State-of-the-Art 4D CT

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4D CT Contents

- 4D diagnostic CT
- 4D cone-beam CT
- More than that?

Electrocardiogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart

Marc Kachelriess and Willi A. Kalender[a)]
Institute of Medical Physics, University of Erlangen-Nürnberg, Erlangen, Germany

(Received 31 December 1997; accepted for publication 17 September 1998)

Subsecond computed tomography (CT) scanning offers potential for improved heart imaging. We therefore developed and validated dedicated reconstruction algorithms for imaging the heart with subsecond spiral CT utilizing electrocardiogram (ECG) information. We modified spiral CT z-interpolation algorithms on a subsecond spiral CT scanner. Two new classes of algorithms were investigated: (a) 180°CI (cardio interpolation), a piecewise linear interpolation between adjacent spiral data segments belonging to the same heart phase where segments are selected by correlation with the simultaneously recorded ECG signal and (b) 180°CD (cardio delta), a partial scan recon-

Circulation
JOURNAL OF THE AMERICAN HEART ASSOCIATION

American Heart Association®

Noninvasive Coronary Angiography by Retrospectively ECG-Gated Multislice Spiral CT

Stephan Achenbach, Stefan Ulzheimer, Ulrich Baum, Marc Kachelrieß, Dieter Ropers, Tom Giesler, Werner Bautz, Werner G. Daniel, Willi A. Kalender and Werner Moshage

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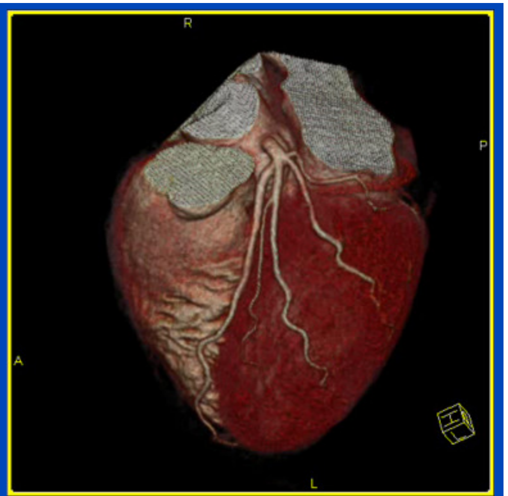
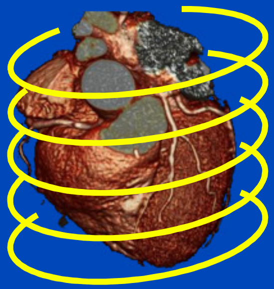
Kachelrieß, Kalender, Med. Phys. 25(12), December 1998
Achenbach, Kachelrieß et al., Circulation 102, December 2000

Imaging the Heart with CT
(Cardiac-CT = phase-correlated CT)



- Periodic motion
- Synchronisation (ECG, Kymogram, …)
- Phase-correlated scanning = <u>Prospective Gating</u>
  - Used in the 80s and 90s with little success.
  - Comes into use again due to large cone-angles.
- Phase-correlated reconstruction = <u>Retrospective Gating</u>
  - Single-phase (partial scan) approaches, e.g. 180°MCD
  - Bi-phase approaches, e.g. ACV (Flohr et al.)
  - Multi-phase Cardio Interpolation methods, e.g. 180°MCI (gold-standard)
  - Generations
    - » Single-slice spiral CT: 180°CD, 180°CI (introduced 1996[1])
    - » Multi-slice spiral CT: 180°MCD, 180°MCI (introduced 1998[2])
    - » Cone-beam spiral CT: ASSR CD, ASSR CI (introduced 2000[3])
    - » Wide cone-beam CT: EPBP (introduced 2002[4])
    - » Multi-source CBCT: EPBP (introduced 2005[5])

[1]Med. Phys. 25(12):2417-2431 (1998), [2]Med. Phys. 27(8):1881-1902 (2000), [3]Proc. Fully 3D-2001:179-182 (2001), [4]Med. Phys. 31(6): 1623-1641 (2004), [5]Med. Phys. 33(7): 2435-2447 (2006)



Retrospective Gating

=

Standard scan + ECG-correlated recon

Standard spiral scan with low pitch value ($p \leq f_H \cdot t_{rot}$)

Phase-correlated reconstruction

$p \cdot T_{rot}$ / 2 ≤ Temp. resolution ≤ T_{rot} / 2

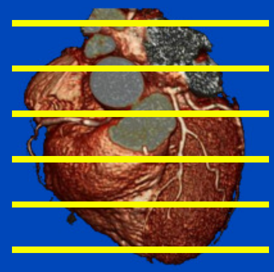
Works also at high heart rates

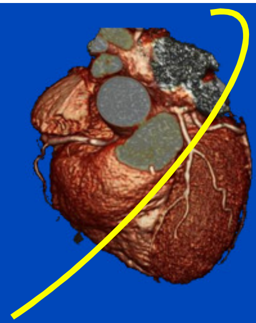
Dose management: ECG-based TCM

Full phase selectivity

Highly robust (also with arrhythmia)

Good dose usage





Prospective Gating

=

ECG-triggered scan + standard recon

ECG-triggered sequence- or spiral scan with high pitch value

Standard image reconstruction

Temporal resolution = T_{rot} / 2

Good at low heart rates

Dose management: inherent

No phase selectivity

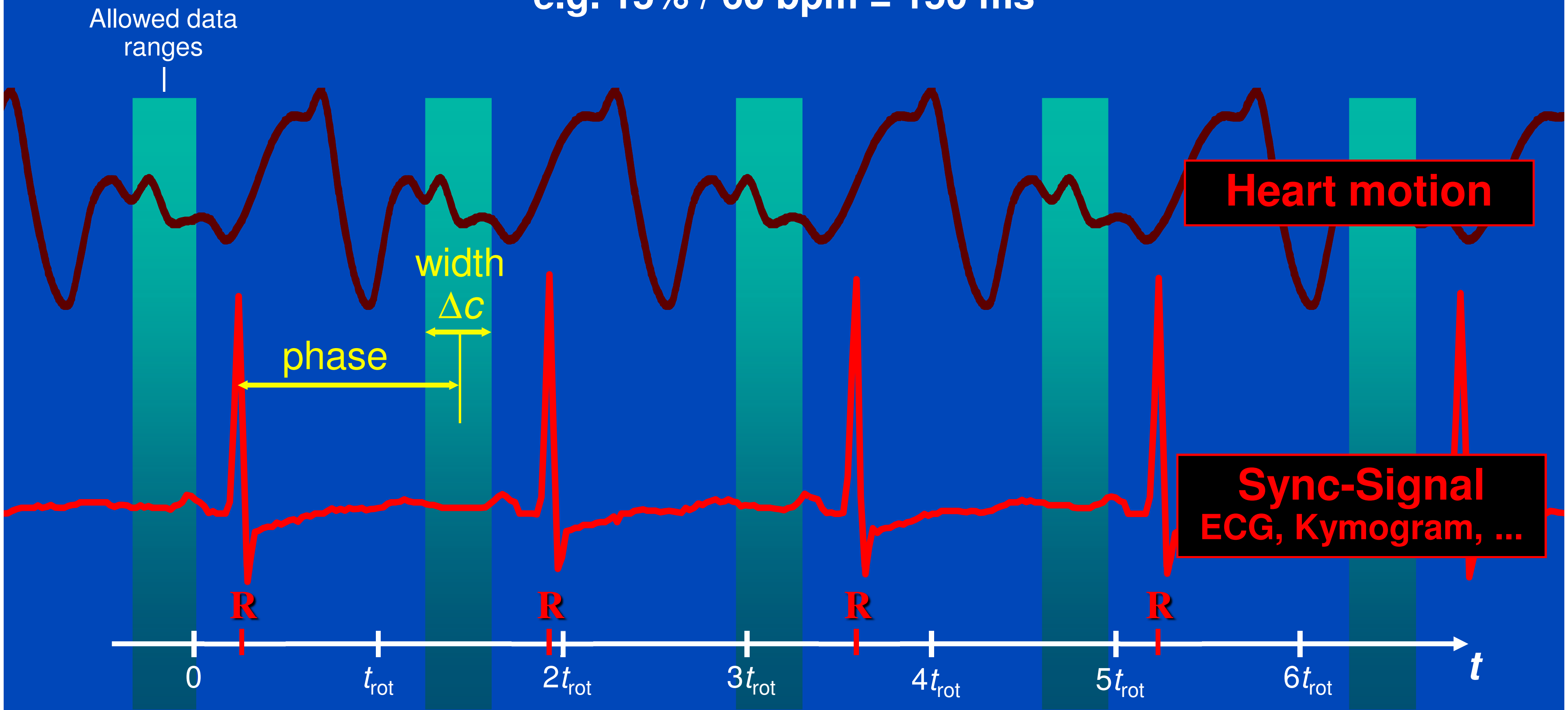
Sufficiently robust (not with arrythmia)

