Quality and accuracy of cone beam computed tomography gated by active breathing control

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The purpose of this study was to evaluate the quality and accuracy of cone beam computed tomography (CBCT) gated by active breathing control (ABC), which may be useful for image guidance in the presence of respiration. Comparisons were made between conventional ABC-CBCT (stop and go), fast ABC-CBCT (a method to speed up the acquisition by slowing the gantry instead of stopping during free breathing), and free breathing respiration correlated CBCT. Image quality was assessed in phantom. Accuracy of reconstructed voxel intensity, uniformity, and root mean square error were evaluated. Registration accuracy (bony and soft tissue) was quantified with both an anthropomorphic and a quality assurance phantom. Gantry angle accuracy was measured with respect to gantry speed modulation. Conventional ABC-CBCT scan time ranged from 2.3 to 5.8 min. Fast ABC-CBCT scan time ranged from 1.4 to 1.8 min, and respiratory correlated CBCT scans took 2.1 min to complete. Voxel intensity value for ABC gated scans was accurate relative to a normal clinical scan with all projections. Uniformity and root mean square error performance degraded as the number of projections used in the reconstruction of the fast ABC-CBCT scans decreased (shortest breath hold, longest free breathing segment). Registration accuracy for small, large, and rotational corrections was within 1 mm and 1°. Gantry angle accuracy was within 1° for all scans. For high-contrast targets, performance for image-guidance purposes was similar for fast and conventional ABC-CBCT scans and respiration correlated CBCT. © 2008 American Association of Physicists in Medicine. [DOI: [10.1118/1.3013568](https://doi.org/10.1118/1.3013568)]

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I. INTRODUCTION

Free breathing during imaging causes artifacts and blurring and can obscure the structures in the image,¹ for sites affected by respiration such as the thorax and upper abdomen. Methods to reduce the effect of respiratory motion during imaging include correlating the scan to a free breathing signal then retrospectively sorting the projections to reconstruct an image of a stable segment of the breathing cycle,^{2–6} or respiratory gating where images would only be acquired during breath hold or during a specific portion of the breathing cycle.^{7,8}

Cone beam computed tomography (CBCT) is a CT imaging technique that can be performed on the treatment table with the patient in treatment position. CBCT can be acquired with a megavoltage beam from the head of the Linac,^{9,10} or by a gantry mounted x-ray tube for kilovoltage (kV) acquisition.^{11,12} A pretreatment CBCT can be acquired and registered to the planning CT to perform a setup correction based on internal anatomy instead of bony or external landmarks as a form of image guided radiotherapy.

For image guided radiotherapy where respiratory motion is a concern, respiratory correlated or respiratory-gated techniques can be used with CBCT.^{2,13–16} A respiratory correlated CBCT is acquired while the patient is free breathing, and the resulting image quality is highly dependent on the ability of

the patient to maintain a stable breathing cycle.^{17–19} At the study institution (William Beaumont Hospital, Royal Oak, MI), respiratory correlated CBCT scans are acquired at a slower gantry speed, and then sorted into six breathing phases based on diaphragm position. The images corresponding to each breathing phase are then reconstructed into a separate volume, resulting in six distinct reconstructed images.

Active breathing control (ABC) is a method of respiration management using relative spirometry.^{20–24} With ABC, the patient inhales or exhales beyond a set threshold, and then a balloon valve inflates actively preventing the patient from further inhaling or exhaling for a specified duration. Beam delivery would only occur during the breath hold. For an accurate evaluation of target location for treatment with ABC, the CBCT should also be acquired during breath hold.

A common concern with ABC is patient compliance with a moderate deep or a deep inspiration breath hold of long duration. To achieve better compliance, the authors have developed a technique based on short (3–10 s) breath hold length at the end of normal inspiration. This hybrid ABC gating approach requires integration of the ABC device into the Linac and imaging control systems.

The primary purpose of this study was to develop methods for ABC-CBCT and to evaluate the quality and accuracy

of ABC-CBCT for image guidance. The secondary purpose was the development of a fast ABC-CBCT technique to reduce the required number of breath holds necessary to complete a scan. In addition, ABC-CBCT was compared to other methods for managing respiratory motion such as respiratory correlated cone beam computed tomography (RC-CBCT).

II. METHODS AND MATERIALS

For this study a series of phantom images were acquired. The scans were performed both with simulated and actual ABC controlled speed modulation, evaluating a series of breath hold and free breathing patterns. The acquired phantom images were used to evaluate the methods of respiratory management for image guidance purposes.

II.A. Image acquisition

Image acquisition was performed on a linear accelerator equipped with an on board kV imager (Synergy, Elekta, Inc., Crawley, UK). The linear accelerator was modified in-house to acquire cone beam computed tomography projections at two calibrated gantry speeds: a clinical imaging speed of $3.2^\circ/\text{s}$, and a slower speed of $1.6^\circ/\text{s}$. The system was further modified to enable the ABC equipment (Active Breathing Coordinator, Elekta, Inc.) to directly modulate the gantry speed. The commercial clinical algorithm (XVI R4.0, Elekta, Inc.) was used for image reconstruction and image registration.

II.A.1. Scan type overview

Three scan types were evaluated: free breathing RC-CBCT, conventional ABC-CBCT, and fast ABC-CBCT. All scans were acquired with a field of view producing a cube of side length 25.6 cm, a half-rotation scan (200°), 120 kV, and 1.6 mAs/projection.

Free breathing RC-CBCT is a scan acquired at a slow gantry speed ($1.6^\circ/\text{s}$) with the projections retrospectively sorted into six breathing phases. The RC-CBCT is dependent on a stable breathing pattern by the patient to achieve a reliable reconstruction. The total scan time included the acquisition of projections for all breathing phases.

Conventional ABC-CBCT is a respiration-managed scan where the gantry rotates at the clinical imaging speed of $3.2^\circ/\text{s}$ during breath holds, and stops during the free breathing segments between breath holds. In our in-house system, the ABC initiated the stopping and starting of gantry rotation. The image content of the reconstructed scan is equivalent to a normal clinical scan reconstructed with all of the projections. In this study, a normal clinical scan was used to represent this method. The total scan time included both the free breathing time when the gantry is not moving between breath holds, and the time spent acquiring projections during breath holds.

Fast ABC-CBCT is a respiration-managed scan where the gantry rotates at the clinical imaging speed of $3.2^\circ/\text{s}$ during breath holds, then rotates at the slower $1.6^\circ/\text{s}$ speed during free breathing between breath holds. The goal of this fast

ABC-CBCT scan was to reduce the required number of breath holds and overall scan time, and to diminish wear on the gantry motors by eliminating stop and start. The ABC initiated the gantry speed modulation during this scan. For the current study, the x-ray tube itself was not gated to breath hold. For clinical implementation, gating the tube output would be warranted to reduce unnecessary patient exposure. Image reconstruction included projections acquired during breath hold only. Total scan time included time spent at both the clinical imaging speed during breath holds and the slow speed during free breathing.

