Evaluation of respiration-correlated digital tomosynthesis in lung^{a)}

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Digital tomosynthesis (DTS) with a linear accelerator-mounted imaging system provides a means of reconstructing tomographic images from radiographic projections over a limited gantry arc, thus requiring only a few seconds to acquire. Its application in the thorax, however, often results in blurred images from respiration-induced motion. This work evaluates the feasibility of respiration-correlated (RC) DTS for soft-tissue visualization and patient positioning. Image data acquired with a gantry-mounted kilovoltage imaging system while recording respiration were retrospectively analyzed from patients receiving radiotherapy for non-small-cell lung carcinoma. Projection images spanning an approximately 30° gantry arc were sorted into four respiration phase bins prior to DTS reconstruction, which uses a backprojection, followed by a procedure to suppress structures above and below the reconstruction plane of interest. The DTS images were reconstructed in planes at different depths through the patient and normal to a user-selected angle close to the center of the arc. The localization accuracy of RC-DTS was assessed via a comparison with CBCT. Evaluation of RC-DTS in eight tumors shows visible reduction in image blur caused by the respiratory motion. It also allows the visualization of tumor motion extent. The best image quality is achieved at the end-exhalation phase of the respiratory motion. Comparison of RC-DTS with respiration-correlated cone-beam CT in determining tumor position, motion extent and displacement between treatment sessions shows agreement in most cases within 2–3 mm, comparable in magnitude to the intraobserver repeatability of the measurement. These results suggest the method's applicability for soft-tissue image guidance in lung, but must be confirmed with further studies in larger numbers of patients. © 2010 American Association of Physicists in Medicine. [DOI: [10.1118/1.3312276](https://doi.org/10.1118/1.3312276)]

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I. INTRODUCTION

Gantry mounted kilovoltage (kV) imaging systems are increasingly becoming a common feature of linear accelerators. Such imaging systems have radiographic, fluoroscopic, and cone-beam CT (CBCT) capabilities for image-guided radiation therapy. CBCT provides soft-tissue visualization at treatment.¹ It is usually acquired with a 360° gantry rotation, requiring 1 min, or with a ~200° rotation requiring ~40 s and resulting in a smaller reconstructed volume. In either case, respiratory motion in lung or abdomen causes blur^{2–4} that deteriorates the localization accuracy. To address this problem, respiration-correlated (RC) CBCT can be used.^{2,4–11} Two approaches have been proposed: *Retrospective*,^{3–7,9} in which projection images are acquired with continuous gantry motion, followed by sorting of the projections into phase bins for reconstruction; and *prospective*,^{3,10,11} in which the gantry moves intermittently

and projections are acquired only during the desired phase interval. The latter approach is sometimes referred to as gated CBCT.

Both RC-CBCT methods require longer acquisition times, usually 4 min or more.^{3–11} In the retrospective scheme, a slower gantry rotation, hence longer time is needed to avoid large angular intervals with missing projections in each phase bin, resulting in artifacts and poorer quality reconstructed images.⁴ In the prospective scheme, the longer acquisition time is a consequence of the limited gantry rotation speed and the gating duty cycle of ~20%–25%.

Tomographic images can be reconstructed from a partial arc, e.g., only 25°–35° rotation of the kV imaging system, as illustrated in Fig. 1, thus requiring a shorter acquisition time than CBCT. This approach is referred to as digital tomosynthesis (DTS).^{12–15} As Fig. 1 indicates, DTS reconstruction planes are approximately perpendicular to the direction of

FIG. 1. Schematic illustrating DTS acquisition. Dashed arcs indicate x-ray source and detector trajectories. Dashed horizontal lines indicate reconstruction planes at varying depths in the patient.

the x-ray beam at the arc center. They do not have to go through the isocenter, but can be at different depths in the patient. DTS has been proposed or used in mammography,^{16–19} imaging of skeletal joints,^{20,21} and angiography.^{22–24} Angiographic DTS imaging has been proposed for tumor localization.²⁵

Soft tissue and skeletal visualization with DTS has been shown using megavoltage (MV) therapeutic x rays^{26,27} and gantry mounted kV imaging systems.²⁸ DTS has been used in positioning of head and neck patients.^{28–30} We note that these studies^{26–30} used a filtered backprojection (BP) algorithm³¹ for image reconstruction, which is different from the reconstruction method used in the current work (described later).

