients were used: 75 kVp, 80 mA and 50 ms for anterior images and 120 kVp, 80 mA, and 250 ms for lateral images. The pixel size of 2D radiographs was $0.19 \times 0.19 \text{ mm}^2$.

After the acquisition of the 2D images, the CBCT images were acquired and used as an on-board image set for 3D positioning verification. For the CBCT scans, a total of 600–700 projections were acquired (~ 1 image per 0.5°) with a technique of 125 kVp, 80 mA and 25 ms per projection. When the detector is centered about the rotational axis, the reconstructed axial field-of-view (FOV) is 24-cm in diameter. This acquisition mode is termed “full-fan” and is used for small anatomic sites or for a truncated region of a large anatomic site. For larger

anatomic sites, the detector is shifted by 14.8cm laterally to obtain a larger FOV. Only a part of the final reconstructed FOV is viewed in any single projection. The entire object is reconstructed by merging information from projections acquired 180° apart. This acquisition mode is termed “half-fan”. The axial FOV in the half-fan mode is 45-cm in diameter. The pixel size of the half-fan mode CBCT was $1.0 \times 1.0 \text{ mm}^2$ and a slice thickness was 2.5 mm. Figure 1 illustrates the full-fan and half-fan modes. All 9 patients included in this study were scanned using the half-fan mode with a bowtie filter and 2.5 mm slice thickness for CBCT reconstruction.

On-board DTS images are reconstructed using projection images acquired over a limited scan angle. Figure 2 shows differences in the acquisition of 2D radiography, CBCT and DTS. The stacks of coronal-DTS planes are reconstructed using the anterior-like projections acquired from limited scan rotation about the 0° (or 180°) source axis as illustrated in figure 3–(a). The stacks of sagittal-DTS planes are reconstructed using the lateral-like projections acquired from the limited scan rotation about the 90° (or 270°) source axis as illustrated in figure 3–(b). Although a clinical application of DTS should be acquired in the full-fan mode, for this study, we extracted a subset of currently available half-fan projections acquired for CBCT to reconstruct on-board DTS images (rather than acquiring additional separate full-fan DTS scans). The DTS planes were reconstructed using the Feldkamp filtered back-projection algorithm with 1-mm plane spacing (13). DTS images were reconstructed such that the viewing-planes (or slices) were oriented normal to the central projection axis. Accordingly, the coronal planes were the viewing-planes for the coronal-DTS and the sagittal planes were the viewing-planes for the sagittal-DTS. For this study, we chose a 45° scan angle that contained about 80 projection images.

In the half-fan CBCT mode, the left-to-right lateral projection, Figure 4-(a-1), acquires a lateral image of the posterior part of the patient, Figure 4-(a-2). Similarly, the anterior-to-posterior projection, Figure 4-(b-1), acquires an anterior image of the left part of the patient., Figure 4-(b-2) Figure 4 shows the diagrams of the half-fan x-ray projections and corresponding projection images and DTS images. We stitched two sets of DTS images reconstructed from the opposite centering angles to obtain complete information; one set centered at 0° and the other set centered at 180° for coronal-DTS, and one set at 90° and the other set at 270° for sagittal-DTS. After the stitching process, the DTS images were cropped in order to simulate the full-fan mode DTS. Figure 5 displays the stitched DTS images and the cropped DTS images in the dotted box. The pixel size of final DTS was $0.5 \times 0.5 \text{ mm}^2$ and plane spacing was 1.0 mm.

Reference image sets

Patients were scanned with a GE light-speed RT CT simulator (GE Medical System, Milwaukee, WI). The CT scans were imported into the ECLIPSE™ treatment planning system (Varian Medical Systems, Inc.). The prostate and seminal vesicles were delineated, and a 1-cm margin was added to generate the planning target volume (PTV), except in the posterior direction, where the margin was 0.7 cm. The margin was determined based on the experience from daily localization (2). A dose of 46–54 Gy (2 Gy per fraction) was prescribed to the PTV. An additional 22–30 Gy (2 Gy per fraction) was prescribed to a smaller PTV that includes the prostate only as a boost. IMRT plans were generated based on the planning CT, which was also used as a reference image set for the 3D CBCT method. The DRRs for orthogonal setup fields were reconstructed in the Eclipse, and were used as a reference image set for the 2D method. Reference-DTS (RDTS) images were synthesized from simulated cone-beam projections through the planning CT (8) in the same fashion as the on-board DTS images. RDTS images contain information that, ideally, exactly matches that from on-board DTS, relative to using other types of reference image data. Coronal- and sagittal-RDTS images were

