CBCT Motion Artifacts and Approaches to Avoid or Correct Them

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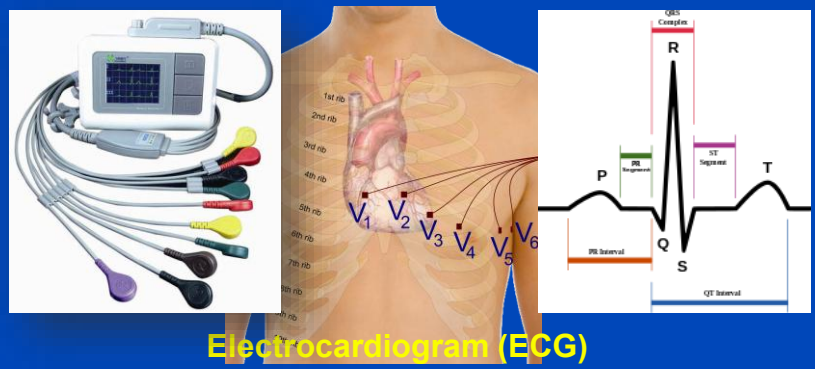
dkfz. DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

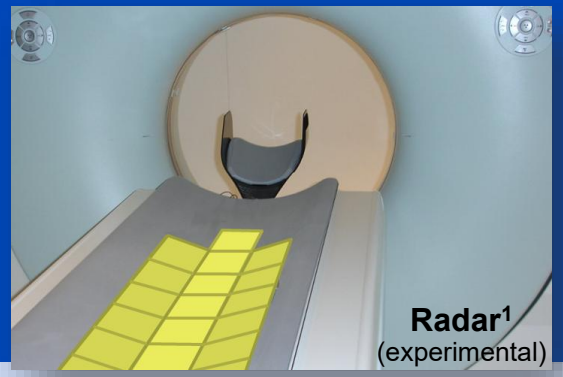
External Gating Signals

Respiratory

Cardiac



Both



Other

[1]Pfanner, Kachelrieß. Med. Phys. 40(9) September 2013 and Med. Phys. 41(8) August 2014

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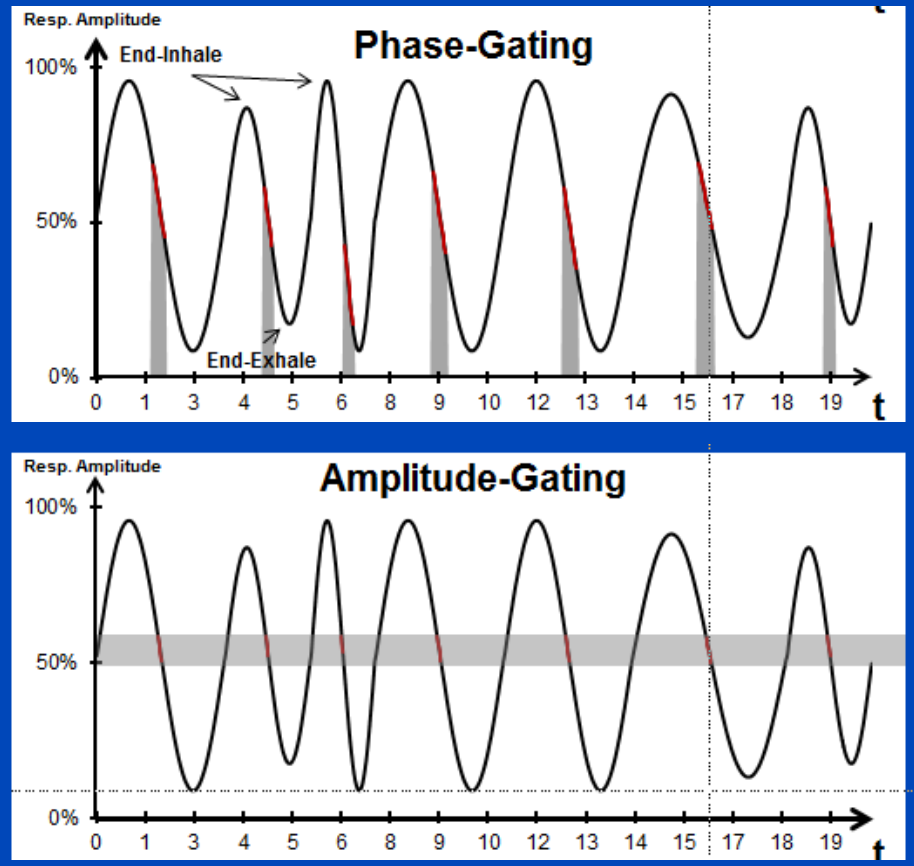
Phase- and Amplitude Gating

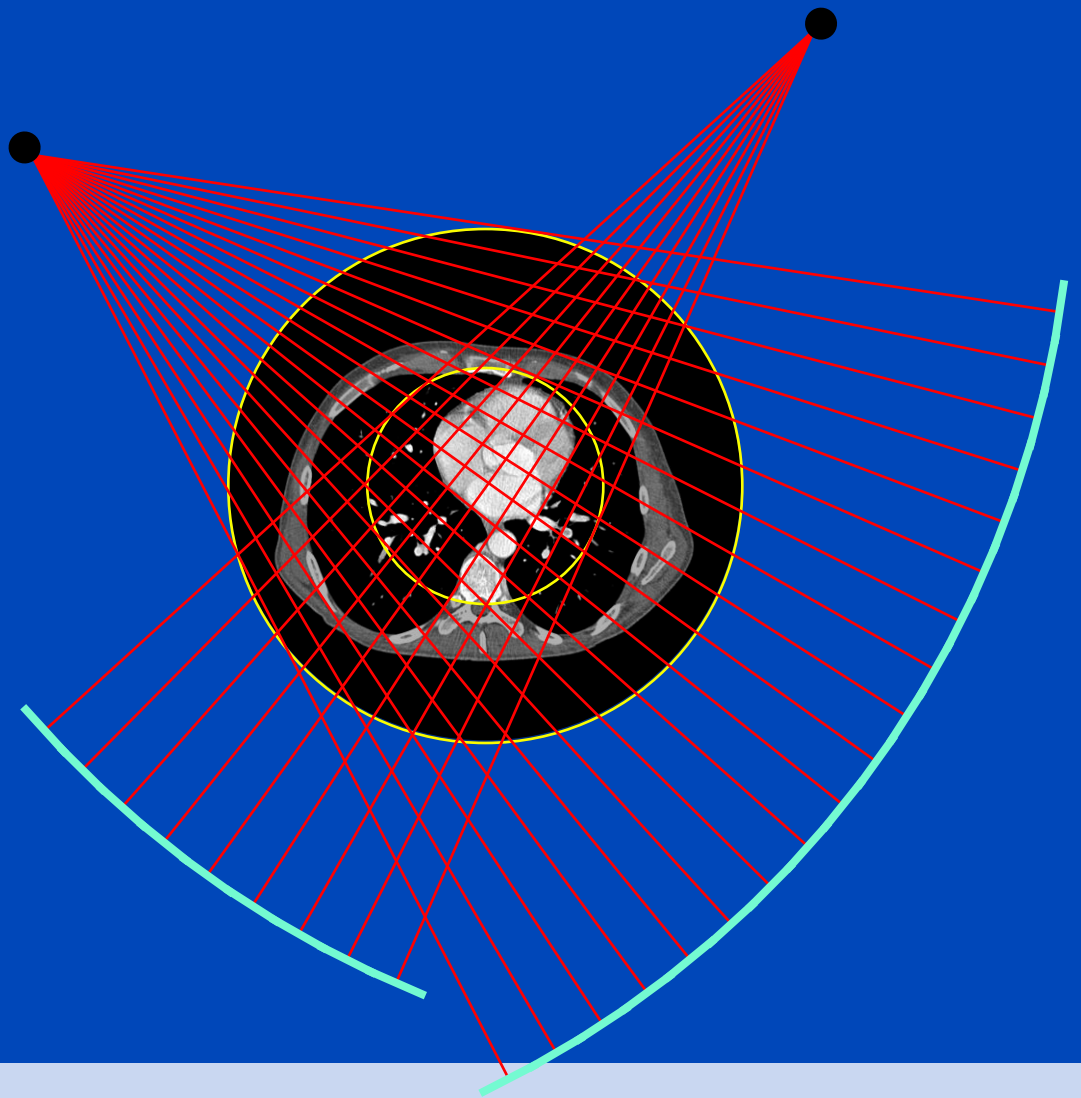
- **Phase gating**
  - Assumes periodicity in time and amplitude
  - Used in cardiac 3D CT (pro- and retrospective)
  - Used in cardiac 4D CT (retrospective)
  - Assumptions well-justified apart from extrasystoles
- **Amplitude gating**
  - Assumes periodicity in time
  - More robust against amplitude variations
  - Used for respiratory 3D CT (prospective)
  - Used for respiratory 4D CT (retrospective)
  - Assumptions not really justified because motion patterns change with changing amplitude