II.A.2. Fast ABC-CBCT

The goal of the fast ABC-CBCT scan is to reduce the number of breath holds required during image acquisition, as compared to conventional ABC-CBCT. A reduced number of breath holds per scan may improve patient compliance, but must be evaluated to see if there will be degradation of image quality or registration accuracy leading to a result unusable for image guidance purposes.

During a fast ABC-CBCT scan, the patient would breathe through the spirometer for the ABC, with a threshold and duration for breath hold set in the ABC software. Once the patient's air volume crosses above the set threshold, the balloon valve inflates, preventing the patient from further inhaling or exhaling. For the scans in this study, the authors instrumented the balloon valve with a mechanical switch, which closes a circuit when the balloon valve inflates. This open/closed signal was used as input into a gantry speed modulator to change speed upon breath hold activation. The gantry speed modulator is a box built in house that switches current through two circuits—one for the faster clinical imaging speed, the other for the slower free breathing speed. These circuits interfaced with the motion board on the linear accelerator. Figure 1 is a diagram representing how these components worked together for this scan technique.

II.A.3. Breathing patterns

The breathing patterns for the respiratory-gated scans in this study were simulated with both computer control and actual breathing through the ABC. Computer controlled patterns enabled consistency in the comparison, and actual breathing introduced some pattern uncertainty. In both cases the breath hold times were set, but in the actual breathing method, the free breathing times varied. The patterns studied were: 3 s breath holds with 15 s of free breathing, 5 s breath holds with 10 s of free breathing, and 10 s breath holds with 15 s of free breathing. Breathing patterns were chosen to be realistic yet conservative for patients where ABC-CBCT imaging could be beneficial.

As no motion was induced for any of the phantom scans, sorting of the projections for RC-CBCT reconstruction was performed using a projection phase mapping from an example patient scan. We selected an example phase mapping from a patient with reproducible, regular breathing, and applied the phase mapping to the phantom RC-CBCT scan to

FIG. 1. Flow chart of the fast ABC-CBCT scan acquisition process. FB: Free breathing, BH: Breath hold.

determine the projections to reconstruct for each respiration phase. Only the end of exhalation phase ("Phase 1") was reconstructed.

II.B. Image quality

A Catphan 600 series image quality phantom (The Phantom Laboratory, Salem, NY) was used for image quality assessment with high contrast, low contrast, and uniformity inserts. Images were acquired with and without an additional annulus surrounding the phantom. The Catphan was not moved between scans to eliminate the necessity of image registration prior to analysis. Three image quality metrics were evaluated: accuracy of reconstructed voxel intensity, uniformity, and relative root mean square error.

In the reconstructed images, the voxel intensity values were not true Hounsfield units as they would be in a calibrated CT scanner. In these reconstructions they were representations of the voxel grayscale value within the image. Therefore, the voxel intensity was compared both to the nominal value and to a gold standard of a conventional CBCT acquisition.

II.B.1. Accuracy of reconstructed voxel intensities

Accuracy of reconstructed voxel intensity was evaluated on the eight sensitometric objects contained in the low contrast resolution insert of the Catphan. Axial views of the slices for a subset of the scan techniques are shown in Fig. 2 with and without the additional annulus. A region of interest was selected within each of the objects and the mean voxel intensity value and standard deviation of each was determined. The eight sensitometric objects consisted of air (two),

FIG. 2. Catphan low contrast resolution insert, axial images of (a)–(c) Catphan without annulus and (d)–(f) Catphan with annulus. (a) Conventional ABC-CBCT, (b) RC-CBCT Phase 1, (c) fast ABC-CBCT 5 s BH, 10 s FB, patient, (d) conventional ABC-CBCT, (e) RC-CBCT Phase 1, and (f) fast ABC-CBCT 5 s BH, 10 s FB, patient.

low-density polyurethane, polymethyl pentane, polystyrene, acrylic, Delrin™, and Teflon™. The mean voxel intensity values within a small (1-cm-diameter) region inside each object from each of the reconstructed scans were compared.

II.B.2. Uniformity

Uniformity was evaluated on the uniformity insert of the Catphan. Due to a potential false sensitivity of the calculation by dark streaking artifacts present in the RC-CBCT and fast ABC-CBCT techniques, the typical profile or region of interest methods for calculating uniformity were not used. Instead, we used a histogram analysis on a subset of the volume within the uniformity insert. The uniformity insert was a cylinder of approximately 15 cm diameter and 4 cm length. The analysis was performed on a cylinder of 14 cm diameter and 1 cm length centered in the uniformity insert. The voxel intensity values within the volume were normalized to the mean of the values in the normal clinical CBCT. The standard deviation of each histogram was calculated.

II.B.3. Relative root mean square error

To assess low contrast resolution, the relative root mean square error method was used instead of a contrast to noise ratio because previous studies have shown that images with significant artifacts may have an artificially high contrast to noise ratio.²⁵ If a streak artifact runs through the region of interest selected to calculate this quantity, a high contrast to noise ratio may be calculated based on an artifact and not true image content. Similar to Li and Xing, a relative root mean square error was calculated to measure the strength of

correlation between image quality and gantry rotation speed.²⁵ Relative root mean square error (rms) was calculated by

$$\text{rms} = \sqrt{\frac{\sum_i (S_{\text{compare}}(i) - S_{\text{control}}(i))^2}{\sum_i S_{\text{control}}^2(i)}},$$

where S_{control} is the control scan (in this case it is represented by the normal clinical CBCT reconstructed with all projections), S_{compare} is the comparison scan, and i is the voxel index.

rms was evaluated on a subset of the phantom volume. The central section of the phantom holds the inserts, and is approximately 15 cm in diameter and 16 cm from the center of the first insert to the center of the fourth insert. In the phantom used in this study, the inserts are arranged in the order of low contrast, high contrast, uniformity (1), and uniformity (2). The subset volume was selected to be a cylinder 13 cm in diameter and 15.5 cm in length to include the low contrast resolution, high contrast resolution, and uniformity sections.

The values in each subset were normalized to the mean voxel intensity value of a small subset of the uniformity insert. The mean voxel intensity value was calculated within a 1-cm-diameter, 1-cm-length cylinder in the center of the uniformity insert for both the comparison and the control scans. The comparison scan values were then shifted by the difference between the two in order to normalize to the mean voxel intensity value of the control scan.

II.C. Registration accuracy

Registration accuracy was evaluated by two methods. Two soft-tissue registration algorithms in a commercial treatment planning system (SYNTEGRA v1.2b, Philips Radiation Oncology Systems, Fitchburg, WI) and in a commercial guidance system (XVI R4.0, Elekta, Inc.) were evaluated using images of an anthropomorphic Rando phantom. A bony registration algorithm in XVI was evaluated using an in-house quality assurance phantom constructed of Teflon and water, shown in Fig. 3.

