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Respiratory motion

# Comparative study of respiratory motion correction techniques in cone-beam computed tomography

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ABSTRACT

*Background and purpose:* To validate the clinical usefulness of motion-compensated (MC) cone-beam (CB) computed tomography (CT) for image-guided radiotherapy (IGRT) in comparison to four-dimensional (4D) CBCT and three-dimensional (3D) CBCT.
*Material and methods:* Forty-eight stereotactic body radiation therapy (SBRT) patients were selected. Each patient had 5–12 long CB acquisitions (4 min) and 1–7 short CB acquisitions (1 min), with a total of 349 and 150 acquisitions, respectively. 3D, 4D and MC CBCT images of every acquisition were reconstructed. Image quality, tumor positioning accuracy and tumor motion amplitude were quantified.
*Results:* The mean image quality of long short acquisitions, measured using the correlation ratio with the planning CT was 74%/70%, 67%/47% and 79%/74% for 3D, 4D and MC CBCT, respectively; both 4D and MC CBCT were corrected for respiratory motion artifacts but 4D CBCTs suffered from streak artifacts. Tumor positioning with MC CBCT was significantly closer to 4D CBCT than 3D CBCT ($p < 0.0001$). Detailed patient analysis showed that motion correction was not required for tumors with less than 1 cm motion amplitude.
*Conclusions:* 4D and MC CBCT both allow accurate tumor position analysis under respiratory motion but 4D CBCT requires longer acquisition time than MC CBCT for adequate image quality. MC CBCT can therefore advantageously replace 4D CBCT in clinical protocols for patients with large motion to improve image quality and reduce acquisition time.
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Image-guided radiotherapy (IGRT) has been a rapidly growing field of this past decade [1]. Among other techniques, cone-beam (CB) computed tomography (CT) has been developed to improve the localization of treatment targets [2]. This is particularly important in stereotactic treatments which deliver high doses in a very few fractions [3]. One difficulty is the respiratory motion which causes blur and streaks in CBCT images around moving organs and limits the accuracy of tumor positioning.

Respiratory motion artifacts have been an early concern in the development of CBCT scanners for IGRT and have led to the development of several correction techniques. The first solution that has been investigated is 4D respiration-correlated CBCT [4]. 4D CBCT consists in sorting CB projections prior to reconstruction according to a respiratory signal. Subsets of CB projections are then used to reconstruct frames of the 4D CBCT representing different phases of the respiratory cycle. However, 4D CBCT images suffer from streak artifacts due to large angular gaps between consecutive projection images. Streak artifacts can be reduced by slowing down the gantry rotation to improve the sampling of projection images [4].

Another class of correction techniques is motion-compensated (MC) CBCT. MC CBCT uses an estimate of the respiratory motion, generally described by a deformation vector field (DVF), to compensate for the respiratory motion during the reconstruction of a single 3D CBCT image [5,6]. For clinical usability, we have proposed the use of a prior motion model to reconstruct the MC CBCT during the CB acquisition and obtain the resulting image within a few seconds after the acquisition [6]. The model uses the 4D DVF estimated on the 4D planning CT and assumes similar motion during planning and CBCT acquisition.

For SBRT treatments of lung cancer patients, 4D CBCT had been used since 2006 in clinical practice, using 4 min of acquisition time [4,7]. MC CBCT is a promising new technique to improve image quality while reducing the acquisition time to 1 min [6]. The purpose of this study was to validate the clinical usefulness of MC CBCT in comparison to 4D CBCT and 3D CBCT on a large set of SBRT patients.

## Material and methods

### Patients

We retrospectively analyzed lung cancer patients that underwent stereotactic body radiotherapy at the Netherlands Cancer

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Institute-Antoni van Leeuwenhoek Hospital (NKI-AVL) between February 2008 and November 2009. The treatment protocol is detailed in [7], we focused in this study on image guidance for patients with relatively large tumor motion measured on the 4D planning CT [8]. We only selected the group of patients with a peak-to-peak amplitude greater than 5 mm in one of the three directions of the image coordinate system. In total, 48 patients were selected for this study.

### *Planning image*

Respiration-correlated images were acquired on a helical CT scanner (24-slice Somatom Sensation Open, Siemens, Forchheim, Germany) synchronized to the respiration using the temperature variations in a nasobuccal mask [9]. The field-of-view encompassed the whole lungs. 4D CTs were reconstructed with a voxel resolution of $1 \times 1 \times 3$ mm$^3$ in 10 frames.

The respiratory motion was retrospectively estimated on each 4D CT by registering the 5th frame (exhale) of the 4D CT to the other frames using deformable registration, resulting in a 4D deformation vector field (DVF). The 4D DVF was used to process a time-averaged mid-position (MidP) 3D CT image [10] which was used as reference image during registration.