generated corresponding to their respective on-board DTS scan angles. The two sets of simulated half-fan RDTs were stitched and cropped in the same manner as the on-board DTS data were processed. The planning CT scans were reconstructed with a pixel size of $1.0 \times 1.0 \text{ mm}^2$ with 2.5 mm or 3 mm slice thickness. Thus, all the reference images (e.g. DRR and RDTs) had an inherent voxel resolution limit imposed by the planning CT. As in the on-board DTS, the plane spacing was set 1.0 mm for RDTs.

Positioning verification methods

The 2D method refers to the positioning verification method using 2D orthogonal image sets (DRR vs on-board kV radiographs). Since each projection image provided only 2D information, pairs of orthogonal images were reviewed as one set. Registration was performed retrospectively in the platform of the commercial registration software Offline Review (V1.0 Varian Medical Systems, Inc). In this paper, “yaw”, “pitch” and “roll” are the rotations about the anterior-posterior axis, the left-right axis, and the superior-inferior axis, respectively. Registration results for lateral, vertical, longitudinal, yaw and pitch were determined, but roll was not included for the 2D registration method. For the 2D method, all registration was performed using bony anatomy only, as soft-tissue visibility was nearly non-existent in the 2D radiographs.

The 3D CBCT method refers to the positioning verification method using the planning CT as a reference image set and the CBCT as an on-board image set. Image registration was performed to match the bony anatomy first, and then the image registration was performed again to match soft tissues. Bony registration resulted in six parameters: three shifts and three rotations. We did not include rotation in our soft-tissue registration, as it was ambiguous to determine the rotation of the prostate.

The DTS method refers to the positioning verification method using the RDTs as a reference image set and the DTS as an on-board image set. Since DTS images provided pseudo 3D information, the coronal-DTS and the sagittal-DTS were evaluated as independent image sets. The image registration was initially performed to match bony anatomies, following which the image registration was performed again to match soft tissues. When the soft tissue was not discernible due to the image quality, the bony anatomy was used as a surrogate. Again, registration based on soft tissues did not include rotations.

For registration based on bony anatomy, the pubic symphysis was the main landmark and the left/right acetabulum bones were the secondary landmarks to determine rotations. For registration based on soft tissues, the main landmarks were the junctions between the rectum/bladder and prostate. We focused on the soft tissues near the isocenter region where the central prostate remained. The perineal muscles were also useful landmarks to determine the soft tissues. We did not take the seminal vesicles into account.

A research version of the commercial registration software, Offline Review V1.1 (Varian Medical Systems, Inc.), was used as a platform to perform image registration for 3D CBCT and DTS methods. DTS yields 3D images with excellent resolution in the viewing-plane (e.g. reconstruction plane), though low plane-to-plane (e.g. the direction perpendicular to the viewing-plane) resolution (14–16). Although registration was performed in all three views (e.g., coronal, sagittal and axial views) in the Offline Review V1.1 platform, the on-board DTS set could be effectively compared to the reference DTS set in the view of the viewing-plane only. In the coronal-DTS method, when shifts and rotations of an on-board DTS image set were performed in the sagittal and axial views, in order to ensure registration on the same planes from DTS and RDTs, its image content was continuously verified in the coronal view to best match that from the corresponding reference DTS. Figure 6 shows five neighboring

planes of coronal-DTS with arrows indicating some landmarks that were used to distinguish one plane from other adjacent planes during registration.

The registration results of all image sessions for every patient from all methods were analyzed. The mean shifts/rotations and standard deviations (SDs) were computed per patient. The mean systematic error (M) and the standard deviation (Σ) of the mean systematic errors were computed from the mean error of the individual patients (17,18). The random error (σ) was calculated using the root-mean square (RMS) error with respect to the individual patient means (18). Each verification method returned a shift vector (x_a, y_a, z_a) in lateral, longitudinal and vertical directions where the subscript 'a' refers to a method. The magnitude of the vector difference between shift vectors from two independent verification methods was computed as

$\sqrt{(x_a - x_b)^2 + (y_a - y_b)^2 + (z_a - z_b)^2}$ where subscripts a and b refer to the two methods. The performance of the DTS methods vs. the CBCT method was evaluated by their mean differences and the Pearson correlation coefficients.