Similar to CBCT, respiration correlation is possible with DTS. In this approach, projections within the desired respiratory phase interval are used for reconstruction. Maurer *et al.*³² examined RC-DTS in a motion phantom, using radiopaque markers detected in the projection images to correlate with phase.

In this article, we examine the feasibility of retrospective RC-DTS using an external surrogate to correlate the image projections with respiratory motion. In addition, we use a DTS reconstruction method consisting of backprojection, followed by an operation suppressing objects outside the reconstruction plane of interest. We investigate the ability of RC-DTS to reduce motion blur and visualize motion of tumors and other anatomic structures in lung. We also examine RC-DTS as a tool for soft-tissue localization by comparison to RC-CBCT.

II. MATERIALS AND METHODS

II.A. Data acquisition

Data from seven patients (eight tumors) treated for non-small-cell lung carcinoma were analyzed in this study. The patients received CBCT-guided position correction prior to treatment, using a gantry-mounted kV on-board imaging system (Varian Medical Systems, Palo Alto, CA). During the 1

min CBCT scans, the projection image and respiratory trace data were passively recorded for retrospective analysis with IRB approval. We did not acquire additional projection images for DTS reconstruction, but instead selected a subset of projection images from the CBCT scans. The data acquisition did not affect patient's image-guided positioning and treatment procedures. Data were deidentified for retrospective analysis. Details of the kV imaging system have been presented elsewhere³³ and are briefly described here. CBCT projection images were acquired with the following parameters: 100 cm source-to-isocenter distance, 150 cm source-to-detector distance, pulsed x rays of 120 kVp, 80 mA, and 25 ms per pulse, aluminum bow-tie filtration, 10 image/s acquisition rate, and a total of 660 images over the 360° rotation. The CBCT scans were acquired in a so-called half-fan configuration, with the detector laterally offset approximately 15 cm in order to achieve a larger (45 cm) CBCT reconstruction diameter. Imaging dose from a CBCT scan, measured in a 32 cm diameter Lucite phantom, was 2.4 cGy at the isocenter. The projection images consisted of 768 rows by 1024 columns with pixel pitch of 0.39 cm at the image receptor plane.

For the initial evaluation of RC-DTS, we used a phantom simulating respiratory motion. A head phantom was placed on a platform moving in superior-inferior (SI) direction with 2.5 cm amplitude and 4 s period, representing the upper range of diaphragm motion that is clinically observed.

II.B. Retrospective sorting of projections

A position-sensitive monitor (Real-time Position Management RPM, Varian Medical Systems, Palo Alto, CA) recorded patient respiration and phantom motion during the CBCT scan. The infrared video-based system tracked the motion of a reflective block placed on the patient's abdomen.^{34,35} Special circuitry enabled simultaneous recording of the respiration trace with the x ray on/off from the kV imaging system for tagging the projection images with respiration phase.⁴

The projection images were sorted into phase bins prior to reconstruction.³⁶ We used an algorithm in which the times of two neighboring peaks in the respiration trace, corresponding to end inspiration at the start and end of a cycle, were assigned percent phases of 0% and 100%. The percent phase assigned to a projection image is the percent ratio of the time difference between projection image and the previous (0%) peak to the 0%-to-100% time difference in that cycle, i.e., percent phase = $100\% \cdot (t_{\text{proj}} - t_{0\%}) / (t_{100\%} - t_{0\%})$, where t_{proj} , $t_{0\%}$, and $t_{100\%}$ are the projection image, 0% peak and 100% peak times, respectively.

The data were sorted into four respiratory phase intervals with an approximately equal number of projections in each. The phase intervals corresponded to end exhalation, midinhalation, end inhalation, and midexhalation. Phantom data were divided into six approximately equal phase bins.

