Respiratory correlated cone beam CT

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A cone beam computed tomography (CBCT) scanner integrated with a linear accelerator is a powerful tool for image guided radiotherapy. Respiratory motion, however, induces artifacts in CBCT, while the respiratory correlated procedures, developed to reduce motion artifacts in axial and helical CT are not suitable for such CBCT scanners. We have developed an alternative respiratory correlated procedure for CBCT and evaluated its performance. This respiratory correlated CBCT procedure consists of retrospective sorting in projection space, yielding subsets of projections that each corresponds to a certain breathing phase. Subsequently, these subsets are reconstructed into a four-dimensional (4D) CBCT dataset. The breathing signal, required for respiratory correlation, was directly extracted from the 2D projection data, removing the need for an additional respiratory monitor system. Due to the reduced number of projections per phase, the contrast-to-noise ratio in a 4D scan reduced by a factor 2.6–3.7 compared to a 3D scan based on all projections. Projection data of a spherical phantom moving with a 3 and 5 s period with and without simulated breathing irregularities were acquired and reconstructed into 3D and 4D CBCT datasets. The positional deviations of the phantoms center of gravity between 4D CBCT and fluoroscopy were small: 0.13±0.09 mm for the regular motion and 0.39±0.24 mm for the irregular motion. Motion artifacts, clearly present in the 3D CBCT datasets, were substantially reduced in the 4D datasets, even in the presence of breathing irregularities, such that the shape of the moving structures could be identified more accurately. Moreover, the 4D CBCT dataset provided information on the 3D trajectory of the moving structures, absent in the 3D data. Considerable breathing irregularities, however, substantially reduces the image quality. Data presented for three different lung cancer patients were in line with the results obtained from the phantom study. In conclusion, we have successfully implemented a respiratory correlated CBCT procedure yielding a 4D dataset. With respiratory correlated CBCT on a linear accelerator, the mean position, trajectory, and shape of a moving tumor can be verified just prior to treatment. Such verification reduces respiration induced geometrical uncertainties, enabling safe delivery of 4D radiotherapy such as gated radiotherapy with small margins. © 2005 American Association of Physicists in Medicine. [DOI: 10.1118/1.1869074]

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I. INTRODUCTION

In the thoracoabdominal region, parts of the lung, liver, and other organs move appreciably due to breathing, influencing the accuracy of imaging, treatment planning, and delivery. Respiratory motion causes significant artifacts during three-dimensional (3D) computed tomography (CT) imaging, due to the interference of the scanning process and respiration. This affects delineation of anatomical structures and leads to erroneous position, shape, and volume information for the target or any other region of interest that is affected by such motion. In order to improve image quality, a number of centers have developed so-called respiratory-correlated CT (RCCT). By retrospectively sorting images obtained from an axial or helical CT scan using an external respiratory signal, a 4D CT dataset is obtained containing 3D CT images at multiple respiratory phases. RCCT reduces motion artifacts in CT images and provides respiratory motion information facilitating 4D radiotherapy.

In our hospital, we recently implemented a cone beam CT (CBCT) scanner integrated with a medical linear accelerator (Elekta Synergy, Elekta Oncology Systems Ltd., Crawley, West Sussex, United Kingdom). A CBCT guided linac allows contactless and fast localization of soft-tissue structures. Hence, such a machine is a powerful tool for image guided radiotherapy (IGRT). IGRT utilizes imaging equipment to provide images of the patients anatomy in the treatment position, just prior or at the time of treatment, to further increasing the accuracy and precision of the radiotherapy. Considerable respiratory motion, however, also induces artifacts in CBCT, while the RCCT procedures developed for axial and helical CT are not suitable for such CBCT scanners. The aim of this study is to develop a respiratory correlated CBCT procedure and to evaluate its performance.