Very good dose usage

Synchronization with the Heart Phase

t_{eff} **= width / heart rate**

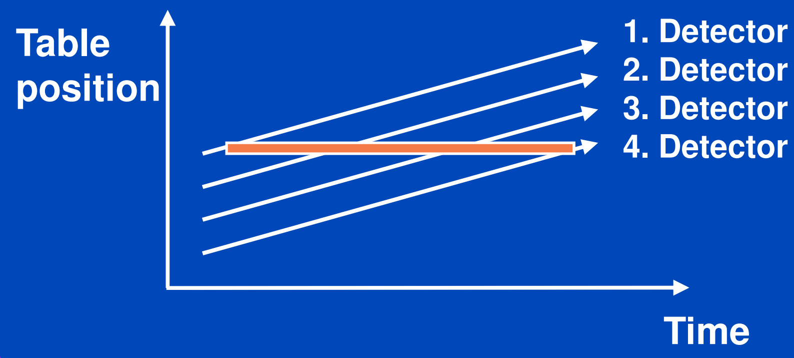
e.g. 15% / 60 bpm = 150 ms

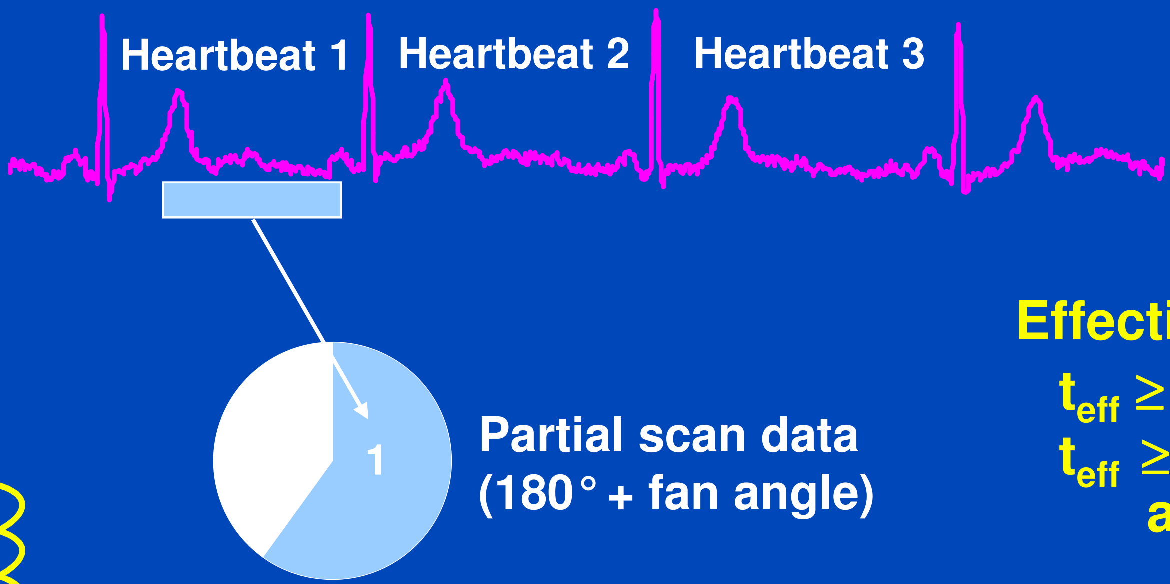


Width, and thus t_{eff}, corresponds to the FWTM of the phase contribution profile.

Partial Scan Reconstruction

Use one segment
of 180°+δ data
of phase-coherent data
for a selected heart phase





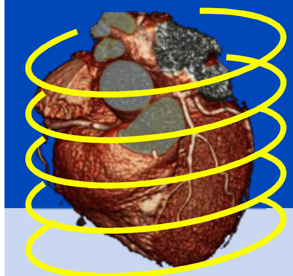
Partial scan data
(180° + fan angle)

Effective scan time

$t_{eff} \geq t_{rot}/2$

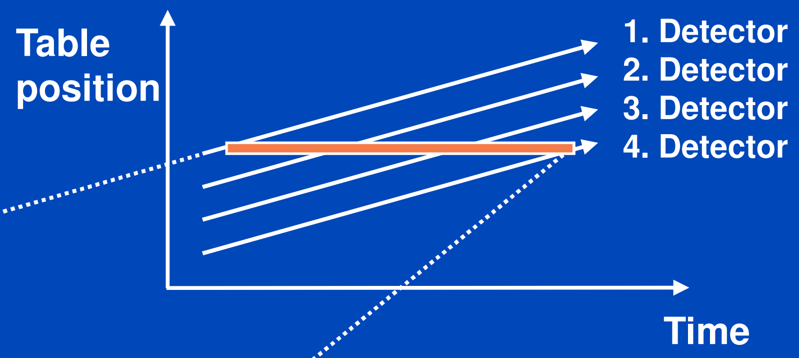
$t_{eff} \geq 200$ ms

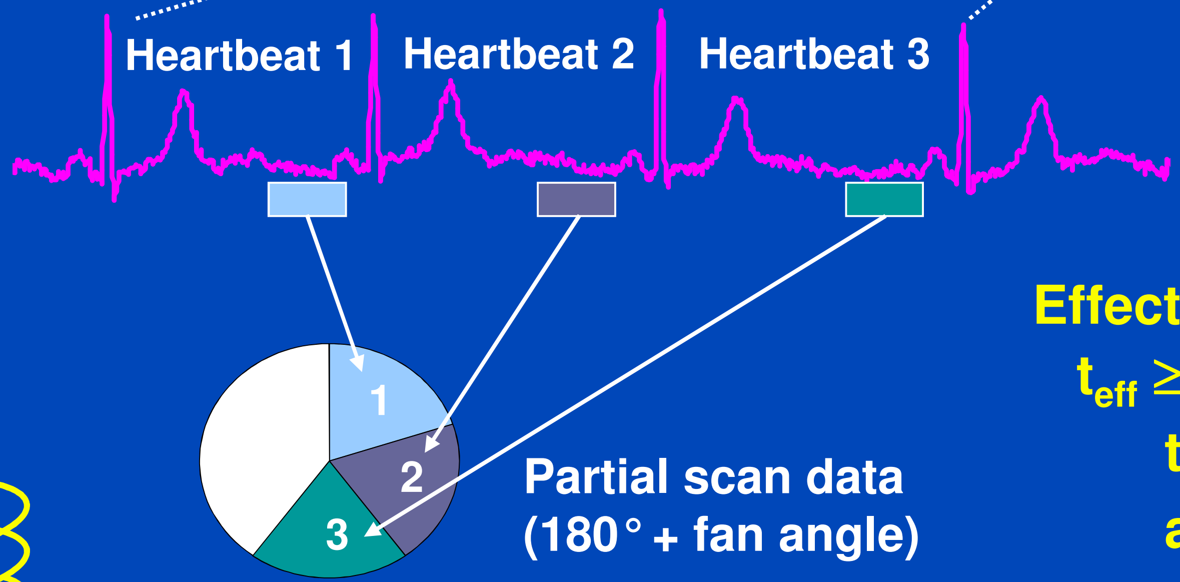
at $t_{rot} = 0.4$ s



Multi-Segment Reconstruction

Combine n segments to obtain 180°+δ of phase-coherent data for a selected heart phase



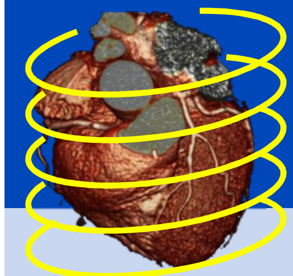


Effective scan time

$t_{eff} \geq 48$ ms

typ. 75-150 ms

at $t_{rot} = 0.4$ s



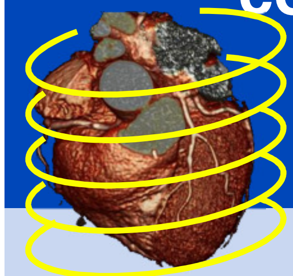
Kachelrieß, Ulzheimer, Kalender, Med. Phys. 27(8):1881-1902 (2000)

