Robust Motion Estimation for On–Board CBCT Imaging using an Angular Sampling Artifact Model

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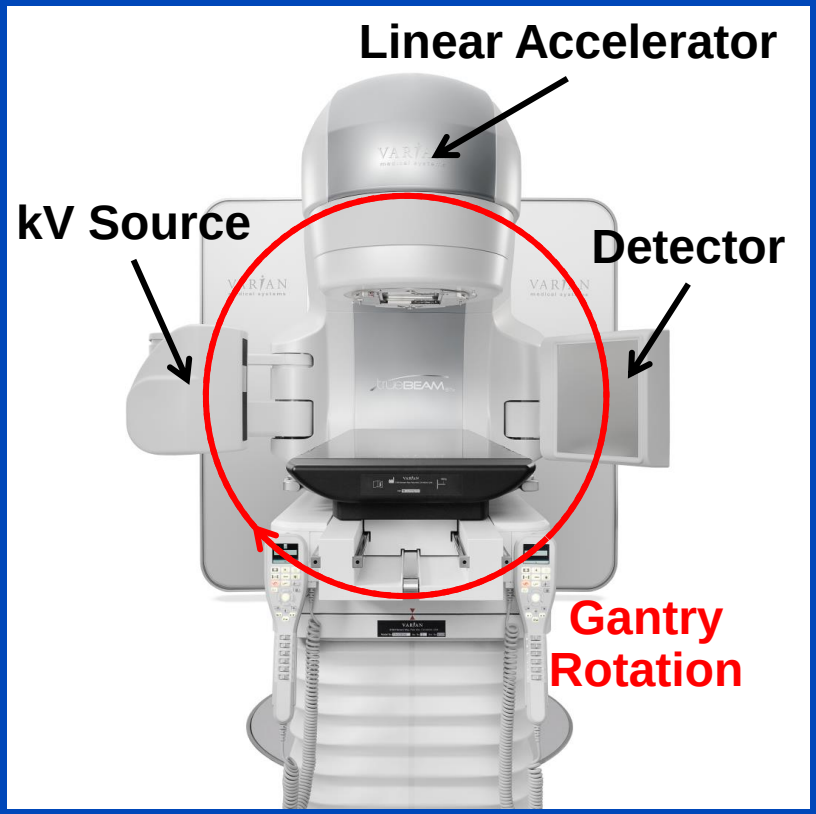
Slowly Rotating CBCT Devices

- **Image-guided radiation therapy (IGRT)**
  - CBCT imaging unit mounted on gantry of a LINAC treatment system
  - E.g. used for patient positioning
- **Maximum gantry rotation speed of 6° per second**
  - Much slower than clinical CT devices (60 s and more vs. about 0.28 s per rotation)
- **Breathing cycle about 2 to 5 seconds**
  - i.e. 12 to 30 respirations per minute (rpm) and thus per scan



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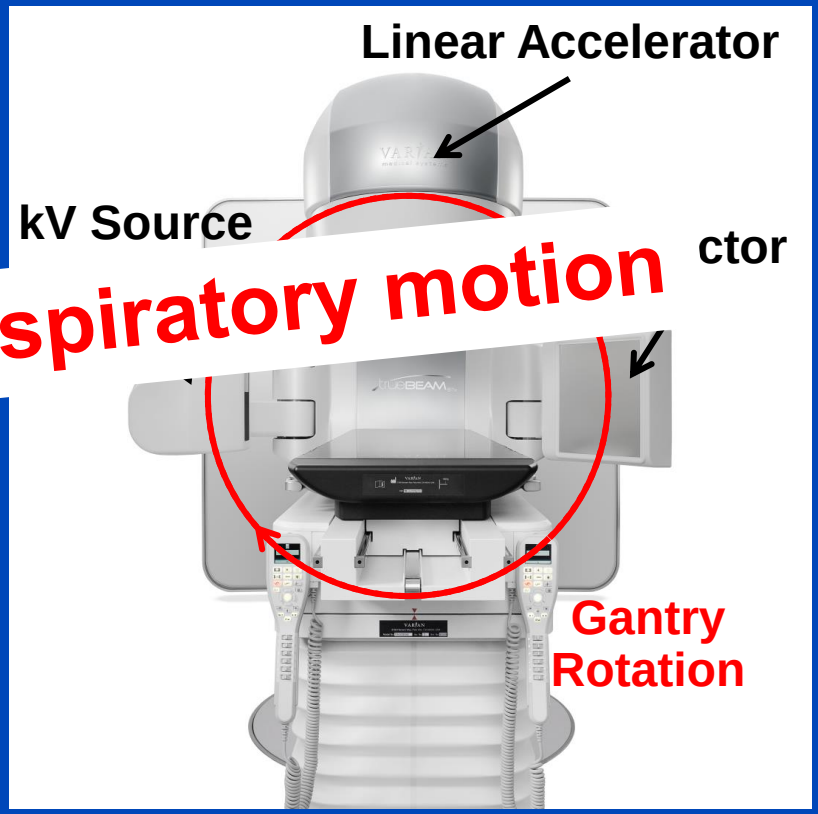
Task: Account for respiratory motion



Prior Art in IGRT
(Respiratory-Correlated Reconstructions)

- **Respiratory binning and independent reconstruction**
  - Sonke et al., "*Respiratory correlated cone beam CT*," Med. Phys. 32(4), 1176–1186 (2005).
  - Dietrich et al., "*Linac–integrated 4D cone beam CT: First experimental results*," Phys. Med. Biol. 51(11), 2939–2952 (2006).
  - Li et al., "*Four–dimensional cone–beam computed tomography using an on–board imager*," Med. Phys. 33(10), 3825–3833 (2006).
- **Dedicated acquisition techniques**
  - Lu et al., "*Four–dimensional cone beam CT with adaptive gantry rotation and adaptive data sampling*," Med. Phys. 34(9), 3520–3529 (2007).
  - Li et al., "*Optimizing 4D cone–beam CT acquisition protocol for external beam radiotherapy*," Int. J. Radiat. Oncol., Biol., Phys. 67(4), 1211–1219 (2007).
- **Not each region is affected by motion**
  - Leng et al., "*Streaking artifacts reduction in four–dimensional cone–beam computed tomography*," Med. Phys. 35(10), 4649–4659 (2008).
  - Bergner et al., "*Autoadaptive phase–correlated (AAPC) reconstruction for 4D CBCT*," Med. Phys. 36(12), 5695–5706 (2009).
  - Ahmad et al., "*Four–dimensional volume–of–interest reconstruction for cone–beam computed tomography–guided radiation therapy*," Med. Phys. 38(9), 5646–5656 (2011).
- **Motion-compensated reconstruction**
  - Li et al., "*Motion correction for improved target localization with on-board cone–beam CT*," Phys. Med. Biol. 51(2), 253–267 (2006).
  - Rit et al., "*On–the–fly motion–compensated cone–beam CT using an a priori model of the respiratory motion*," Med. Phys. 36(6), 2283–2296 (2009).
  - Li et al., "*Enhanced 4D cone–beam CT with inter–phase motion model*," Med. Phys. 51(9), 3688–3695 (2007).