CT

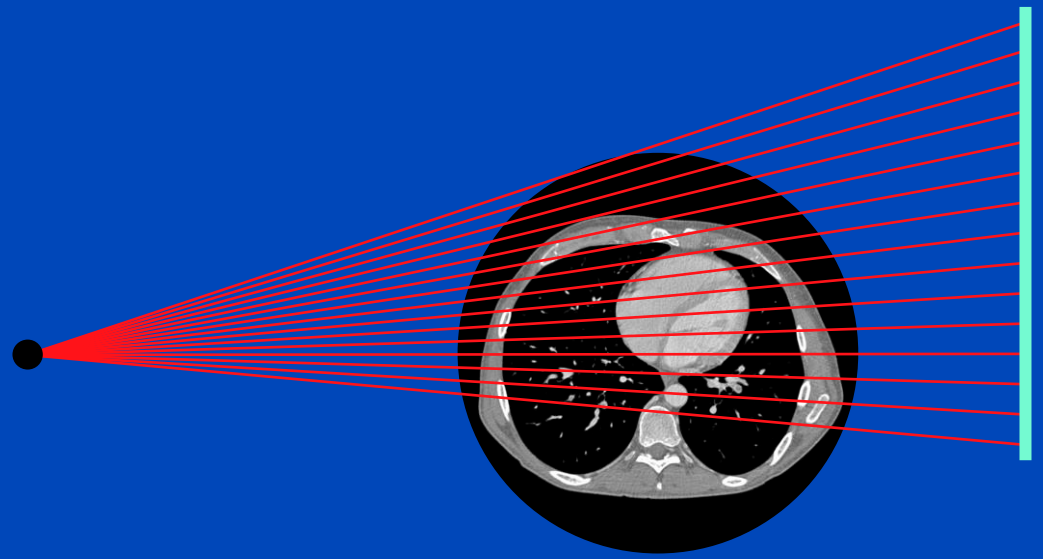
CT is much faster than one motion cycle!

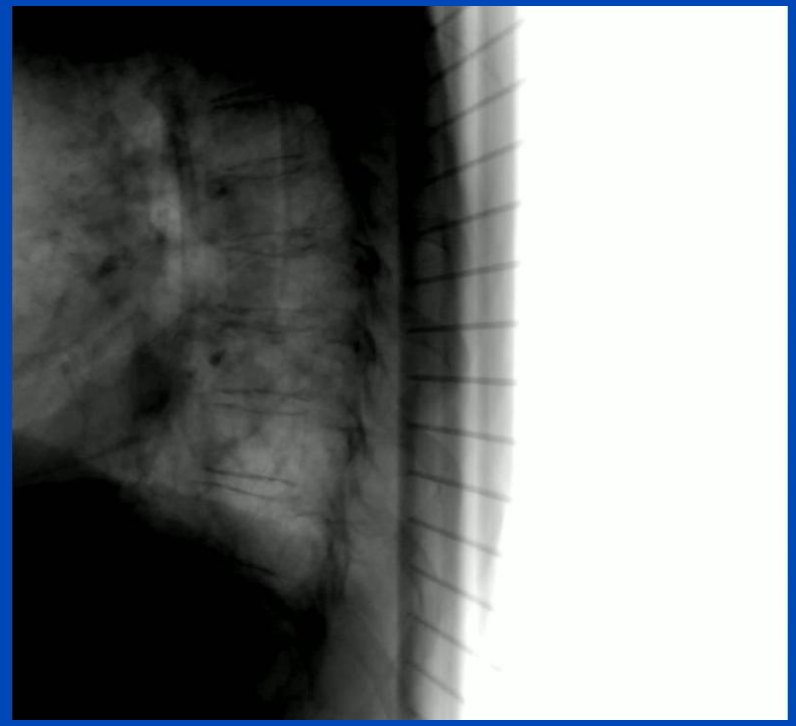
Siemens SOMATOM Force
dual source cone-beam spiral CT



CBCT

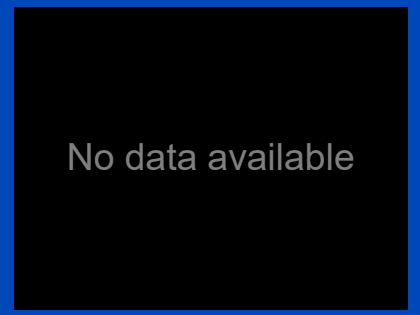
CBCT is much slower than one motion cycle!

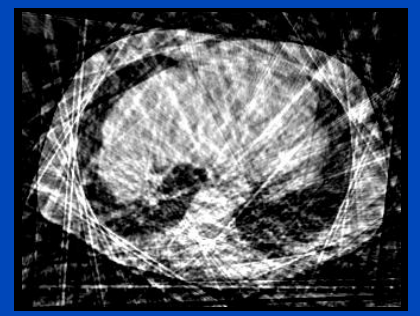




Faster, Equal or Slower Rotation Compared with Motion Cycle?

- **Much faster ☺**
  - Always good, since motion is (nearly) frozen.
  - Requires fast scanners, very high tube power and detector frame rate.
  - Not available in CBCT. Only CT.
- **Close to equal ☹**
  - For each view angle the patient is seen in a different motion state.
  - Weird artifacts may occur.
  - Not in use, today.
- **Much slower 😐**
  - Allows for gating, if motion is quasi-periodic.
  - Gating results in sparseness artifacts (sparse angular sampling).
  - The slower the better: more motion cycles = less pronounced artifacts.
- **Exception**
  - Single breath-hold scan, if scan is fast enough (e.g. less than 10 s).
  - However, organ motion can no longer be resolved.