Pitch Value and Full Phase Selectivity

- **Each voxel must be illuminated by the x-rays at least as long as one motion cycle of the heart takes**
- **The table increment per motion cycle must not be larger than the collimation of the scanner**

$$p \leq f_{\mathrm{H}} t_{\mathrm{rot}}$$

- **For example t_{rot} = 0.5 s and f_H = 60 bpm imply that a pitch value of p < 0.5 must be chosen.**
- **The lower the pitch value the more segments can be combined in multi-segment image reconstruction.**



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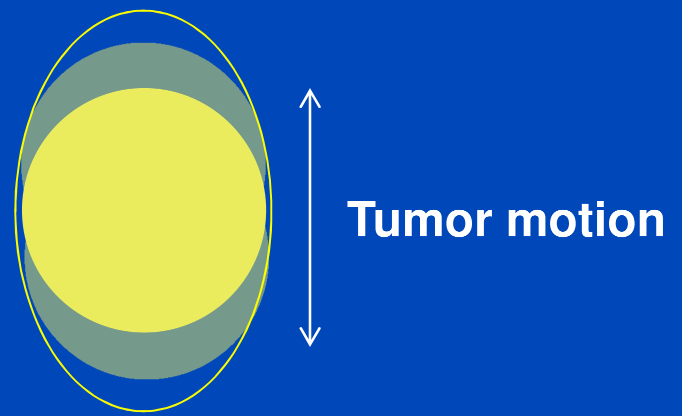
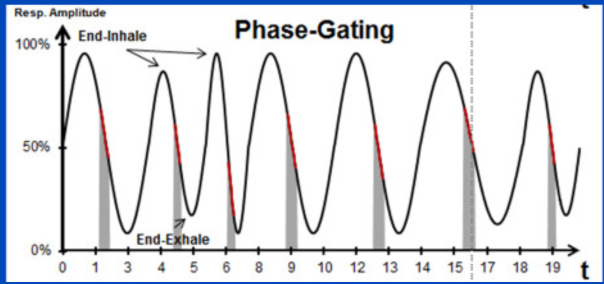
Tumor Motion

- During radiation treatment the patient's tumor will move due to respiratory (and cardiac) motion
- To avoid missing the tumor:
  - Clinical target volume (CTV) needs to be significantly larger than the gross tumor volume (GTV)
  - Increase portal size
  - Increase irradiation to healthy tissue

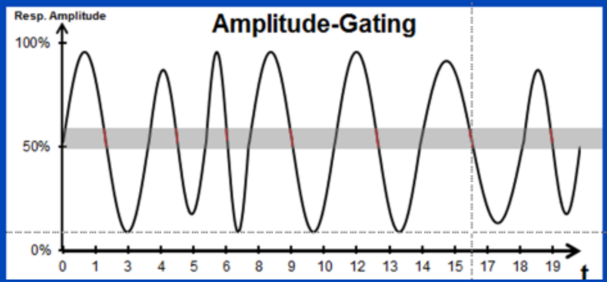


Phase- and Amplitude Gating

- 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

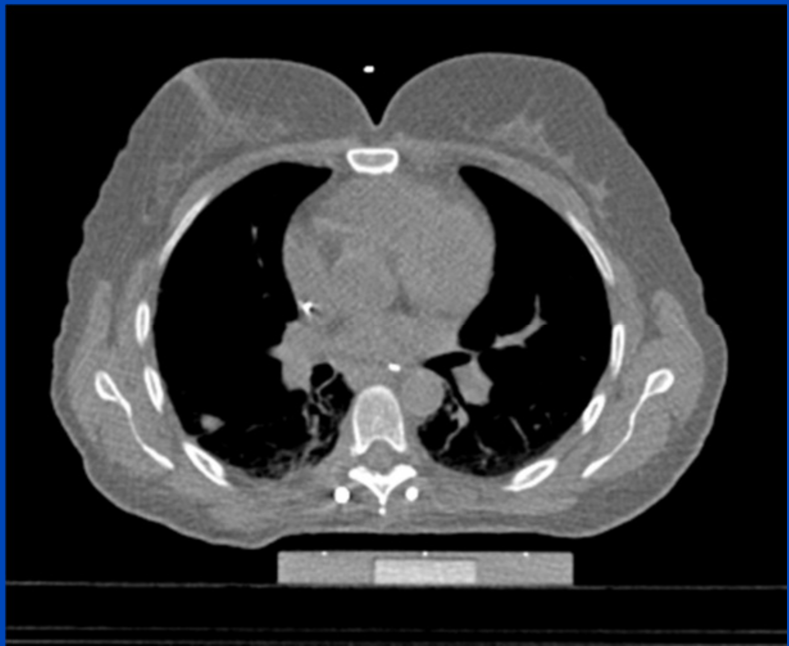


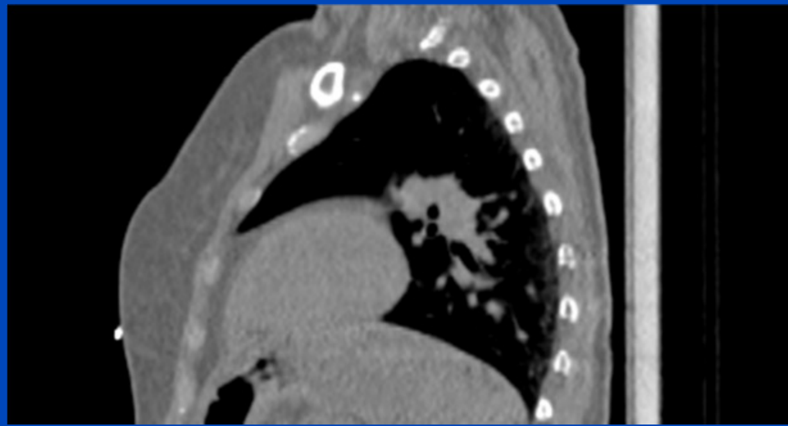
- Amplitude gating
  - Assumes periodicity in time
  - More robust against amplitude variations
  - Used for respiratory 3D CT (prospective)
  - Used for respiratory 4D CT (retrospective)
  - Assumptions not really justified because motion patterns change with changing amplitude

