Managing Cardiac Motion with CT and CBCT: Conventional Approaches and Motion Compensating Techniques

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DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Coronary Motion

Publication	Mean Velocity		
	RCA	LAD	LCX
Achenbach et al.	69.5 mm/s	22.4 mm/s	48.4 mm/s
Vembar et al.	47.0 mm/s	30.0 mm/s	31.0 mm/s
Husmann et al.	35.8 mm/s	20.2 mm/s	24.9 mm/s

Achenbach S., Ropers D., Holle J., Muschiol G., Daniel W. G., Moshage W. In-Plane Coronary Arterial Motion Velocity: Measurement with Electron-Beam CT. Radiology 216(2):457-463, 2000.

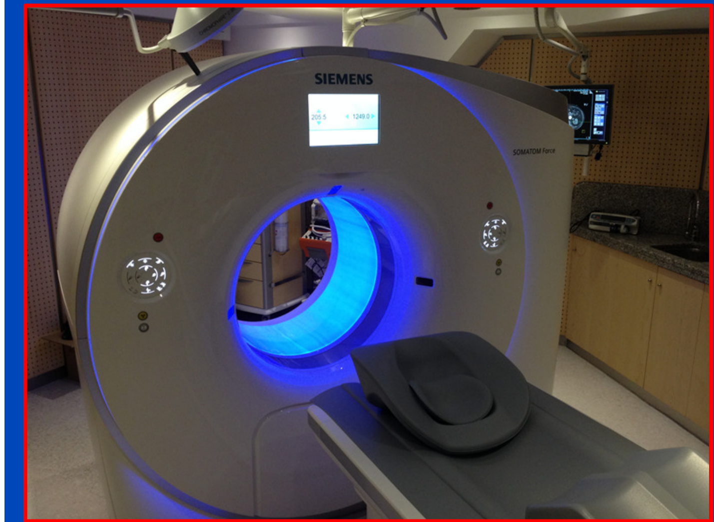
Vembar M., Garcia M. J., Heuscher D. J., Matthews R. H., Böhme G. E., Greenberg N. L. A dynamic approach to identify desired physiological phases for cardiac imaging using multislice spiral CT. Med. Phys. 30(7):1683-1693, 2003.

Husmann L., Leschka S., Desbiolles L., Schepis T., Gaemperli O., Seifert P., Cattin P., Frauenfelder T., Flohr T., Marincek B., Kaufmann P., Alkhadi H. Coronary Artery Motion and Cardiac Phases: Dependency on Heart Rate – Implications for CT Image Reconstruction. Radiology 245(2):567-576, 2007.

