On-the-Fly Motion-Compensated Cone-Beam CT Using an a Priori Motion Model

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Abstract. Respiratory motion causes artifacts in slow-rotating cone-beam (CB) computed tomography (CT) images acquired for example for image guidance of radiotherapy. Respiration-correlated CBCT has been proposed to correct for the respiratory motion, but the use of a subset of the CB projections to reconstruct each frame of the 4D CBCT image limits their quality, thus requiring a longer acquisition time. Another solution is motion-compensated CBCT which consists of reconstructing a single 3D CBCT image at a reference position from all the CB projections by using an estimate of the respiratory motion in the reconstruction algorithm. In this paper, we propose a method for motion-compensated CBCT which allows to reconstruct the image on-the-fly, i.e. concurrent with acquisition. Before the CB acquisition, a model of the patient motion over the respiratory cycle is estimated from the planning 4D CT. The respiratory motion is then computed on-the-fly from this model using a respiratory signal extracted from the CB projections and incorporated into the motion-compensated CBCT reconstruction algorithm. The proposed method is evaluated on 26 CBCT scans of 3 patients acquired with two protocols used for static and respiration-correlated CBCT respectively. Our results show that this method provides CBCT images within a few seconds after the end of the acquisition where most of the motion artifacts have been removed.

1 Introduction

Recently, cone-beam (CB) computed tomography (CT) scanners have been integrated with linear accelerators to acquire 3D images of the patient during the fractions of the radiotherapy treatment. These CBCT images allow to correct for the tumor misalignments and, if necessary, to adapt the treatment plan. However, respiratory motion causes artifacts in the thoracic and upper abdominal regions, such as blur and streaks, which can disturb the extracted information.

A first solution to account for the respiratory motion is respiration-correlated CBCT imaging which consists in sorting the CB projections using a respiratory signal depending on their position in the respiratory cycle [1]. Each subset of CB projections is then used to reconstruct a 3D image (or frame) representing one phase of the respiratory cycle, thus obtaining a 4D image over the respiratory

D. Metaxas et al. (Eds.): MICCAI 2008, Part I, LNCS 5241, pp. 729–736, 2008.
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cycle. This approach has been successfully implemented clinically in our institution [2] but the use of only a subset of the CB projections to reconstruct each frame limits the image quality due to view-aliasing artifacts. These artifacts were reduced by slowing down the gantry rotation from 200°/min to 50°/min but this caused a longer acquisition time (4 min instead of 1 min) while view-aliasing was still present. Even longer acquisition times were not feasible in clinical practice.

Another solution is to compensate for the respiratory motion in the reconstruction. The non-rigid motion of the patient during the acquisition is estimated and used in the reconstruction algorithm to obtain a 3D CBCT image at a reference position using all the CB projections [3]. It has been shown on simulated data that this method can correct for the respiratory motion without view-aliasing artifacts [3], but the motion estimation on real CB projections is still a challenge. Several solutions have been proposed [4] but their computational cost has prevented the use of motion-compensated CBCT concurrent with acquisition.

In this paper, we propose a solution for on-the-fly motion-compensated CBCT reconstruction. Before acquisition, we estimate a model of the patient motion over the respiratory cycle from a 4D CT image acquired on a conventional scanner. The estimated motion model allows estimation of the respiratory motion from the CB projections on-the-fly, i.e. concurrent with acquisition, using a respiratory signal extracted from the CB projections. The estimated motion is then used in a motion-compensated CBCT reconstruction algorithm. The proposed method is evaluated on patient images and compared to non-corrected and respiration-correlated CBCT images.

2 Method

The complete method is summarized in Fig. 1. Each step is described in detail below.

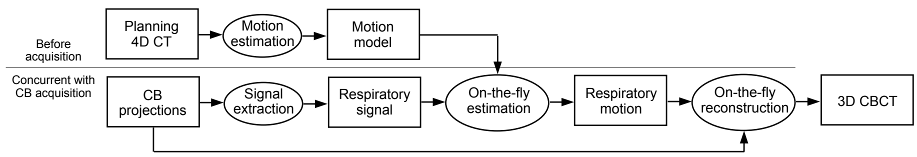

Fig. 1. Flow chart description of the method. Rectangles represent data and ellipses represent processes.

2.1 Motion Model of the Respiratory Cycle

A model of the patient motion over the respiratory cycle was built from the 4D CT image obtained for each patient on a multislice spiral CT scanner. This 4D CT image is acquired approximately 2 weeks prior to the the first treatment fraction and used for the treatment planning. A phase-based optical flow method

[5] adapted for thoracic images [6] was used to estimate the 3D deformation vector fields (DVF) from the end-exhale frame to the other frames of the planning 4D CT. We obtained thus a 4D motion model described by a 4D DVF which represents the piece-wise linear motion of each voxel over the respiratory cycle described by the planning 4D CT image. The average 3D DVF over the frames was subtracted from each frame of the 4D DVF to use the mean position as a reference.