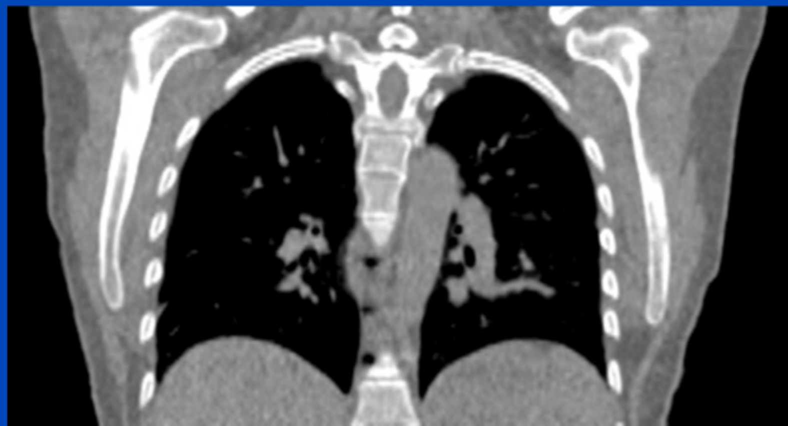


4D CT SCAN

SIEMENS SOMATOM Definition Flash

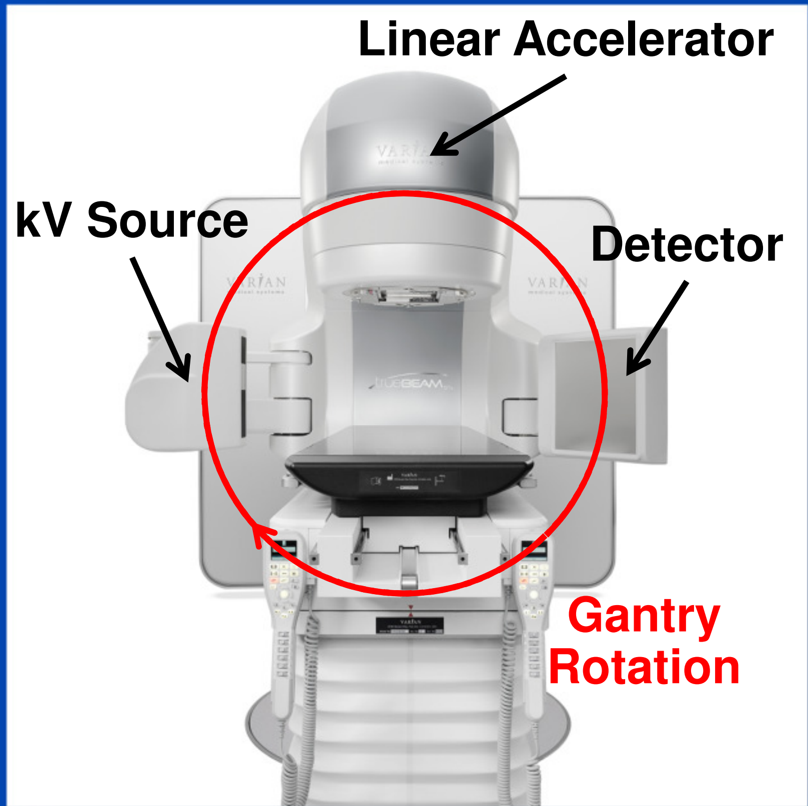




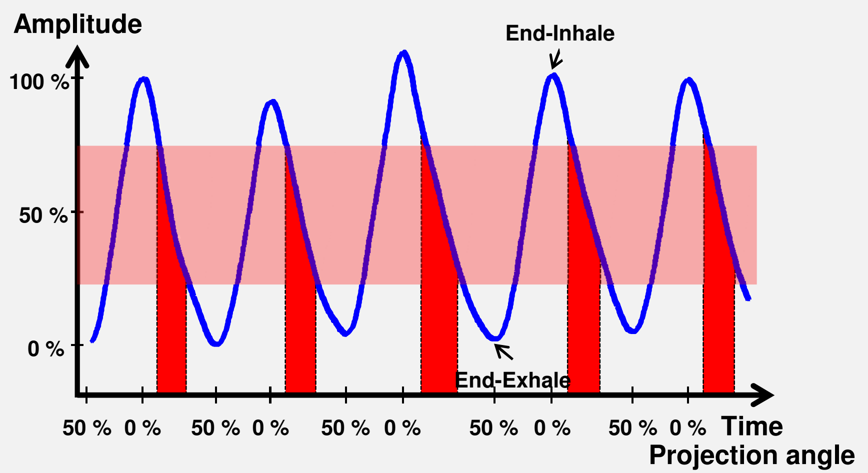


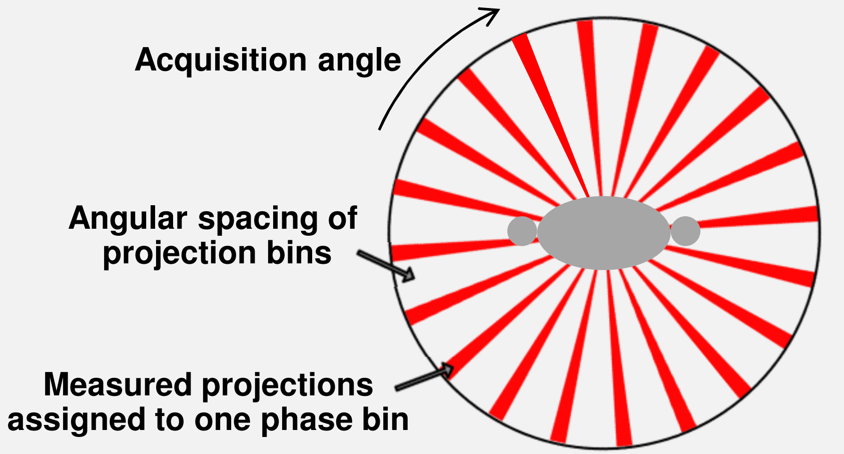
C = 0 HU, W = 1000 HU

What about Cone-Beam CT (CBCT)?