II.C.1. Anthropomorphic phantom registration

In a method similar to Sykes *et al.*,²⁶ the registration accuracy for the RC-CBCT and ABC-CBCT scans was evaluated using both the SYNTEGRA cross correlation²⁷ algorithm and the correlation ratio²⁸ algorithm in XVI. A helical CT was acquired of the anthropomorphic Rando phantom. The Rando phantom was set up on the planning table with small, large, and rotational offsets. A high quality (1024×1024) CBCT scan was acquired to determine the true registration. Without moving the phantom from the setup position, the RC-CBCT and ABC-CBCT scans were acquired. The difference between the “true” registration and the results from the other scans was calculated to evaluate the accuracy of registration.

To perform the registration, a mask region was first placed around the mediastinum and proximal regions of both lungs,

Fig. 3. In-house quality assurance phantom. The phantom is a water-filled acrylic cylinder with Teflon spheres of radius 1 cm mounted on acrylic posts.

to remove the rest of the image information. This mask region was approximately 18.4 cm in the SI dimension, 7.6 cm in the AP dimension, and 18.2 cm in the lateral dimension. Registration was performed with each algorithm independently, using only the image information within the region. This region was selected because it contained a region with density similar to a lung tumor (which was not available within the phantom), surrounded by lung. Registration with this region enabled a reasonable measurement of soft-tissue registration accuracy.

The small shift was set up to be on the order of ± 1 –2 mm in the X , Y , and Z directions with minimal rotational offset (less than 0.5°). The large shift was set up to be on the order of ± 1 –2 cm in the X , Y , and Z directions with a minimal rotational offset (less than 0.5°). The rotational shift was set up to be on the order of ± 0 –1 cm in the X , Y , and Z directions with a rotational offset of ± 1 –2°.

II.C.2. Known target registration

An in-house quality assurance phantom (Fig. 3) with four peripherally and one centrally located Teflon ball bearings was positioned at isocenter on the treatment table. A clinical quality scan (512×512) was acquired and registered to a reference image of the phantom using the bony (chamfer matching) registration algorithm in XVI.²⁹ Similar to the anthropomorphic registration, a mask was designed such that only the Teflon spheres were used in the registration, not the entire phantom. This was defined as the true registration. Conventional ABC-CBCT, fast ABC-CBCT, and RC-CBCT scans were acquired and registered to the reference image. The difference between the true registration and the registration values for each of the scans was compared to determine the registration accuracy.

A geometric model of the phantom was constructed and used as the reference image. The reference model image of the phantom had a planning isocenter placed at the centroid of the central Teflon sphere, which allowed assessment of the registration to determine if gantry speed modulation affected

TABLE I. Scan statistics for the three scan methods and various breathing patterns. PT: Patient simulated, CP: Computer simulated breathing pattern.

Scan type	Breath hold duration (s)	Free-breathing duration (s)	Number of projections used (acquired)	Projections used (%)	Angular coverage (%)	Total scan time (s)
Conventional ABC-CBCT	Various	Various	345 (345)	100	100	63+free breathing
Fast ABC-CBCT, PT	3	15	109 (586)	18	33	106
Fast ABC-CBCT, PT	5	10	168 (524)	28	49	95
Fast ABC-CBCT, PT	10	15	208 (475)	35	63	86
Fast ABC-CBCT, CP	3	15	100 (595)	16	31	109
Fast ABC-CBCT, CP	5	10	172 (517)	29	52	95
Fast ABC-CBCT, CP	10	15	202 (493)	35	60	89
Respiration correlated-CBCT	N/A	Entire scan	126 (710)	20	18	129

the geometric (isocenter) calibration of the CBCT system. An additional scan was performed with a 3 s breath hold and 3 s of free breathing (computer simulated) to evaluate a worst-case motion technique, which we believed to have the greatest potential (the most gantry speed modulation) to affect isocenter accuracy.

II.D. Gantry angle accuracy

Gantry angle accuracy was assessed with respect to gantry speed modulation. A geometric calibration phantom as described in Cho *et al.*³⁰ was used with 16 steel ball bearings located in a known geometry. A theoretical gantry angle was calculated by localizing each ball bearing position within each projection image. The theoretical gantry angle was compared to the gantry angle readout via the controller area network bus of the Linac.

Four scan types were evaluated for gantry angle accuracy: a scan with no gantry speed modulation, a fast ABC-CBCT with 3 s breath holds and 3 s free breathing (to simulate a worst-case fast switching breathing pattern), a conventional ABC-CBCT, and an extreme stop and start scan where the gantry was abruptly started and stopped throughout the duration of the scan. The scans were each acquired with clockwise and counterclockwise rotation.

II.D.1. Mean absolute error

The gantry angle accuracy was quantified by calculating a mean absolute error. First, the difference between the theoretical and measured gantry angle values was determined for each projection acquired within a scan. The absolute value was taken of each of these differences, and the absolute differences were averaged over each scan. The average of the clockwise and counterclockwise versions of each scan was taken. The mean absolute errors were compared among the

three scan types acquired to assess if there was any difference in mean absolute error based on variations in gantry speed modulation.

III. RESULTS

III.A. Scan statistics

Table I highlights some characteristics of the scan types evaluated in this study. The simulated conventional ABC-CBCT total scan time varied based on the duration of any free breathing segments; the total breath hold acquisition time was always around 61 s. All other scan times were in total. Free breathing RC-CBCT scans acquired the most data. The fast ABC-CBCT scan could potentially result in more stable images for short breath holds than a conventional ABC-CBCT scan due to the decrease in overall scan time.

III.B. Image quality

III.B.1. Accuracy of reconstructed voxel intensities

Qualitatively, Fig. 2 demonstrates the variation in image quality related to low contrast resolution. Figures 2(a) and 2(d) show the conventional ABC-CBCT images without and with the annulus, respectively. The image quality of these two axial slices was the direct equivalent of a normal clinical CBCT scan. Figures 2(b) and 2(e) show a RC-CBCT image without and with the annulus. Here, streaking artifacts were evident, and were spaced at a relatively high frequency. This was due to the nature of the distribution of used projections in a RC-CBCT scan. Approximately 26 groupings of four to five projections made up this RC-CBCT image reconstruction. Figures 2(d) and 2(f) show an example of a fast ABC-CBCT scan without and with the annulus. These images showed wider streaking artifacts spaced more infrequently. The image reconstruction of the 5 s breath hold with 10 s

FIG. 4. Catphan image quality analysis, voxel intensity value linearity. (a) Without annulus, (b) with annulus. Conventional ABC-CBCT is the equivalent to a normal clinical scan with all projections included in the reconstruction. "Fast ABC-CBCT, 3×15 Pt" refers to the patient simulated fast ABC-CBCT scan with 3 s of breath hold and 15 s of free breathing.

free breathing fast ABC-CBCT scan included six to seven breath holds interspersed with groupings of missing projections from the 10 s of free breathing.