2.2 On-the-Fly Extraction of the Respiratory Signal

The respiratory signal was extracted from the CB projections as implemented previously for on-the-fly respiration-correlated CBCT [2]. Each CB projection was processed to enhance the diaphragm with a derivative filter in the cranio-caudal direction and projected on the cranio-caudal axis in a 1D signal. The concatenation of these 1D signals for a few projections gives a 2D image from which the respiratory signal can be extracted with a linear correlation of adjacent columns.

2.3 On-the-Fly Motion Estimation

The on-the-fly motion estimation assumes that the motion over all the respiratory cycles during the acquisition of the CB projections is identical to the motion described by the planning 4D CT. This approximation is based on the observed stability of the shape of the tumor trajectory from fraction to fraction in a large set of patients [7]. A limited number of parameters remains then to be estimated.

First, each voxel of the CBCT image must be linked to a point of the planning CT. This was done by taking into account the rigid transformation from the coordinate system of the planning CT scanner to the one of the CBCT scanner. We thus assume that anatomical changes and patient setup errors do not significantly affect the motion estimation based on the smoothness of the vector fields in the lungs. This assumption was evaluated by comparing the motion-compensated CBCT images reconstructed with and without correcting for the setup error retrospectively measured with a rigid registration of the non-corrected CBCT image on the planning CT image.

Second, the respiratory displacement of each voxel must be known for each CB projection. This was computed from the motion model by interpolating a 3D DVF from the 4D DVF depending on the respiratory phase value.

2.4 On-the-Fly Reconstruction Algorithm

The reconstruction algorithm was similar to that proposed by [3], i.e. motion compensation based on the local application of the Feldkamp algorithm [8]. The only difference with the static filtered backprojection algorithm of Feldkamp *et al.* is that the backprojection is no longer performed along the straight acquisition lines corresponding to X-rays but along the curved lines corresponding to the acquisition lines warped from the acquisition position to the reference position with the estimated motion (Fig. 2). A high-speed version of the algorithm

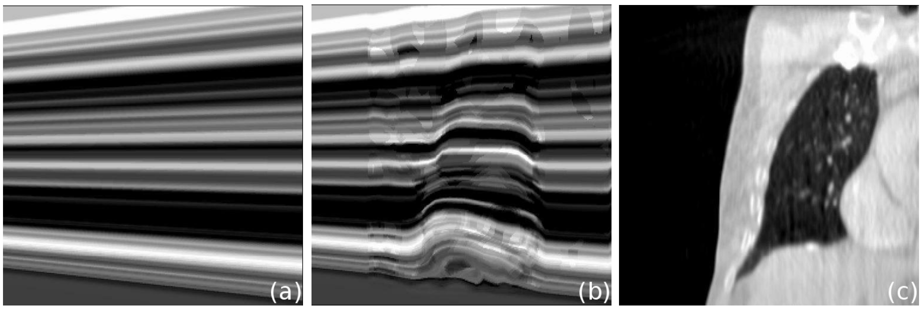

Fig. 2. Coronal slice of one backprojection acquired at end-inhale with the panel perpendicular to the left-right axis in (a) the static case and (b) the motion compensated case. (c) Corresponding slice of the motion-compensated CBCT image of the mean position.

was implemented by optimizing the computation and the memory management and by approximating the respiratory motion in the cranio-caudal direction with a piece-wise linear vector field.

3 Experiments

3.1 Datasets

Three patients were retrospectively selected based on the substantial motion of their lung tumor compared to its volume. For each patient, 3 sets of CB projections were acquired during 3 different fractions using the Elekta Synergy system (Elekta Oncology Systems Ltd., Crawley, West Sussex, UK). Two different gantry rotation speeds were used, a slow acquisition (200° in 4 min), currently used for respiration-correlated CBCT, and a fast acquisition (200° in 1 min), currently used for static CBCT. Table 1 summarizes for each patient the tumor characteristics and the number of scans. Besides the acquisition time, the acquisition and geometric parameters were similar for all acquisitions: X-ray tube: 120 kV, 40 ms and 16 mA; flat-panel: 5.5 fps, 41×41 cm^2, 512×512 pixels; source-to-isocenter distance: 100 cm and source-to-panel distance: 154 cm.