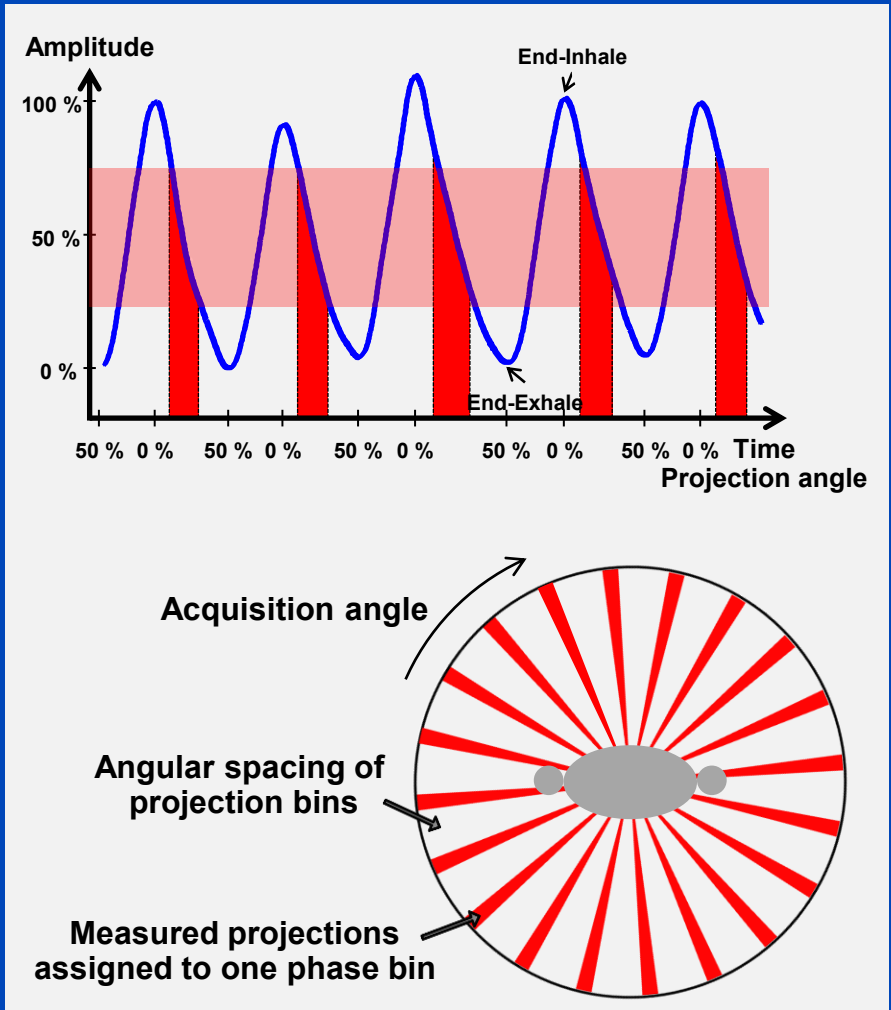




Solutions

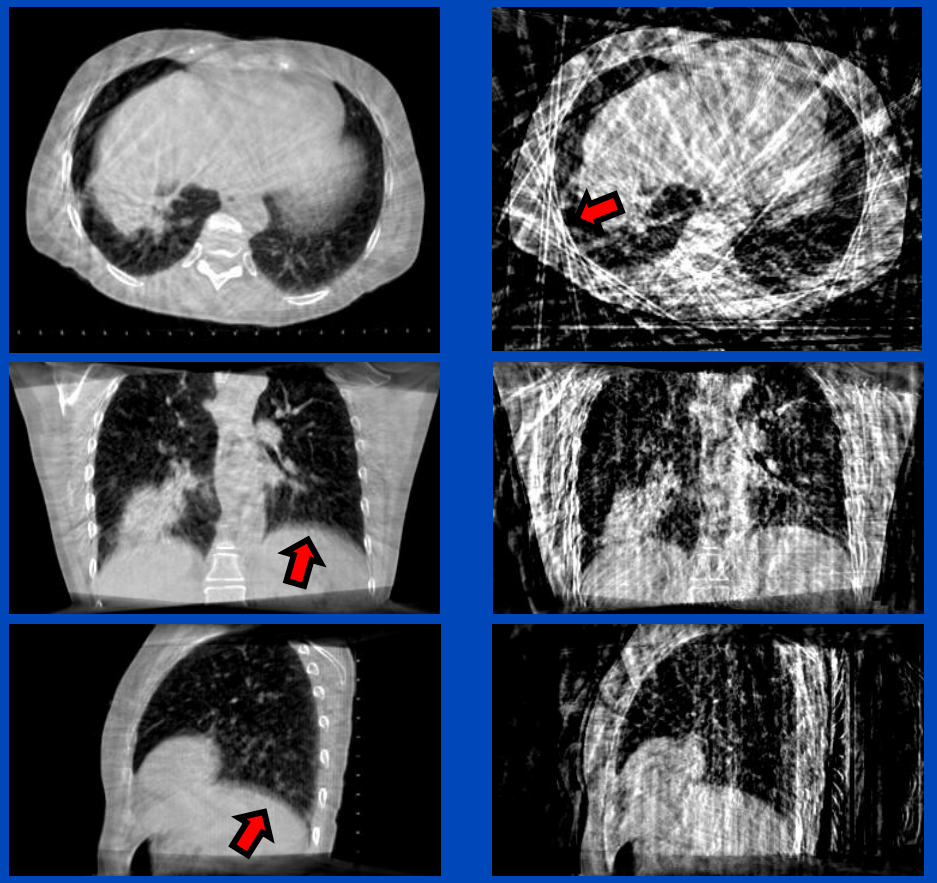
- Control breathing
  - Breathing coaching, e.g. using spirometer with visual feedback, may be of some help.
- Decrease rotation speed
  - Less sparseness artifacts
  - Longer scan time
- Increase rotation speed
  - May allow for single breath-hold acquisition
- Dedicated image reconstruction
  - Iterative reconstruction may be of some help
  - McKinnon-Bates algorithm
  - Related algorithms are provided by the vendor
- Motion-compensated (MoCo) image reconstruction
  - Next slides

4D CBCT Scan with Retrospective Gating



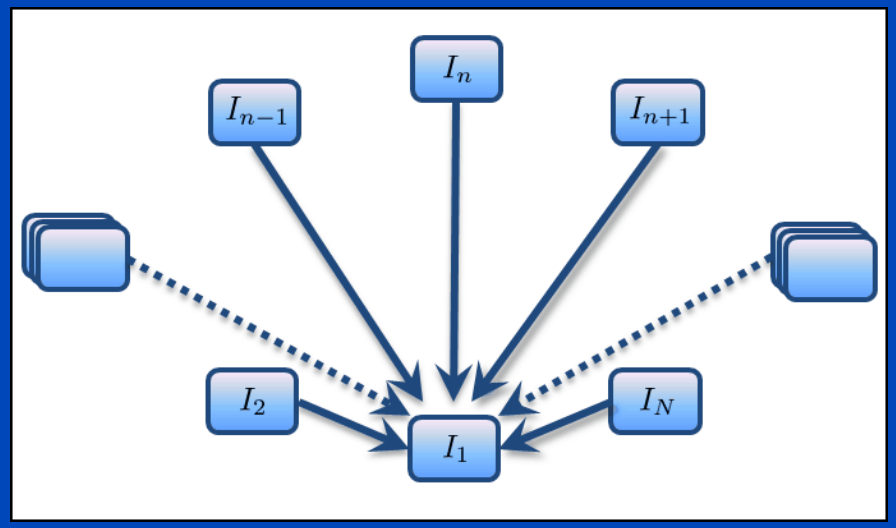
Without gating (3D): Motion artifacts

With gating (4D): Sparse-view artifacts

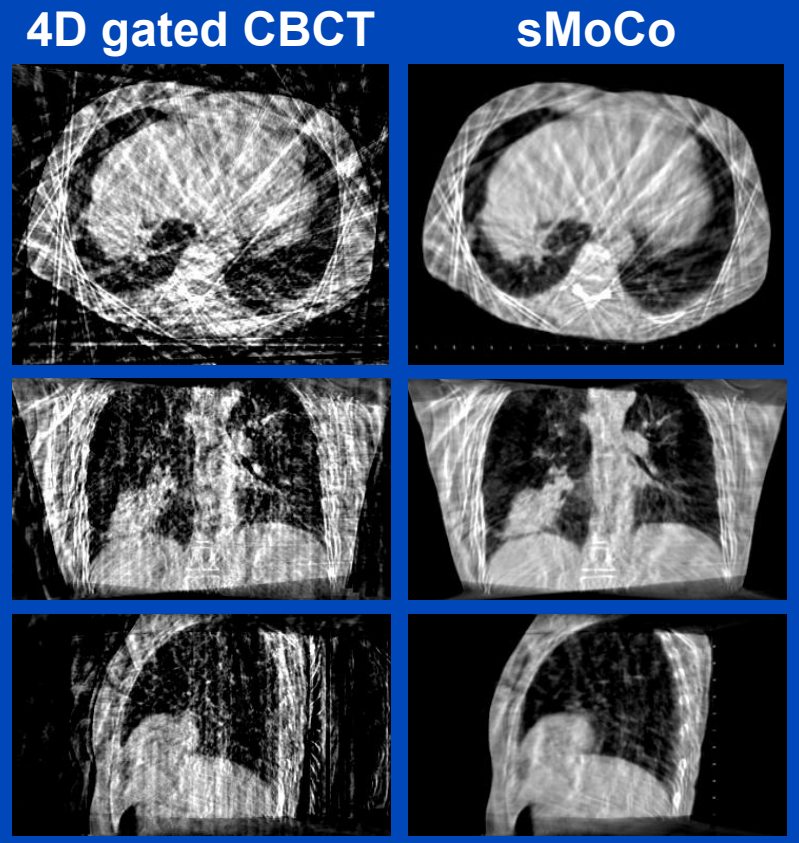


A Standard Motion Estimation and Compensation Approach (sMoCo)

- Motion estimation via standard 3D-3D deformable registration



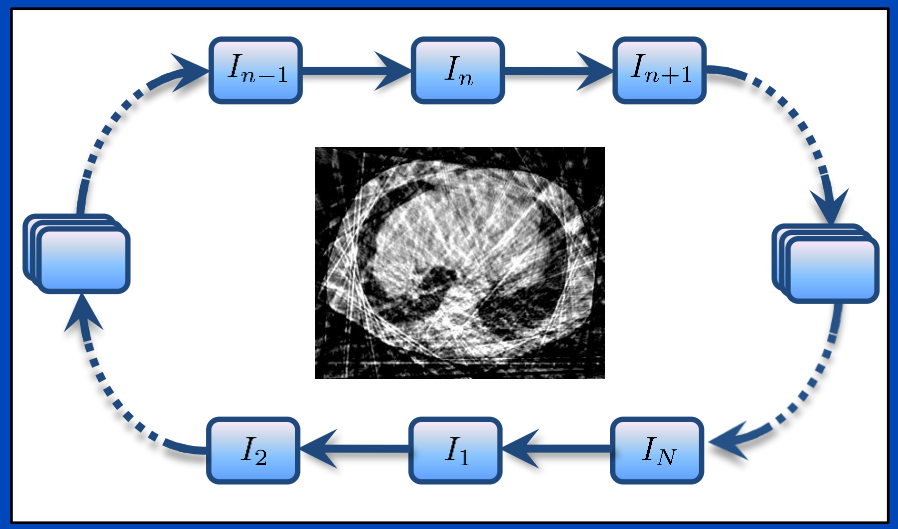
- Has to be repeated for each reconstructed phase
- Streak artifacts from gated reconstructions propagate into sMoCo results

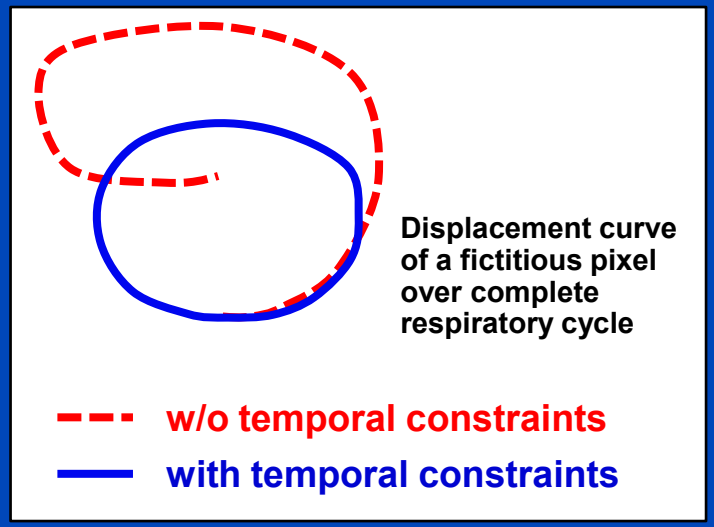


Li, Koong, and Xing, "Enhanced 4D cone–beam CT with inter–phase motion model," Med. Phys. 51(9), 3688–3695 (2007).