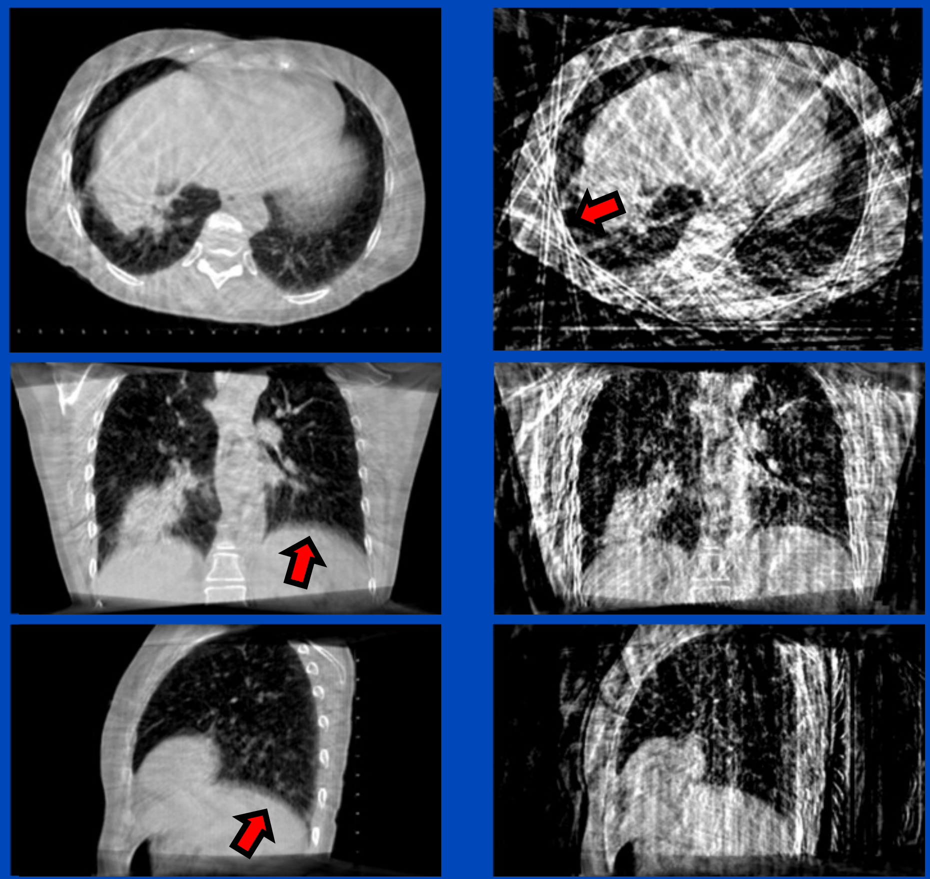
Retrospective Gating





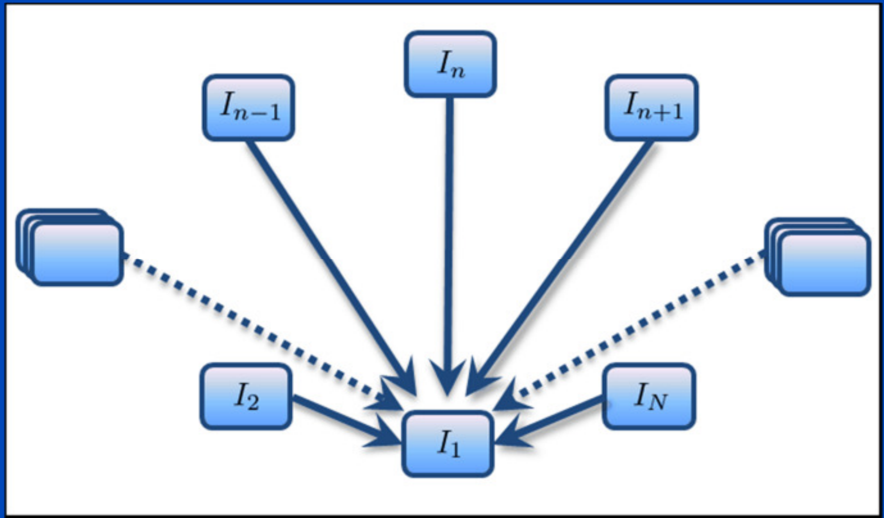
Without gating (3D): Motion artifacts

With gating (4D): Sparse-view artifacts

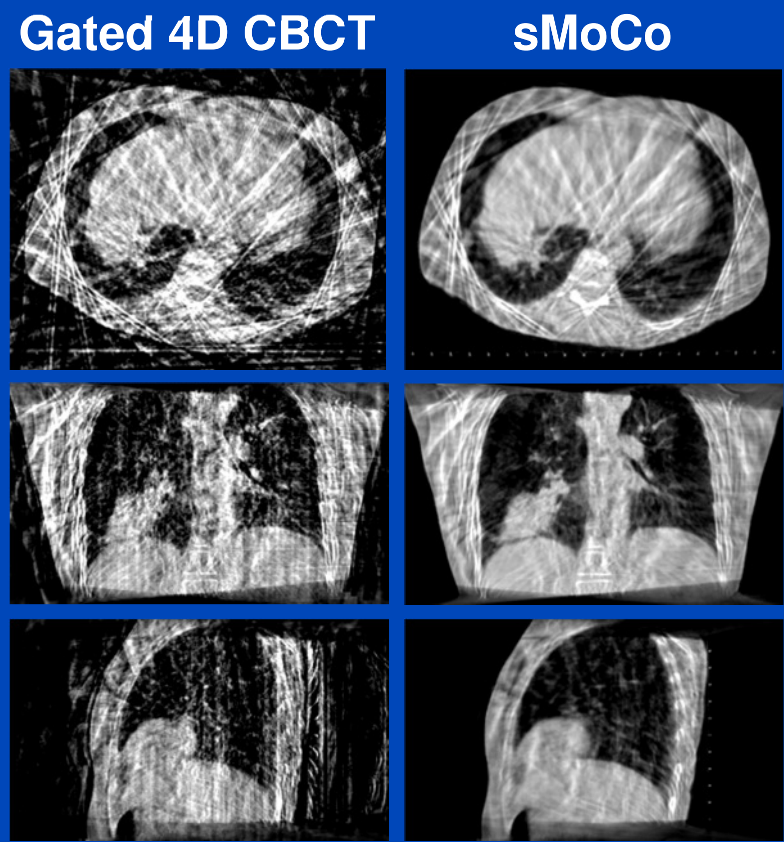


A Standard Motion Estimation and Compensation Approach (sMoCo)

- Motion estimation via standard 3D-3D registration



- Has to be repeated for each reconstructed phase

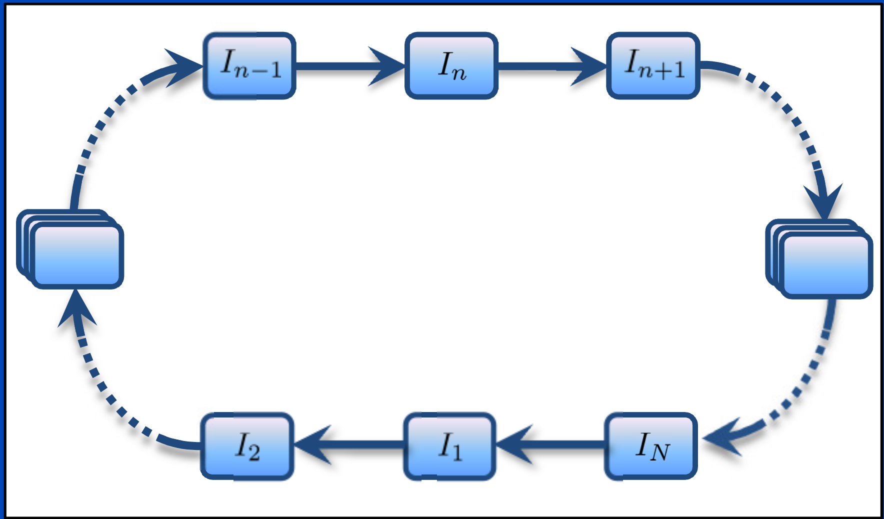


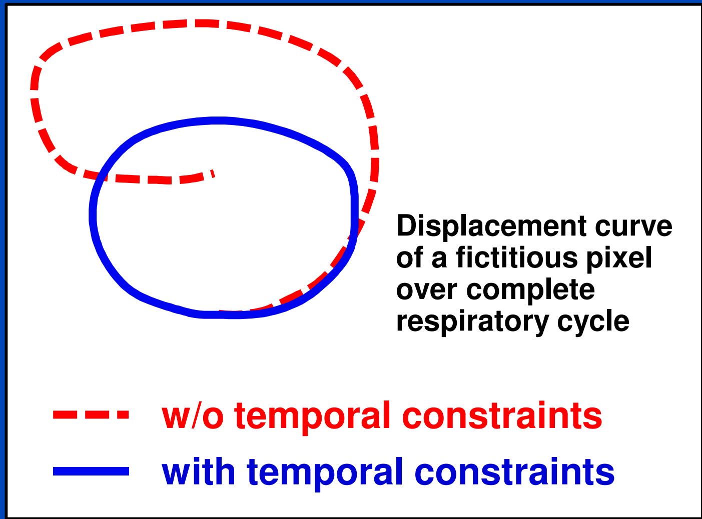
- Streak artifacts from gated reconstructions propagate into sMoCo results

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

A Cyclic Motion Estimation and Compensation Approach (cMoCo)

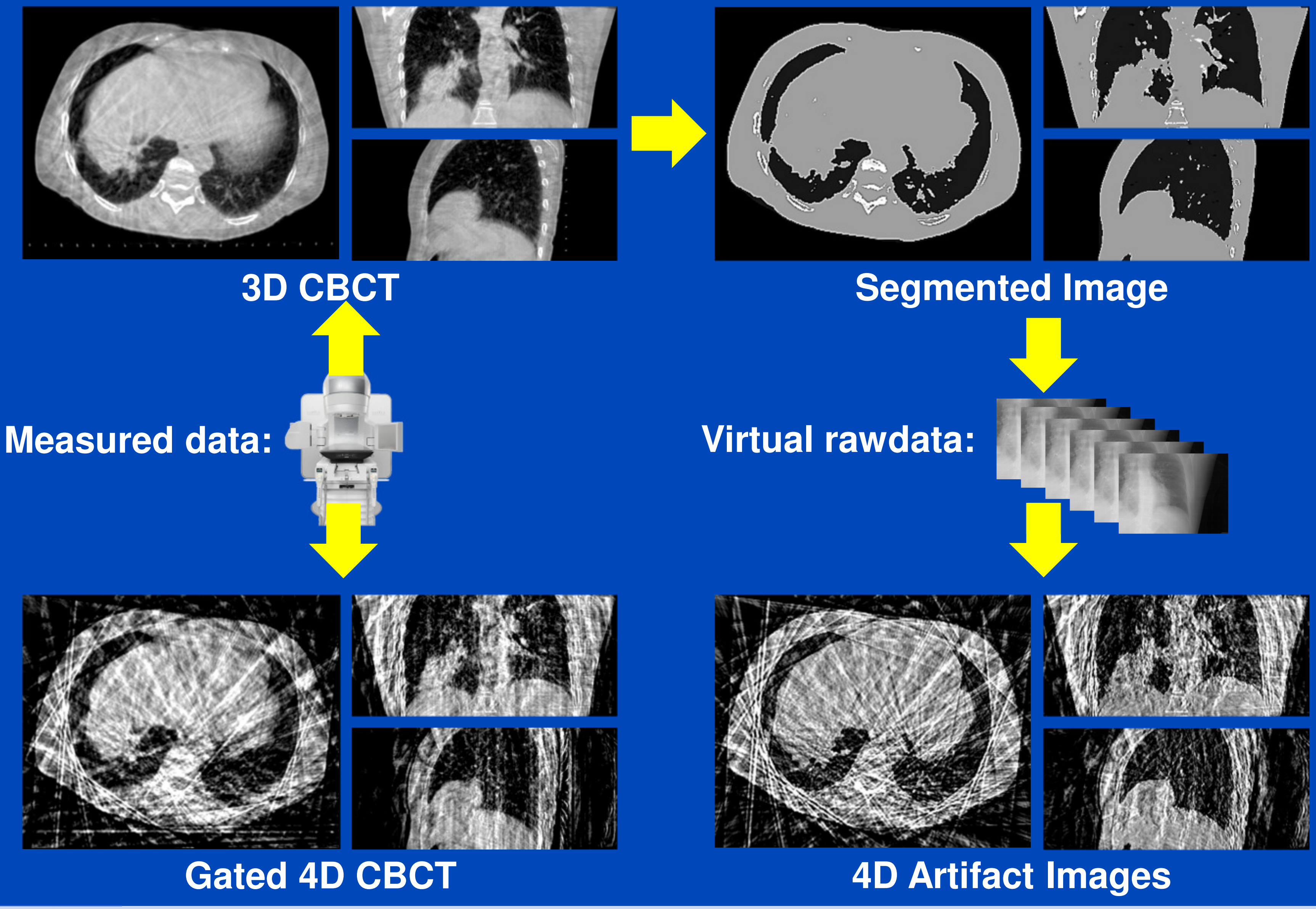
- Motion estimation only between adjacent phases
  - All other MVFs given by concatenation