RESULTS

A total of 92 treatment sessions were evaluated in this study. Each image session included four paired image sets: 2D kV-DRR, 3D CBCT-CT, coronal DTS-RDTS, and sagittal DTS-RDTS, respectively. In this pilot study, a single user performed image registration for all methods and an attending physician verified the resulting registration. (Response to #11) Figure 7 shows reference and on-board images side-by-side for the three imaging modalities (four image sets).

Table 1 summarizes the positioning errors found in verification methods between the reference and an on-board image sets. A positioning error was determined as the differences between the initial position aligned with the skin markers and the resulting position of image registration. M was expected to be close to zero and was indeed close to zero (< 1 mm and $< 1^\circ$) for all methods. All methods showed about 2mm and less than 1° for Σ , when registration was performed to match bony anatomy, whereas Σ in the vertical direction was 5–6mm when matching soft tissue in CBCT and DTS methods. This result suggests that average displacement of soft tissues with respect to the skin markers could vary greater than the bony anatomy displacement for prostate radiation treatment and that the DTS methods provide comparable soft-tissue registration results to the CBCT method. All methods, whether matching of bony anatomy or soft tissue, contain about 3mm in σ in translational shifts. The random errors represent the setup uncertainty from one treatment session to the next.

Table 2 summarizes the differences in setup errors between the methods. Table 2 (a) shows results from the registration performed to match bony anatomy. The mean differences between 2D and CBCT/DTS methods ranged from 0.1–1mm in all shift directions and 0.2° – 1.2° in all rotations. The mean differences between DTS and CBCT methods were < 1 mm/ 0.5° in all directions/rotations. The mean vector differences were about 2 mm between 2D and CBCT/DTS methods whereas they were about 1 mm between CBCT and DTS methods. Table 2(b) shows results from the registration performed to match soft tissues. The soft tissues were discernable for the purpose of registration in all coronal DTS images whereas bony anatomy was used as a surrogate for 13% of the sagittal DTS images due to insufficient soft tissue information. The differences were slightly larger than the differences from the results of matching bony anatomy. In general, the sagittal-DTS method showed larger variation from the CBCT method than did the coronal-DTS method when matching soft tissues.

To understand whether the performance of DTS method is comparable to the CBCT method, the Pearson correlation coefficients were measured between the shift results from two methods. Table 3 summarizes the correlation coefficients among all methods. The correlation coefficients were calculated without rotation parameters. When registration was performed to

match bony anatomy, the correlations between the DTS and CBCT were high: coronal-DTS vs. CBCT (coefficient=0.95) and sagittal-DTS vs. CBCT (coefficient=0.93). The correlations between the 2D and CBCT methods were slightly lower: 2D vs CBCT (coefficient=0.81), 2D vs. coronal-DTS(coefficient=0.83) and 2D vs. sagittal-DTS (coefficient=0.81). When image registration was performed to match soft tissues, the correlation between coronal-DTS and CBCT methods was high (coefficient=0.92). The correlation between sagittal-DTS and CBCT methods was 0.84.

Table 4 shows the correlation coefficients between the DTS and CBCT methods in individual translational directions. The results in the vertical direction had the lowest correlation among all directions in correlation between the coronal-DTS and CBCT as the vertical direction is the plane-to-plane direction for the coronal-DTS. Similarly, the results in the lateral direction had the lowest correlation between the sagittal-DTS and CBCT as the lateral direction is the plane-to-plane direction for the sagittal-DTS. It implies that DTS provides relatively low resolution for the plane-to-plane dimension, thus, less accurate positioning verification in the plane-to-plane direction than in the other two directions contained the viewing-plane is expected.

DISCUSSION

The values of the mean systematic errors provide information on whether there were external and/or inherent systematic errors (18). If there were an external source of error such as laser misalignment or user performance bias, all methods would contain noticeable mean systematic errors to a certain direction. If one verification method contained an inherent systematic error such as errors in image matrix size or reconstruction algorithm, the systematic error in a certain direction should have been noticeable for the specific method relative to the other registration methods. The resulting mean systemic errors present that the DTS methods do not contain any more inherent errors than 2D and CBCT methods. The standard deviations of the systematic errors provide information on positioning variation among patients (17,18). The comparable standard deviations of the systematic errors for all methods imply that the DTS methods perform positioning verification in a manner consistent and reliable with 2D and CBCT methods. It also implies that the relatively large slice thickness (e.g. longitudinal direction) of planning CT and CBCT images, compared to the small pixel size in other directions (e.g. lateral and vertical directions), has only a minimal impact on the performance. This is likely because the interpolated images in-between the actual reconstructed slices (or planes) are displayed in the Offline Review and these are adequate for positioning verification.