II.C. DTS reconstruction

DTS reconstruction was performed using research software (ISODTS version 1.2.4, Varian Medical Systems) and is briefly described here. The first step of DTS reconstruction uses a BP algorithm, in which the value of every pixel from the projection image is added to the reconstruction volume along the line connecting source and pixel positions. The reconstruction volume consists of a set of planes approximately perpendicular to the direction of the x-ray axis (Fig. 1). Hereafter, these reconstructed slices are referred to as raw slices.

A challenge in DTS is the presence of artifacts caused by dense objects above or below the reconstructed plane. For this reason, BP is followed by a procedure to suppress out-of-plane objects.^{14,37–39} This procedure is also referred to as deblurring.⁴⁰ The artifacts in the reconstructed plane of interest are estimated from information in neighboring planes and then subtracted. The neighboring planes are projected back to the reconstructed plane of interest with the appropriate amount of blurring prior to subtraction.

The optimal reconstruction parameters involved a trade-off between out-of-plane artifacts suppression and image sharpness, and were determined through the visual inspection of images in a static thorax using an anthropomorphic phantom. We used an acquisition arc of 25°–35°. The extent of volume used for suppression of out-of-plane artifacts was 7–8 cm in the direction perpendicular to the reconstruction plane. The reconstructed planes were spaced approximately 3 mm apart. DTS image pixel spacing was 0.5 mm in both longitudinal and transverse directions.

The same research software was used for DTS reconstruction with and without respiration correlation. RC-DTS projections were selected within a desired respiration phase interval prior to reconstruction, which is similar to an approach used previously for CBCT.⁴ For a given DTS image orientation, projection images from two to three respiratory cycles were selected (approximately 15 projection images), resulting in disjoint clusters of images spanning a 20°–35° asym-

metric arc (Fig. 2), which, in general, differed from the arc length established for static (non-RC) DTS.

II.D. CBCT reconstruction

For purposes of evaluation, DTS images were compared to CBCT images reconstructed using the Feldkamp algorithm³¹ (Varian Image Viewing and Acquisition—Viva version 2.0, rev. K.04, Varian Medical Systems). The reconstructed voxel size was 1.5 mm in all directions. RC-CBCT reconstruction was done similar to the approach used previously.⁴

II.E. Tumor position determination

We determined positions of tumors at different respiratory phase intervals using RC-DTS images. The end-exhalation phase was used as a reference. Hereafter, we refer to the RC-DTS image from a chosen phase as the study image and the RC-DTS from the reference phase as the reference image. In addition, we registered end-exhalation RC-DTS images from different scans of the same patient. In this case, the end-exhalation RC-DTS from the first scan is the reference DTS and the end-exhalation RC-DTS from the second scan is the study DTS.

The registration of two RC-DTS images proceeded as follows: (1) A reconstructed plane through the tumor was chosen as the reference image. (2) A rectangular region of interest (ROI) was defined on the reference image. (3) One image most similar in appearance to the ROI of the reference image was manually chosen from the study DTS. This step established the registration along the direction perpendicular to the reconstructed image. (4) 2D manual registration was performed between the image features within the reference ROI and the chosen image in the study DTS.

The described procedure can be used to yield the 3D position of the study DTS with respect to the reference DTS. However, the determination of the coordinate perpendicular to the imaging plane is less accurate, which is an inherent characteristic of DTS from a limited arc. Therefore, from each registration we used only the two coordinates coplanar to the reconstruction image.

In order to determine the 3D coordinates of the displacement of the object of interest, for each respiratory phase two DTS images were reconstructed at 90° or 45° angles with respect to each other. As demonstrated in Sec. III, images at a 90° angle were not always possible to use, for two reasons. First, owing to the half-fan configuration in which the detector was laterally offset, some tumors were either outside or near the edge of the projection image over a range of angles. Second, some tumors near the mediastinum were difficult to discern in lateral view DTS. In several cases, an anterior or posterior image in combination with an oblique image was used. This approach is similar to the use of orthogonal or pseudo-orthogonal projections for patient positioning.