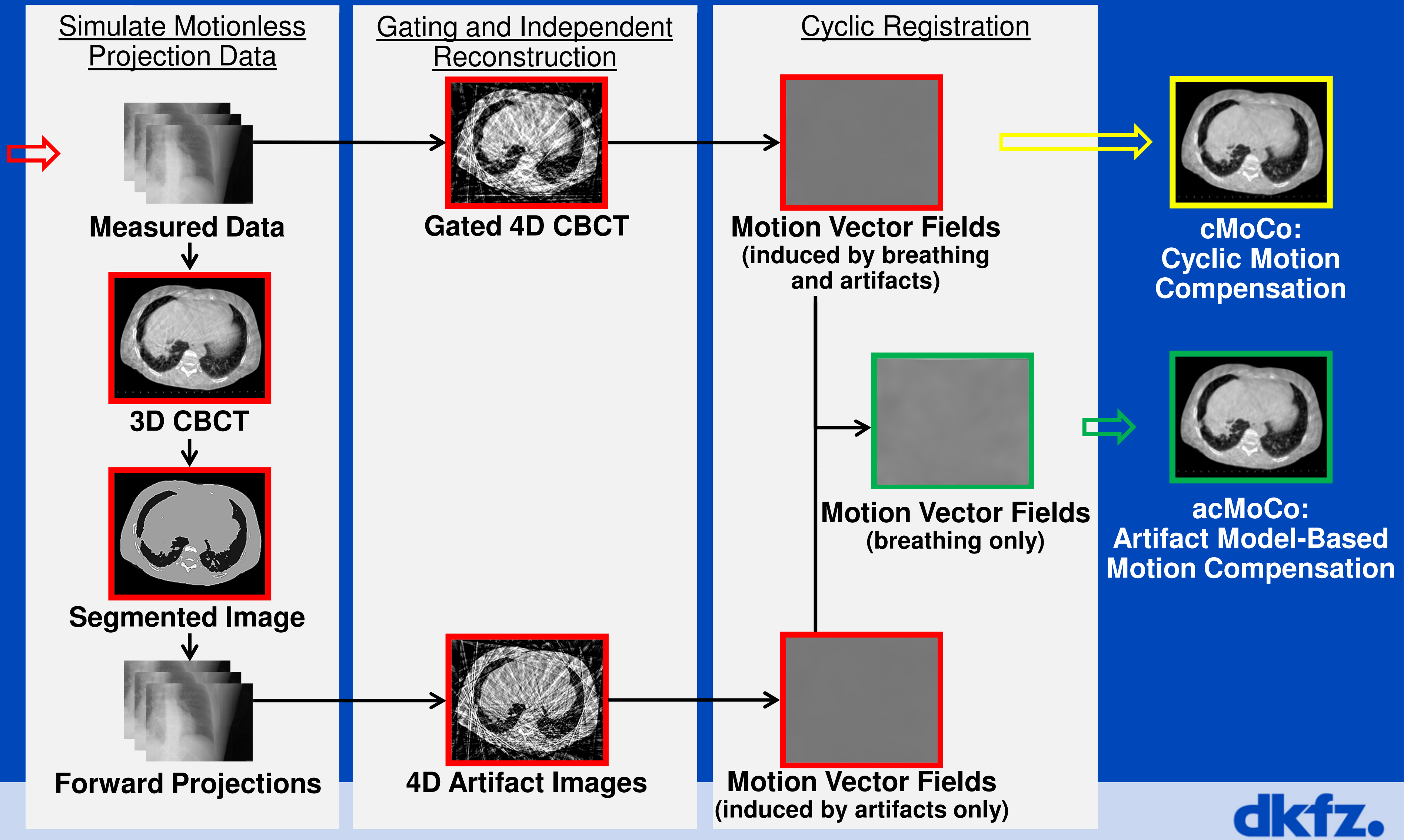
- Incorporate additional knowledge
  - A priori knowledge of quasi periodic breathing pattern
  - Non-cyclic motion is penalized
  - Error propagation due to concatenation is reduced

Artifact Model-Based MoCo (aMoCo)



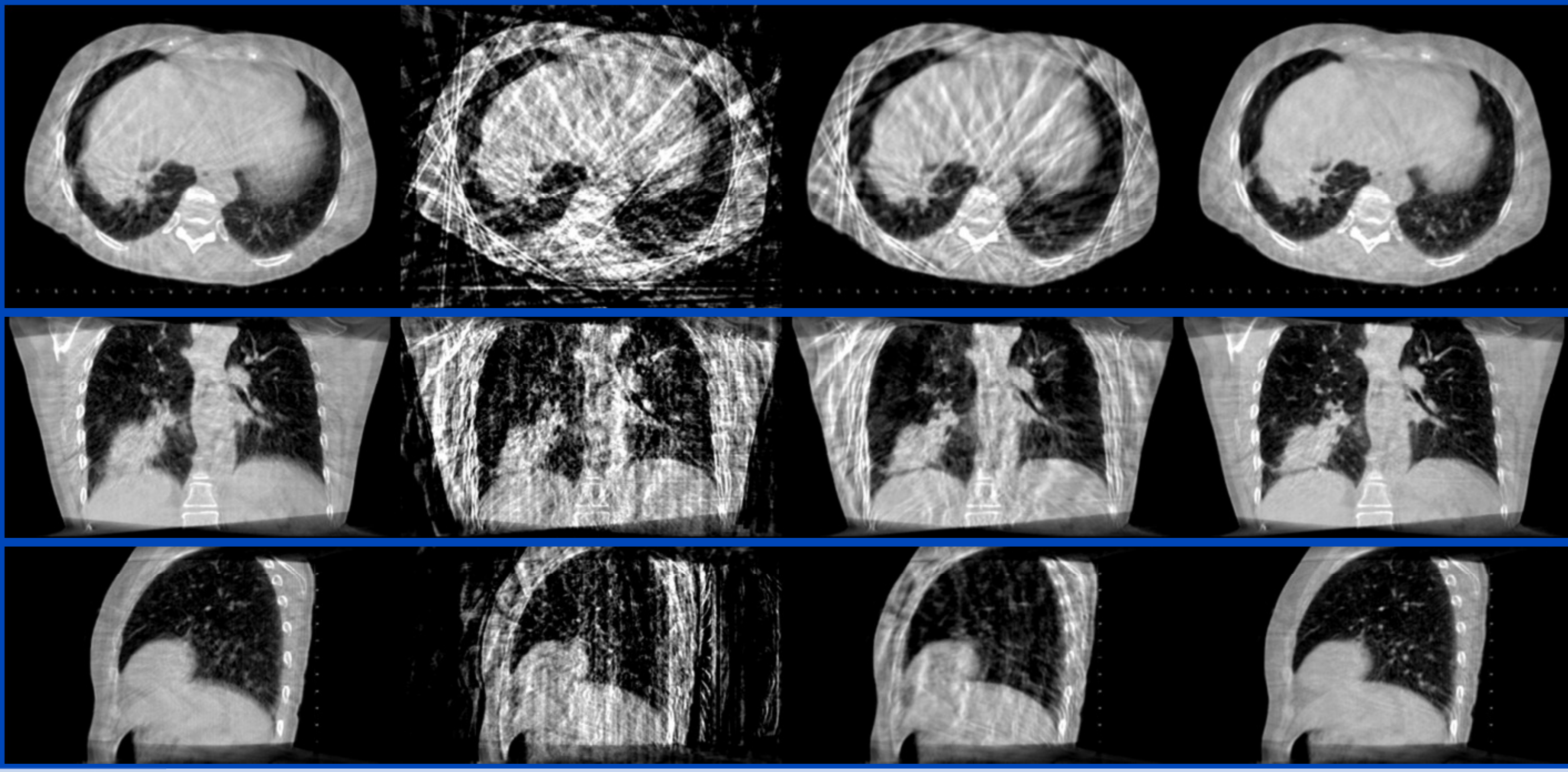
Brehm, Paysan, Oelhafen, and Kachelrieß, "Artifact-resistant motion estimation with a patient-specific artifact model for motion-compensated cone-beam CT" Med. Phys. 40(10):101913 (2013).