II. MATERIALS AND METHODS

A. Cone beam CT scanner

The CBCT scanner consists of a conventional x-ray tube and an a-Si flat panel imager (FPI) mounted to the drum
structure of a linear accelerator. The central axis of the kilovoltage beam is perpendicular to the treatment beam, while the kilovoltage source and megavolt source share approximately the same center of rotation. The field of view of the FPI is 25.6 cm × 25.6 cm at the isocenter plane while projection data is recorded at a resolution of 512 × 512 pixels. The detector operates at a fixed frame rate of 2.7 fps while x-ray pulses are synchronized to the image acquisition such that the gantry rotation speed determines the number of projections per revolution. To acquire a 3D volume, the gantry is rotated over 360° for a full scan or 195° for a short scan. Lung cancer patients are scanned with a short scan protocol acquiring about 670 projections (given a maximally clinical acceptable scanning time of about 4 min the short scan protocol gives more projections per degree gantry rotation and consequently exhibits less view aliasing artifacts, especially in the 4D reconstructions described below). Projections are acquired using 120 kVp, 40 ma, and 25 ms, yielding an estimated imaging dose (based on phantom measurements) at the isocenter of about 1.9 cGy and a skin dose that varies between 0.6 and 3.4 cGy (depending on the position relative to the x-ray source trajectory; note that the relation of the scan parameters and the deposited imaging dose depends on the aperture of the beam, details in the design of the x-ray tube and the x-ray filtration applied). Gantry motion eccentricity is calibrated by acquiring a series of kilovolt projection images of a suspended ball bearing over a 360° gantry rotation, while the scan is calibrated to the linac’s isocenter using a series of megavolt portal images of the same ball bearing.

An in-house developed implementation of the Feldkamp-Davis-Kress filtered back projection algorithm recons 670 projection images into a 256³ volume (1 mm cubic voxel size) in about 41 s using a PC with a 2.8 GHz single Xeon processor, which is considerably faster than the data acquisition time. The code includes a correction algorithm to reduce lateral truncation artifacts (caused by objects extending outside the scan field of view) and a simple scatter correction algorithm based on our earlier work in portal dosimetry.

B. Respiratory signal

Respiratory correlated imaging requires a respiratory signal. A CBCT scanner acquires a series of 2D projection data, showing the internal anatomy, including the position of moving structures as a function of time. We have developed an algorithm that automatically extracts a breathing signal that directly corresponds to the motion of the diaphragm. In short, this method enhances diaphragmlike features in the individual x-ray images, projects these features on the cranio-caudal axis, combines all successive 1D projections to a 2D image, and extracts from this image the region with the most temporal variation. Finally, each 1D signal is aligned to the next, resulting in a sequence of displacements which represents the respiratory signal. This method relies on the fact that frame-by-frame changes in the cranio-caudal direction due to respiratory motion are considerably larger than changes due to gantry rotation. This signal does not describe true diaphragm displacements because it might track different parts of the diaphragm for different gantry angles and the projected amplitude of the displacement depends on the gantry angle. Hence, this signal is best suited for a phase-based sorting 4D reconstruction algorithm. The required momentary phase of the breathing signal was extracted using the Hilbert transform. Currently, the extraction of the breathing signal takes about 20 s on a PC with a 2.8 GHz single Xeon processor, although it is not yet optimized for speed. Preliminary evaluation on ten patients suggest that the algorithm is robust and reliable; only for one patient the extracted breathing signal for the lateral images was clearly inaccurate; the projected diaphragm shape in these lateral projections was strongly distorted by atelectasis which subsequently failed to be sufficiently enhanced.