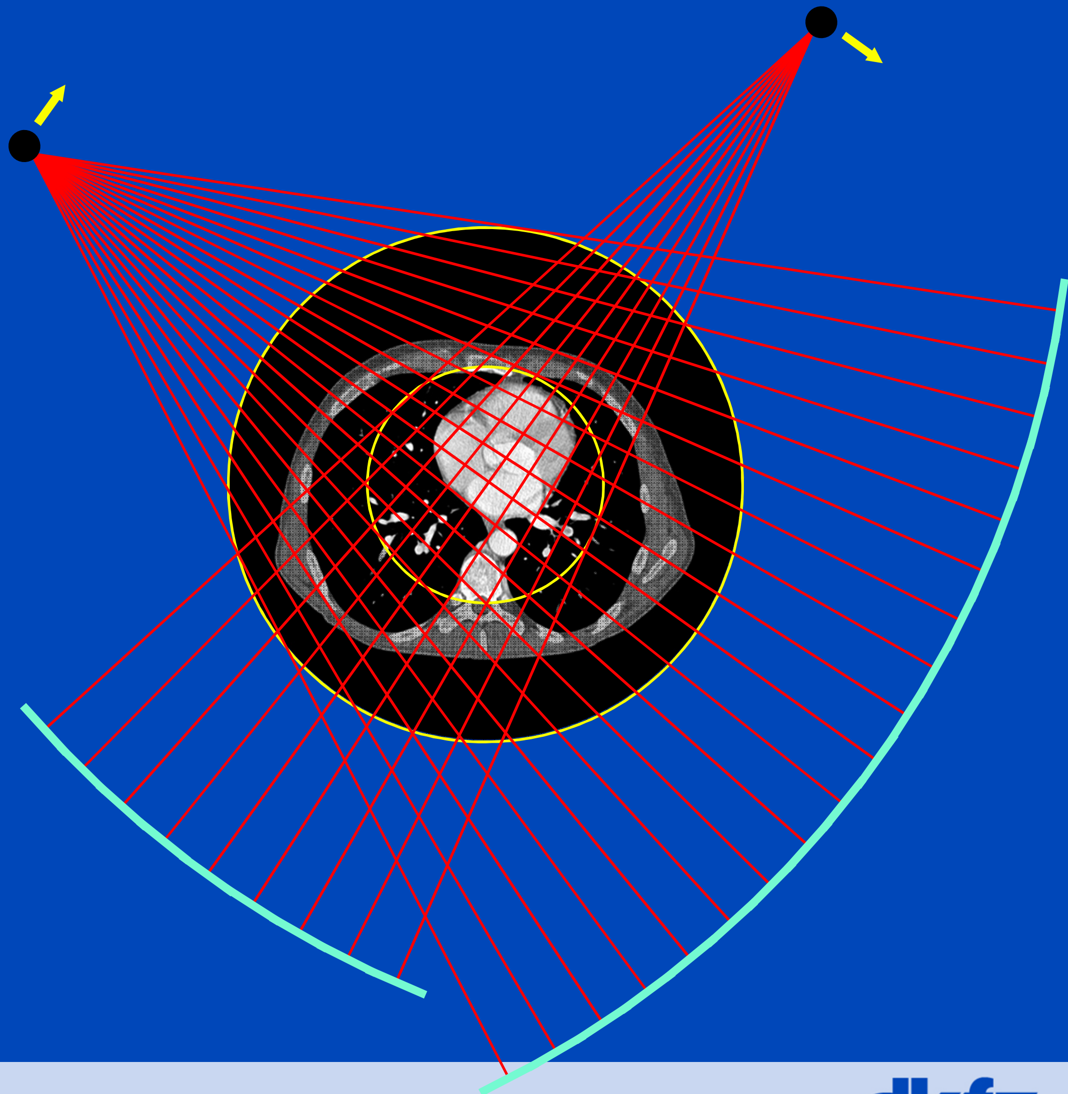
Contents

- Scans much faster than one motion cycle
  - Cardiac CT
- Scans much slower than one motion cycle
  - CBCT of the heart

Cardiac CT

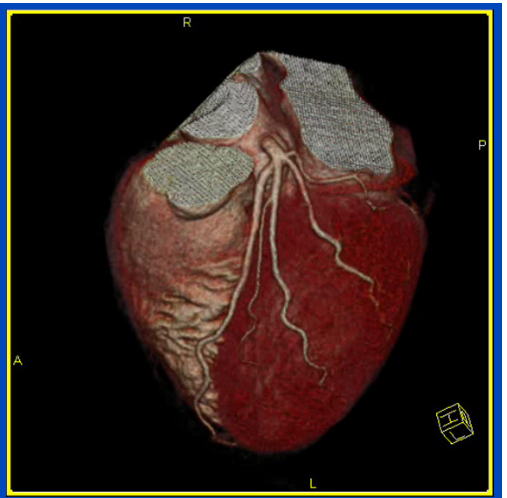


Siemens SOMATOM Force
dual source cone-beam spiral CT



Imaging the Heart with CT

(Cardiac-CT = phase-correlated CT)



- Periodic motion
- Synchronisation (ECG, Kymogram, …)
- Phase-correlated scanning = Prospective Gating
  - Used in the 80s and 90s with little success.
  - Comes into use again due to large cone-angles.
- Phase-correlated reconstruction = Retrospective Gating
  - 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)

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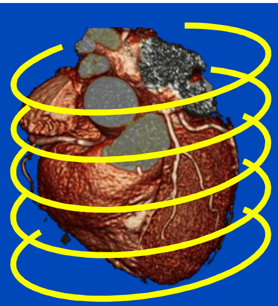