Prior Art in IGRT
(Respiratory-Correlated Reconstructions)

- Respiratory binning and independent reconstruction

Angular sampling artifacts

- Dedicated acquisition techniques

Increased acquisition time

- Not each region is affected by motion

Remaining artifacts in volume–of–interest

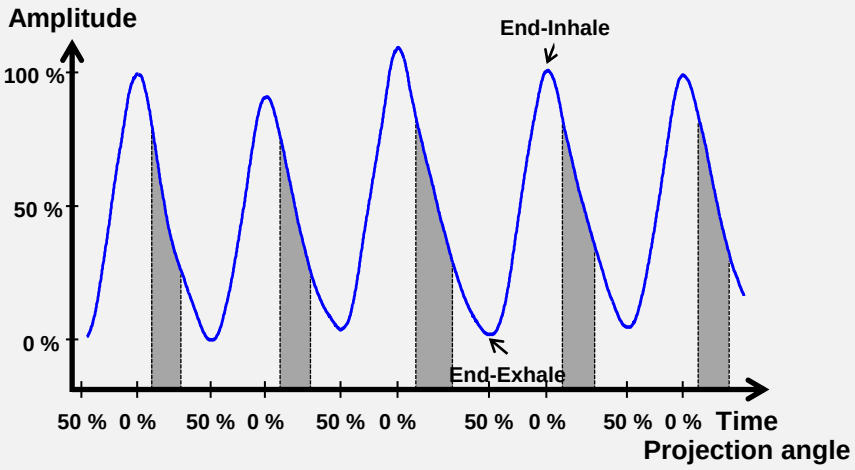
- Motion-compensated reconstruction

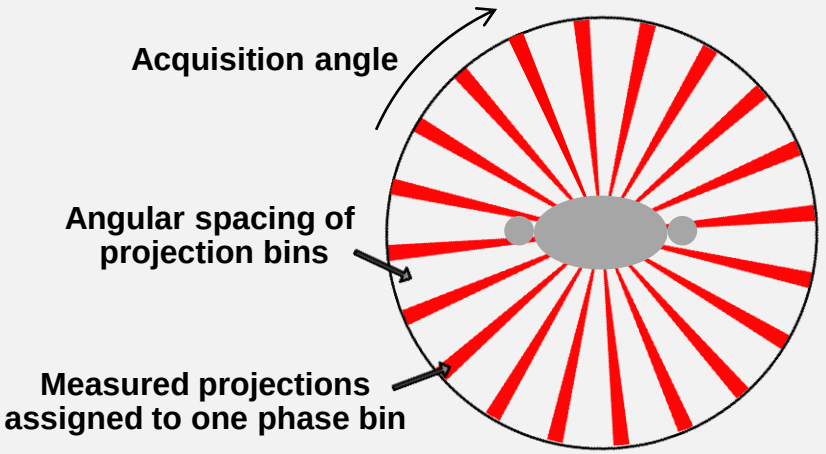
Increased patient dose or
do not account for inter-fractional variations

Aim

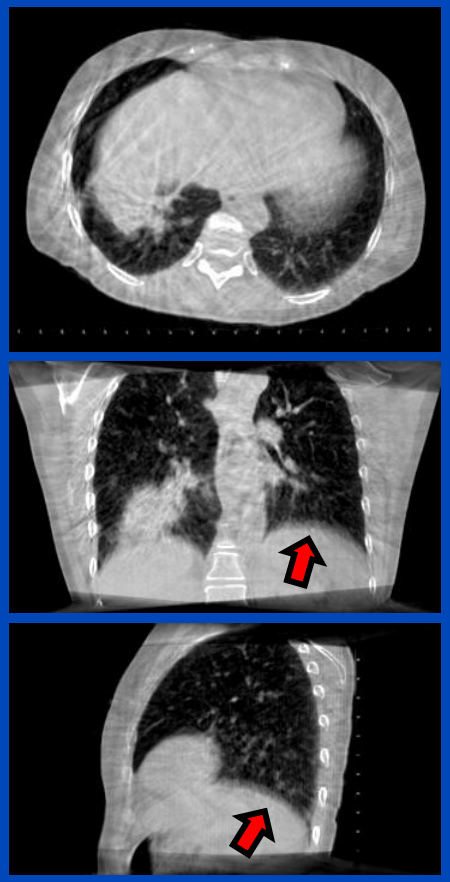
- **Provide high quality respiratory-correlated 4D volumes from on-board CBCT scans**
  - **Image quality comparable to that of motionless regions (e.g. head, neck, …)**
- **Do this with a standard acquisition protocol**
  - **Without any particularly slow, multiple or adaptive gantry rotation technique**
  - **These are not accepted in clinical routine, e.g. due to long acquisition times**
- **Do this without other prior information of higher temporal sampling such as a 4D planning CT**
  - **Account for inter-fractional variations in breathing motion**