The image quality of the sagittal-DTS was not sufficient for soft tissue-based image registration compared to the coronal-DTS images for prostate cases. Poor image quality occurs in the sagittal-DTS images because lateral projections contain substantial x-ray scatter and insufficient signals due to the patient thickness compared to anterior-posterior projections. This could be improved with different scanning techniques such as higher mAs or larger scanning angle. However, increasing mAs or scanning angle will also increase imaging dose (14). Another cause of poor image quality in the sagittal-DTS is that the sagittal view of a pelvic region itself does not always contain considerable anatomical variation in soft tissues. This fact is also apparent in CBCT and CT as shown in Figure 5 (f-1) and (f-2). Without bladder contrast and rectal gas, the junctions between prostate and rectum/bladder are unclear in the sagittal view of CBCT and CT. Nevertheless, the CBCT method provides good soft tissue information for positioning verification because the axial view minimizes this limitation of the sagittal view. This implies that the sagittal-view alone cannot be adequate for soft-tissue based positioning verification using either 3D CBCT or DTS images.

DTS images with various scan angles have been investigated prior to this study (11,14,16). The effective DTS slice thickness (i.e. the resolution in the plane-to-plane dimension) is limited

by the narrow scan angle (9,10). Therefore, increasing the scan angle improves visibility and the registration accuracy in the plane-to-plane dimension. The difference in images appearance comes from the blurring effect, where shadows from objects in distant appear in the plane of interest. This effect appears more significant with smaller scan-angle DTS. The adjacent planes might provide somewhat similar information in smaller scan-angle DTS and the positioning accuracy in the plane-to-plane direction could get affected. On the other hand, larger scan-angle DTS displays a clearer rendition of cross-sectional information compared to narrower scan-angle DTS. This implies that the adjacent planes rather provide distinct image information and more accurate positioning along the plane-to-plane direction (11). However, since the major advantages of DTS are tied to its limited scan angle, it is important to select a narrow scan angle to minimize scanning time and imaging dose without sacrificing image quality significantly. We selected a 45° scan angle for this study as a narrow angle with adequate image quality based on previous studies (8,11,16).

Although this study did not involve measurement or calculation of imaging doses from DTS scanning, actual DTS imaging doses can be estimated based on other studies of imaging doses. Table 5 summarizes imaging doses from MV and KV imaging systems. 2D radiographs using MV imaging systems deliver 1–8 cGy (19–21) depending on MU delivered whereas images using KV imaging systems deliver 0.02–0.04 cGy (20,21). For 3D CT images, the imaging doses are higher than the 2D radiographs: the imaging doses range between 1 and 9 cGy depending on the number of projections and techniques (15,19–25). Since KV imaging doses are proportional to the x-ray technique (mAs) and the number of projections, dose from kV DTS scan is estimated to be 1/8 of the CBCT dose. That is about 0.5 cGy to the center or 0.5–1cGy to the periphery of a prostate patient for a 45° scan-angle (e.g. 80 projections) with a total of ~180mAs using the current CBCT system (23).

Although the DTS data for this study were generated from our existing half-fan CBCT scans, we wish to emphasize that the full-fan mode should be used for DTS imaging. Furthermore, as our clinical interest remains in the central area, the half-fan mode DTS scanning is arguably unnecessary for the purpose of positioning verification. Since the purpose of the study is to evaluate the performance of DTS images for positioning verification, we cropped the stitched DTS images reconstructed from the half-fan mode projections and were able to simulate full-fan mode DTS images. DTS scanning, if the on-board x-ray imaging system mounted on the linear accelerator is permitted to scan the limited angle for DTS, should be performed in the full-fan mode.