All scan types demonstrated strong linearity of voxel intensity values both with and without the annulus. Figures 4(a) and 4(b) show the relationship of the measured voxel intensity value for each of the scans versus the ideal CT number specified by the Catphan manufacturer with and without the additional annulus, respectively. The dark solid line is the normal clinical CBCT scan, which has the equivalent image content as a conventional ABC-CBCT. Both of the fast ABC-CBCT scans shown and the RC-CBCT scan showed linearity and slopes comparable to the normal clinical CBCT scan result. The variation in slopes for the scans with and without the annulus relates to the effect of the additional attenuation and scatter for the scans with the annulus and the resultant measured voxel intensity value.

To further evaluate the relationship between each of the fast ABC-CBCT scans and the RC-CBCT scan with the normal clinical CBCT scan (equivalent to the conventional ABC-CBCT scan), the comparison scan voxel intensity value was plotted against the normal clinical CBCT scan. This relationship for the Catphan without the annulus is shown in Fig. 5(a) for the fast ABC-CBCT scan with 5 s breath holds

and 10 s of free breathing and in Fig. 5(c) for the RC-CBCT scan. Figures 6(a) and 6(c) show this comparison for scans with the annulus. All scan types showed significant ($P < 0.01$) linearity.

Bland-Altman³¹ plots were evaluated for each scan type to evaluate any potential for error trends in the relationship between the normal clinical CBCT scan and the comparison ABC-CBCT or RC-CBCT scan type. The difference between each voxel intensity value (voxel intensity error) was plotted against the mean of both voxel intensity values. In all cases the error values were within ± 2 s.d. These results are shown for the Catphan without the annulus in Fig. 5(b) for the fast ABC-CBCT scan with 5 s breath holds and 10 s of free breathing and in Fig. 5(d) for the RC-CBCT scan. Figures 6(b) and 6(d) demonstrate the results with the annulus for the same two scans.

Bland-Altman plots indicating error without a trend were interpreted as random error. Error dependence on object nominal intensity was observed in the RC-CBCT scan without the annulus [Fig. 5(d)], and the fast ABC-CBCT scan with the annulus and a breathing pattern of 10 s breath holds with 15 s of free breathing (not shown). All other scan types demonstrated no trend. The RC-CBCT scan without the annulus demonstrated a Pearson product moment correlation R value of 0.91 ($P < 0.01$) and a slope of 0.06 ($P < 0.01$). The fast ABC-CBCT (10 s breath hold, 15 s free breathing) with the annulus demonstrated a product moment correlation R value of 0.84 ($P < 0.01$) and a slope of 0.10 ($P < 0.01$). There was a trend evident in those two scans; however, the actual error values and the slope were small.

III.B.2. Uniformity

The histogram analysis both with and without the annulus represents the effect of each of the scan types on uniformity. Figures 7(a) and 7(b) show frequency versus normalized voxel intensity value for the conventional ABC-CBCT, RC-CBCT, and one of the fast ABC-CBCT scans without and with the annulus, respectively. The scans without the annulus, Fig. 7(a), centered on a voxel intensity value of 730, and showed a more centralized distribution with the conventional ABC-CBCT being the most peaked. The scans with the annulus, Fig. 7(b), centered on a voxel intensity value of 780 and were generally flatter distributions when compared to Fig. 7(a). The conventional ABC-CBCT scan was still the most peaked.

Figure 8 summarizes the standard deviation results for all scans with and without the annulus. The fast ABC-CBCT scans with 3 s breath holds and 15 s free breathing had the highest standard deviation results. The 3 s breath hold scans also contained the least number of projections (approximately 100) in the reconstructed image. The conventional ABC-CBCT scans exhibited the smallest standard deviation with and without the annulus. The RC-CBCT scans as well as the 5 and 10 s breath hold fast ABC-CBCT scans all had relatively comparable standard deviation results.

Overall the fast ABC-CBCT scans with the computer simulated breath hold had lower standard deviation results as

FIG. 5. Voxel intensity value error without annulus. Nominal scan in all plots is a normal clinical CBCT. (a) Voxel intensity value accuracy of 5 s breath hold, 10 s free breathing, patient breathing, fast ABC-CBCT. Correlation $R=0.9960$ ($p<0.01$). Slope $=0.9791$ ($p<0.01$). Intercept $=-16.67$ ($p=0.51$). (b) Bland and Altman plot of the fast ABC-CBCT CT number vs normal clinical scan voxel intensity (equivalent to conventional ABC-CBCT). Correlation $R=0.1897$ ($p=0.65$). Slope $=-0.0172$ ($p=0.65$). Intercept $=-19.15$ ($p=0.45$). (c) Voxel intensity value accuracy of RC-CBCT, Phase 1. Correlation $R=0.9996$ ($p<0.01$). Slope $=1.0636$ ($p<0.01$). Intercept $=-20.62$ ($p=0.05$). (d) Bland and Altman plot of the RC-CBCT, Phase 1 vs normal clinical scan (equivalent to conventional ABC-CBCT) voxel intensity value. Correlation $R=0.9088$ ($P<0.01$). Slope $=0.0620$ ($P<0.01$). Intercept $=-20.24$ ($P=0.04$).

FIG. 6. Voxel intensity value error with annulus. Nominal scan in all plots is a normal clinical CBCT. (a) Intensity value accuracy of 5 s breath hold, 10 s free breathing, patient breathing, fast ABC-CBCT. Correlation $R=0.9873$ ($p<0.01$). Slope $=1.1344$ ($p<0.01$). Intercept $=-64.75$ ($p=0.19$). (b) Bland and Altman plot of the fast ABC-CBCT voxel intensity value vs normal clinical scan voxel intensity value (equivalent to conventional ABC-CBCT). Correlation $R=0.6590$ ($p=0.08$). Slope $=0.1396$ ($p=0.08$). Intercept $=-68.61$ ($p=0.13$). (c) Voxel intensity value linearity of RC-CBCT, Phase 1. Correlation $R=0.9982$ ($p<0.01$). Slope $=1.0576$ ($p<0.01$). Intercept $=-13.70$ ($p=0.40$). (d) Bland and Altman plot of the RC-CBCT CT number vs normal clinical scan voxel intensity value (equivalent to conventional ABC-CBCT). Correlation $R=0.6945$ ($p=0.06$). Slope $=0.0578$ ($p=0.06$). Intercept $=-14.40$ ($p=0.36$).

FIG. 7. Uniformity histogram analysis. (a) Catphan without annulus. Frequency vs normalized voxel intensity value for a subset of scans. (b) Catphan with annulus. Frequency vs normalized voxel intensity value for a subset of scans.

compared to the patient simulated scans of each type. This likely related to the consistent free breathing time in the computer simulated breathing pattern, and thus consistently spaced groupings of breath hold projections.