Retrospective Gating

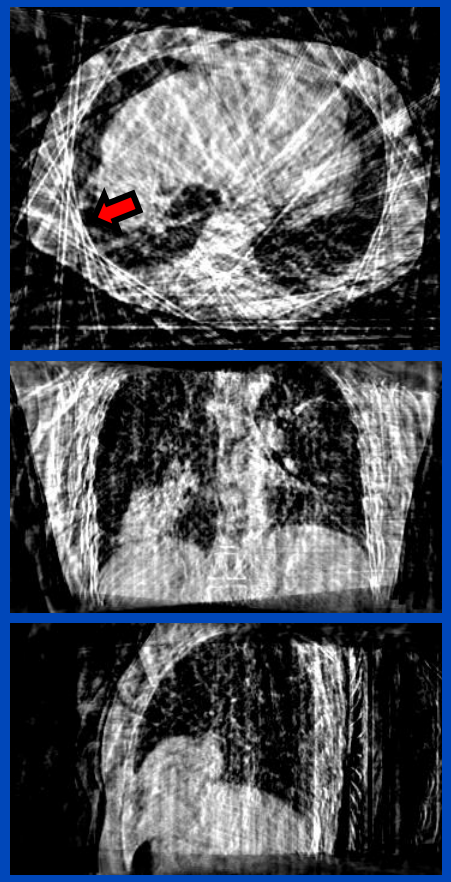




Without gating (3D): Motion artifacts



With gating (4D): Sparse-view artifacts

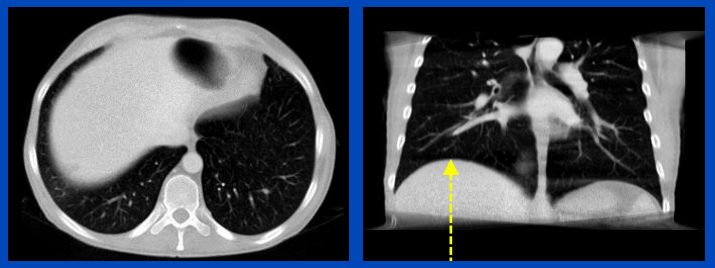


Motion Compensation (MoCo)

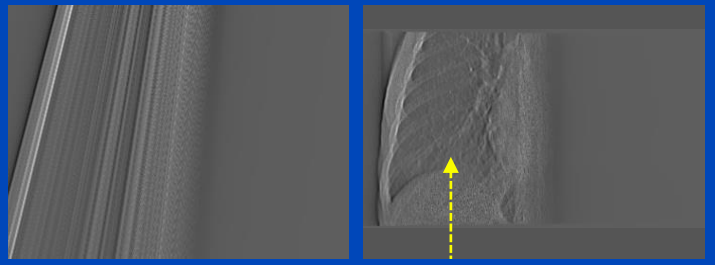
- **Use all projection data for each phase to be reconstructed**
  - Even those of other phase bins
  - Compensate for motion using motion vector fields (MVFs)
  - In our case MVFs are estimated from phase-correlated (gated) reconstructions
- **Backproject-than-warp**
  - Backproject sparse data along straight lines, warp with respect to the MVFs, and superimpose warped backprojections of all sparse data
  - Projection data p, phase-correlated reconstruction operator $\mathrm{X}_{\mathrm{PCF}}^{-1}$, MVF T_j^i from phase bin j to phase bin i

$$f_{\mathrm{MoCo}(i)} := \sum_j \left(\mathrm{X}_{\mathrm{PCF}(j)}^{-1} \, p \right) \circ \mathrm{T}_j^i$$

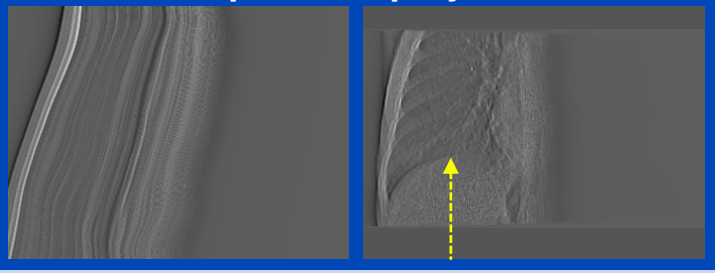
Ground truth in end-exhale



Backprojection on (straight) acquisition lines of a projection acquired in end-inhale

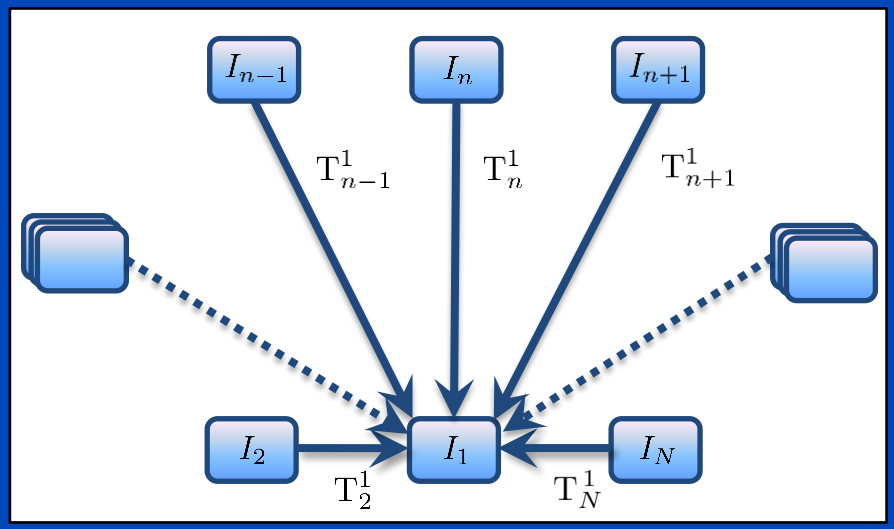


Warped backprojection

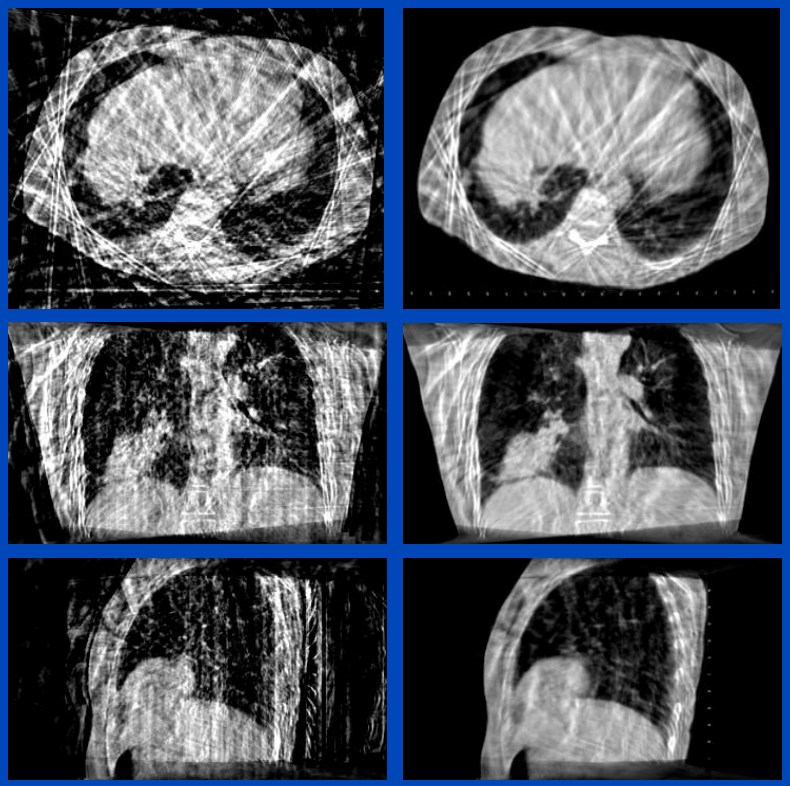


A Standard Motion Estimation and Compensation Approach (sMoCo)