We examined the automatic image registration capabilities of the research software. Automatic registration was similar to the above steps (1)–(4) of the manual registration procedure. Each reconstructed plane in the study DTS was

FIG. 2. Schematic illustrating differences between standard DTS and RC DTS. Dashed circle shows the x-ray source trajectory, solid curve at 12 o'clock position indicates the optimal arc for DTS reconstruction without respiration correlation. Dashed radial lines at 11 and 1 o'clock positions indicate x-ray directions of two DTS disjoint arcs within a respiration phase bin (over two breathing cycles) that are chosen for RC-DTS reconstruction.

FIG. 3. Images of a head phantom. (a) DTS image of static phantom. (b) Standard DTS image (without respiration correlation) of a moving phantom. (c) RC-DTS image at end-exhalation phase. (d) RC-DTS image in midexhalation phase. [(e)–(h)] CBCT images corresponding to (a)–(d), respectively.

registered to the ROI from the reference image by maximizing a normalized cross correlation function. The displacement coordinates were chosen from the study image with the largest normalized cross correlation value. Automatic registration was performed separately for each of the DTS images separated by 90° or 45° and the results combined to obtain 3D displacement coordinates. In order to determine the reliability of the automatic registration, the 3D coordinates obtained from it were compared to those from the manual registration. The former were used in the subsequent analysis when they agreed within 1 cm of the latter; otherwise the latter coordinates were used.

For comparison with DTS, tumor displacements at different respiratory phase intervals and from different scans were calculated with RC-CBCT images. The manual 3D registration procedure between RC-CBCT images used software written at our institution. Each RC-DTS or RC-CBCT registration was repeated three to five times by the same observer to determine the repeatability of the measurement.

In order to validate the calculation of tumor position in RC-DTS, tumor centroid coordinates from the RC-DTS for all four phase intervals were compared to those determined from the RC-CBCT images. Dedicated software was written to permit the direct registration of a CBCT image slice to a DTS image in the same coordinate system with the isocenter as origin. For each patient and phase interval, the tumor observed in the coronal RC-DTS image was manually aligned to the tumor in the corresponding RC-CBCT image to obtain the quantity $\Delta_{\text{DTS-CBCT}}$ in the left-right (LR) and superior-inferior directions. In addition, oblique-angle CBCT images were generated and registered to the oblique-angle DTS images. The quantities obtained from the oblique-angle images were used to calculate tumor centroid coordinates and $\Delta_{\text{DTS-CBCT}}$ in the anterior-posterior (AP) direction using the method described by Hanley *et al.*⁴²

III. RESULTS

DTS processing time (including out-of-plane artifact suppression) to reconstruct a volume consisting of eleven $14 \times 14 \text{ cm}^2$ slices with $0.5 \times 0.5 \text{ mm}^2$ pixel size (7.7 cm volume depth) from a 20° arc (35 projections) was 15 s on a Pentium-4 3.2GHz computer. Processing time for automatic registration of a $5 \times 5 \text{ cm}^2$ reference image region of interest onto the DTS volume was 55 s. Manual registration required approximately 1 min per DTS image set (~ 2 min for paired DTS sets).

Figure 3 shows the results of the phantom study. Figure 3(a) shows a standard DTS image (without respiration correlation) of a static head phantom. Simulated respiratory motion significantly blurs and distorts the image [Fig. 3(b)]. RC-DTS reduces image blur and distortion [Figs. 3(c) and 3(d)]. Images with the least blurring occur at end-exhalation [Fig. 3(c)] or end-inhalation phases, at extremes of the motion. The CBCT images show similar behavior [Figs. 3(e)–3(h)].

Figure 4 shows images of a tumor attached to the diaphragm (patient 1). While out-of-plane features, primarily the ribs, are visible in the DTS images, tumor can be clearly visualized. In addition to the tumor, some lung features can be identified in both the CBCT and DTS images (arrows).