C. Respiratory correlated reconstruction

The mathematical model of computed tomography relies on the fact that the scanned object is static. In case of respiratory motion, this condition is violated causing artifacts in the CT reconstruction. The type and magnitude of these motion artifacts are related to various scan parameters such as the relationship between the CT-data acquisition period and the respiratory cycle. For modern conventional and helical CT scanners, the rotation of the gantry is fast compared to the breathing cycle, such that a single slice of a 3D CT scan represents a certain respiratory phase, while different slices represent different respiratory phases. A 4D CT dataset can be obtained from a single CT scan by subsequently selecting the slices corresponding to a certain breathing phase.
For a CBCT integrated with a linac, the gantry rotation is slow compared to the breathing cycle. As a consequence, the reconstructed volume shows a blurring of the moving object within all slices, as depicted in Figs. 1(c) and 1(d). Hence, the slice selecting procedure described above does not work. Nevertheless, reconstructed volumes at multiple respiratory phases can be obtained by retrospective sorting in projection space. That is, cone beam projections are snapshots recorded with, e.g., 25 ms x-ray pulses representing a certain respiratory phase while different projections represent different respiratory phases. By sorting the breathing signal and the corresponding projections into several phase bins and subsequently feeding each subset of projections to the reconstruction algorithm, a 4D CBCT dataset is generated. For each breathing cycle, the projection closest to each breathing phase is selected. In case of breathing frequency irregularities, the selected projections will be distributed nonuniformly over the gantry sweep. In order to prevent artifacts, the projections are therefore weighted during the reconstruction by the gantry angle increment between projections to account for such irregularities. This respiratory correlated CBCT procedure resembles the approach described by Wang et al. for dynamic volumetric cardiac imaging using a fast rotating helical CBCT scanner. The reconstruction of a 4D volume based on 670 projection images takes about 67 s on a PC with a 2.8 GHz single Xeon processor including the time to extract the breathing signal. The computational load is dominated by the total number of processed projections and the number of voxels of the 3D volume. The reconstruction of eight instead of one 3D volume gives only a small overhead of 6 s.

D. Contrast resolution

The respiratory correlated reconstruction procedure described above, utilizes only one projection per breathing cycle to reconstruct a certain breathing phase. Given a scanning time of 4 min and breathing periods of 3–6 s, the number of projections per reconstructed phase is in the order of 40–80. In order to study the effect of a reduced number of projections on the contrast resolution of the reconstruction, we have scanned a contrast detail phantom using our clinical lung protocol described in Sec. II A. The phantom consists of a 20 cm diameter cylinder filled with demineralized water and low contrast cylindrical inserts (Gammex rmi, Middleton, WI) with electron densities relative to water \( \rho_{w} \) of 1.09, 1.02, 1.0, and 0.95. The phantom was reconstructed using all, \( \frac{1}{2} \), \( \frac{1}{4} \), \( \frac{1}{8} \), and \( \frac{1}{16} \) of all projections corresponding to gantry angle increments per projection \( \Delta \theta = 0.3^\circ \), 0.6°, 1.2°, 2.4°, and 4.8°, respectively. The contrast-to-noise ratio (CNR) as a function of the number of projections \( N \) was analyzed for the \( \rho_{w} = 0.95 \) cylindrical insert according to:

\[
\text{CNR}(N) = \frac{|\langle S(N) \rangle - \langle S_{w}(N) \rangle|}{\sigma(N)},
\]

where \( \langle S \rangle \) and \( \langle S_{w} \rangle \) denote the average signal within a region of interest for the cylindrical insert and water, respectively, and \( \sigma \) denotes the standard deviation within the cylindrical insert. Theoretically, the CNR is proportional to the square root of the dose, while the dose scales linearly with the number of projections.
E. Phantom study