- Motion estimation via standard 3D-3D registration



Gated 4D CBCT | sMoCo

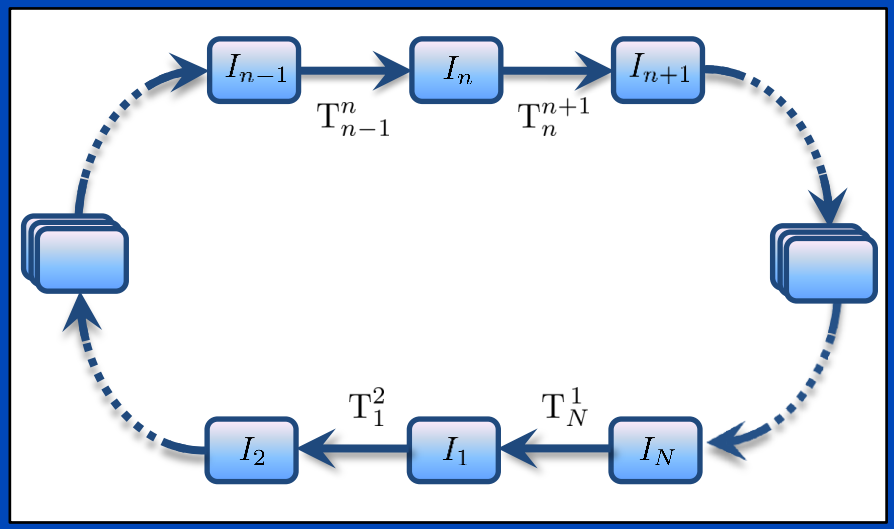


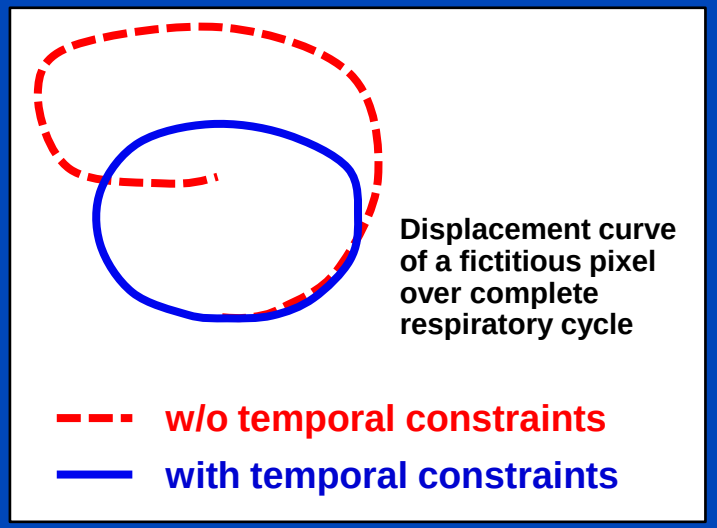
- Has to be repeated for each reconstructed phase
- Streak artifacts from gated reconstructions propagate into sMoCo results

Li et al., "*Enhanced 4D cone–beam CT with inter–phase motion model*," Med. Phys. 51(9), 3688–3695 (2007).

A Cyclic Motion Estimation and Compensation Approach

- **Motion estimation only between adjacent phases**
  - **All other MVFs given by concatenation**

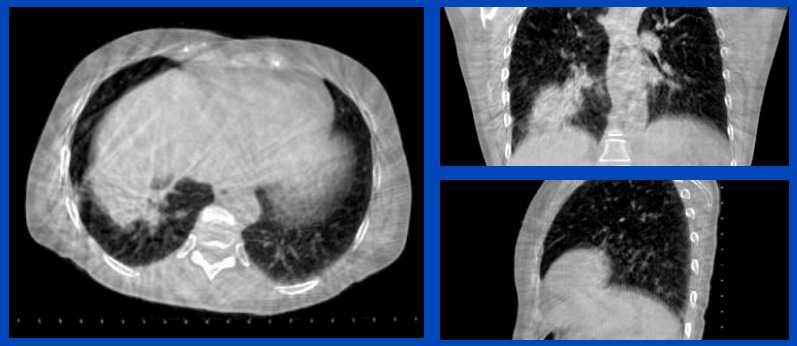




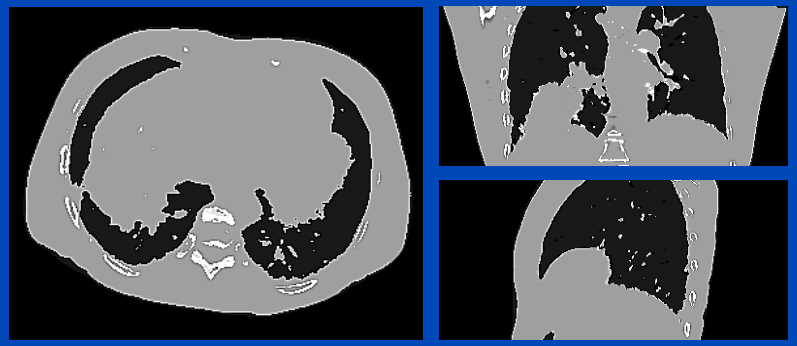
- **Incorporate additional knowledge**
  - **A priori knowledge of quasi periodic breathing pattern**
  - **Non-cyclic motion is penalized**
  - **Error propagation due to concatenation is reduced**

Angular Sampling Artifact Model

- Create second series of images with sparse-view artifacts but without breathing motion
- Eliminate breathing motion information
  - Threshold-based segmentation of 3D CBCT
- Simulate measurement and reconstruction process
  - Forward projection of segmented image
  - Backprojection at same angles as for gated 4D CBCT