Retrospective Gating

=

Standard scan + ECG-correlated recon

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

Phase-correlated reconstruction

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

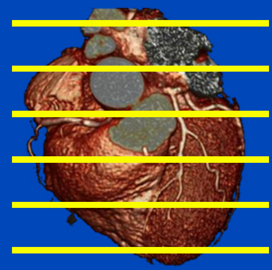
Works also at high heart rates

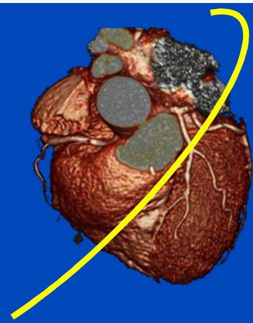
Dose management: ECG-based TCM

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

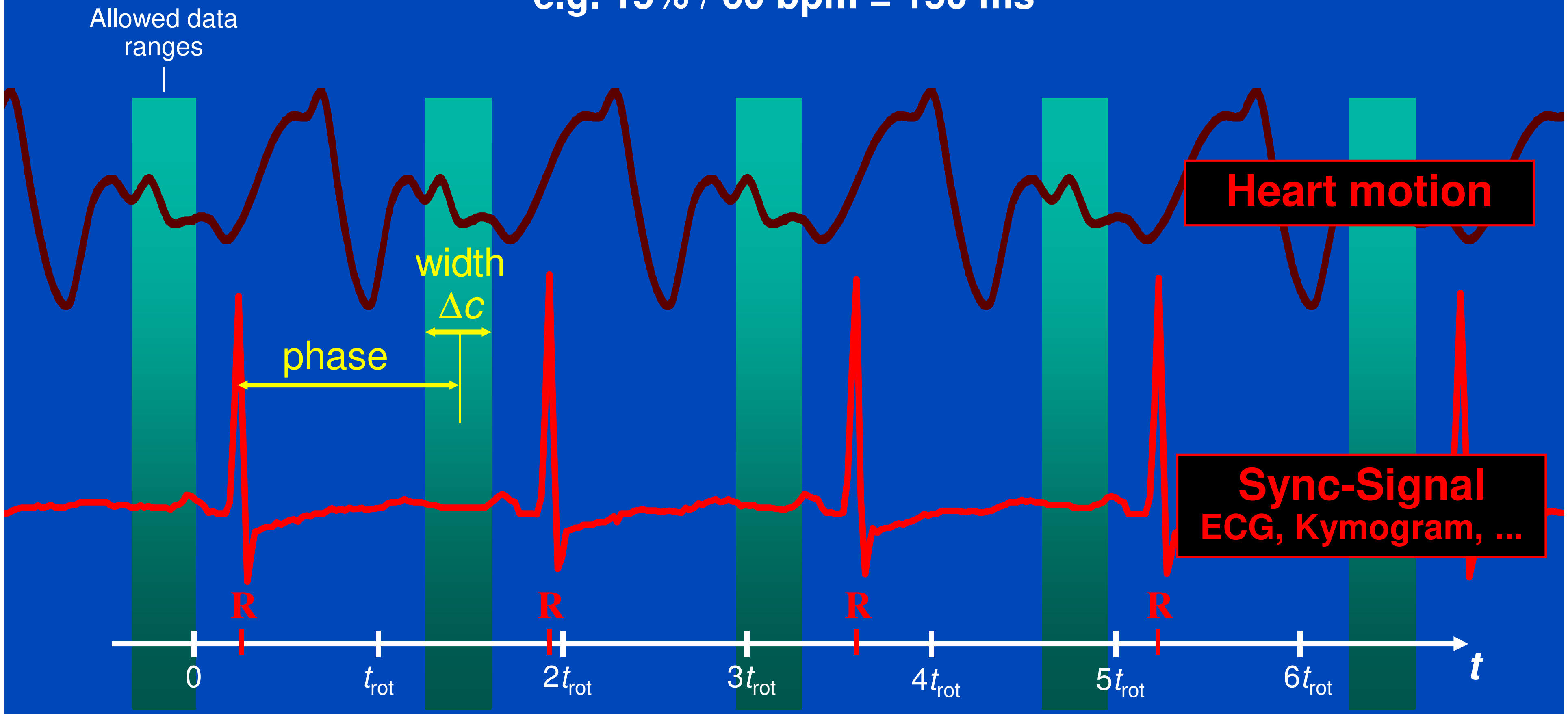
Sufficiently robust (not with arrythmia)