We have performed validation measurements on a spherical polystyrene phantom (diameter 5 cm) moving with a 3 or 5 s period and an excursion of 2.5 cm in the longitudinal [superior-inferior (SI)] direction and 2.0 cm in the vertical [anterior-posterior (AP)] direction. The electromotor driving the phantom was also connected to a continuous potentiometer providing a phase signal. This signal was digitized and fed to a PC, which changed the voltage of the electromotor and thus the speed of the phantom as a function of phase, creating nonsinusoidal motion. Additionally, the PC controlled a traversing table, introducing random Gaussian positional deviations for the peak-inhale phase with zero mean and 6 mm standard deviation simulating breathing irregularities. No positional deviations were introduced for the peak-exhale phase, while the positional deviations were linearly interpolated for the intermediate phases. The phantom was scanned without the treatment couch in the beam using our lung protocol described in Sec. II A acquiring about 670 frames in about 4 min. For each scan, a 4D data set was reconstructed containing eight phases: peak-exhale, early-inhale, mid-inhale, late-inhale, peak-inhale, early-exhale, mid-exhale and late-exhale. Given 670 acquired frames, a frame rate of 2.7 fps and a 3 s motion period, each phase was reconstructed using 83 projections (gantry angle increment $\Delta \theta=2.4^\circ$), while each phase bin covers $360^\circ/(3 \times 2.7)=45^\circ$ of the motion (assuming sinusoidal motion). Projections outside this bin, however, could be selected if for a certain breathing cycle no projection within the bin was available. For the 5 s motion period, each phase was reconstructed using $\sim$50 projections ($\Delta \theta=4.0^\circ$) while each phase bin covers $\sim27^\circ$ of the motion. As a reference, we have also recorded sagittal fluoroscopic projections (regular motion only), i.e., with a stationary gantry position. Additionally, we have scanned the phantom statically at positions corresponding to peak-exhale, mid-exhale, and peak-inhale.

F. Patient cases

Currently, patients treated at our CBCT equipped linac are routinely scanned and reconstructed in 3D for an off-line shrinking action level set-up verification protocol based on bony anatomy. From our clinical database, we have selected three lung cancer patients with considerable tumor motion in the middle or lower lobe. All three patients were scanned according to the protocol described in Sec. II A. Subsequently, a 3D volume and a 4D volume (eight phases) were reconstructed.
III. RESULTS

A. Contrast resolution

Figure 2 depicts a schematic representation of the contrast detail phantom and its reconstructions based on different number of projections \(N\). The inserts with electron density \(e_w = 0.95\) and \(e_w = 1.1\) can be easily recognized in all reconstructions. The inset with \(e_w = 1.02\) can be just recognized for the reconstructions based on \(N = 670\), \(N = 335\), and \(N = 168\). For \(N = 84\) and \(N = 42\), the streak artifacts induced by view aliasing hamper the recognition of this inset. These streak artifacts originated from the treatment couch on which the phantom was positioned. Figure 3 shows the CNR analyzed for the \(e_w = 0.95\) insert as a function of the number of projections. Through the data points a curve of the form \(a\sqrt{N} + b\) was fitted,\(^{30}\) describing the theoretical relationship between CNR and the number of projections. Deviations of the data from the fitted curve indicate there were additional sources of noise such as view aliasing artifacts. The data shows that by reducing the number of projections to values typically for a single phase of a 4D CBCT scan (between 40 and 80) the CNR reduced by a factor of 3.7 to 2.6 compared to a 3D scan based on all projections.

B. Phantom study

Figure 4 shows the displacements of the spherical phantom obtained from fluoroscopy for the 3 and 5 s period in the superior-inferior direction for the regular motion (grey curves) and irregular motion (black curves). Due to the simplicity of the control system, the motion period of the phantom varied slightly over time and between experiments. Inspection reveals the asymmetry of the motion pattern (63% inhale-to-exhale versus 37% exhale-to-inhale) and gives an indication of the simulated breathing irregularities. The CBCT scanning time is approximately twice as long as the fluoroscopic data shown here.

Figure 5 depicts the central sagittal slice of the 3D CBCT and eight phases of the 4D CBCT reconstruction of the spherical phantom moving regularly with a period of 5 s. The motion blurring, present in the 3D reconstruction, was almost completely removed in the 4D reconstruction, revealing the shape of the moving phantom obscured in the 3D data. The 4D data also reveals the phantoms trajectory.