### *Image guidance*

Cone-beam (CB) CT images were acquired in the treatment room using a scanner attached to the gantry of the linear accelerator (Elekta Synergy 4.2; Elekta Oncology Systems Ltd., Crawley, West Sussex, UK). Three CB images were acquired during each of the three fractions. The first CBCT image was acquired to assess and correct the misalignment of the time-weighted average position of the target and avoid critical structures with respect to the treatment plan. The second CBCT image was acquired to validate the target alignment after couch shift and prior to the treatment delivery. The third CBCT image was acquired at the end of the treatment fraction to measure the intrafraction stability.

CB acquisition time was 4 min for the first two acquisitions and 1 min for the last acquisition. The long acquisitions were obtained by slowing down the gantry for improved image quality of 4D CBCT [4]. The short acquisitions were acquired at the standard gantry speed for 3D CBCT. The rest of the acquisition parameters were 120 kVp, with various exposures ranging from 0.16 to 0.64 mAs per frame.

Adjustments in the guidance protocol were allowed depending on the course of the treatment, e.g. the need for an extra CBCT image to confirm the setup, failures in adequately setting up the patient, or patient intolerance to the length of the fraction. As a consequence of such events, extra CBCT images were acquired, a few fractions were adjourned, or the last CBCT image was not acquired, respectively. All images were analyzed, regardless of those events.

Each patient had 5–12 long acquisitions and 1–7 short acquisitions. In total, there were 349 long and 150 short acquisitions.

### *Image reconstruction*

Three different CBCT reconstruction techniques were retrospectively investigated. The first technique was standard 3D CBCT filtered backprojection reconstruction, without respiratory motion correction [11]. The second technique was 4D respiration correlated CBCT [4] which is in current clinical use for SBRT of tumors moving more than 8 mm with breathing [7]. The third technique was motion-compensated (MC) CBCT based on the 4D DVF derived from the 4D planning CT as a prior model [6]. The resulting 3D MC CBCT represents the time-averaged anatomy of the patient during the CB acquisition.

### *Tumor registration*

Image guidance requires the assessment of tumor position at treatment time. Each CBCT image was automatically registered on the MidP reference CT image in the two-step procedure detailed in [7] which is clinically used at the NKI-AVL. First, the rigid motion (translations and rotations) of the bony anatomy were assessed in a rectangular region of interest (ROI) encompassing a large part of the spine. Second, the translations of the gross tumor volume (GTV) enlarged with a 5 mm margin were estimated assuming similar rotations as the bony anatomy for robustness to round-shaped tumors. For 4D CBCT images, each frame was separately registered and the time-averaged displacement was used to derive the couch correction. At each step, the registration was visually checked and, when failing, was reinitialized until the target of the step, i.e. bony anatomy or tumor, was accurately aligned by the automated registration.

### *Quantitative assessment*

Image quality of the three reconstructed CBCTs was assessed using the correlation ratio between the evaluated CBCT image and the MidP image after registration within the ROI used for tumor registration, which corresponds to the optimum of the similarity measure found by the automated tumor registration.

Accuracy of tumor registration was assessed with respect to 4D CBCT registrations which are currently used in our clinical protocols as the most accurate estimate of the tumor under respiratory motion (submillimetric for a moving phantom [12]). The accuracy of 3D and MC CBCT tumor registration was measured as the difference between the derived couch corrections of these methods compared to the 4D CBCT analysis.

Accuracy of the prior motion model used for MC CBCT was assessed by reconstructing a 4D MC CBCT, i.e. applying motion compensation but sorting the projections and reconstructing image frames in the same way as in 4D CBCT. If the assumption of the *a priori* motion model were correct, the respiratory motion would have been perfectly compensated for and 4D MC CBCT would not display any residual motion. Therefore, the amplitude of the tumor motion was measured on 4D CBCT and 4D MC CBCT using the aforementioned registration technique to assess the accuracy of the *a priori* motion model.

## Results

Fig. 1 illustrates the three CBCT techniques for a long and a short acquisitions with respect to the MidP reference CT and Table 1 summarizes the quantitative assessment of the image quality. The results were significantly different between reconstruction techniques ($p < 0.0001$, paired *t*-test). 4D CBCT images had the lowest image quality in the correlation ratio sense due to streak artifacts. 3D CBCT image quality was better although it does not account for respiratory motion. MC CBCT had the best image quality because it uses all projection images and corrects for motion blur. Long acquisitions were only slightly superior for 3D and MC CBCT with 3.5% and 5.5% difference on average ($p = 0.09$ and $p = 0.006$, unpaired *t*-test) but the difference was larger and very significant for 4D CBCT with 20.6% difference ($p < 0.0001$). In many cases, the low image quality of 4D CBCT images with short acquisitions made automated registration and its visual inspection difficult. Therefore, short acquisitions were not part of the subsequent quantitative analysis.

Table 2 contains the quantitative assessment of tumor registration accuracy using 4D CBCT registrations as a reference. The group means were not significantly different from 0 ($p > 0.36$) except the cranio-caudal positioning with 3D CBCT ($p = 0.0001$) which was significantly worse than MC CBCT ($p < 0.0001$) with a 0.7 mm group

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