

Iterative Motion-Compensated Reconstruction for Image-Guided Radiation Therapy

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Purpose:

In Image-Guided Radiation Therapy (IGRT) an additional kV imaging system orthogonal to the linear particle accelerator provides information for an accurate patient positioning. However, due to the limited gantry rotation speed during treatment the typical acquisition time is much longer than the patient's breathing cycle resulting in low image quality. In particular, respiratory motion causes severe artifacts such as blurring and streaks in tomographic images.

Compensating for motion is an interesting option and capable of providing high quality respiratory-correlated 4D volumes. Our purpose is to estimate the motion and compensate for it in case of 4D cone-beam CT (4DCBCT) scans and in particular 4D on-board CBCT scans for IGRT [1]. The particular challenge is to do this without knowledge from prior scans and without specific requirements on the acquisition as done in references [2,3].

Materials and Methods:

Standard CBCT reconstruction approaches, e.g. using Feldkamp algorithm [4], backproject all projection data without considering patient motion properly and thereby suffer from motion artifacts. Retrospective phase gating in case of 4DCBCT sorts the data into different sets according to the respiratory motion phase. Performing a separate reconstruction of each phase reduces motion artifacts, but results in artifacts due to an increased angular spacing. Thus, sparse-view artifacts deteriorate the image quality.

State-of-the-art methods for estimation of the motion vector fields suffer from the low sampling of the data and thus from image artifacts that appear in the reconstructions. In applications like ours conventional registration algorithms tend to register artifacts rather than anatomy. Our idea is to address this problem by a new deformable registration algorithm mainly based on a cyclic regularization that avoids the algorithm being sensitive to the above-mentioned streak artifacts. Our new deformable registrations algorithm consists of a spatial registration method [5] and a temporal correction part given by constraints

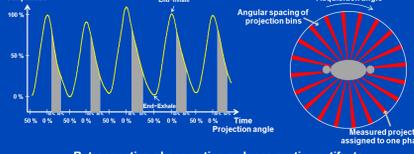
Slowly Rotating CBCT Devices



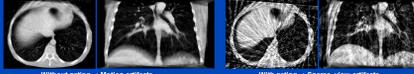
- CBCT imaging unit (kV source and flat panel detector) mounted on the gantry of a linear particle accelerator (LINAC) treatment system
- Comes with a maximum gantry rotation speed of 6° per second
- Much slower than clinical CT devices (60 s/360° versus 0.3 s/360°)
- Cycle of respiratory motion usually in the magnitude of 2 - 5 seconds, i.e. 12 - 30 respirations per minute (rpm)

The motivation for the presented work is to provide high quality respiratory-correlated 4D volumes from on-board CBCT scans without any particular slow, multiple or adaptive gantry rotation technique and without knowledge from prior scans like planning CTs.

Phase Gating – Angular Spacing



Retrospective phase gating reduces motion artifacts, BUT: Gating results in an enlarged angular spacing of projection bins.



Estimation of Motion Vector Fields (MVF)

- MVFs for adjacent phases first
 - Apply error information equally on MVFs
 - Constant gantry rotation speed
 - Almost regular breathing pattern
 - Almost constant angular spacing
 - CEV by CEV
 - With refinement after each CEV
- MVFs for non-adjacent phase pairs given by concatenation
 - Cyclic breathing motion patterns
 - Minimization of cost function
 - Concatenation error vector fields (CEV) E_k
- Incorporate temporal constraints
 - Displacement curve Δx is a breathing cycle over complete respiratory cycle
 - Temporal constraints with temporal constraints

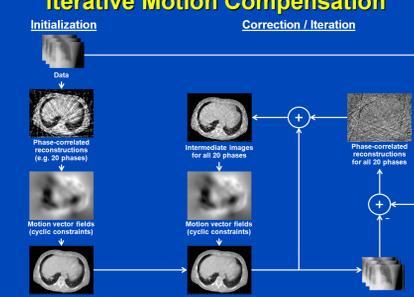
Nomenclature: $T_j^{i+1} = T_j^i \circ T_j^{i+1} \circ \dots \circ T_j^1$, $T_j^{i+1} \rightarrow T_j^{i+1}$

Motion Compensation (MoCo)