As a part of our investigation of DTS for positioning verification, this study was designed to evaluate the DTS method for prostate cancer patients undergoing IMRT treatment. Certainly 2D radiographs are adequate for positioning verification registering bony anatomy as our results also presented (2). However, the fact, that our resulting standard deviations (Σ) of the mean systematic errors were larger with soft tissue matching than those with bony anatomy matching, reemphasizes the necessity of soft tissue-based positioning verification for prostate radiation treatment (2). The technique using implanted fiducial markers with 2D radiographs demonstrates accurate pseudo soft-tissue based positioning verification with low imaging dose and fast imaging time (26,27). However, fiducial markers involve an invasive procedure, which some patients are reluctant to choose. 3D in-room CT provides information for both bony anatomy and soft tissues. Unfortunately, the CT imaging dose is relatively high and imaging time is relatively long. DTS, as a modality in-between 2D and 3D, provides information of bony anatomy and soft tissues sufficiently for positioning verification with imaging dose and scanning time falling somewhere in-between the 2D and 3D imaging modalities. We believe that the choice of a positioning verification method depends on balancing the various pros and cons of the different techniques.

CONCLUSION

This study investigated feasibility of DTS for positioning verification. The positioning verification method using DTS images was compared to the methods using 2D radiographs and 3D CBCT for prostate IMRT treatment. The results of positioning verification using DTS, CBCT and 2D radiographs were all similar when bony anatomy was used as landmarks. However, DTS images exhibit improved visibility of pseudo-3D bony anatomy and soft tissues compared to 2D radiographs. Coronal-DTS produced equivalent results to CBCT although sagittal-DTS alone was insufficient for soft tissue-based positioning verification. DTS could allow comparable soft tissue-based target localization on the daily basis with faster scanning time and less imaging dose compared to CBCT.

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Figure 1.
Schematic view of Full-fan (a) and half-fan mode CBCTs.

Figure 2. Diagrams of (a) 2D anterior-radiography acquisition, (b) 3D CBCT full 360s scanning, and (c) limited angle coronal-DTS scanning.

Figure 3.

Diagram of DTS imaging. (A) is one of axial slices of CBCT. The x-ray source (in black) scans the patient through the limited angle with the anterior-like projections, which are used to reconstruct the stacks of coronal-DTS planes (a-e). (B) is the same image as (A). The x-ray source (in hashed-line pattern) scans the patient through the limited angle with the lateral-like projections, which are used to reconstruct stacks of sagittal-DTS planes (1-5).

Figure 4.

Diagrams of left-to-right projection (a-1), anterior-to-posterior projection (b-1), right-to-left project (c-1) and the posterior-to-anterior projection (d-1) in the half-fan mode. (a-2) to (d-2) are the corresponding projection images in the detector's-eye-view. (a-3) to (d-3) are the corresponding DTS images reconstructed using the projections acquired from (a-1) to (d-1) at the isocenter plane.

Figure 5. Stacked DTS: (a) Coronal-DTS and (b) Sagittal-DTS. The dotted boxes indicate FOV for DTS reconstructed using full-fan mode projections without stitching process.

Figure 6.

Five neighboring planes of coronal-DTS with 2mm apart. The arrows indicate landmarks used to distinguish one plane from other adjacent planes during registration.

Figure 7. Reference images and on-board images. (a-1) AP DRR, (a-2) AP kV radiograph, (b-1) Lat DRR, (b-2) Lat kV radiograph, (c-1) Coronal-RDTS, (c-2) Coronal-DTS, (d-1) Sagittal-RDTS, (d-2) Sagittal-DTS, (e-1) Coronal-CT, (e-2) Coronal CBCT, (f-1) Sagittal CT, and (f-2) Sagittal CBCT. All images were extracted at the isocenter plane.

Table 1
The mean systematic errors (M), standard deviation of systematic errors (Σ) and random errors (σ) based on measurements in a population of 9 patients with total of 92 image sets. Unit in mm for Lat, Lng, and Ver direction and in deg for Pitch, Roll and Yaw. NA means not applicable.

(a) Based on matching of bony anatomy														
	2D OBI method			3D CBCT method			Coronal-DTS method			Sagittal-DTS method				
	M	Σ	σ	M	Σ	σ	M	Σ	σ	M	Σ	σ		
Lat	-0.7	1.6	3.4	-0.1	2.0	3.2	-0.2	2.0	3.3	-0.3	1.9	3.2		
Lng	-0.6	1.6	2.9	-0.5	2.0	3.3	-0.5	1.8	3.3	-0.7	1.9	3.3		
Ver	-0.5	1.7	2.5	-0.8	2.1	2.9	-0.7	2.1	3.0	-0.4	2.3	3.0		
Pitch	0.12	0.16	0.35	0.04	0.06	0.16	0.01	0.03	0.09	0.02	0.12	0.22		
Roll	NA	NA	NA	-0.94	0.79	1.18	-0.79	0.73	1.08	-0.68	0.63	1.09		
Yaw	0.07	0.54	0.60	0.18	0.48	0.49	0.15	0.70	0.57	0.17	0.48	0.47		