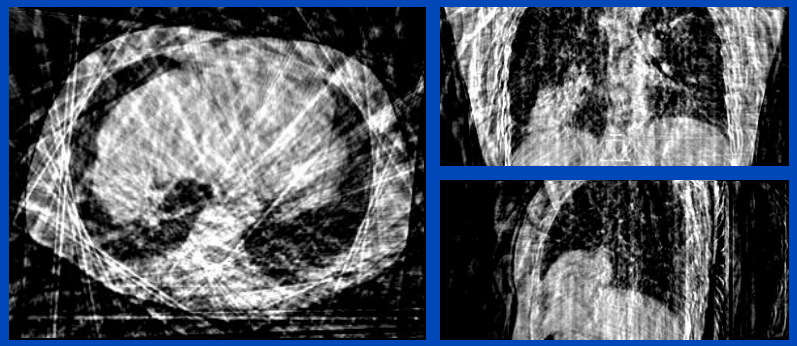
3D CBCT



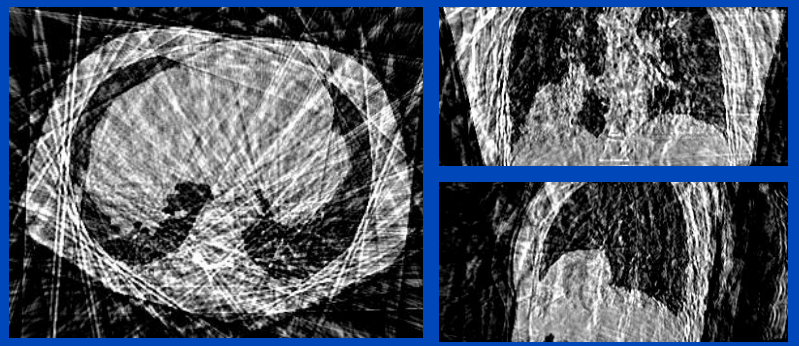
Segmented Image

Angular Sampling Artifact Model

- Create second series of images with sparse-view artifacts but without breathing motion
- Eliminate breathing motion information
  - Threshold-based segmentation of 3D CBCT
- Simulate measurement and reconstruction process
  - Forward projection of segmented image
  - Backprojection at same angles as for gated 4D CBCT

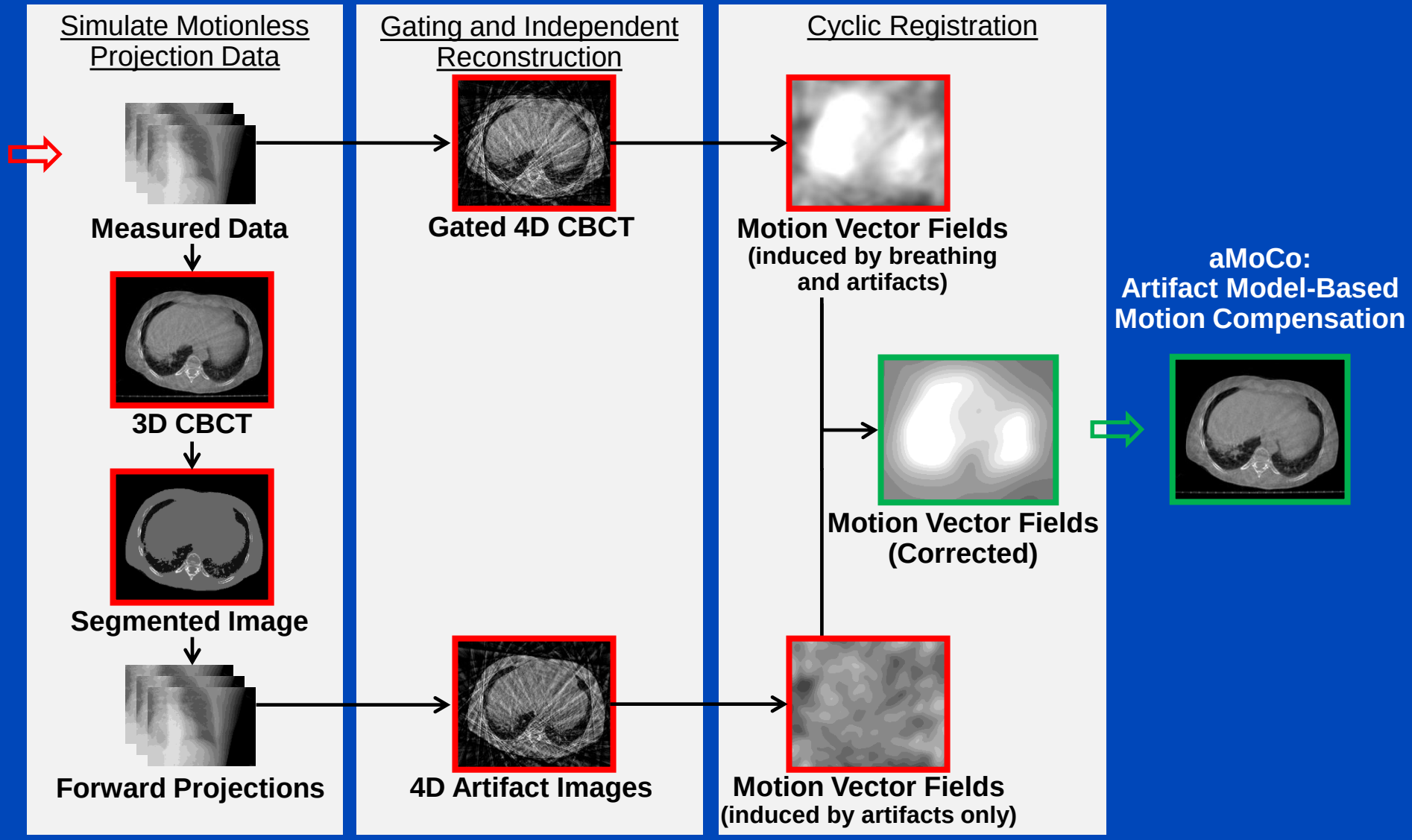


Gated 4D CBCT



4D Artifact Images

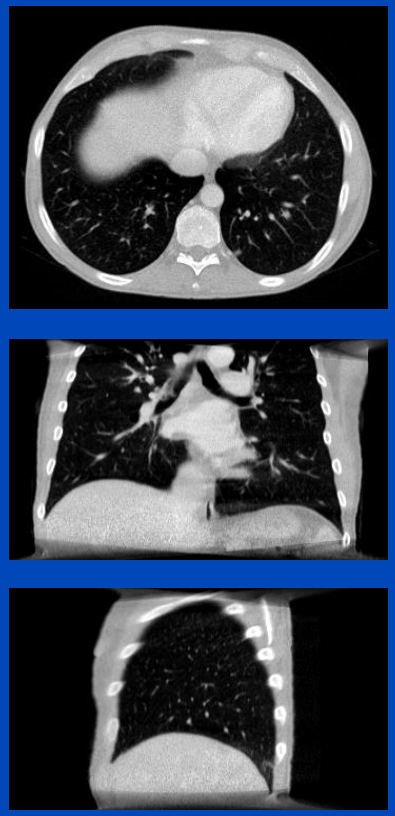
Motion Estimation using an Angular Sampling Artifact Model