The positions of the sphere’s center of gravity (COG) in the 4D CBCT data for both the 3 and 5 s period and the regular as well as the irregular motion have been compared.
with the fluoroscopic data as shown in Fig. 6. The 4D CBCT COGs are positioned closely to the trajectory obtained from fluoroscopy for all four data-sets, with a mean distance of 0.13±0.09 mm (SD) for the regular motion and 0.39±0.24 mm for the irregular motion. The irregularity of the motion hardly influenced the COGs position. The trajectory measured from the 4D CBCT data, however, is slightly smaller than measured from fluoroscopy due to the averaging within each phase bin in the respiratory correlated CBCT reconstruction procedure. Moreover, this also gave rise to phase-shifts toward the slower part of the trajectory compared to the predicted phase from fluoroscopy (dashed lines) for those phase bins describing parts of the curve with a nonlinear phase-time relationship. That is, slower parts of the trajectory within a phase bin were more likely to be imaged. This is more apparent for the shorter 3 s period where the phase bins were wider. (A similar effect is expected for RCCT.) Additionally, the frame rate of the imager was too low to accurately sample the nonsinusoidal motion. This gave rise to aliasing and inaccuracies of the extracted phase signal using the Hilbert transform. This is most apparent for the 3 s early-inhale phase.

Figures 7 and 8 show the central sagittal and transverse slices of the spherical phantom in the peak-inhale, mid-exhale, and peak-inhale phase/position for static situation, both for the 3 and 5 s period and the regular as well as the
irregular motion. For the peak-exhale phase, where the phantom moved slowly, the reconstructions of the moving phantom show a close correspondence with reconstruction of the static phantom for all four scans. The sagittal slices of the mid-exhale phases, reveal the effect of residual motion, i.e., by sorting the projections into a limited number of phase bins, some variability in the position of the phantom will remain in each phase of the 4D data resulting in remnants of blurring of the phantom in the direction of motion within that phase bin. This is most apparent for the phases representing the position where the phantom had the highest speed. For the 3 s motion period, residual motion dominated the effect of irregular motion. This irregularity effectively had a 3 mm SD half way between inhale and exhale, due to the linear interpolation of the irregularity. For the 5 s motion period a small reduction of image quality due to irregular motion is noticeable. Sagittal and transverse slices of the peak-exhale phase clearly show that the irregular trajectory reduced the image quality of the reconstructions for both the 3 and the 5 s motion period. The respiratory correlated CBCT procedure is based on the assumption that a certain phase of the breathing cycle corresponds with a certain position in the trajectory of a moving object. For the irregular motion this assumption is violated. Inspection of the transverse slices shows that data inconsistency caused more streak artifacts in the transverse slices than view aliasing (low number of projections). That is, in the peak-exhale and peak-inhale phases, where the residual motion was mostly in the transverse plane, streak artifacts are more pronounced than in the mid-exhale phase. Moreover, for all phases, streak artifacts are similar or more pronounced for the 3 s period than for the 5 s period despite the fact that the 3 s period phases are based on more projections than the 5 s period phases (see Sec. II E).

C. Patient cases

Figure 9 shows the extracted breathing signal for the three patients, where the maxima represent the peak-exhale phase and the minima represent the peak-inhale phase. The average breathing cycle analyzed on the basis of the inhale peaks equals 3.3±0.2 s (1 SD) for patient I, 6.2±1.4 s for patient II, and 4.2±1.4 s for patient III. As already stated in Sec. II B, the extracted breathing signal does not describe true displacements. Nevertheless, Fig. 9 suggests that the breathing patterns of patients I and II were reasonably regular in amplitude while for patient III the amplitude was highly variable. It should be noted that such severe breathing irregularities are rare.