The Cyclic Motion Estimation and Compensation Approach (cMoCo)

- Motion estimation only between adjacent phases
- Incorporate additional knowledge
  - A priori knowledge of quasi periodic breathing pattern
  - Non-cyclic motion is penalized
  - Error propagation due to concatenation is reduced

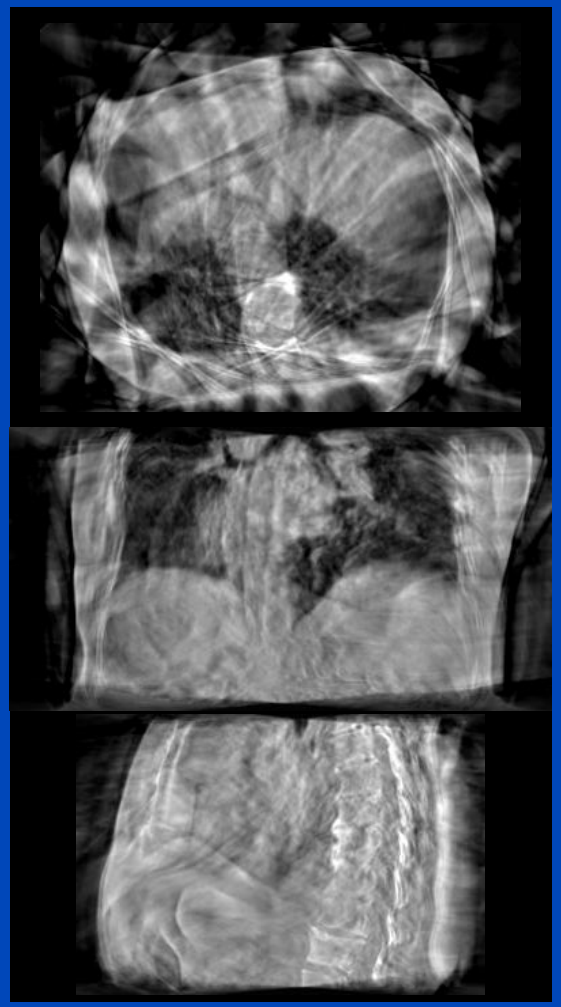




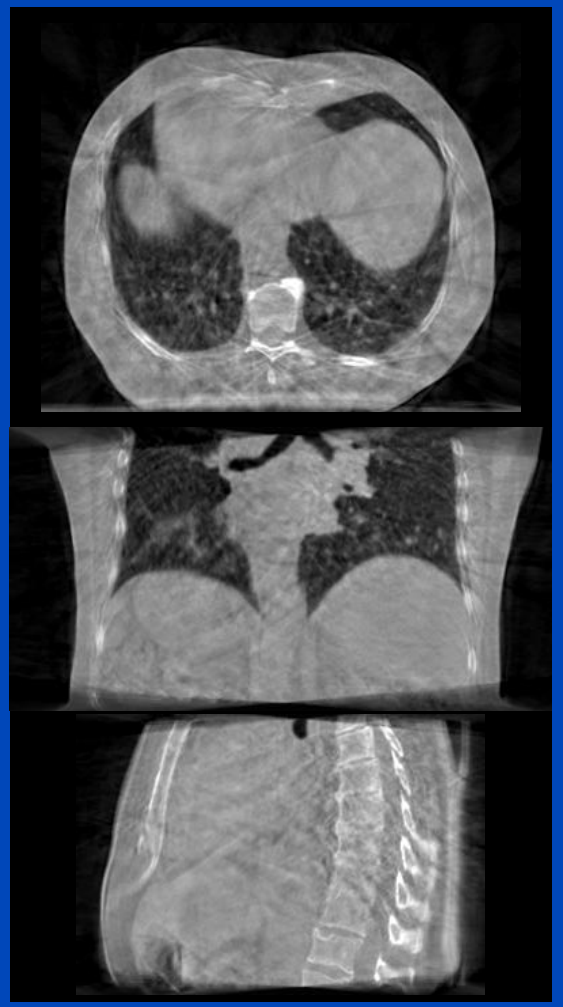
Brehm, Paysan, Oelhafen, Kunz, and Kachelrieß, "Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy," Med. Phys. 39(12):7603-7618, 2012.

cMoCo without and with Cyclic Regularization

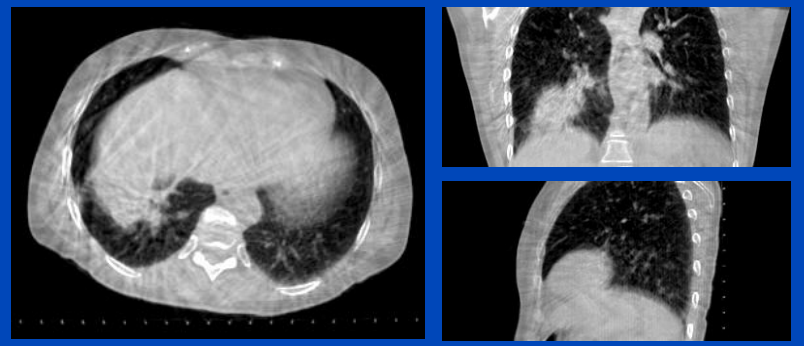
no cyclic penalty



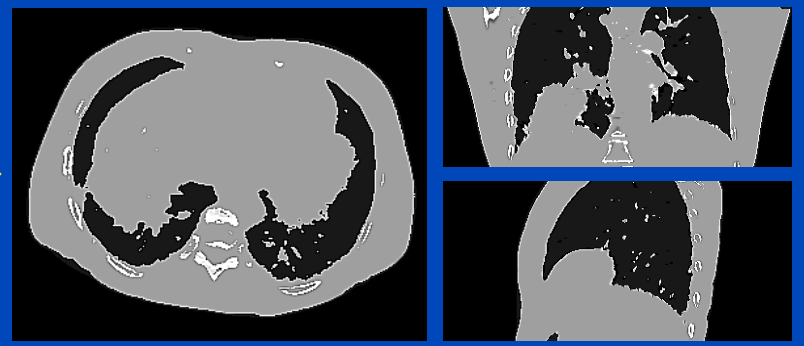
With cyclic penalty



Artifact Model-Based MoCo (aMoCo)



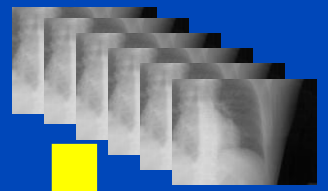
3D CBCT

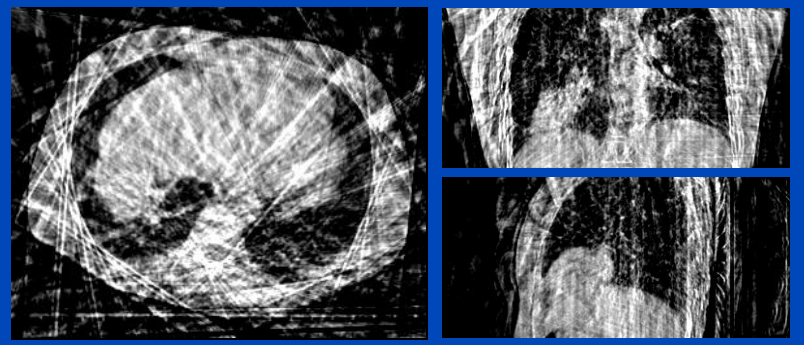


Segmented Image

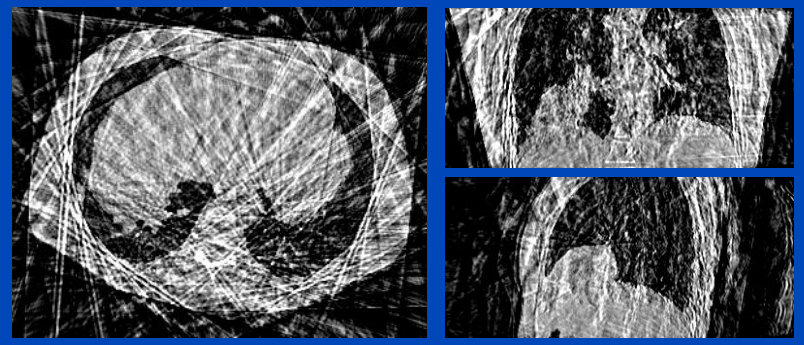
Measured data:

Virtual rawdata:





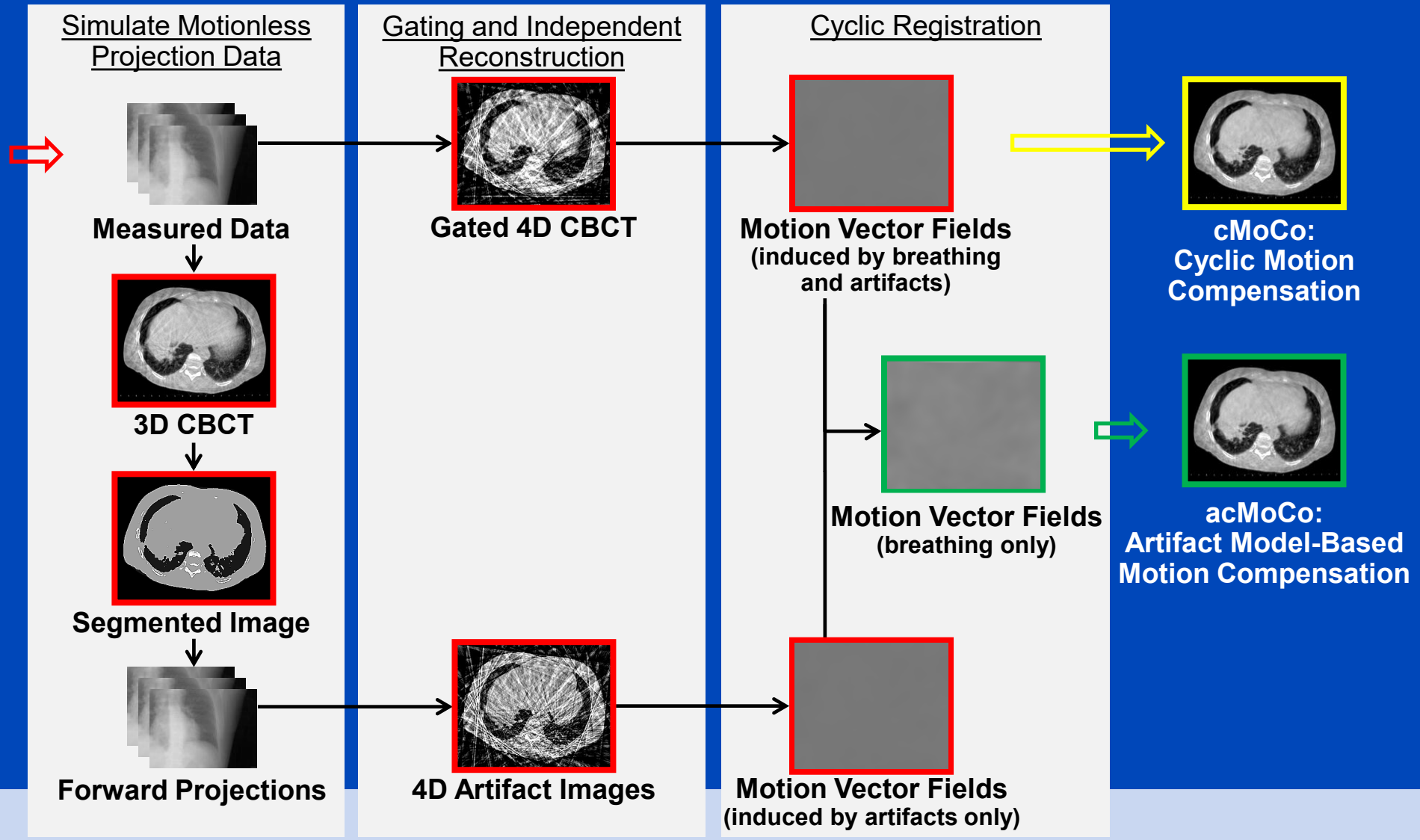
4D gated CBCT



4D Artifact Images

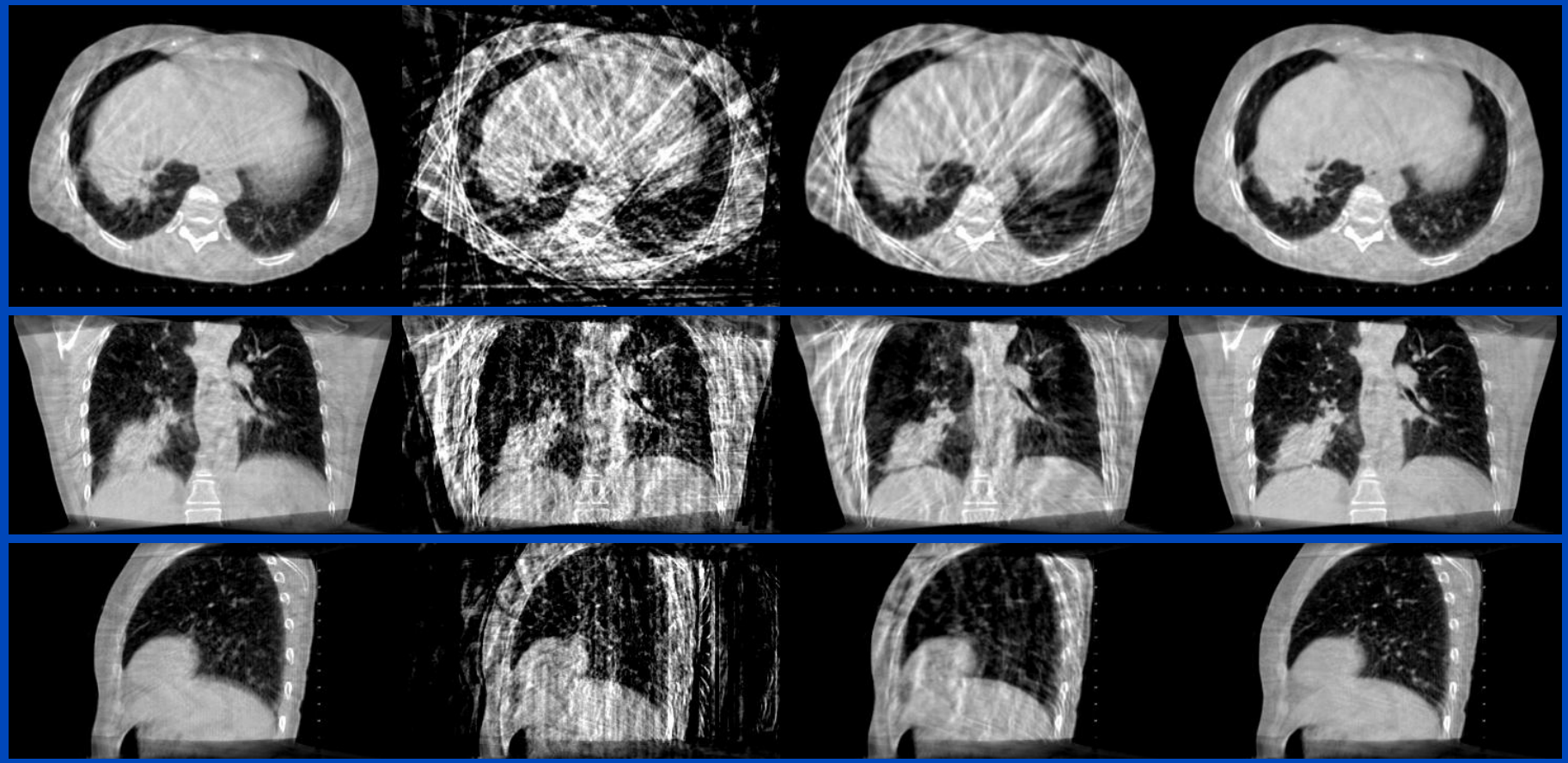
Brehm, Paysan, Oelhafen, and Kachelrieß, "Artifact-resistant motion estimation with a patient-specific artifact model for motion-compensated cone-beam CT" Med. Phys. 40(10):101913, 2013.