Very good dose usage

Synchronization with the Heart Phase

t_{eff} = width / heart rate

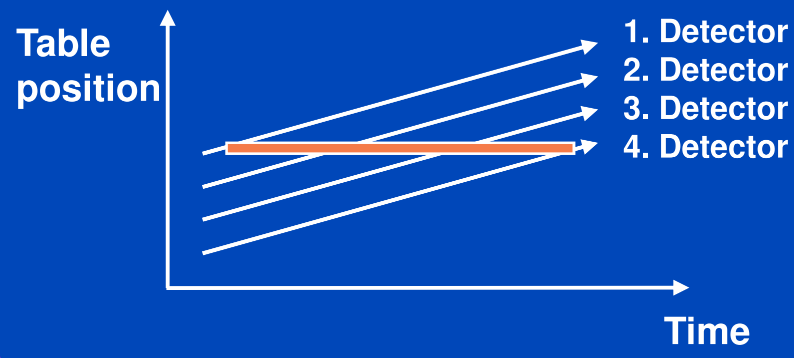
e.g. 15% / 60 bpm = 150 ms

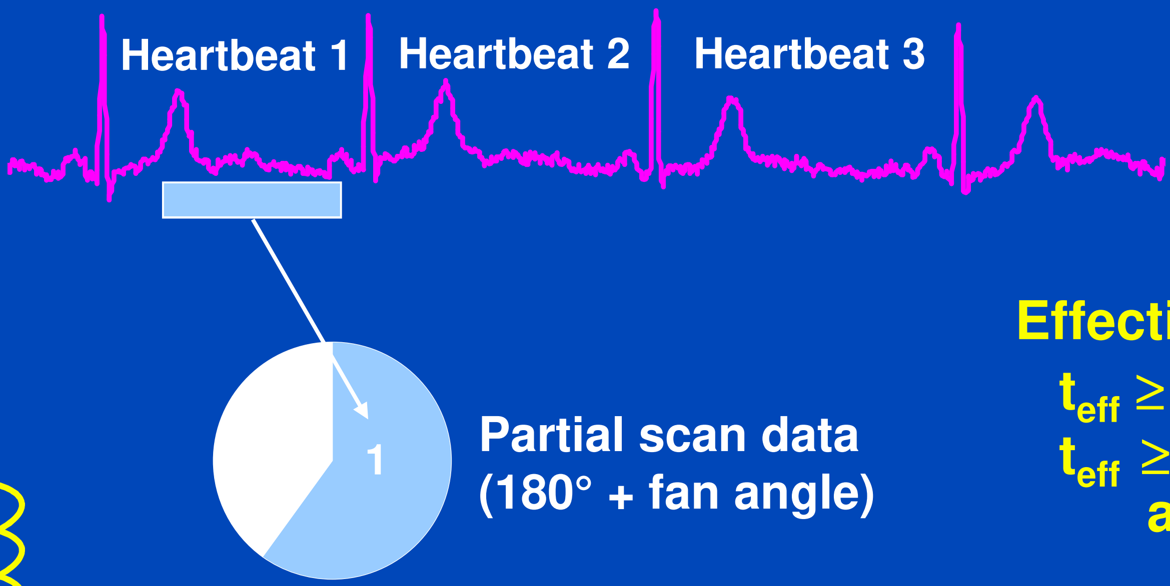


Width, and thus t_{eff}, corresponds to the FWTM of the phase contribution profile.