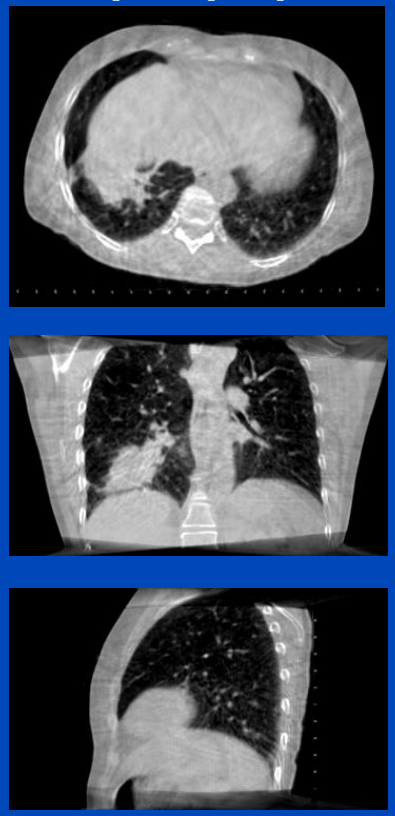
Simulation and Measurements

- **Acquisition data:**
  - Varian OBI geometry
    - » RF = 1000 mm,
    - » RD = 500 mm,
    - » 1024 × 768 Pixel (0.388^2 mm^2)
  - Half Fan – Full Scan
  - Number of projections: ~650
  - Time for 360° rotation: T_{rot} = 60 s
- **Reconstruction data:**
  - Volume size: 512 × 512 × 210
  - Voxel spacing: 1 × 1 × 1 mm^3
  - Number phases: N = 20
  - Phase bin width: 10%

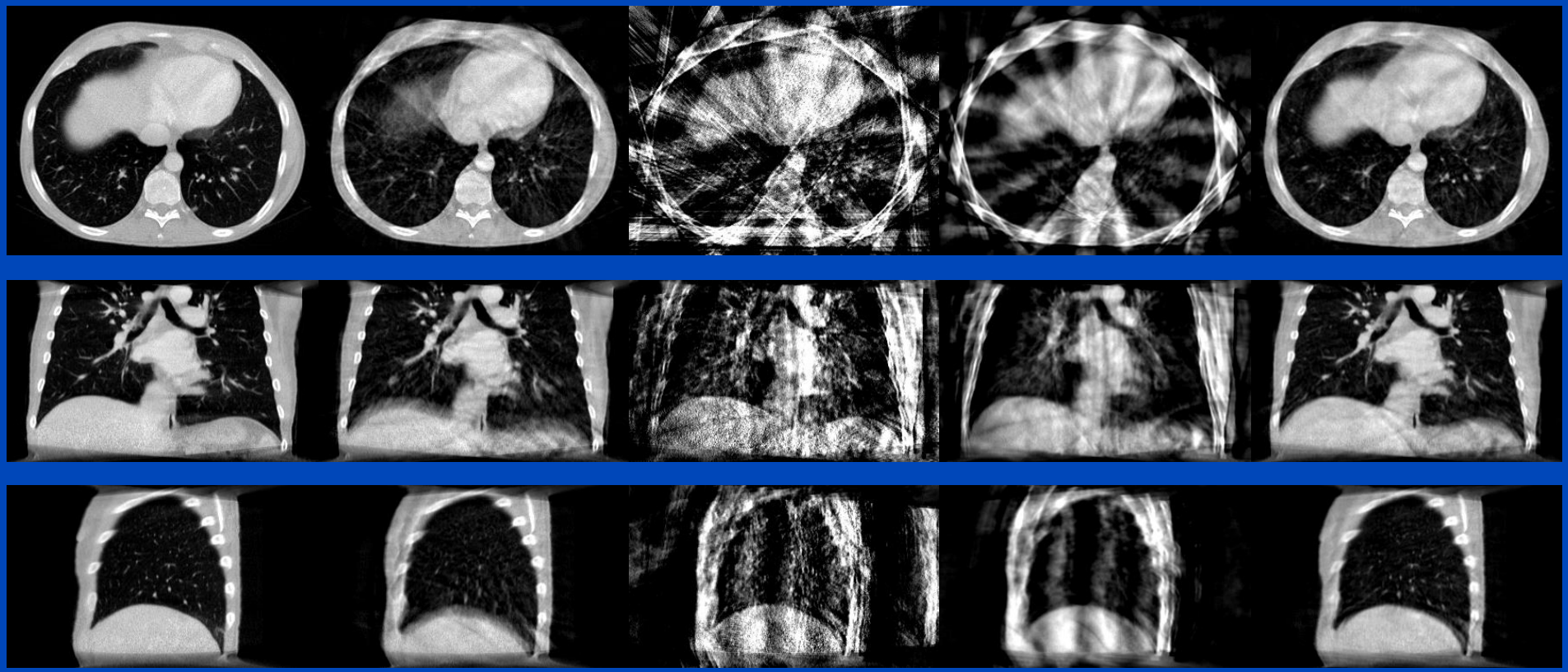
Ground Truth of Simulation (15 rpm)



Patient Dataset (26 rpm)



Simulated Data – Results



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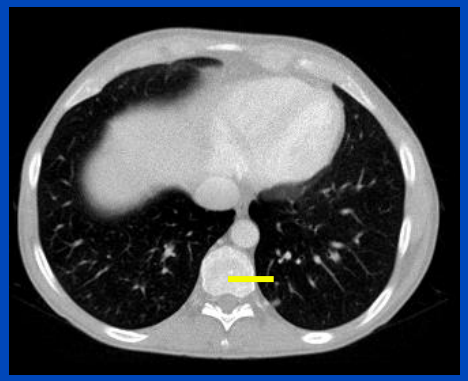
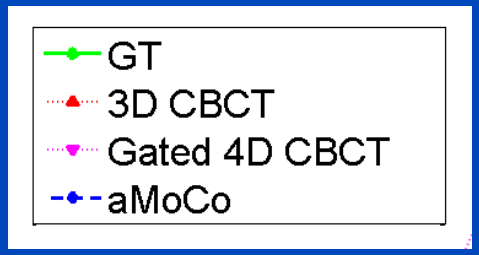
C = -200 HU, *W* = 1400 HU