(b) Based on matching of soft-tissue														
	3D CBCT method			Coronal-DTS method			Sagittal-DTS method							
	M	Σ	σ	M	Σ	σ	M	Σ	σ					
Lat	0.2	1.9	3.3	0.1	1.9	3.5	-0.6	1.6	3.4					
Lng	-0.5	2.4	3.4	-0.8	2.2	3.4	-0.7	2.0	3.3					
Ver	-0.2	5.3	3.7	-0.6	4.9	3.5	-0.7	6.2	3.6					

Table 2
Mean difference in matching results between two verification methods (unit in mm or degree) and the *p*-values. NA means not applicable.

(a) Based on matching of bony anatomy				
	2D:CBCT	2D:Cor-DTS	2D:Sag-DTS	
Lat	1.1 ± 1.1	0.3 ± 0.6	0.7 ± 0.8	
	1.1 ± 1.0			
	0.6 ± 1.1			
Lng	0.1 ± 1.3	0.1 ± 1.1	0.3 ± 1.2	0.3 ± 0.6
Ver	0.9 ± 0.9	0.9 ± 1.0	1.2 ± 0.9	0.5 ± 0.7
Pitch	0.23 ± 0.34	0.20 ± 0.33	0.27 ± 0.36	0.06 ± 0.18
Roll	NA	NA	NA	0.41 ± 0.48
Yaw	0.53 ± 0.40	0.53 ± 0.47	0.54 ± 0.47	0.25 ± 0.36
Vector	2.1 ± 1.1	2.0 ± 1.1	2.0 ± 1.2	1.4 ± 0.7

(b) Based on matching of soft tissue				
	CBCT:Cor-DTS		CBCT:Sag-DTS	
Lat	0.8 ± 0.7		1.5 ± 1.4	
Lng	0.6 ± 0.6		0.9 ± 0.9	
Ver	1.1 ± 1.2		1.7 ± 1.7	
Vector	1.8 ± 1.1		2.9 ± 1.7	

Table 3
Pearson correlation coefficients among positioning verification methods

Variable	(a) Based on matching of bony anatomy				(b) Based on matching of soft tissue			
	2D	CBCT	Cor-DTS	Sag-DTS	CBCT	Cor-DTS	Sag-DTS	
2D	1.00							
CBCT	0.81	1.00			1.00			
Cor-DTS	0.83	0.95	1.00		0.92	1.00		
Sag-DTS	0.81	0.93	0.92	1.00	0.84	0.83	1.00	

Table 4
Pearson product-moment correlation between CBCT methods and DTS method for individual directions when registration was performed to match bony anatomy

Variable	Cor-DTS			Sag-DTS		
	Lat	Lng	Vrt	Lat	Lng	Vrt
CBCT	Lat	0.96		0.90		
	Lng		0.96		0.96	
	Vrt		0.92			0.92

Table 5

Doses to prostate (or pelvis) patients or a 30-cm diameter phantom from MV and kV imaging systems

Imaging system	Imaging doses
XVI™ (Elekta, Crawley, UK) (9,21,24)	MV orthogonal image set: 1.2cGy to the rectum or maximum 7 cGy KV orthogonal image set (120kV): 0.2–0.4 mGy to the rectum or maximum 0.25mGy KV CBCT (120kV): 2.3–4 cGy to the surface and 1.6–2.2 cGy to the center (~ 660 – 1000 mAs);
OBI™ (Varian Medical Systems) (23–25)	KV CBCT (125 kV): 3–8 cGy to the peripheral dose of patients with 30-cm separation and 3–4 cGy to the center of a phantom for 370° scan (total ~1300 mAs with a bowtie filter)
Hi-ART II™ (TomoTherapy, Inc. Madison, WI) (22)	Helical MVCT (3.5 MeV): ~1cGy to the center with pitch of 2
MVision™ (Siemens Medical Solutions, Inc. Concord, CA) (16,20)	MV orthogonal image set: mean of 4.6cGy MV CBCT: 7cGy per scan with 9MU MV DTS (6MV): 4.2 cGy with 6 MU for 10° scan