FIG. 8. Standard deviation of histogram analysis for uniformity section of the Catphan. Comparison of standard deviation results with and without the annulus for all scan types. Fast ABC-CBCT scan types are labeled BH $\times$ FB = breath hold seconds $\times$ free breathing seconds. Comp: computer simulated, Pt: patient simulated.

III.B.3. Root mean square error

The root mean square error results are summarized in Fig. 9. A lower root mean square error indicates an image quality more similar to the conventional ABC-CBCT scan (which is equivalent image content to a normal clinical CBCT). The RC-CBCT scan performed the best, even with its low number of used projections (126). This was likely a result of relatively evenly spaced frequent groupings of projections within the reconstruction. The fast ABC-CBCT scans included approximately four to seven breath holds (groupings of active projections) per reconstruction. The fast ABC-CBCT with 3 s breath holds had the highest root mean square error result, and also had the lowest number of projections used in the reconstruction. For the scans with the annulus, the results for the 5 s and 10 s breath holds are very similar. The results for these scans were comparable to those without the annulus, although there is more variation.

The relationship between number of projections used and the root mean square error result for the fast ABC-CBCT scans evaluated in this study is investigated further in Fig. 10. The results with the annulus demonstrated a significant linear relationship of root mean square error and number of projections used in the reconstruction of the image. The results without the annulus show the same general trend, although with a weaker correlation. Overall the patient simulated scans performed worse than the computer simulated scans, likely related to the pattern consistency achieved with the computer simulation. Generally speaking we see the same relationship of increased root mean square error with decreasing number of projections.

III.C. Registration accuracy

III.C.1. Anthropomorphic phantom registration

Figure 11 shows the CBCT images of the anthropomorphic phantom for the conventional ABC-CBCT, RC-CBCT, and a fast ABC-CBCT technique. The registration accuracy assessment for the correlation ratio algorithm in XVI is shown in Tables II–IV for the small, large, and rotational shift phantom setups, respectively. All three sets of evaluations demonstrated registration error less than 1 mm and 1° for all scan types. In 16 out of 24 cases, the correlation ratio algorithm resulted in (66.7%) less than $\frac{1}{2}$ mm translational

FIG. 9. Root mean square error analysis for central cylindrical volume of Catphan. Comparison of root mean square error results with and without the annulus for all scan types. Fast ABC-CBCT scan types are labeled BH×FB=breath hold seconds×free breathing seconds. Comp: computer simulated, Pt: patient simulated.

error, and in 19 out of 24 cases (79.2%) less than $\frac{1}{2}^\circ$ rotational error. The registration results for the cross-correlation algorithm in SYNTegra are not shown, but demonstrated similar results with registration error less than 1 mm and 1° for all three types of shifts. In 10 out of 24 cases (41.7%) the cross-correlation algorithm resulted in less than a $\frac{1}{2}$ mm translational error, and in 24 out of 24 cases (100%) less than a $\frac{1}{2}^\circ$ rotational error.

III.C.2. Known target registration

The registration accuracy assessment for the known target registration (chamfer matching of the Teflon sphere phantom), is shown in Table V. All scan types evaluated exhibited a registration error less than 1 mm and up to but not exceeding 1° . The 3 s breath hold, 3 s free breathing scan results were also comparable to the scans with less or no gantry speed modulation. This indicates the accuracy of the isocenter in the image reconstruction is not affected even by worst-case gantry speed modulation.

FIG. 10. Root mean square error relationship with number of projections. There is a linear trend for the Catphan results with the annulus ($R=0.96$).

III.D. Gantry angle accuracy

III.D.1. Mean absolute error

The gantry angle accuracy results are shown in Table VI. The mean absolute errors are all within one hundredth of a degree of each other for the four scan types evaluated. This indicates there is no increase in gantry angle error with gantry speed modulation. The standard deviation of the mean absolute error was approximately one tenth of a degree in all cases, and the maximum gantry angle error seen in any of the scans was the highest at 1.25° for the fast ABC-CBCT scan tested and the lowest at 1.09° for the control scan.

FIG. 11. Cone beam CT images of the anthropomorphic phantom. (a) axial and (b) coronal slices, conventional ABC-CBCT, (c) axial, and (d) coronal slices, Respiration correlated CBCT, (e) axial and (f) coronal slices, fast ABC-CBCT (10 s breath hold, 15 s free-breathing). The ROI used to register the images is indicated on (a) and (b) by a dashed line rectangle.

TABLE II. Small displacement setup of anthropomorphic Rando phantom registered with xvi correlation ratio algorithm. Small displacement is defined as a translational shift of the phantom in treatment position vs the planning CT location of 1–2 mm with a minimal ($<0.5^\circ$) rotational shift. The registration error values are the difference between the registration results with a high quality (1024×1024) CBCT and each of the scan types listed. PT: patient simulated, CP: Computer simulated breathing pattern.

Scan type	Translation error (cm)			Rotation error (deg)			Orthogonal distance (cm) ($x^2+y^2+z^2$) ^{1/2}
	X	Y	Z	X	Y	Z	
Simulated conventional ABC-CBCT	0.02	0.01	0.00	0.0	0.1	−0.1	0.02
Fast ABC-CBCT 3 s BH, 15 s FB, PT	0.01	0.06	0.03	0.4	−0.4	−0.1	0.07
Fast ABC-CBCT 5 s BH 10 s FB, PT	0.03	0.06	−0.01	0.3	−0.1	0.1	0.07
Fast ABC-CBCT 10 s BH, 15 s FB, PT	0.02	0.03	−0.02	−0.1	0.8	0.3	0.04
Fast ABC-CBCT 3 s BH, 15 s FB, CP	0.00	0.07	−0.02	0.3	−0.3	0.0	0.07
Fast ABC-CBCT 5 s BH, 10 s FB, CP	0.02	0.07	0.02	0.2	−0.2	0.0	0.08
Fast ABC-CBCT 10 s BH, 15 s FB, CP	0.04	0.06	0.01	−0.4	−0.8	0.1	0.07
Respiratory correlated CBCT— Phase 1	0.03	0.07	0.01	0.1	−0.2	0.0	0.08

III.E. Scan time

A comparison of the time it takes to acquire each of the scans is shown in Table VII. Table VII reports the average scan time across all scans of each type acquired during this study. The fast ABC-CBCT and RC-CBCT scans are the most time efficient. As the breath hold time decreases, and the free breathing time increases, the improvement when comparing the fast versus conventional ABC-CBCT increases.

III.F. Dose evaluation

Dose per scan is summarized in Table VIII. The estimated patient dose was calculated from ion chamber measurements in phantom following the method of Letourneau *et al.*¹¹ The higher surface dose values are reported. The measurements were scaled to 1.6 mA s per projection and to the number of projections per scan. The doses were estimated for the fast ABC-CBCT scan with and without kV gating—the ability to turn off the kV image acquisition during free breathing. The

TABLE III. Large displacement setup of anthropomorphic Rando phantom registered xvi correlation ratio algorithm. Large displacement is defined as a translational shift of the phantom in treatment position vs the planning CT location of 1–2 cm with a minimal ($<0.5^\circ$) rotational shift. The registration error values are the difference between the registration results with a high quality (1024×1024) CBCT and each of the scan types listed.