In standard (non-respiration-correlated) DTS and CBCT reconstruction, respiratory motion results in blurring of tumor, diaphragm, and other structures in lung [Figs. 4(a) and 4(f)], whereas respiration-correlated reconstruction decreases image blur in DTS [Figs. 4(b)–4(e)] and CBCT [Figs. 4(g)–4(j)]. The sharpest image is at end exhalation [Figs. 4(e) and 4(j)], owing to less residual motion within that interval. In addition, RC reconstruction allows visualization of tumor motion extent. For example, it is clearly seen that the tumor is at the most inferior position in Figs. 4(c) and 4(h). The observed tumor and diaphragm displacements are con-

FIG. 4. [(a)–(e)] DTS and [(f)–(j)] CBCT images of a lung tumor (patient 1) attached to a diaphragm. Images are viewed from posterior direction. [(a) and (f)] Standard reconstruction without respiration correlation. Other images are respiration-correlated [(b) and (g)] at midinhalation, [(c) and (h)] at end inhalation, [(d) and (i)] at midexhalation, and [(e) and (j)] at end exhalation. Dashed lines are a visual aid to indicate tumor motion. Arrows (f) indicate tumor and structure in the lung.

sistent between the RC-CBCT and RC-DTS images. Moreover, RC reconstruction allows visualization of the change in the shape of structures in the lung, for example, the structure indicated by the right arrow in Fig. 4(f). The shape changes are consistent between DTS and CBCT. Similar results were observed for two other patients with tumor attached to the diaphragm (patients 2 and 3).

Figure 5 shows an example of a lung tumor not attached to the diaphragm (patient 4). Similar to patients 1–3, we observe that RC reconstruction decreases image blur and enables the visualization of tumor motion extent. Because the diaphragm is not visible in the projection images, identifica-

tion of the end-exhalation phase is based on the RPM signal. We assume that end exhalation corresponds to roughly 50% RPM phase [Figs. 5(d) and 5(i)].

To illustrate circumstances in which an oblique pair of DTS is preferred to an orthogonal pair for determining 3D coordinates, Fig. 6 shows right lateral images for patient 4. The tumor is difficult to discern [Figs. 6(a)–6(c) and 6(e)] or not visible at all [Figs. 6(d)]. In addition, there are vertical band artifacts caused by the closeness of tumor to the detector edge in the lateral projection images (described in Sec. IV). Therefore, it was not always possible to use lateral projections and oblique images were used instead. Figure 7

FIG. 5. Posterior view DTS (upper row) and CBCT (lower row) images of patient 4: [(a) and (f)] Without respiration correlation, [(b) and (g)] at end inhalation, [(c) and (h)] at midexhalation, [(d) and (i)] at end exhalation, and [(e) and (j)] at midinhalation.

FIG. 6. Right lateral DTS (upper row) and CBCT (lower row) images of patient 4: [(a) and (f)] Without respiration correlation, [(b) and (g)] at end inhalation, [(c) and (h)] at midexhalation, [(d) and (i)] at end exhalation, and [(e) and (j)] at midinhalation. Respiration correlation is based on patient's RPM trace.

shows the corresponding left posterior oblique images of patient 4, in which the tumor is more clearly visible. We therefore used image pairs from Figs. 5 and 7 to determine the tumor's 3D position.

To evaluate RC-DTS capability for quantifying tumor motion, Fig. 8 compares tumor displacement from the end-exhalation phase. The plot abscissas show displacement obtained from registration of RC-CBCT, which is assumed to be ground truth, while the plot ordinates show displacement deduced from RC-DTS. The measurements were obtained from the manual registration, except for patients 1 and 2, for which automatic registration was possible. The error bars indicate 1 standard-deviation variation in the repeatability of

the registration. The plot excludes data from patient 7 (RC-CBCT registration was not possible) and AP and LR data from second tumor of patient 4 for two phases, midinhalation and midexhalation (RC-DTS registration was not possible). In most cases the measurements agree within 2–3 mm between RC-DTS and RC-CBCT, with the exception of patients 4 (second tumor) and 6, which show discrepancies of 5 and 7 mm, respectively. The larger discrepancies between RC-DTS and RC-CBCT measurements are correlated with the larger intraobserver variation (larger error bars) in the RC-DTS registration.