Table 1. Tumor characteristics of the 3 patients and number of scans acquired per protocol

	Gross tumor volume (cm^3)	Cranio-caudal tumor motion amplitude (cm)	Number of scans	
			4 min	1 min
Patient 1	6	1.1	3	6
Patient 2	10	2.5	3	6
Patient 3	31	1.9	5	3

3.2 Reconstructed CBCT Images

For each set of CB projections, four different CBCT images were reconstructed: the non-corrected 3D CBCT image (reconstructed as in the static case), the respiration-correlated 4D CBCT image and two motion-compensated 3D CBCT images, with and without a setup error correction for the motion estimation (Sec. 2.3). The 3D CBCT images were reconstructed at a 256^3 grid with 1-mm^3 voxel size and the 4D CBCT images were reconstructed in 10 equidistant phases at a 128^3 grid with 2-mm^3 voxel size.

3.3 Image Analysis

Reconstructed CBCT images were analyzed in two groups depending on the acquisition protocol used for the acquisition (4 min vs. 1 min). Two different criteria were used.

Image quality. The image quality was evaluated relative to the planning CT within a shaped region-of-interest (ROI) manually drawn on the mean position 3D CT to encompass the tumor. The mean position 3D CT was obtained from the planning 4D CT by averaging the frames after warping them to the mean position of each voxel with the estimated motion model. The resulting CT was rigidly registered on each reconstructed CBCT image (or each frame for the 4D CBCT images) using the correlation ratio in the ROI as a similarity measure. After registration, the correlation ratio in the ROI was used to evaluate quantitatively the image quality of reconstructed CBCT images compared to the planning CT. For a fair comparison, all 3D CBCT images were downsampled at a 128^3 grid before performing this evaluation.

Tumor position error. The ROI registration described above is currently used clinically with respiration-correlated 4D CBCT images to correct the position of the patient before the treatment by computing the time-weighted average of the registrations of the tumor in each frame [7]. We compared the position obtained with respiration-correlated 4D CBCT images (reference) with the position obtained with the non-corrected and motion-compensated 3D CBCT images by measuring the Euclidian distance of the misalignment processed by the ROI registration.

4 Results

Fig. 3 shows coronal slices of reconstructed CBCT images of a same patient with two different sets of CB projections, one with the 4 min protocol and the other with the 1 min protocol. For both protocols, the blur induced by the respiratory motion is clearly visible on non-corrected CBCT images around the tumor (center of the slice) and the diaphragm (bottom of the slice). This blur is substantially reduced on respiration-correlated CBCT images but the images are then degraded by view-aliasing artifacts, particularly with the 1 min protocol, as

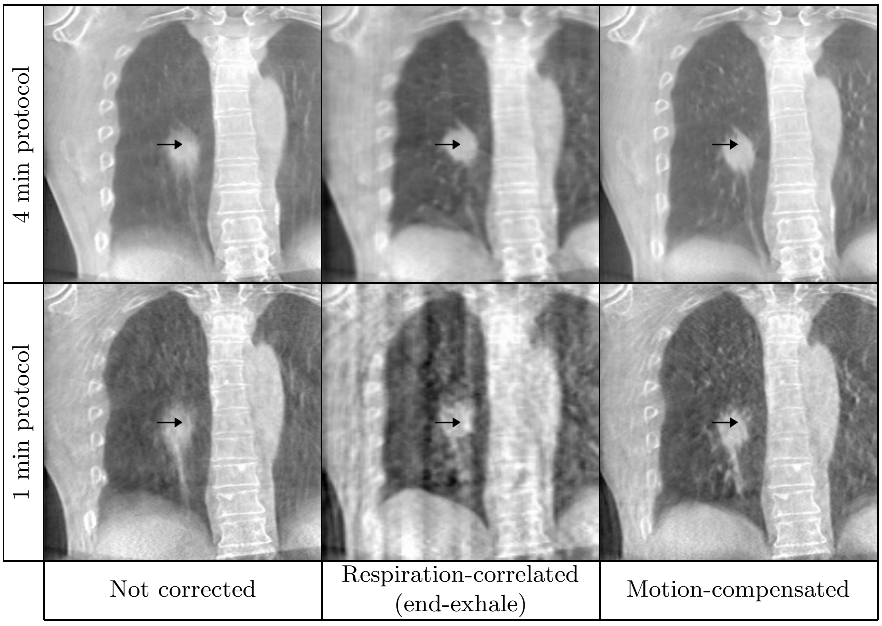

Fig. 3. Coronal slices of reconstructed CBCT images from sets of CB projections acquired with the two different protocols. The motion-compensated CBCT images have been reconstructed without taking into account the setup error. Arrows indicate the isocenter, i.e. the tumor location.

only around 10% of the CB projections are used to reconstruct each frame of the 4D CBCT. Finally, motion-compensated CBCT allows removal of most of the motion artifacts without degradation of the image quality with both protocols.