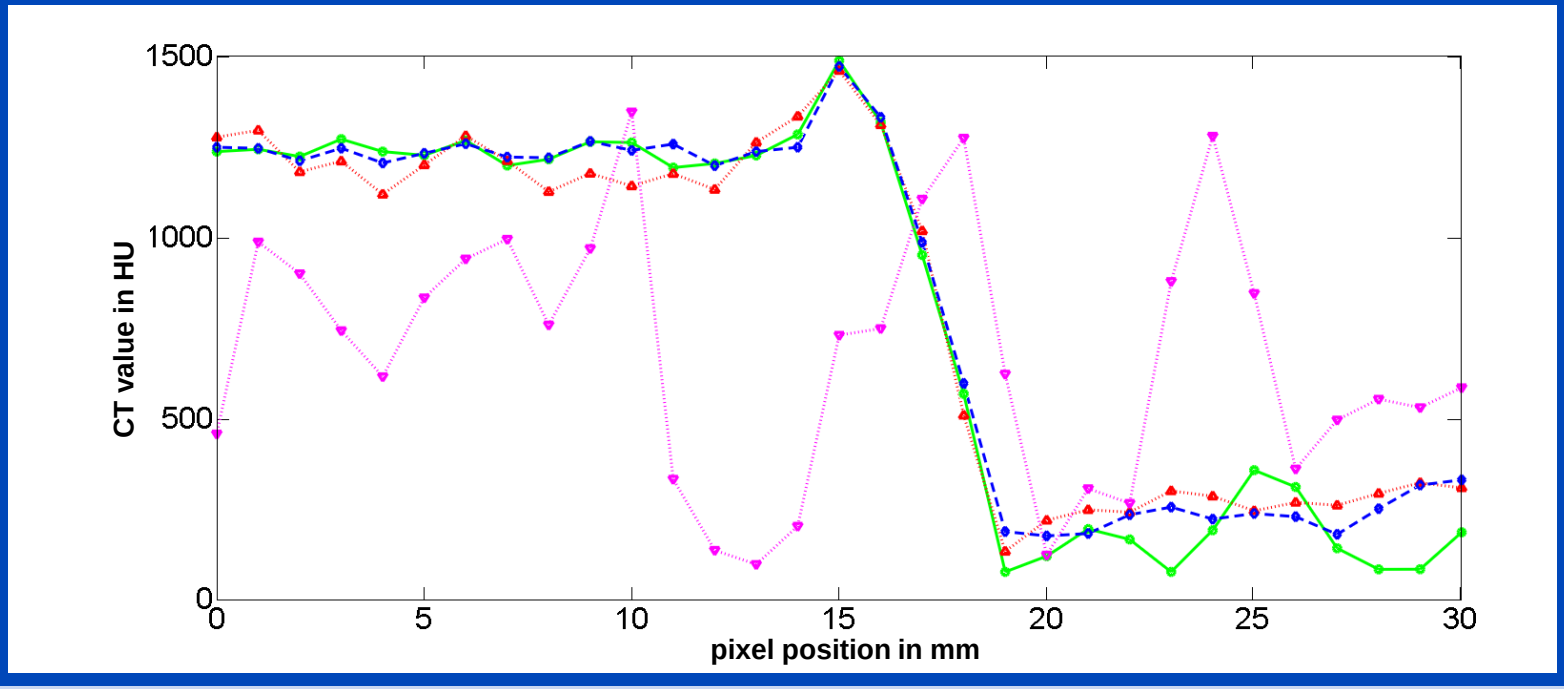
dkfz.

Simulated Data – Edge Profiles





Motionless edge (vertebral body)



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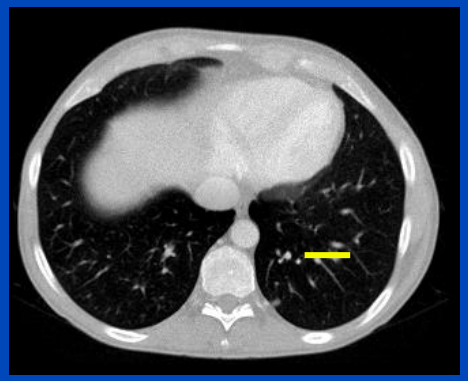
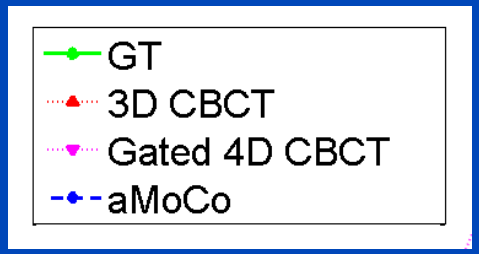
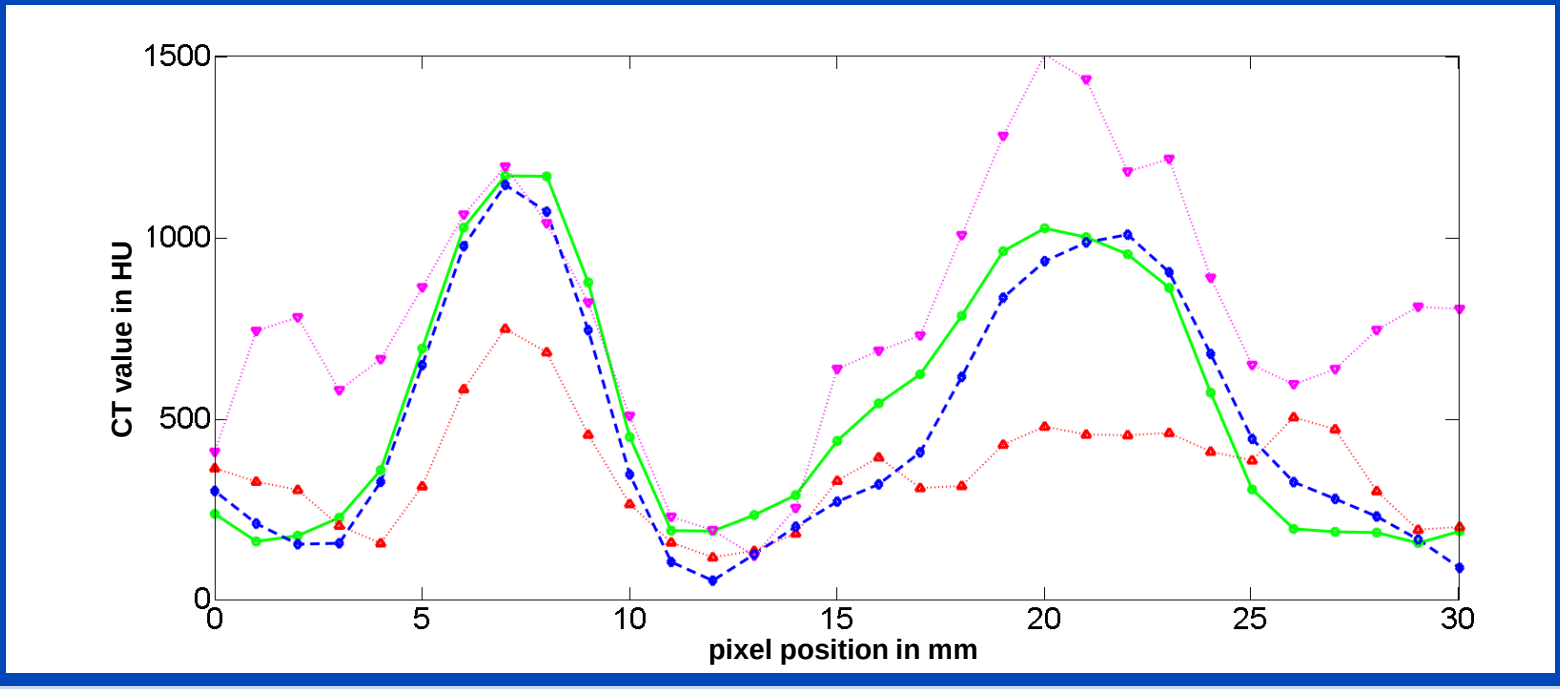