Scan type	Translation error (cm)			Rotation error (deg)			Orthogonal distance (cm) ($x^2+y^2+z^2$) ^{1/2}
	X	Y	Z	X	Y	Z	
Simulated conventional ABC-CBCT	0.01	0.01	−0.01	−0.2	0.4	−0.1	0.02
Fast ABC-CBCT 3 s BH, 15 s FB, PT	0.04	−0.07	−0.08	0.2	−0.4	0.2	0.11
Fast ABC-CBCT 5 s BH 10 s FB, PT	0.04	−0.02	−0.03	0.0	−0.8	−0.1	0.05
Fast ABC-CBCT 10 s BH, 15 s FB, PT	−0.01	0.03	0.04	−0.3	−0.1	−0.1	0.05
Fast ABC-CBCT 3 s BH, 15 s FB, CP	−0.01	−0.01	0.05	0.4	−0.2	−0.1	0.05
Fast ABC-CBCT 5 s BH, 10 s FB, CP	0.00	−0.03	0.00	−0.2	−0.2	0.1	0.03
Fast ABC-CBCT 10 s BH, 15 s FB, CP	−0.01	0.08	−0.02	0.3	−0.1	−0.1	0.08
Respiratory correlated CBCT— Phase 1	0.00	−0.01	−0.03	0.1	−0.1	−0.1	0.03

TABLE IV. Rotational shift setup of anthropomorphic Rando phantom registered with XVI correlation ratio algorithm. Rotational displacement is defined as a translational shift of the phantom in treatment position vs the planning CT location of 0–1 cm with a rotational shift of 1°–2°. The registration error values are the difference between the registration results with a high quality (1024 × 1024) CBCT and each of the scan types listed.

Scan type	Translation error (cm)			Rotation error (deg)			Orthogonal distance (cm) ($x^2+y^2+z^2$)
	X	Y	Z	X	Y	Z	
Simulated							
conventional ABC-CBCT	0.02	−0.01	−0.01	0.0	0.1	−0.2	0.02
Fast ABC-CBCT							
3 s BH, 15 s FB, PT	0.02	0.05	−0.02	0.4	−0.2	−0.1	0.06
Fast ABC-CBCT							
5 s BH 10 s FB, PT	0.01	0.04	0.04	0.1	−0.5	0.0	0.06
Fast ABC-CBCT							
10 s BH, 15 s FB, PT	0.00	0.04	0.02	0.0	0.6	0.1	0.04
Fast ABC-CBCT							
3 s BH, 15 s FB, CP	0.01	0.04	0.03	−0.5	−0.7	0.0	0.05
Fast ABC-CBCT							
5 s BH, 10 s FB, CP	0.02	0.03	0.01	0.2	−0.2	0.1	0.04
Fast ABC-CBCT							
10 s BH, 15 s FB, CP	0.02	0.05	−0.04	−0.2	0.0	0.1	0.07
Respiratory correlated CBCT—Phase 1	0.02	0.03	−0.01	−0.1	−0.3	−0.1	0.04

conventional ABC-CBCT scan assumes dose is only accumulated during breath holds. The highest dose is from the respiratory correlated CBCT (entire 200° scan done at the slower gantry speed of 1.6°/s). The lowest dose scan is the fast ABC-CBCT with kV gating. There is a dose improvement of 1.1–2.8 cGy when comparing the fast ABC-CBCT with kV gating to the conventional ABC-CBCT scan and an improvement of 3.8–4.6 cGy compared to the respiratory correlated CBCT. The fast ABC-CBCT scans without kV gating still show a dose improvement of 0.9–1.7 cGy when compared with the RC-CBCT scan.

IV. DISCUSSION

The image quality of the fast ABC-CBCT and the RC-CBCT scans was inferior to the normal clinical image quality of the conventional ABC-CBCT. However, it is possible to have inferior image quality, and still have a usable image for the purpose of image guidance. For the purposes of this study, the authors felt a usable image would be accurately registered, have an accurately reconstructed isocenter, and be without any additional error in the measured gantry angle. The conventional ABC-CBCT has the best image quality

TABLE V. Registration accuracy for the known target phantom registration (using the phantom shown in Fig. 3). The registration error values reported are the difference between the registration result with a normal clinical CBCT and each of the scan types listed.

Scan type	Translation error (cm)			Rotation error (deg)			Orthogonal distance (cm) ($x^2+y^2+z^2$) ^{1/2}
	X	Y	Z	X	Y	Z	
Worst case motion,							
3 s BH, 3 s FB, Computer	−0.01	0.01	−0.05	0.1	0.0	−1.0	0.05
Fast ABC-CBCT							
3 s BH, 15 s FB, PT	0.05	−0.01	−0.04	0.4	1.0	0.0	0.06
Fast ABC-CBCT							
5 s BH, 10 s FB, PT	−0.01	0.00	−0.02	0.4	0.0	−1.0	0.02
Fast ABC-CBCT							
10 s BH, 15 s FB, PT	0.03	0.01	−0.03	0.4	0.0	−1.0	0.04
Fast ABC-CBCT							
3 s BH, 15 s FB, CP	0.04	−0.01	−0.03	0.3	1.0	−1.0	0.05
Fast ABC-CBCT							
5 s BH, 10 s FB, CP	−0.01	−0.02	−0.06	0.4	0.0	−1.0	0.06
Fast ABC-CBCT							
10 s BH, 15 s FB, CP	0.01	−0.01	0.00	0.2	0.0	−1.0	0.01
Respiratory correlated CBCT—Phase 1	0.01	0.0	0.01	0.1	0.0	0.0	0.01

TABLE VI. Gantry angle accuracy assessment results. Mean absolute error is the mean across each individual scan of the absolute value of the difference between the actual gantry angle readout from the linear accelerator and the theoretical calculated gantry angle from the phantom results. BH: Breath hold time, FB: Free breathing time.

Scan type	Mean absolute error (deg)	Std. dev. of mean absolute error	Maximum absolute error (deg)
Control scan (constant speed, no stops)	0.82	0.13	1.09
Fast ABC-CBCT, 3 s BH, 3 s FB, CP	0.81	0.11	1.25
Conventional ABC-CBCT (stop and go)	0.81	0.10	1.15
Extreme stops (harsh stop and go)	0.82	0.08	1.10

(equivalent to a normal clinical CBCT scan), but the fast ABC-CBCT images demonstrated similar registration accuracy for high-contrast targets, while reducing overall scan time and number of breath holds required. The registration accuracy results shown in this study are the equivalent of registering large high-contrast tumors in lung; further study is required to quantify the accuracy of registration for small or low-contrast tumors.