Fig. 4 depicts the quantitative results. In terms of image quality in the shaped ROI, respiration-correlated CBCT only improves the result with the 4 min acquisition protocol compared to non-corrected CBCT, whereas motion-compensated CBCT improves the image quality with both protocols. Motion-compensated CBCT images reconstructed with the 1 min protocol even have a quality comparable to respiration-correlated CBCT images reconstructed with the 4 min protocol. On average, the distance from the tumor position registered with the respiration-correlated CBCT image was higher with the non-corrected CBCT image (1.9 mm/1.3 mm with the 4 min/1 min protocol) than with the motion-compensated CBCT images (0.4 mm/0.6 mm with the 4 min/1 min protocol). No substantial difference was observed in the ROI between the motion-compensated CBCT images reconstructed with and without setup error correction for the motion estimation.

Computation times were estimated on a desktop computer (dual-core Pentium 4 3.2 GHz station with 3.5 GB RAM). The pre-acquisition part, i.e. the estimation of the motion vector fields of the motion model, took around 3 hours. The per-acquisition part, i.e. the on-the-fly motion estimation and image

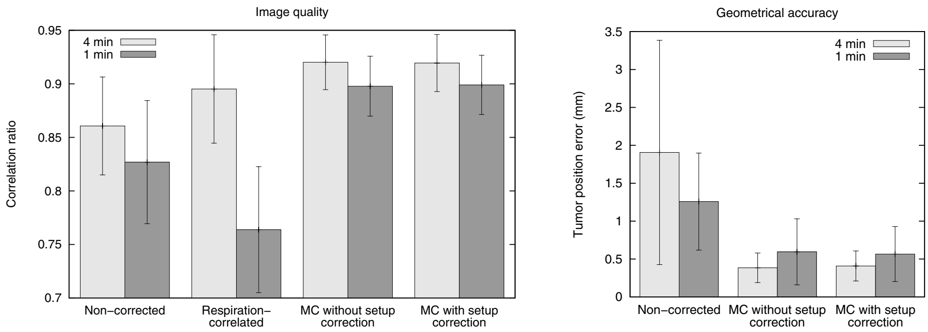

Fig. 4. Average of quantitative criteria over all 4 min and 1 min scans with plus or minus one standard deviation error bars. Left: image quality measured with the correlation ratio between the reconstructed CBCT images and the planning CT image in a shaped ROI encompassing the tumor. Right: tumor position accuracy measured with the respiration-correlated CBCT image as a reference.

reconstruction, took on average 230 s/67 s for the 4 min/1 min protocol (to process the 1360/370 CB projections), i.e. within the order of the acquisition time, such that on-the-fly implementation is possible.

5 Discussion and Conclusion

In this work, we proposed a motion-compensated CBCT method which is suitable for on-the-fly reconstruction, and evaluated it on several CB acquisitions acquired on 3 patients with two different protocols. To minimize the computational time during the acquisition, the patient motion was estimated based on a model computed from the planning 4D CT which was supposed to be still valid for all the respiratory cycles during the CB acquisition. We thus assumed that the respiratory cycle is stable both inter- and intra-fractions. Although this seems to be a strong approximation, the visual (Fig. 3) and quantitative (Fig. 4) results indicate that most of the respiratory artifacts are still corrected. This confirms previous observations of good inter-fraction motion stability measured on respiration-correlated CBCT images which also assumes no intra-fraction variability [7].

The comparison between the two CB acquisition protocols highlights the advantages of motion-compensated CBCT compared to respiration-correlated CBCT. Indeed, the image quality of respiration-correlated CBCT images acquired with a 1 min protocol is not acceptable for clinical applications due to the low number of CB projections per frame subset. The induced view-aliasing artifacts made us change the protocol to a 4 min acquisition. In comparison, the motion-compensated method produces CBCT images with the 1 min protocol where the respiratory motion artifacts are reduced without loss of image quality because all the CB projections are used to correct a single 3D CBCT image.

The proposed method can only be used on-the-fly, i.e. concurrent with the acquisition of the CB projections, if the patient setup error is neglected for the motion estimation because the setup error is usually measured from the reconstructed CBCT image. The quantitative comparison indicates no appreciable improvement when the setup error was taken into account (Fig. 4) which can be explained by the observed smoothness of the vector fields in the lungs. Combined with the fast reconstruction time, ignoring the setup error allows then to have the motion-compensated CBCT image available within a few seconds after the end of the acquisition, keeping thus an important advantage of our current implementation of static and respiration-correlated CBCT. Lower image quality should nevertheless be expected for tumors near the lung walls where the gradient of the vector fields is higher due to the so-called sliding tissue effect. The setup error could then be measured from the non-corrected image and a new reconstruction performed, in which case the time gained by using the 4 min protocol instead of the 1 min one would be partially lost but other advantages kept.

Future work will include validation on more patients as well as more elaborated motion estimation or reconstruction methods to improve the image quality off-line (outside the fractions). The degradation of the image quality due to a wrongly estimated respiratory motion will also be evaluated quantitatively on simulated data.

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