- Combine benefits
 - High temporal resolution of phase-correlated images
 - Low noise level from standard reconstructions
- Use of all projections
 - Even those of other phase bins
 - Compensate for motion using motion vector fields (MVF) determined via motion estimation
 - In our case motion estimation is performed on phase-correlated Feldkamp images
- Backproject along straight lines, then warp with respect to the MVFs (corresponds to backprojection along curved lines)
 - Projection data p_j , phase-correlated reconstruction operator X_{PCF}^j , MVF T_j^i from phase bin j to phase bin i

$$J_{MoCo(i)} := \sum_j (X_{PCF}^j \circ T_j^i) \circ T_j^i$$


Iterative Motion Compensation



Simulation Data – Results

Ground Truth (GT)	Feldkamp (FC)	Phase-Correlated Feldkamp (PCF)	Motion-Compensated (MoCo)

End-exhale phase bin shown at grayscale window of C = -200 HU / W = 1400 HU.

Simulation Data – Results

Initial MoCo - GT (end-exhale)	Corrected MoCo - GT (end-exhale)	Initial MoCo - GT (mid-inhale)	Corrected MoCo - GT (mid-inhale)

End-exhale phase bin shown at grayscale window of C = -200 HU / W = 1400 HU.

Simulation Data – Results

Initial MoCo - GT (end-exhale)	Corrected MoCo - GT (end-exhale)	Initial MoCo - GT (mid-inhale)	Corrected MoCo - GT (mid-inhale)

C/W = 0 HU / 1000 HU.

Patient Data – Results

	Patient 1	Patient 2	
	PCF	MoCo	MoCo - PCF
Sagittal EE			
Sagittal EI			
Coronal EE			
Coronal EI			
Transversal EE			
Transversal EI			

For two different patients the end-exhale (EE) and end-inhale (EI) phase bin are shown at grayscale window of C = -200 HU / W = 1400 HU. Difference images are shown at C = 0 HU / W = 2000 HU and the dotted lines mark edge positions in end-exhale.

like the cyclic motion patterns of respiration. A potential overcorrection by the temporal part is avoided by iterative refinement.

Results:

The test set consists of synthesized data, obtained by deforming a clinical patient dataset, and patient scans including RPM information acquired with the On-Board Imager's[®] and the TrueBeam's[™] integrated kV imaging unit (Varian Medical Systems, Palo Alto, USA).

The standard Feldkamp CBCT reconstruction results in a poor temporal resolution. The respiratory-correlated 4DCBCT reconstruction comes with a high temporal resolution and reduced motion blurring, but image quality is deteriorated due to the increased angular spacing of applied projections. Our motion compensation with cyclic motion estimation shows a good temporal resolution and highly reduced impact of few-view artifacts at the same time. The registration algorithm shows low sensitivity on image artifacts and is able to recover respiratory motion. Finer details like pulmonary vessels hidden by motion or streak artifacts become visible in motion-compensated images. The drawback of potential underestimation of motion in case of initial motion compensation is reduced by a correction step.

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References:

- [1] M. Brehm, P. Paysan, M. Oelhafen, P. Kunz, and M. Kachelrieß, "Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy," *Med. Phys.*, in Press.
- [2] J. Lu, T. M. Guerrero, P. Munro, A. Jeung, P.-C. M. Chi, P. Balter, X. R. Zhu, R. Mohan, and T. Pan, "Four-dimensional cone beam CT with adaptive gantry rotation and adaptive data sampling," *Med. Phys.*, vol. 34, no. 9, pp. 3520-3529, Sep. 2007.
- [3] S. Rit, D. Sarrut, and L. Desbat, "On-the-fly motion-compensated cone-beam CT using an a priori model of the respiratory motion," *Med. Phys.*, vol. 36, no. 6, pp. 2283-2296, Jun. 2009.
- [4] L. Feldkamp, L. Davis, and J. Kress, "Practical cone-beam algorithm," *Journal of the Optical Society of America*, vol. 1, no. 6, pp. 612-619, Jun. 1984.
- [5] J.-P. Thirion, "Image matching as a diffusion process: An analogy with Maxwell's demons," *Medical Image Analysis*, vol. 2, no. 3, pp. 243-260, Sep. 1998.