Partial Scan Reconstruction

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



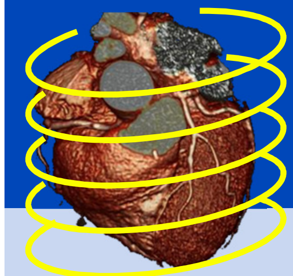


Effective scan time

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

$t_{eff} \geq 200$ ms

at $t_{rot} = 0.4$ s



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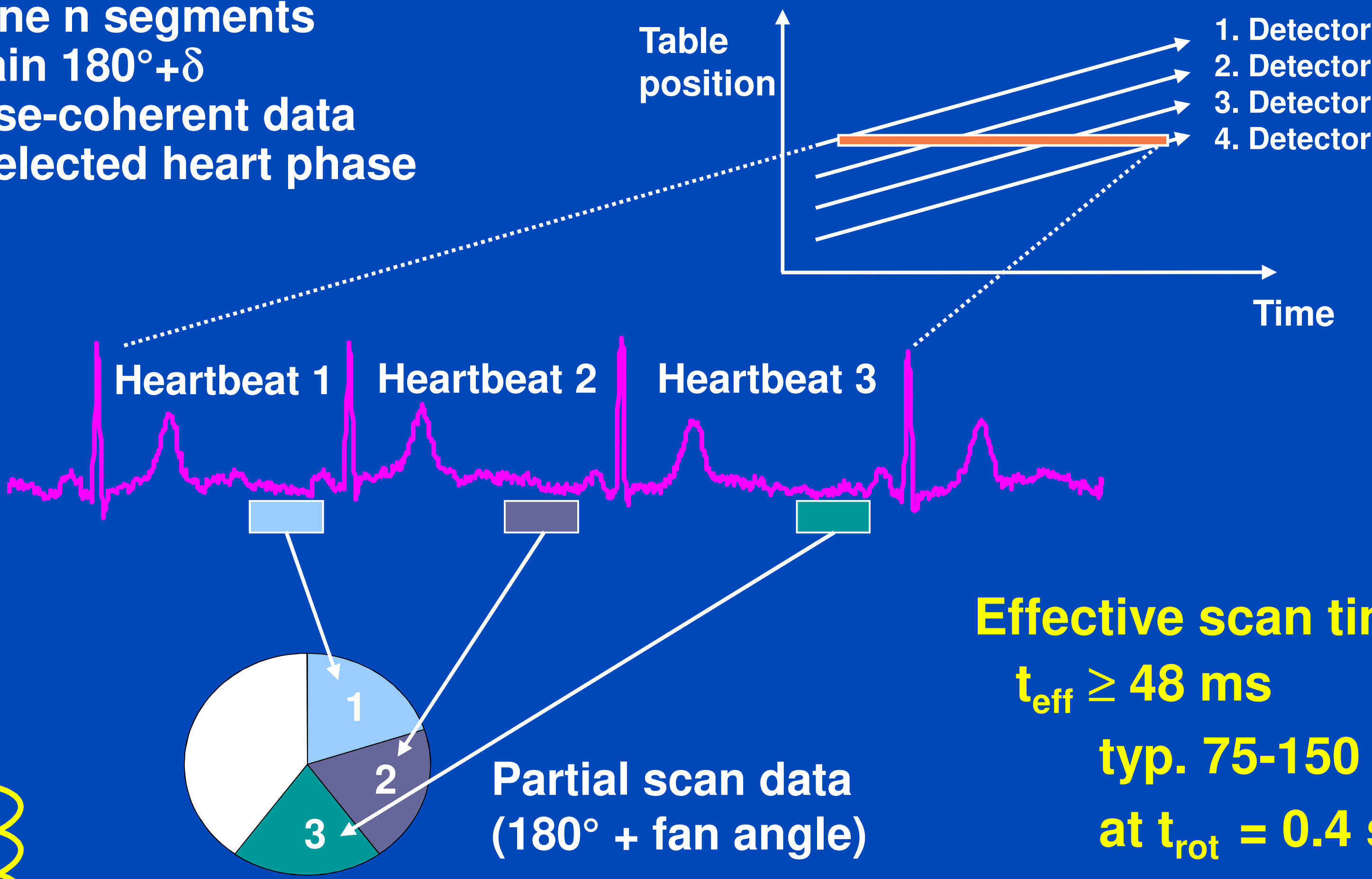
Multi-Segment Reconstruction