We examine the accuracy of RC-DTS for lung tumor localization by comparison to CBCT as a ground truth. Figure

FIG. 7. Left posterior oblique DTS (upper row) and CBCT (lower row) images of patient 4: [(a) and (f)] Without respiration correlation, [(b) and (g)] at end inhalation, [(c) and (h)] at midexhalation, [(d) and (i)] at end exhalation, and [(e) and (j)] at midinhalation. Respiration correlation is based on patient's RPM trace.

FIG. 8. Displacement of tumor from end exhalation in RC-DTS vs RC-CBCT for patients 1–6. Three displacements per patient were determined from image registration between the reference image at end exhalation and images at midinhalation, end inhalation, and midexhalation. Plots in the upper row show patients with the tumor attached to the diaphragm, plots in the lower row show all other patients. Dashed lines along diagonal of each plot indicate exact agreement between RC-DTS and RC-CBCT, whereas dashed lines on either side of the diagonal indicate the boundaries of agreement within 2 mm. Error bars represent the repeatability of the displacement determination.

9 compares DTS-determined and CBCT-determined tumor displacement relative to the room isocenter between two imaging sessions. DTS displacements are obtained from the manual image registration. In both the DTS and CBCT measurement, the end-exhalation image from the first image session served as a reference image to which the end-exhalation image from the second image set was registered by aligning the tumor. Figure 9 thus compares RC-DTS and RC-CBCT when used for tumor localization and is a measure of the image registration accuracy. The agreement is within 2–3 mm except for the AP data from patient 7, which shows a 6 mm discrepancy. This data point also shows large variability in repeat registrations, as indicated by the large error bar. Figure 9 does not include data for patient 6 because the poor tumor visibility in the RC-CBCT images precluded registration.

As a further test of localization accuracy, Fig. 10 compares tumor centroid position between DTS and CBCT. The

FIG. 9. Tumor displacement relative to room isocenter between two imaging sessions for patients 1–5 and 7 (see Table I for time between scans). Horizontal axes show displacement measured from registration of RC-CBCT images at end-exhalation and vertical axes show corresponding displacement measured from RC-DTS. Dashed lines along diagonal of each plot indicate exact agreement between RC-DTS and RC-CBCT, whereas dashed lines on either side of the diagonal indicate the boundaries of agreement within 2 mm. Error bars represent the repeatability of the displacement determination.

top row plots tumor coordinates from RC-DTS for the four phases versus those from RC-CBCT in six patients (seven tumors), in the LR, SI, and AP directions. The dotted black line indicates perfect agreement between DTS and CBCT. The lower row plots the difference between DTS and CBCT tumor coordinates, $\Delta_{\text{DTS-CBCT}}$, where the error bars indicate the intraobserver repeatability in the registration of the end-expiration images; the error bars are of similar magnitude for the other phase images. The data show similar agreement between DTS and CBCT to that observed in Figs. 8 and 9 and comparable to the uncertainty in the registration. We also note that $\Delta_{\text{DTS-CBCT}}$ from the end-expiration images (points with error bars) is similar in magnitude to that from images at other phases (points with no error bars).

IV. DISCUSSION

Our findings indicate that DTS reconstruction consisting of backprojection, followed by the removal of out-of-plane artifacts is capable of soft-tissue visualization in the thorax with acquisition arc lengths as short as 20° . In addition, respiration-correlated DTS is shown to be feasible for reducing image blur caused by respiratory motion and can provide information on motion extent through reconstruction at different respiratory time points.

TABLE I. Characteristics of patients who participated in the study. Description of tumor location, tumor size, motion amplitude, and time between the consecutive scans are given. Patient 4 had two tumors. Displacement data are deduced from RC-CBCT registration, except for patient 7 when tumor motion was visually estimated on RC-CBCT scans.