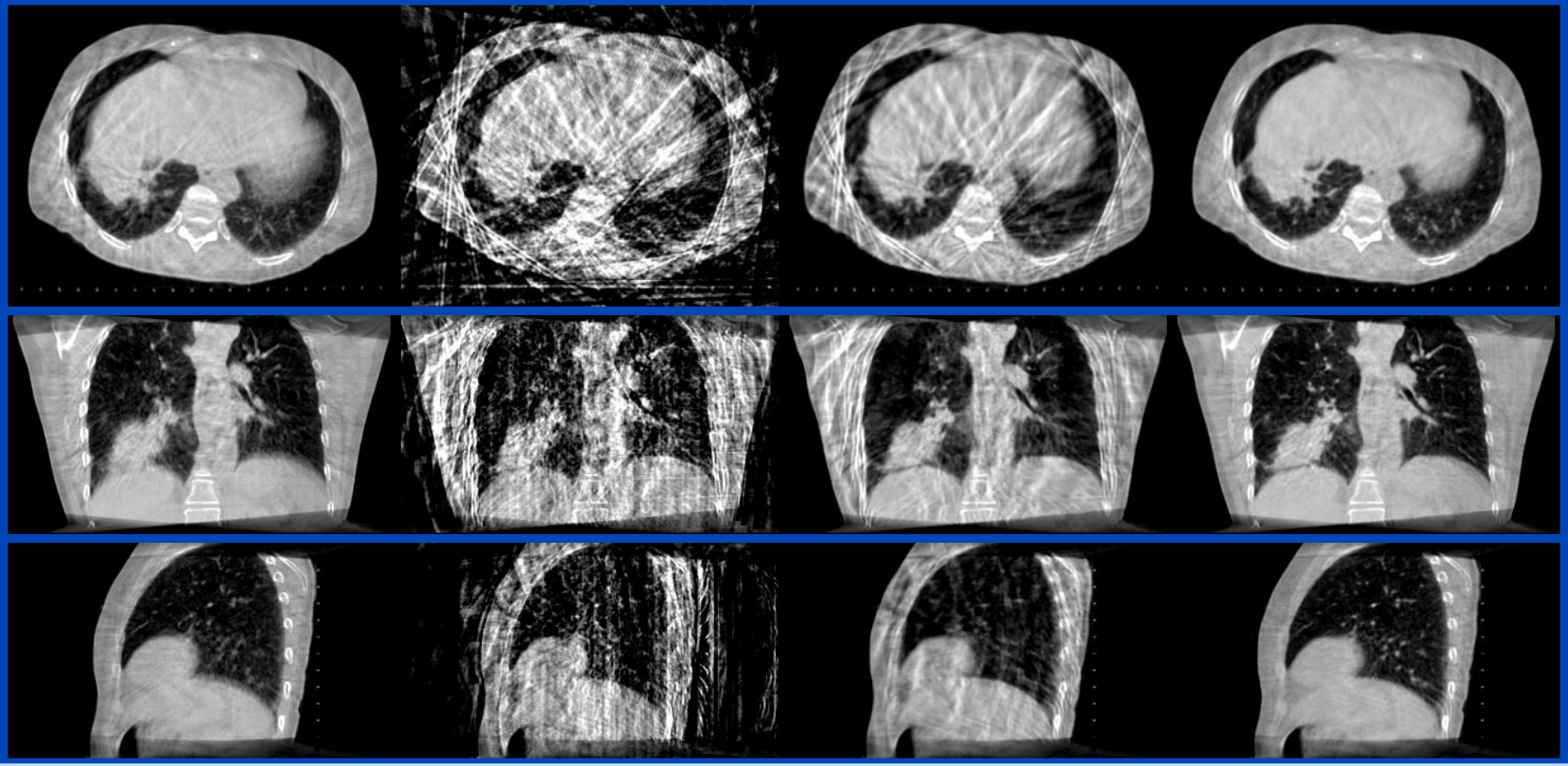


Pulmonary blood vessels



Patient Data – Results

3D CBCT Standard	Gated 4D CBCT Conventional Phase-Correlated	sMoCo Standard Motion Compensation	aMoCo Artifact Model-Based Motion Compensation



C = -200 HU, *W* = 1400 HU

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Summary

- **Severe sparse-view artifacts**
  - deteriorate image quality of conventional phase-correlated images (gated 4D CBCT) from slowly rotating devices,
  - negatively affect motion estimation on these images.
- **Motion estimation**
  - based on standard deformable 3D-3D registration is highly sensitive to these artifacts and in addition heavily time consuming,
  - based on cyclic registration has a reduced amount of computations,
    - » In addition, this allows to incorporate temporal constraints to reduce error propagation and to reduce artifact sensitivity
  - using an correction based on an artifact model shows a highly decreased sensitivity to sparse-view artifacts.
- **Motion–compensated image reconstruction**
  - using MVFs obtained by combination of cyclic registration and artifact model is suitable for application in IGRT

Thank You!

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