Figures 10–12 show sagittal, coronal, and transverse slices of the 3D data as well as for the respiratory phases peak-exhale, mid-inhale, peak-inhale, and mid-exhale of the 4D data for patients, I, II, and III, respectively. The 4D scans were reconstructed using 75, 40, and 51 projections per breathing phase, on average corresponding to $\Delta \theta = 2.7^\circ, 5.0^\circ, \text{and } 3.9^\circ$ gantry angle increment per projection. The white dashes in each view identify the displayed slices in the corresponding views. The dashed lines in the coronal and sagittal views are drawn as a reference to appreciate the motion of the tumor in the 4D scan. The tumor motion in the left-right-, SI-, and AP-direction measured from the 4D scans was $0.2, 1.2, 0.2$ cm, $0.0, 1.9, 0.4$ cm, $0.1, 1.7, 0.3$ cm.
for patients I, II and III, respectively. The estimated gross tumor volumes were 35 cm$^3$ (patient I), 171 cm$^3$ (patient II), and 34 cm$^3$ (patient III).

The resulting patient data are inline with the results obtained from the moving spherical phantom. In the 4D scans of patients I and II, having a reasonable regular breathing pattern, motion artifacts are reduced considerably such that the shape of the moving structures can be identified more accurately and the scan provides information on the trajectory of these structures, absent in the 3D data. Furthermore, the irregular breathing pattern of patient III, as observed in Fig. 9, reduces the image quality of the peak-inhale phase in Fig. 12. In contrast to the phantom measurements, however, where residual motion artifacts dominated view aliasing artifacts, view aliasing artifacts in the patients data originating from the treatment couch (vertical lines in the coronal and sagittal plane) and high contrast anatomy seem to dominate the residual motion artifacts from the moving anatomy. That is, the 4D scans of patient I, based on the highest number of projections exhibits the highest image quality.

Figure 13 shows the profiles along the intersection of the coronal and sagittal planes shown in Figs. 10–12. Clearly, the contrast increased considerably and boundaries of the tumor are better defined in the 4D scans. Only for the peak-inhale phase of patient III, contrast and tumor boundaries decreased due to breathing irregularities. Again tumor displacement during the respiratory cycle can be identified.

IV. DISCUSSION

In this paper, a procedure has been described to obtain a 4D data using a CBCT scanner integrated with a linear accelerator. The number of slices of modern multi-slice CT scanners are increasing rapidly, more and more approaching a CBCT geometry. These scanners, however, have a fast rotating gantry and therefore, the RCCT procedures developed for single and multislice CT scanners are more applicable to obtain 4D CT data with such scanner types.

Respiratory motion induces blurring of moving structures in a 3D CBCT scan. For an object with a homogeneous density in a homogeneous background with different density, such a blurred object represents the coverage probability. In case of an inhomogeneous object and/or background, however, one cannot distinguish between coverage probability and inhomogeneities. Therefore, a 4D CBCT scan is required to identify the shape and mean position of a moving object.

In this paper, the effect of irregularities in breathing amplitude on the image quality of 4D CBCT was evaluated. It is interesting to note that, despite the detrimental effect of these irregularities on the image quality, the introduced blurring represents in a way the uncertainty in the position of the irregular moving object for a certain breathing phase. Breathing irregularities can also occur with respect to frequency and distribution of phases over the breathing cycle. Although the image quality of 4D CBCT depends on the respiratory frequency and temporal phase distribution, as demonstrated in this paper, the phase based sorting approach is not inconsistent with irregularities regarding these parameters and therefore will not introduce additional artifacts. Hence, these irregularities were not evaluated in this study. All types of irregularities (amplitude, frequency, temporal phase distribution), however, are relevant for various types of 4D RT de-
elivery and should accordingly be measured, evaluated and taken into account in the treatment planning process and/or corrections strategies.

With respiratory correlated CBCT on a linear accelerator, a 4D patient model can be generated just prior to treatment, reducing systematic errors due to imaging and random errors due to interfraction variations (when using an online setup protocol). Random errors due to intrafraction variations, however, cannot be eliminated by this method. First, changes in respiratory motion pattern during scanning introduce artifacts as illustrated in, e.g., Fig. 7. Second, changes after scanning introduce discrepancies between the constructed 4D patient model and the actual patient. Large geometrical uncertainties, however, are not expected given the fact that the patient model is obtained only a few minutes before treatment. Nevertheless, a further refinement might be possible by updating the patient model using fluoroscopic data acquired during actual treatment or by acquiring another scan after dose delivery.