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

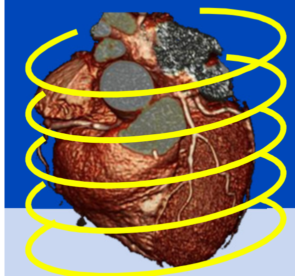


Effective scan time

$t_{eff} \geq 48$ ms

typ. 75-150 ms

at t_{rot} = 0.4 s



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

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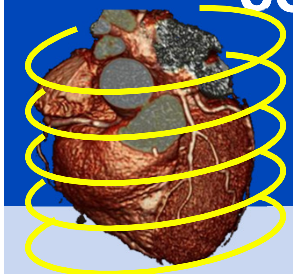
Pitch Value and Full Phase Selectivity

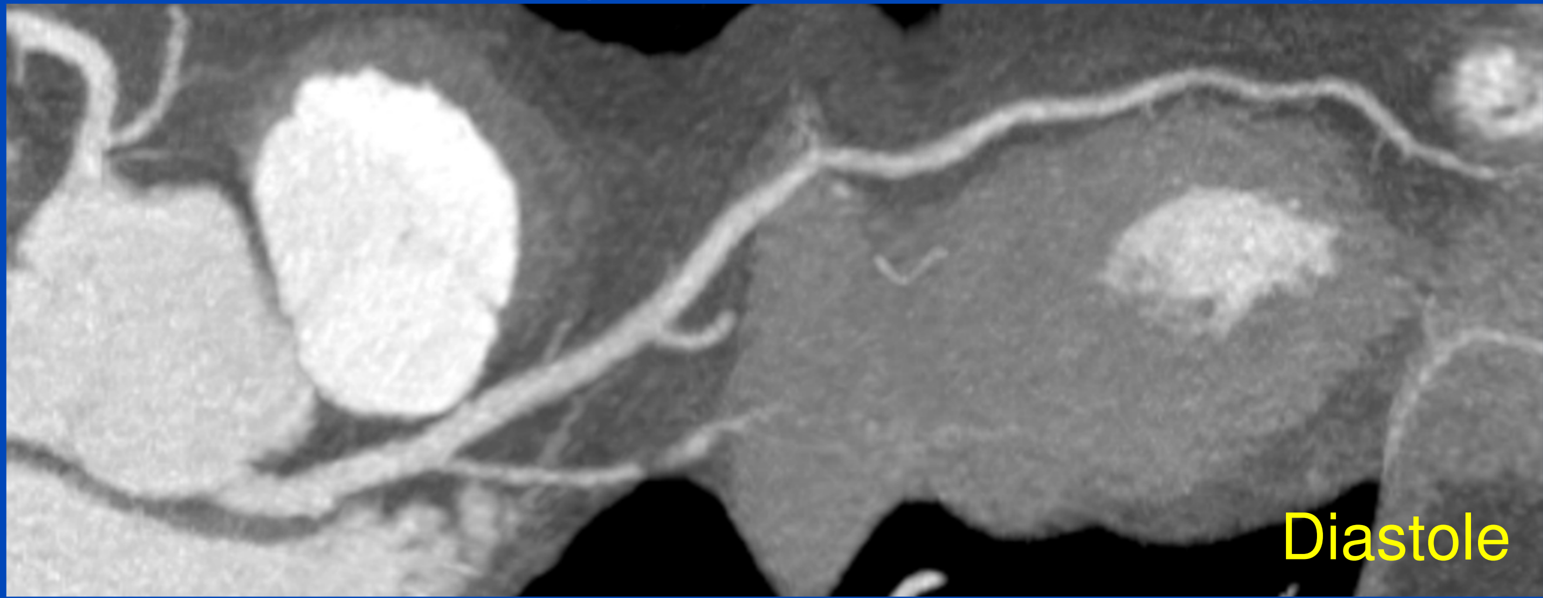
- Each voxel must be illuminated by the x-rays at least as long as one motion cycle of the heart takes
- The table increment per motion cycle must not be larger than the collimation of the scanner