Motion Estimation using a Patient-Specific Artifact Model



Examples for CBCT MoCo

3D CBCT Standard	4D gated CBCT Conventional Phase-Correlated	sMoCo Standard Motion Compensation	acMoCo Artifact Model-Based Cyclic MoCo



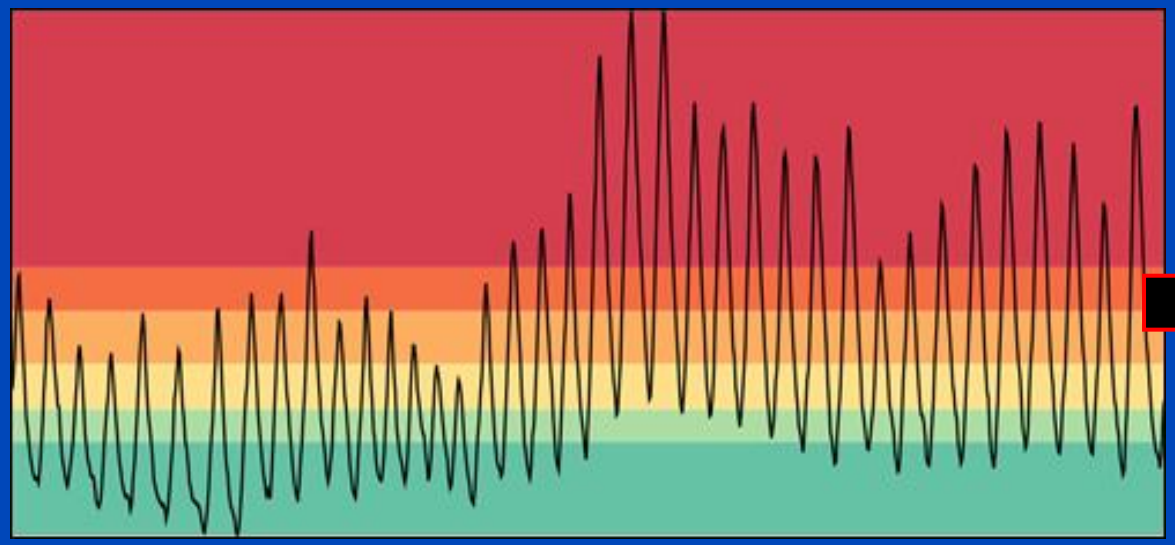
sMoCo: Li, Koong, and Xing, "Enhanced 4D cone–beam CT with inter–phase motion model," Med. Phys. 51(9), 3688–3695, 2007.
cMoCo: Brehm, Paysan, Oelhafen, Kunz, and Kachelrieß, "Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy," Med. Phys. 39(12):7603-7618, 2012.
acMoCo: Brehm, Paysan, Oelhafen, and Kachelrieß, "Artifact-resistant motion estimation with a patient-specific artifact model for motion-compensated cone-beam CT" Med. Phys. 40(10):101913, 2013.

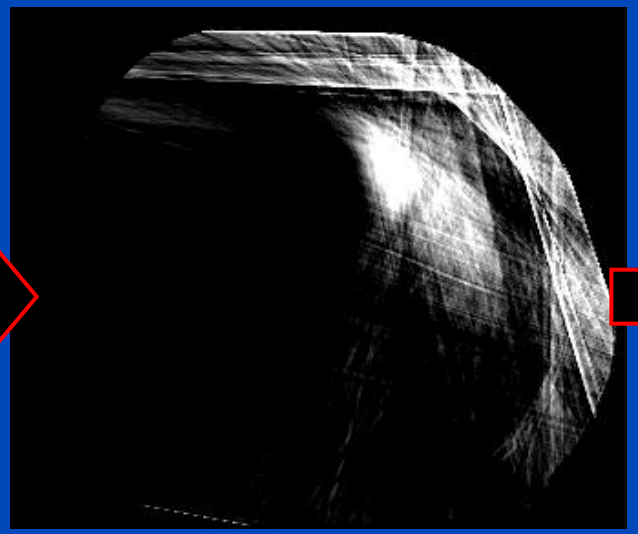
1 min shifted detector CBCT scan with about 12 respiratory cycles, displayed with 30 rpm.
Patient data provided by Memorial Sloan–Kettering Cancer Center, New York, NY. *C* = -200 HU, *W* = 1400 HU

Yet Unsolved Problems

Gating and gating-based motion compensation (MoCo)

- require gating signal,
- assume periodic motion,
- have low temporal resolution,
- fail on irregular breathing:





Gating = bad

Gating + MoCo = still bad

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RESEARCH ARTICLE

MEDICAL PHYSICS

Deep learning-based cone-beam CT motion compensation with single-view temporal resolution

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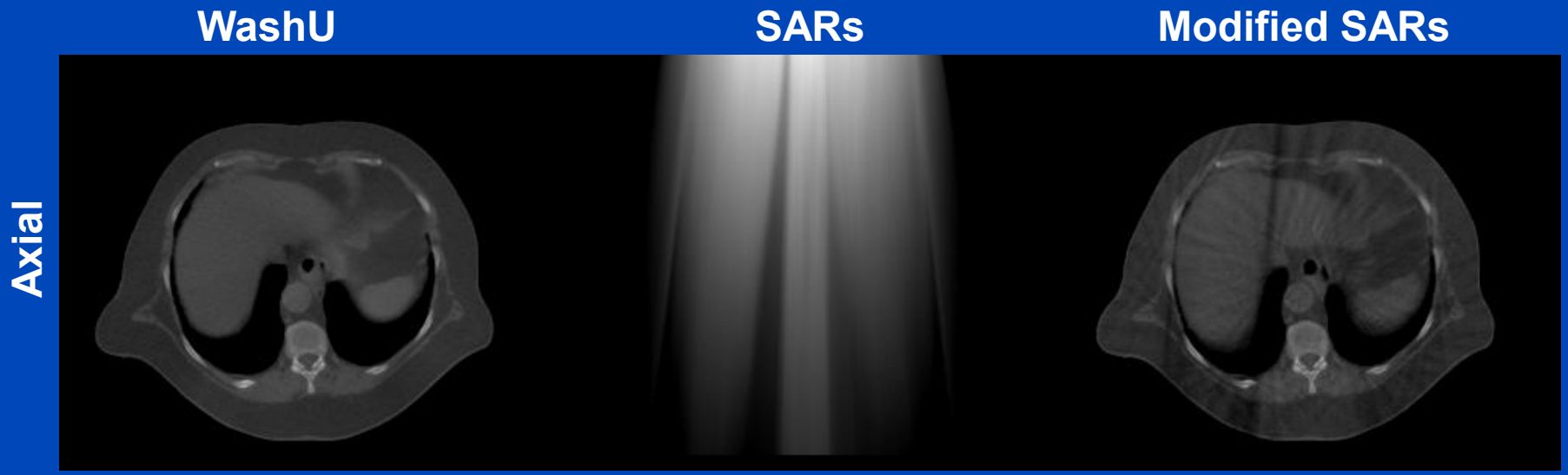
Abstract

Background: Cone-beam CT (CBCT) scans that are affected by motion often require motion compensation to reduce artifacts or to reconstruct 4D (3D+time) representations of the patient. To do so, most existing strategies rely on some sort of gating strategy that sorts the acquired projections into motion bins. Subsequently, these bins can be reconstructed individually before further post-processing may be applied to improve image quality. While this concept is useful for periodic motion patterns, it fails in case of non-periodic motion as observed, for example, in irregularly breathing patients.

Purpose: To address this issue and to increase temporal resolution, we propose the deep single angle-based motion compensation (SAMoCo).

Methods: To avoid gating, and therefore its downsides, the deep SAMoCo trains

Single Angle Reconstructions (SARs)

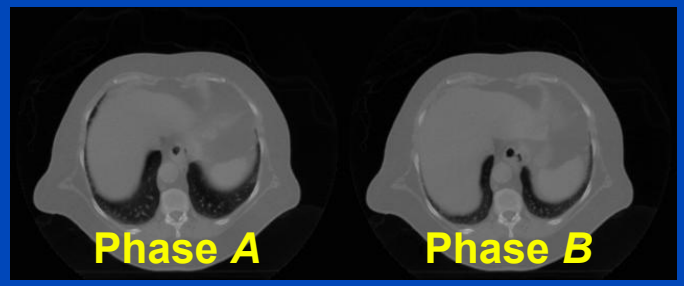


84 4D CT scans (no artifacts, high temporal resolution)

- 10 respiratory phases each (WashU/Colorado dataset)
- 10·10 combinations of phase *A* and *B* possible (including *A*=*B*)
- 84·10·10 displacement vector fields (DVFs) known
- 720 CBCT projections[1] simulated for each CT scan (each phase)
- 84·10·720·10·720 projection pairs with known DVF

[1]The actual projection numbers are between 420 and 900 and depend on the scan mode.