As already stated, patients currently treated at our CBCT equipped linac are routinely scanned and reconstructed in 3D for an off-line shrinking action level set-up verification protocol. This involves matching the bony anatomy in the CBCT scan to the bony anatomy on the planning CT. Currently, we are evaluating a revised protocol for lung cancer patients in which the bone match is followed by a manual alignment of the 4D CBCT to the planned PTV contours. This protocol aims at reducing respiratory induced systematic uncertainties. Therefore, this protocol will still be off line, on average imaging a third of all fractions involving an isocentric imaging dose that is about a fifth of the imaging dose of an off-line portal imaging based protocol. It was demonstrated that very subtle contrast differences are difficult to detect in the 4D CBCT data. The proposed protocol is therefore more suited for well-defined tumors and to a lesser extent for tumors with mediastinal involvement. Fortunately, these tumors also exhibit less respiratory induced motion.

4D CBCT data exhibits view aliasing artifacts due to the limited number of projections acquired per breathing phase. Techniques to alleviate the effects of view aliasing artifacts are described in the literature for axial and helical CT scans such as the intermediate view reprojection method, involving estimates of a set of intermediate views by reprojection followed by a reconstruction using these views, and the error-corrections method, incorporating a correction on the initial reconstruction based on the projection-domain error. We will investigate the applicability of these techniques for CBCT. Alternatively, view aliasing artifacts can be reduced by reducing the gantry-rotation speed even further or by reducing the spatial resolution. Hence, choice of respiratory correlated CBCT parameters involves a trade-off between dose, scanning time, temporal resolution, spatial resolution and image quality. Note that increasing the frame rate of the kilovolts imager does not decrease view aliasing artifacts as only one projection per breathing cycle is used for each breathing phase. Residual motion artifacts, however, will be reduced because the width of each phase bin will reduce proportionally to the increase of the frame rate.

Different methods to register the respiratory signal have been reported for 4D CT reconstruction such as an external

![Profiles along the intersection of the coronal and sagittal planes shown in Figs. 10–12. In the 4D scans, the contrast is considerably higher and boundaries of the tumor are better defined.](image)

**Fig. 13.** Profiles along the intersection of the coronal and sagittal planes shown in Figs. 10–12. In the 4D scans, the contrast is considerably higher and boundaries of the tumor are better defined.
marker combined with an infrared camera\textsuperscript{10,11} or the use of a small thermometer to measure the temperature difference between inhaled and exhaled air.\textsuperscript{25} Given the 2D projection data of a CBCT system, the breathing signal can be directly extracted from the moving internal structures, thus removing the need for such additional respiratory monitor systems and the need to synchronize them with 4D CBCT acquisition. Additionally, no uncertainty in the data is introduced regarding possible phase shifts between external signals and internal motion.

4D CBCT data can be used to validate and refine the 4D patient model used for 4D RT such as gating. Such treatment techniques require the online measurement of a respiratory signal. Currently, we are investigating the use of the kilovolts imaging system combined with breathing extraction software to measure the respiratory signal for such applications as well.

V. CONCLUSIONS

We have developed a respiratory correlated cone beam CT procedure without an external respiratory sensor yielding a 4D dataset. Results obtained from phantom and patient data showed that motion artifacts in such a 4D CBCT dataset were substantially reduced compared to a 3D CBCT scan, even in the presence of irregular respiration. Moreover, with respiratory correlated CBCT on a linear accelerator, the mean position, trajectory, and shape of a moving tumor can be verified just prior to treatment. Such verification eliminates systematic errors due to imaging and enables safe delivery of 4D radiotherapy such as gated RT with small margins.

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