Motion Estimation using an Patient-Specific Artifact Model



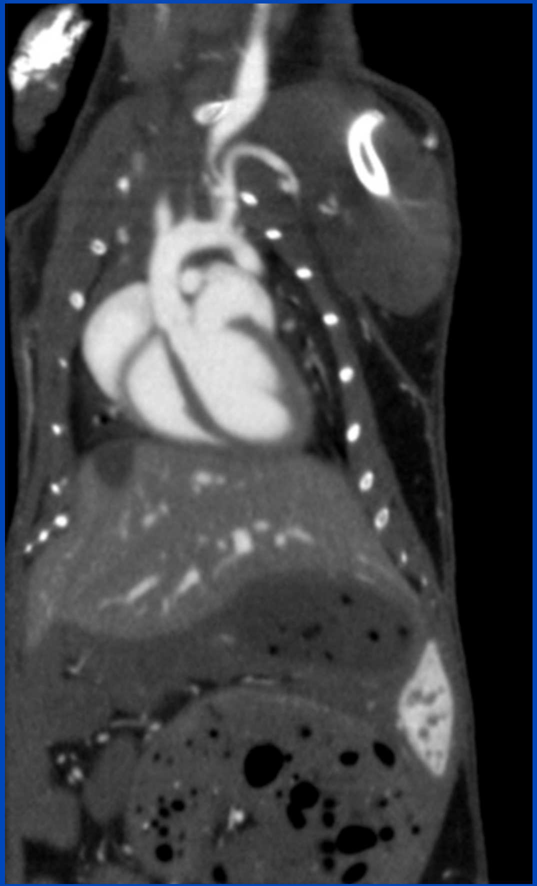
Patient Data – Results

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

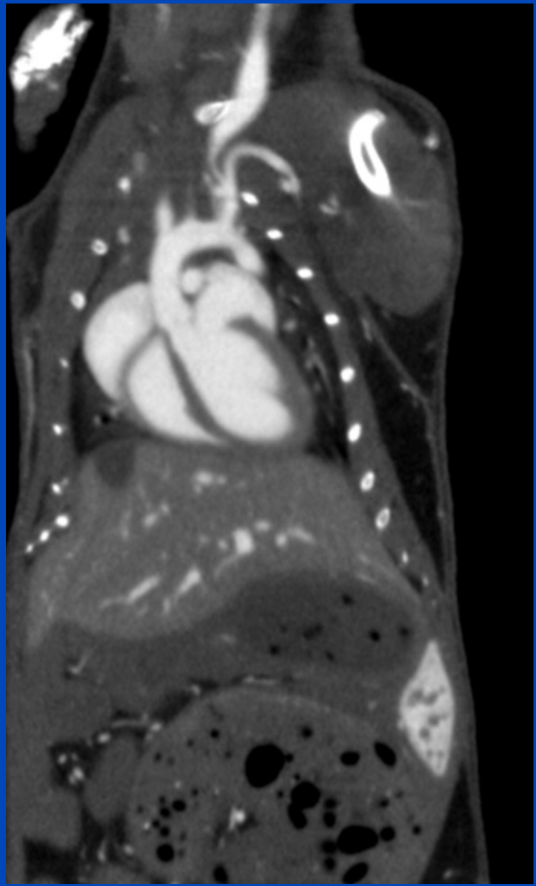


C = -200 HU, W = 1400 HU

More Than That?



Mouse with 240 bpm and 180 rpm.

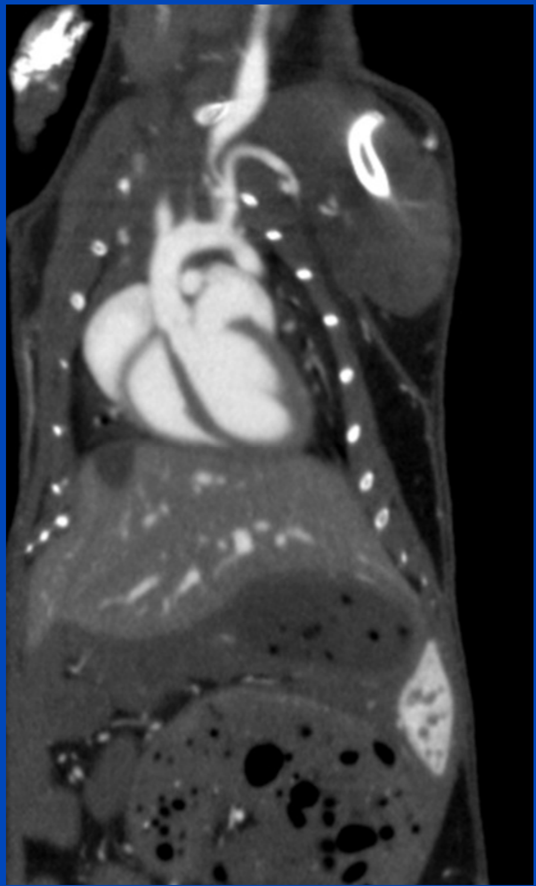


5D data displayed as:

Heart: 180 bpm

Lung: 90 rpm

Mouse with 240 bpm and 180 rpm.

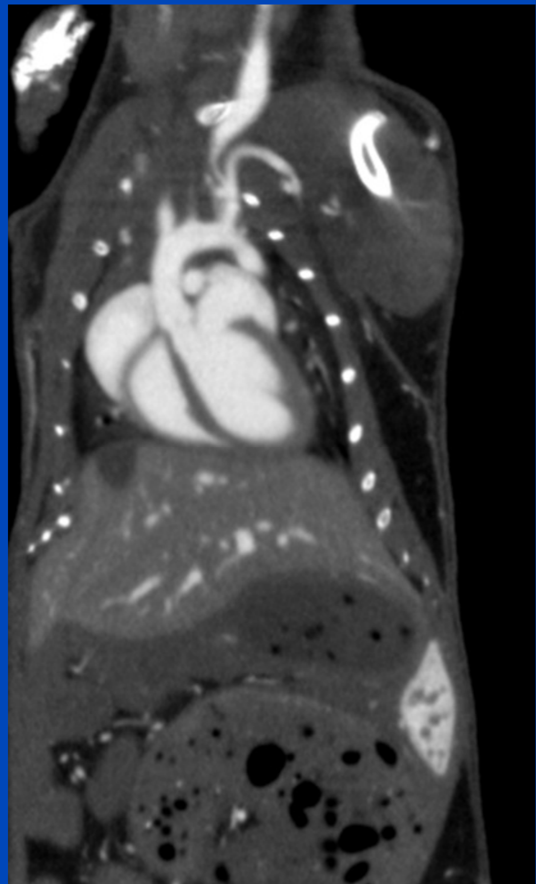


5D data displayed as:

Heart: 90 bpm

Lung: 90 rpm

Mouse with 240 bpm and 180 rpm.

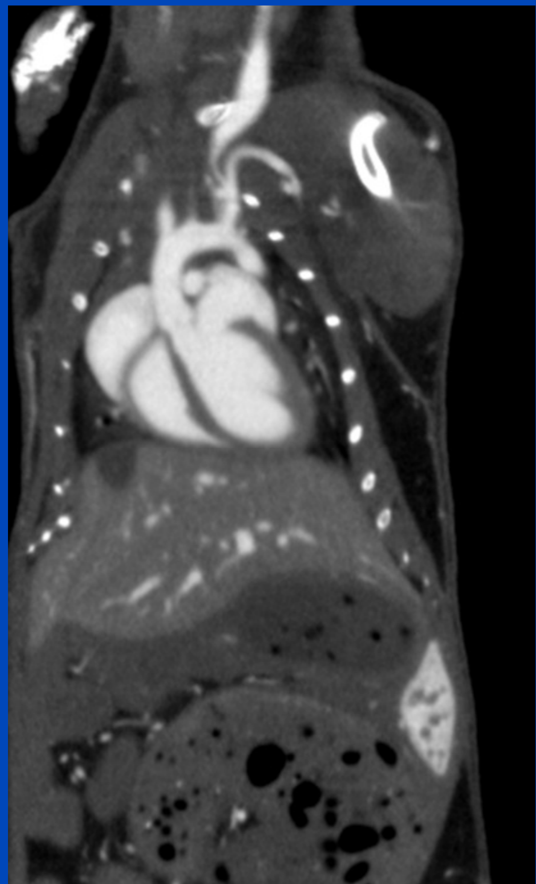


5D data displayed as:

Heart: 0 bpm

Lung: 90 rpm

Mouse with 240 bpm and 180 rpm.