Training Workflow of Deep SAMoCo

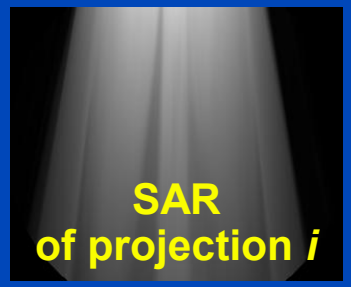


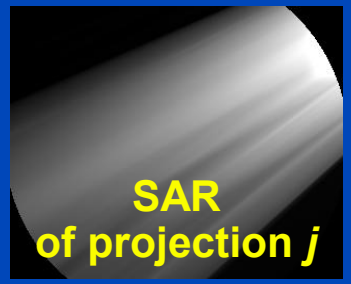
Random patient, random *A* and *B*

Randomly select
- projection *i* from *A*
- projection *j* from *B*

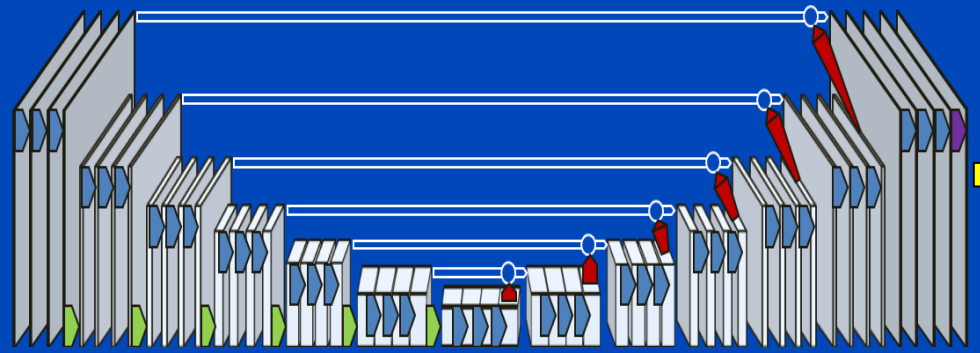
and backproject.

Calculate DVF_{AB} from phase *A* to phase *B* (Demons, Deeds, VoxelMorph, …)

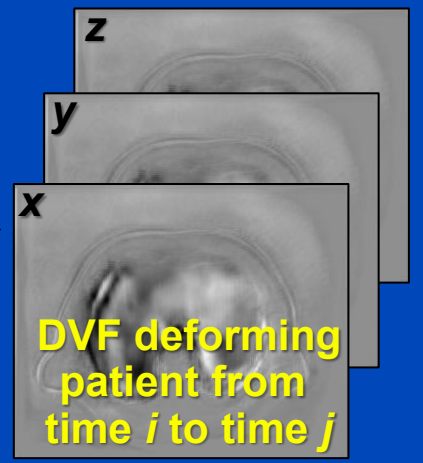




Network input



Network (modified U-Net)



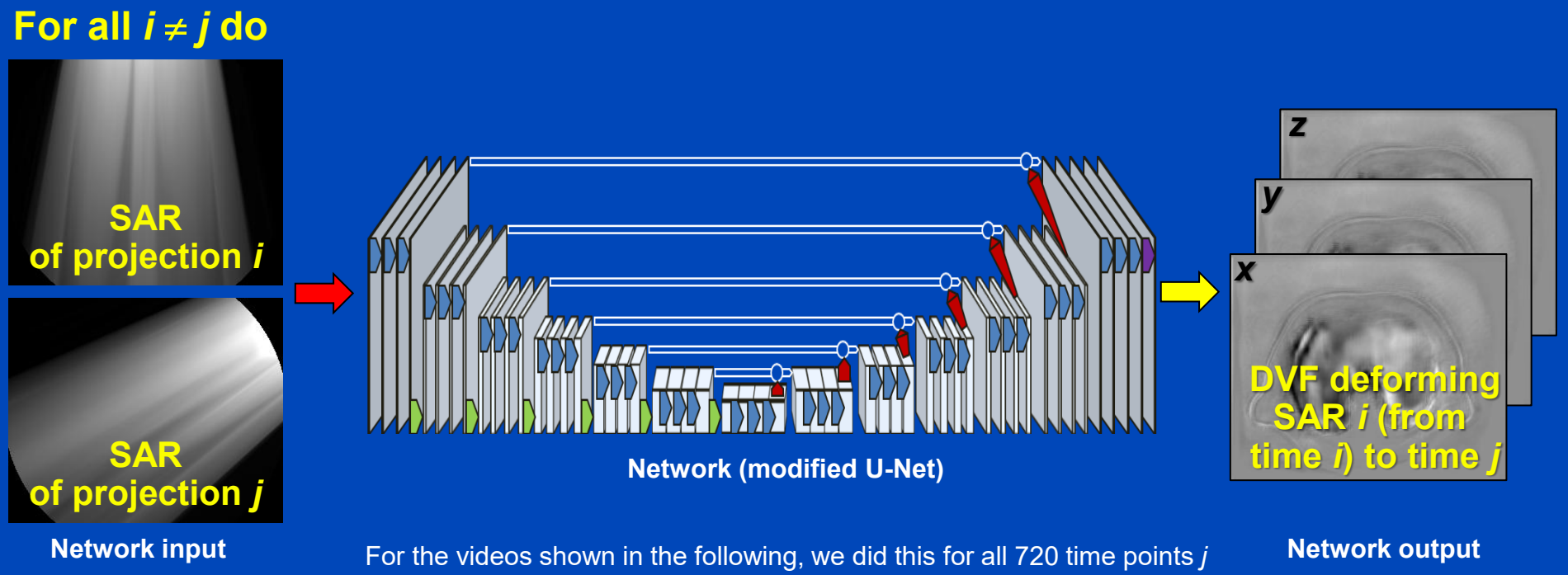
Training labels

All images shown here are volumes of size 512^3.

J. Maier, S. Sawall, M. Arheit, P. Paysan and M. Kachelrieß. Deep learning-based cone-beam CT motion compensation with single-view temporal resolution. Med. Phys. 52(7):e17911, July 2025.

Inference Workflow of Deep SAMoCo

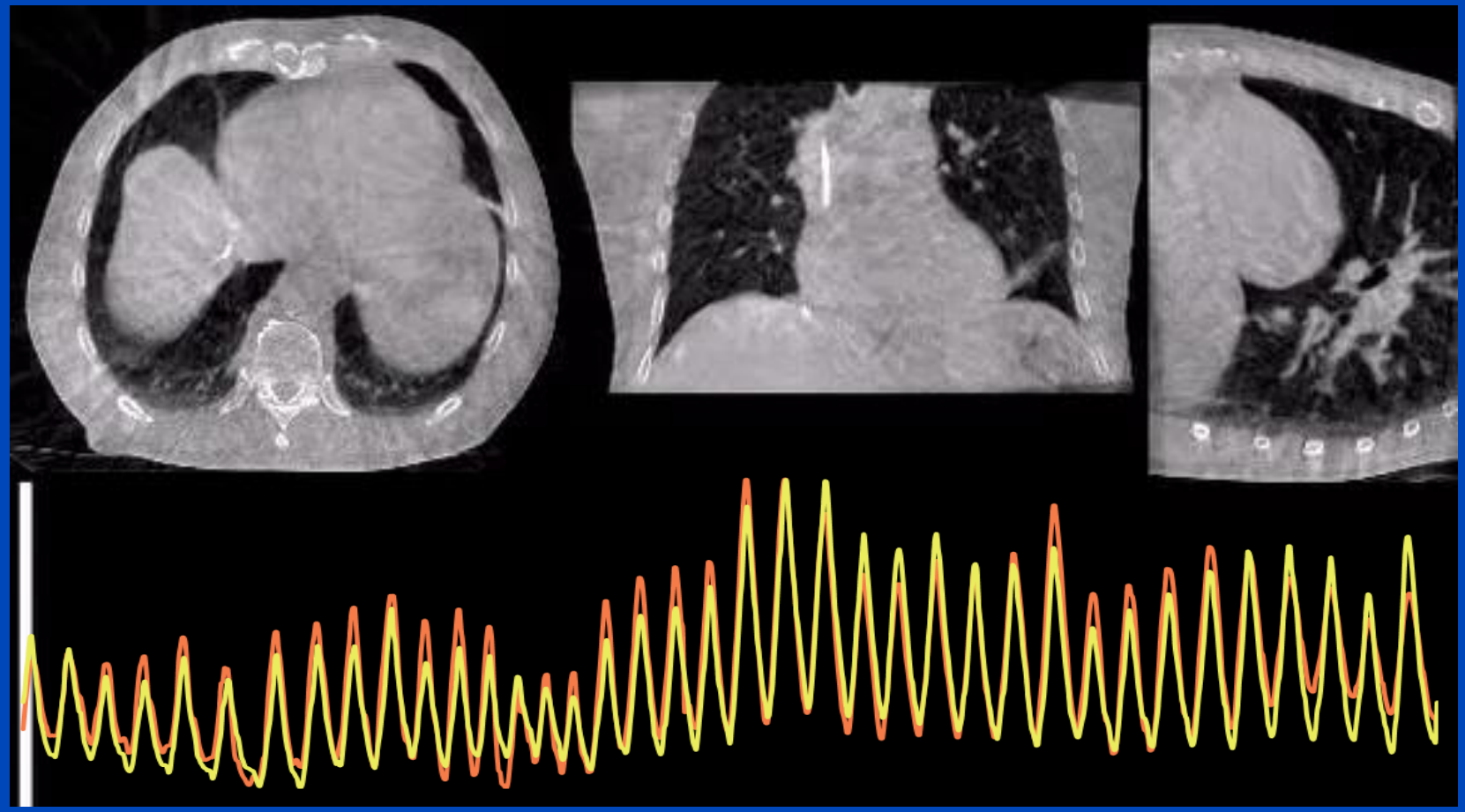
- For a new patient
  - decide for the desired time point *j*, e.g. the one from 1 millisecond ago
  - for all $i \neq j$ get the DVFs pointing from *i* to *j* from the neural network
  - deform SARs for all $i \neq j$ into time point *j*
  - add all the volumes