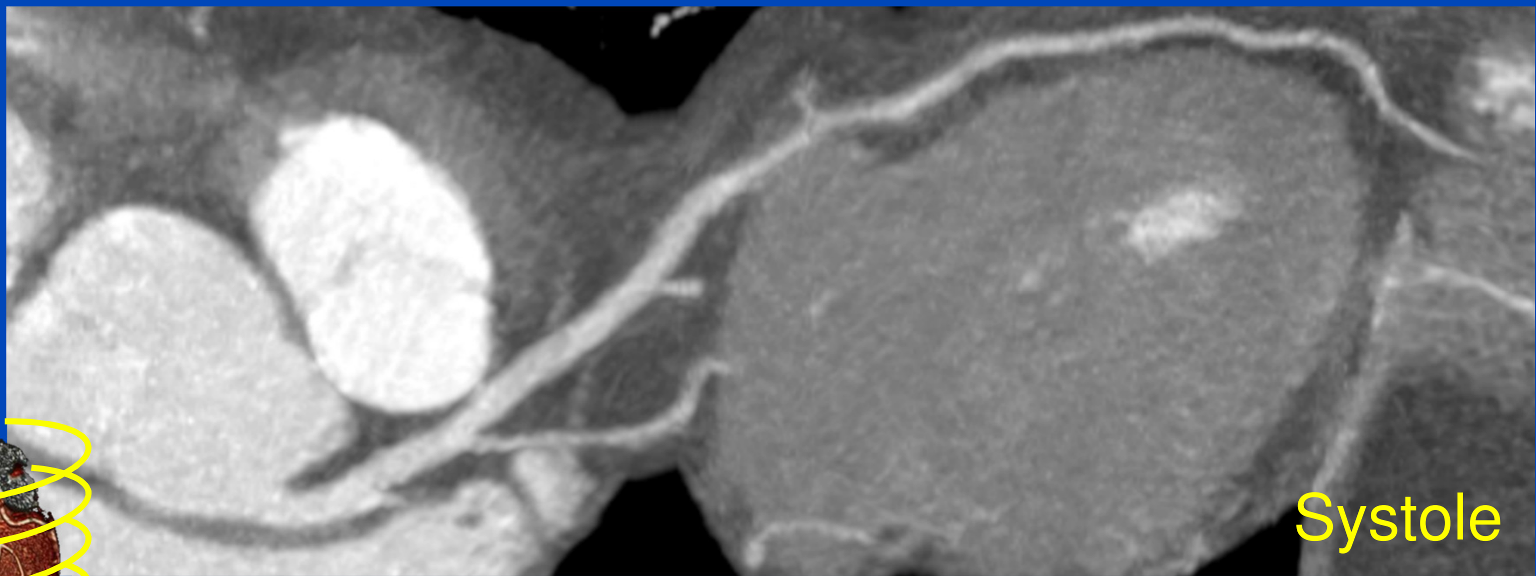
$$p \le f_{\mathrm{H}} t_{\mathrm{rot}}$$

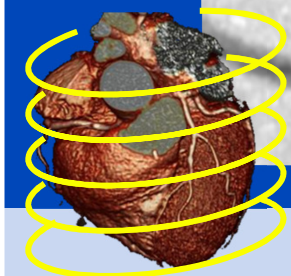
- For example t_{rot} = 0.5 s and f_H = 60 bpm imply that a pitch value of p < 0.5 must be chosen.
- The lower the pitch value the more segments can be combined in multi-segment image reconstruction.



Dual-source-CT, 330 ms rotation, partial scan reconstruction, 83 ms temporal resolution