Patient No.	Tumor location	Motion amplitude (mm)	Time between scans	Tumor size (largest dim.) (cm)
1	On diaphragm	8	15 min	4
2	On diaphragm	4	11 days	6
3	On diaphragm	5	13 min	3
4	Upper lung	4	7 days	2
	Near mediastinum	7		2
5	Near diaphragm	5	11 min	2
6	Upper lung	11	10 min	2
7	Upper lung	~3–6	17 min	5

The principal advantage of DTS is the shorter acquisition time, particularly for respiration-correlated imaging. As shown in this study, two approximately orthogonal short arcs, each over two to three respiratory cycles ($\sim 5\text{--}8$ s per arc), is sufficient to obtain RC-DTS images for 3D determination of tumor position and motion extent. Since each arc is $20^\circ\text{--}35^\circ$ in length, a gantry rotation between arcs of only $55^\circ\text{--}70^\circ$ is needed for orthogonal DTS images, resulting in a total acquisition time (assuming 1 rpm gantry rotation) of 18–21 s. The time can be further reduced to 16–19 s by using DTS images separated by 45° , while still yielding 3D position information, as shown in this study. This is approximately a factor two shorter than the minimum (200°) CBCT acquisition time of 33 s. We point out that the RC-CBCT images used for comparison in this study were reconstructed from sorted projection images over a 360° arc; thus, the imaging dose for CBCT was approximately three to five times that for orthogonal DTS.

In this study, we have examined DTS imaging techniques with patients breathing normally and without breathing instruction. DTS alternatively may be acquired during breath hold; however, treatment should be delivered in the same motion state (i.e., breath-hold or free breathing) in order that imaging accurately represents patient geometry during treatment. An advantage of breath-hold is that residual motion is less than for respiration-correlated imaging. A disadvantage is that not all patients may be able to achieve reproducible breath-holds, particularly for patients with compromised pulmonary status.

Ideally, DTS images reconstructed from the plan CT should be used as an anatomic reference.⁴¹ In this case a set of digitally reconstructed radiographs is generated over a range of orientations, representing an arc of projection im-

ages as input to DTS reconstruction. To accomplish this would require a respiration-correlated CT scan at treatment simulation, which was not available for the patients in this study.

A limitation in the current study is the use of CBCT projection images for reconstructing and evaluating DTS. The CBCT projection images are acquired in a half-fan configuration, in which the detector is offset to increase the CBCT reconstruction field of view.³³ A consequence is that at many angles the tumor is outside the projection field of view or near the detector edge. The latter situation results in vertical line artifacts, as seen in Fig. 6. The preferred acquisition for DTS is to use a detector position that is centered on the tumor at the particular gantry orientation.

While automatic DTS registration succeeded in two cases, it was not possible for most tumors. In most cases the automatic registration's choice of study image in the direction perpendicular to the reconstruction plane (based on the largest normalized cross correlation value) differs from that of the human observer. The miss is apparent to the observer via inspection of nontumor features outside the ROI. An increase in the ROI size can resolve this problem; however, an increase much larger than the tumor is not desirable, as the automatic registration be affected by out-of-plane features. It may be possible to improve the automatic registration performance by limiting the range of study images, but this was not examined in this study.

V. CONCLUSION

Respiration-correlated DTS reconstruction decreases image blur caused by the respiratory motion and is capable of visualizing motion extent of tumors in lung. Features visible on CBCT are also visible on DTS. The best image quality is achieved at the end-exhalation phase of the respiratory motion. Comparison of RC-DTS and RC-CBCT in determining tumor position, motion extent, and displacement between treatment sessions in most cases shows agreement within 2–3 mm, comparable in magnitude to the intraobserver repeatability of the measurement. These results suggest the method's applicability for soft-tissue image guidance in lung, but must be confirmed with further studies in larger numbers of patients.

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FIG. 10. Tumor centroid position (relative to room isocenter) as determined from RC-DTS vs RC-CBCT for patients 1–6 at each phase (4 data points per patient) (a) in the LR direction, (b) in the SI direction, and (c) in the AP direction. Dashed black line indicates exact agreement between RC-DTS and RC-CBCT. Plots (d), (e), and (f) are the difference in tumor centroid position ($\Delta_{DTS-CBCT}$). Error bars represent the intraobserver reproducibility in the DTS-to-CBCT registration. Error bars are shown for the end-expiration data points only and are of similar magnitude for the other phases.

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