For the videos shown in the following, we did this for all 720 time points *j*

J. Maier, S. Sawall, M. Arheit, P. Paysan and M. Kachelrieß. Deep learning-based cone-beam CT motion compensation with single-view temporal resolution. Med. Phys. 52(7):e17911, July 2025.

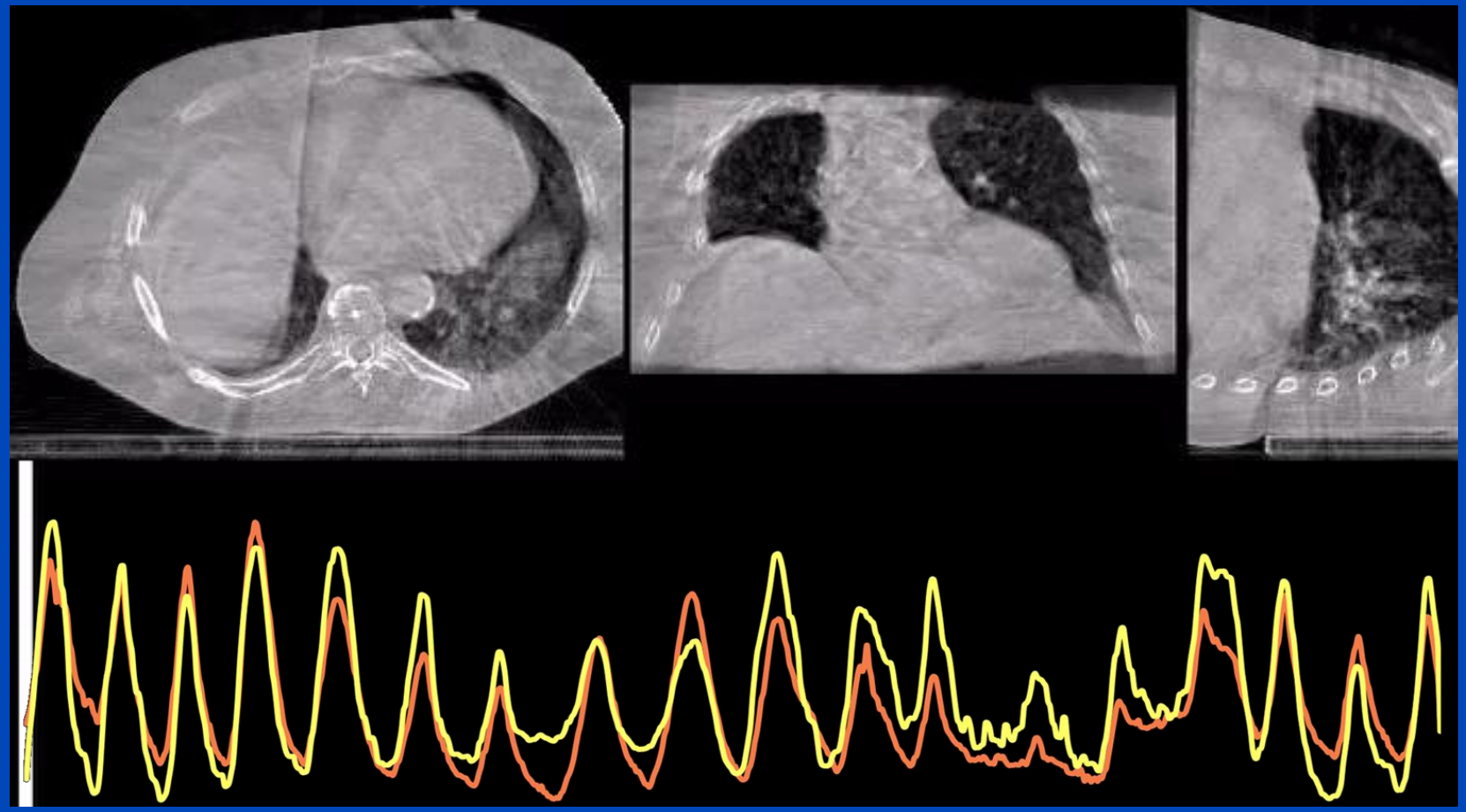
VUMC_4DThorax



Red: RPM signal (external signal – not used for recon)
Yellow: Diaphragm motion (intrinsic signal – from PAMoCo recon)

J. Maier, S. Sawall, M. Arheit, P. Paysan and M. Kachelrieß. Deep learning-based cone-beam CT motion compensation with single-view temporal resolution. Med. Phys. 52(7):e17911, July 2025.

MSK 1



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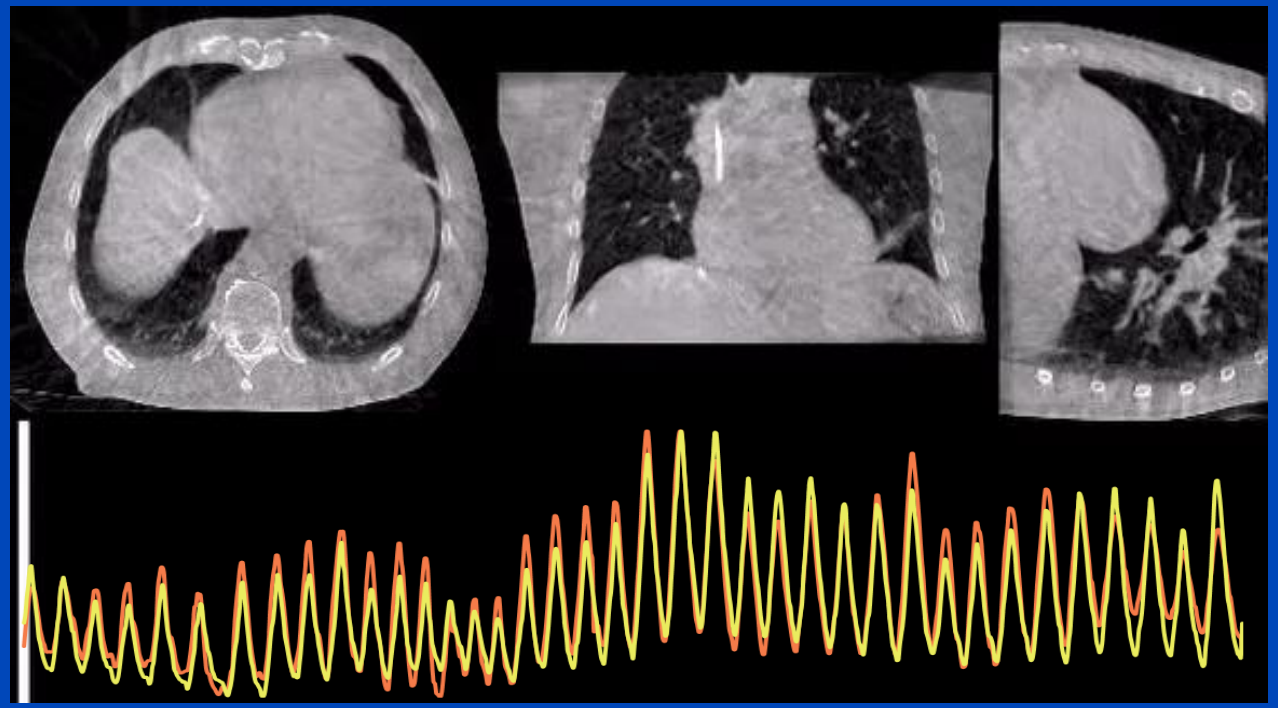

Upcoming in
2026
(yet to be developed)

Imaging ($t < 0$) Treatment ($t > 0$) t

Thank You!

This presentation will soon be available at www.dkfz.de/ct.

Job opportunities through marc.kachelriess@dkfz.de or through DKFZ's international PhD or Postdoctoral Fellowship programs.

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.