Li and Xing²⁵ established a relationship between relative root mean square error (RE) and gantry speed. As the gantry speed increased, the number of projections used in the image reconstruction decreased with a resulting increase in relative root mean square error. The authors saw similar results in that their fast ABC-CBCT scan with the least number of projections (shortest breath hold time, longest free breathing time) had the worst performance against both the uniformity and root mean square error image quality metrics.

The fast ABC-CBCT scan is more efficient than the conventional ABC-CBCT for patients requiring a short breath hold time with a longer free breathing time between breath holds. However, if the breathing pattern results in a low number of projections (less than 100) used in the reconstructions, it is possible that the image quality may degrade beyond being usable. The lowest number of projections in a reconstructed image in this study was 100 (with the 3 s

breath hold and 15 s free breathing pattern). The authors did not find this lower limit of usable image quality in the current study, as it is anticipated that this limit would require a scan with clinically infeasible parameters, such as a subsecond breath hold time or very long free breathing time.

Variations in patient free breathing cycle to cycle¹⁸ can impact the quality of both the RC-CBCT and the ABC-CBCT images. In the free breathing respiratory correlated CBCT, if there are large cycle to cycle variations, the image quality of the individual phase reconstructions will be affected.^{17,18} ABC may be advantageous in such situations, because it forces the breath hold to be at a set volume threshold, and studies have shown it is reproducible²¹ for deep or moderate deep inspiration breath hold of long duration. We are currently evaluating the reproducibility of short breath hold at normal inspiration, under the hypothesis that such a breath hold arrangement should produce no worse variability than moderate deep breath hold of long duration.

For clinical implementation of ABC-CBCT, it is anticipated that the patient breath hold/free breathing pattern design would be primarily driven by the selection of the pattern that maximizes patient compliance while minimizing imaging and delivery error. If patient compliance necessitated selection of a technique that, for example, produced poor image quality for both the fast and conventional ABC-CBCT methods, it might be possible to adjust the pattern independently for the imaging and delivery components. Since the fast ABC-CBCT method produces a relatively short scan time, the patient could be asked to perform longer breath holds to improve image quality, but perform a short breath hold maneuver for the longer treatment delivery duration. The correspondence between the patient states during short and longer breath holds has yet to be addressed, however.

V. CONCLUSION

The authors have introduced a fast ABC-CBCT (slow gantry between breath holds) scan acquisition technique which produces degraded image quality but can be performed with a lower dose technique to improve the efficiency of the imaging process compared with conventional ABC-CBCT (stop and go). Fast ABC-CBCT demonstrated reduced image quality relative to free breathing respiration correlated CBCT and conventional ABC-CBCT. Image quality improved with increasing breath hold duty cycle (ratio of breath hold duration to free-breathing duration). The fast ABC-CBCT technique and free-breathing respiration correlated CBCT technique, while demonstrating reduced image quality relative to conventional ABC-CBCT, demonstrated no observable performance degradation for image guidance purposes for large and small high-contrast objects. Parameters significant to image guidance (registration accuracy and accuracy of the recorded gantry angle for a projection) were not observed to be affected by any of the scanning techniques relative to the conventional technique for high contrast targets.

TABLE VII. Scan time summary. BH: Breath hold time (s), FB: Free breathing time (s). All ABC-CBCT scan times include time spent during breath hold as well as during free breathing between breath holds. The RC-CBCT scan time includes time to acquire all projections for all breathing phases.

Breathing pattern	Total scan time (min)			Improvement (min)
	Fast ABC-CBCT	Conventional ABC-CBCT	RC-CBCT	Fast vs Conventional ABC-CBCT
3 s BH, 10 s FB	1.8	5.8		3.9
5 s BH, 10 s FB	1.6	2.8	2.2	1.3
10 s BH, 15 s FB	1.5	2.3		0.8

TABLE VIII. Dose per scan summary. Dose measurements taken per 1 mA s in a Perspex phantom with the bowtie filter. Dose values are scaled for 40 ms, 40 mA, and number of projections. BH: Breath hold time (s), FB: Free breathing time (s).

Breathing pattern	Total scan dose at surface (cGy)				Dose improvement (cGy)		
	Fast ABC-CBCT with kV gating	Fast ABC-CBCT without kV gating	Conventional ABC-CBCT	RC-CBCT	Fast (with kV gating) vs Conventional ABC-CBCT	Fast (with kV gating) vs RC-CBCT	Fast (without kV gating) vs RC-CBCT
3 s BH	0.79	4.45			1.81	4.56	0.90
15 s FB							
5 s BH	1.28	3.92	2.60	5.35	1.32	4.07	1.43
10 s FB							
10 s BH	1.54	3.65			1.06	3.81	1.70
15 s FB							

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¹J. M. Balter, R. K. Ten Haken, T. S. Lawrence, K. L. Lam, and J. M. Robertson, "Uncertainties in CT-based radiation therapy treatment planning associated with patient breathing," *Int. J. Radiat. Oncol., Biol., Phys.* **36**, 167–174 (1996).

²J.-J. Sonke, L. Zijp, P. Remeijer, and M. van Herk, "Respiratory correlated cone beam CT," *Med. Phys.* **32**, 1176–1186 (2005).

³P. Keall, "4-dimensional computed tomography imaging and treatment planning," *Semin. Radiat. Oncol.* **14**, 81–90 (2004).

⁴R. Zeng, J. A. Fessler, J. M. Balter, and P. A. Balter, "Iterative sorting for four-dimensional CT images based on internal anatomy motion," *Med. Phys.* **35**, 917–926 (2008).

⁵G. S. Mageras, A. Pevsner, E. D. Yorke, K. E. Rosenzweig, E. C. Ford, A. Hertanto, S. M. Larson, D. M. Lovelock, Y. E. Erdi, S. A. Nehmeh, J. L. Humm, and C. C. Ling, "Measurement of lung tumor motion using respiration-correlated CT," *Int. J. Radiat. Oncol., Biol., Phys.* **60**, 933–941 (2004).

⁶M. Guckenberger, M. Weininger, J. Wilbert, A. Richter, K. Baier, T. Krieger, B. Polat, and M. Flentje, "Influence of retrospective sorting on image quality in respiratory correlated computed tomography," *Radiother. Oncol.* **85**, 223–231 (2007).

⁷P. Giraud, E. Yorke, E. C. Ford, R. Wagman, G. S. Mageras, H. Amols, C. C. Ling, and K. E. Rosenzweig, "Reduction of organ motion in lung tumors with respiratory gating," *Lung Cancer* **51**, 41–51 (2006).

⁸C. Nelson, G. Starkschall, P. Balter, M. J. Fitzpatrick, J. A. Antolak, N. Tolani, and K. Prado, "Respiration-correlated treatment delivery using feedback-guided breath hold: A technical study," *Med. Phys.* **32**, 175–181 (2005).