5D data displayed as:

Heart: 90 bpm

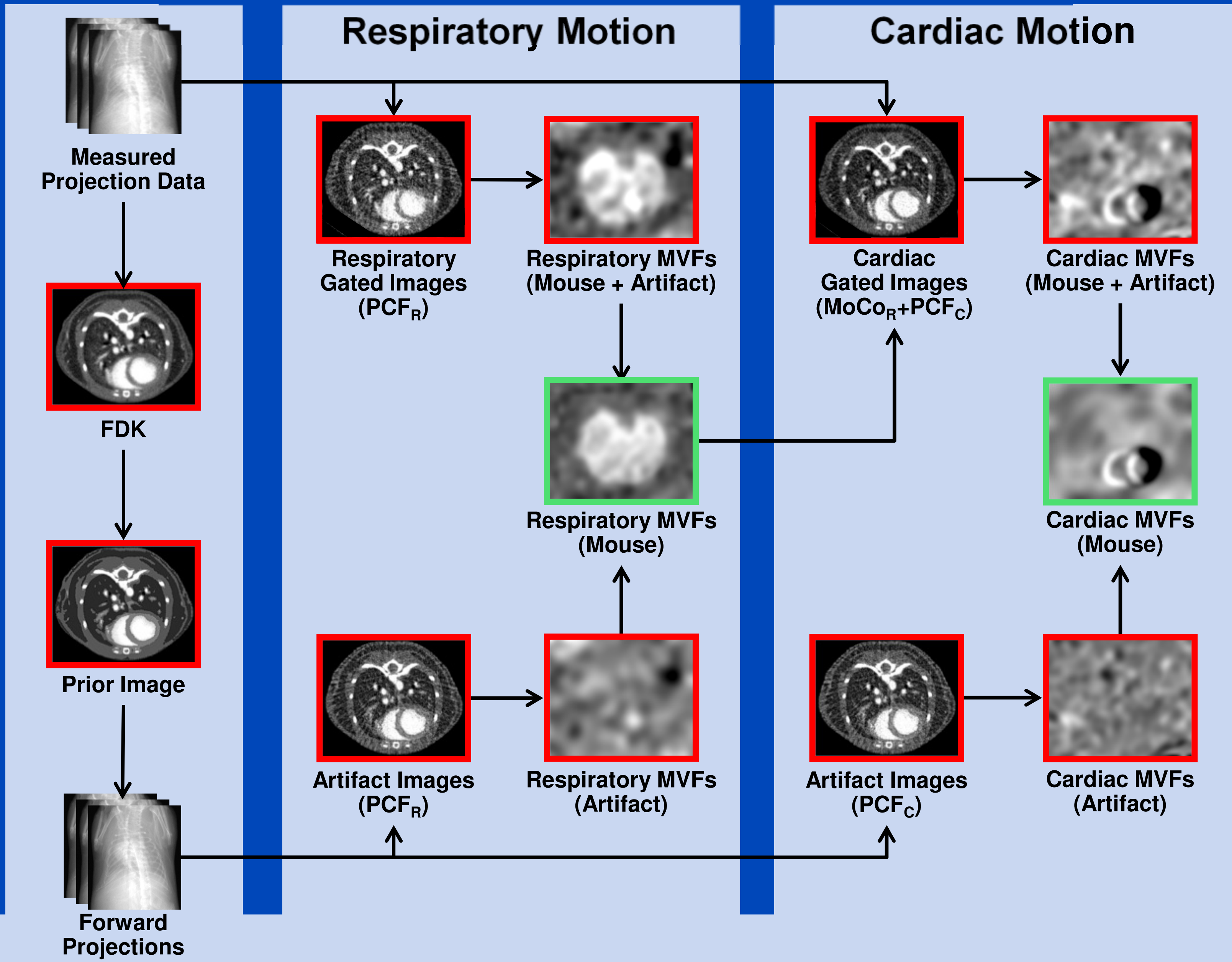
Lung: 0 rpm

Mouse with 240 bpm and 180 rpm.

5D MoCo

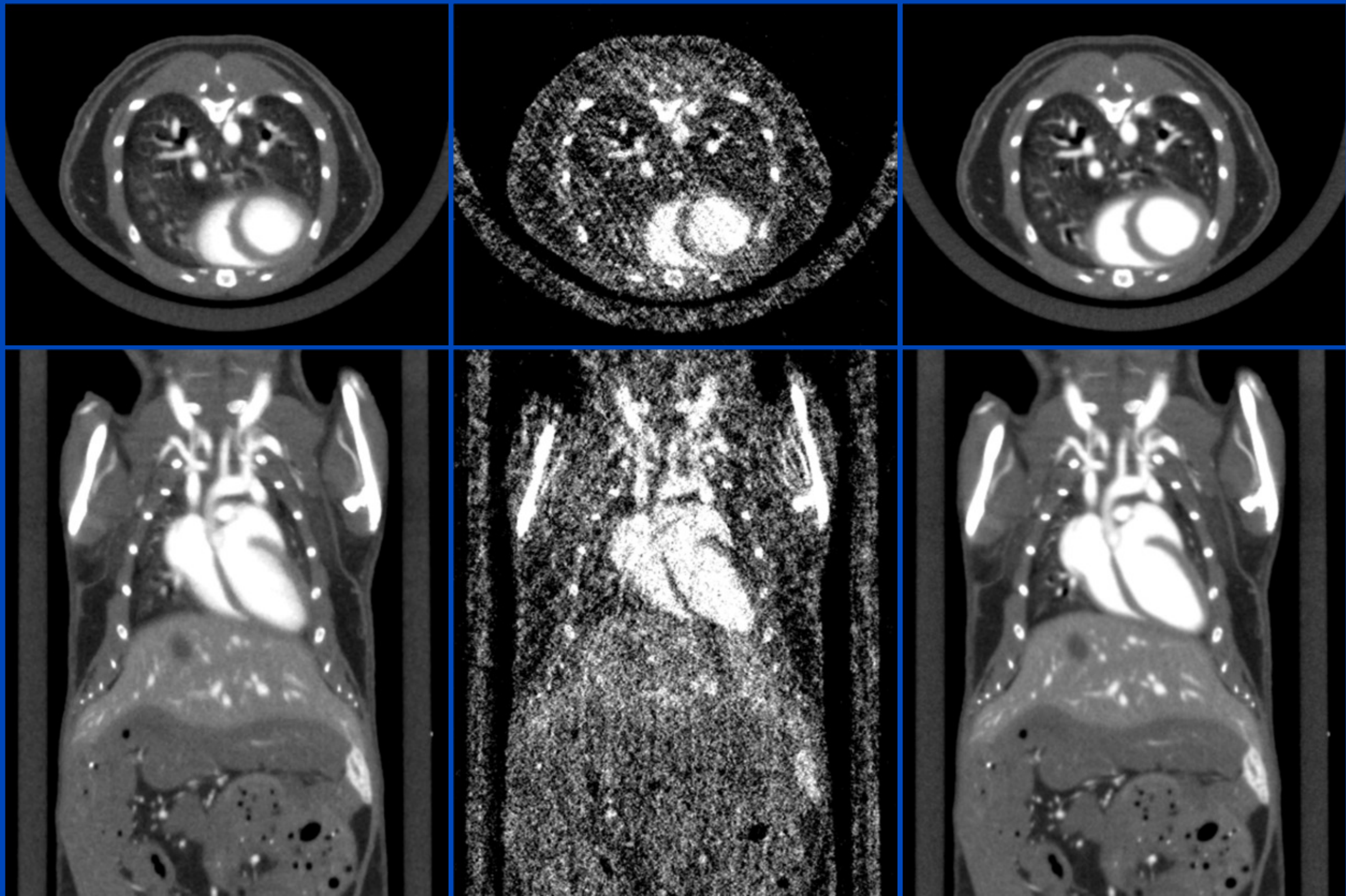
1. Respiratory motion compensation
   - Perform acMoCo wrt the respiratory motion.
   - Compensate for the respiratory motion.
   - Now the data are free of respiratory motion.
2. Cardiac motion compensation
   - Perform acMoCo wrt the cardiac motion.
   - Compensate for the cardiac motion.

Illustration of Workflow



$\Delta r = 10\,\%,\ \Delta c = 20\,\%$

3D CBCT **Double-Gated 5D CBCT** **Sequential acMoCo**



The cardiac motion is shown at a fixed respiratory phase.

Brehm, Sawall, Maier, Sauppe, and Kachelrieß, “Cardiorespiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation” Med. Phys. 42(4), April 2015.

Thank You!

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