⁹J. Pouliot, P. Xia, M. Aubin, L. Verhey, A. Bani-Hashemi, F. Ghelman-sarai, M. Mitschke, and M. Svatos, "Low-dose megavoltage cone-beam CT for dose-guided radiation therapy," *Int. J. Radiat. Oncol., Biol., Phys.* **57**, S183–S184 (2003).

¹⁰K. Sidhu, E. C. Ford, S. Spirou, E. Yorke, J. Chang, K. Mueller, D. Todor, K. Rosenzweig, G. Mageras, C. Chui, C. C. Ling, and H. Amols, "Optimization of conformal thoracic radiotherapy using cone-beam CT imaging for treatment verification," *Int. J. Radiat. Oncol., Biol., Phys.* **55**, 757–767 (2003).

¹¹D. Letourneau, J. W. Wong, M. Oldham, M. Gulam, L. Watt, D. A. Jaffray, J. H. Siewerdsen, and A. A. Martinez, "Cone-beam-CT guided radiation therapy: Technical implementation," *Radiother. Oncol.* **75**, 279–286 (2005).

¹²T. G. Purdie, J.-P. Bissonnette, K. Franks, A. Bezjak, D. Payne, F. Sie, M. B. Sharpe, and D. A. Jaffray, "Cone-beam computed tomography for on-line image guidance of lung stereotactic radiotherapy: Localization, verification, and intrafraction tumor position," *Int. J. Radiat. Oncol., Biol., Phys.* **68**, 243–252 (2007).

¹³T. Li, A. Koong, and L. Xing, "Enhanced 4D cone-beam CT with inter-phase motion model," *Med. Phys.* **34**, 3688–3695 (2007).

¹⁴T. Li and L. Xing, "Four-dimensional cone-beam computed tomography using an on-board imager," *Med. Phys.* **33**, 3825–3833 (2006).

¹⁵M. Guckenberger, R. A. Sweeney, J. Wilbert, T. Krieger, A. Richter, K. Baier, G. Mueller, O. Sauer, and M. Flentje, "Image-guided radiotherapy for liver cancer using respiratory-correlated computed tomography and cone-beam computed tomography," *Int. J. Radiat. Oncol., Biol., Phys.* **71**, 297–304 (2008).

¹⁶J. Chang, G. S. Mageras, E. Yorke, F. De Arruda, J. Sillanpaa, K. E. Rosenzweig, A. Hertanto, H. Pham, E. Seppi, A. Pevsner, C. C. Ling, and H. Amols, "Observation of interfractional variations in lung tumor position using respiratory gated and ungated megavoltage cone-beam computed tomography," *Int. J. Radiat. Oncol., Biol., Phys.* **67**, 1548–1558 (2007).

¹⁷S. B. Jiang, J. Wolfgang, and G. S. Mageras, "Quality assurance challenges for motion-adaptive radiation therapy: Gating, breath holding, and four-dimensional computed tomography," *Int. J. Radiat. Oncol., Biol., Phys.* **71**, S103–S107 (2008).

¹⁸J.-J. Sonke, J. Lebesque, and M. van Herk, "Variability of four-dimensional computed tomography patient models," *Int. J. Radiat. Oncol., Biol., Phys.* **70**, 590–598 (2008).

¹⁹V. R. Kini, S. S. Vedam, P. J. Keall, S. Patil, C. Chen, and R. Mohan, "Patient training in respiratory-gated radiotherapy," *Med. Dosim.* **28**, 7–11 (2003).

²⁰J. K. Wong, M. B. Sharpe, D. A. Jaffray, V. R. Kini, J. M. Robertson, J. S. Stromberg, and A. A. Martinez, "The use of active breathing control (ABC) to reduce margin for breathing motion," *Int. J. Radiat. Oncol., Biol., Phys.* **44**, 911–919 (1999).

²¹P. C. F. Cheung, K. E. Sixel, R. Tirona, and Y. C. Ung, "Reproducibility of lung tumor position and reduction of lung mass within the planning target volume using active breathing control (ABC)," *Int. J. Radiat. Oncol., Biol., Phys.* **57**, 1437–1442 (2003).

²²B. Gagel, C. Demirel, A. Kientopf, M. Pinkawa, M. Piroth, S. Stanzel, C. Breuer, B. Asadpour, T. Jansen, R. Holy, J. E. Wildberger, and M. J. Eble, "Active breathing control (ABC): Determination and reduction of breathing-induced organ motion in the chest," *Int. J. Radiat. Oncol., Biol., Phys.* **67**, 742–749 (2007).

²³R. Koshani, J. M. Balter, J. A. Hayman, G. T. Henning, and M. van Herk, "Short-term and long-term reproducibility of lung tumor position using active breathing control (ABC)," *Int. J. Radiat. Oncol., Biol., Phys.* **65**, 1553–1559 (2006).

²⁴N. Panakis, H. A. McNair, J. A. Christiana, R. Mendes, J. Richard, N. Symonds-Taylor, C. Knowles, P. M. Evans, J. Bedford, and M. Brada, "Defining the margins in the radical radiotherapy of non-small cell lung cancer (NSCLC) with active breathing control (ABC) and the effect on physical lung parameters," *Radiother. Oncol.* **87**, 65–73 (2008).

²⁵T. Li and L. Xing, "Optimizing 4D cone-beam CT acquisition protocol

- for external beam radiotherapy," *Int. J. Radiat. Oncol., Biol., Phys.* **67**, 1211–1219 (2007).
- ²⁶J. R. Sykes, A. Amer, J. Czajka, and C. J. Moore, "A feasibility study for image guided radiotherapy using low dose, high speed, cone beam X-ray volumetric imaging," *Radiother. Oncol.* **77**, 45–52 (2005).
- ²⁷D. H. Hristov and B. G. Fallone, "A grey-level image alignment algorithm for registration of portal images and digitally reconstructed radiographs," *Med. Phys.* **23**, 75–84 (1996).
- ²⁸A. Roche, G. Malandain, X. Pennec, and N. Ayache, "The correlation ratio as a new similarity measure for multimodal image registration," *Proceedings of the First International Conference on Medical Image Computing and Computer-Assisted Intervention*, Cambridge, MA, 11–13 October 1998, pp. 1115–1124.
- ²⁹M. van Herk and H. M. Kooy, "Automatic three-dimensional correlation of CT-CT, CT-MRI, and CT-SPECT using chamfer matching," *Med. Phys.* **21**, 1163–1178 (1994).
- ³⁰Y. Cho, D. J. Moseley, J. H. Siewerdsen, and D. A. Jaffray, "Accurate technique for complete geometric calibration of cone-beam computed tomography systems," *Med. Phys.* **32**, 968–983 (2005).
- ³¹D. G. Altman and J. M. Bland, "Measurement in medicine: The analysis of method comparison studies," *Statistician* **32**, 307–317 (1983).