Data courtesy of Stephan Achenbach, Erlangen, Germany

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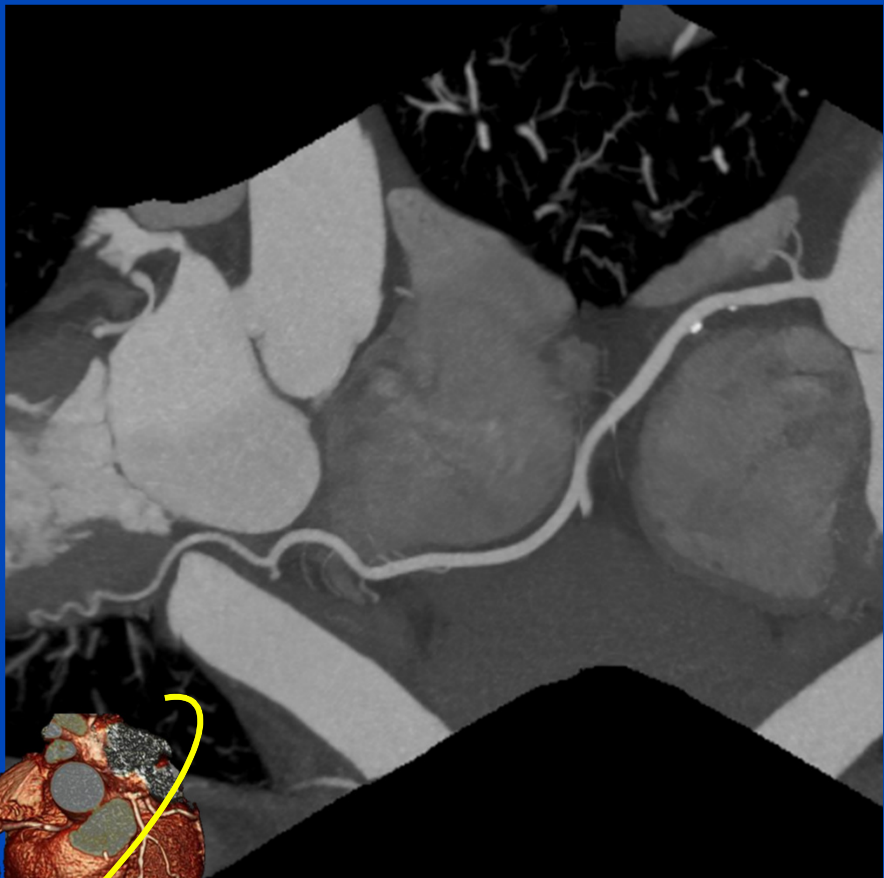
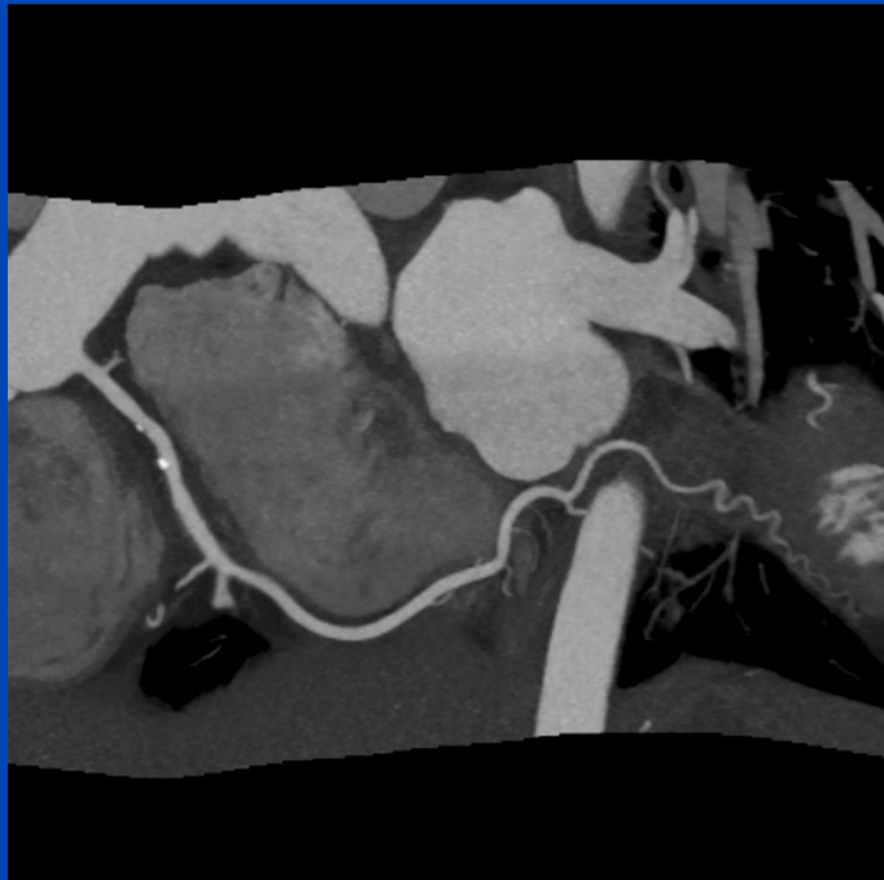
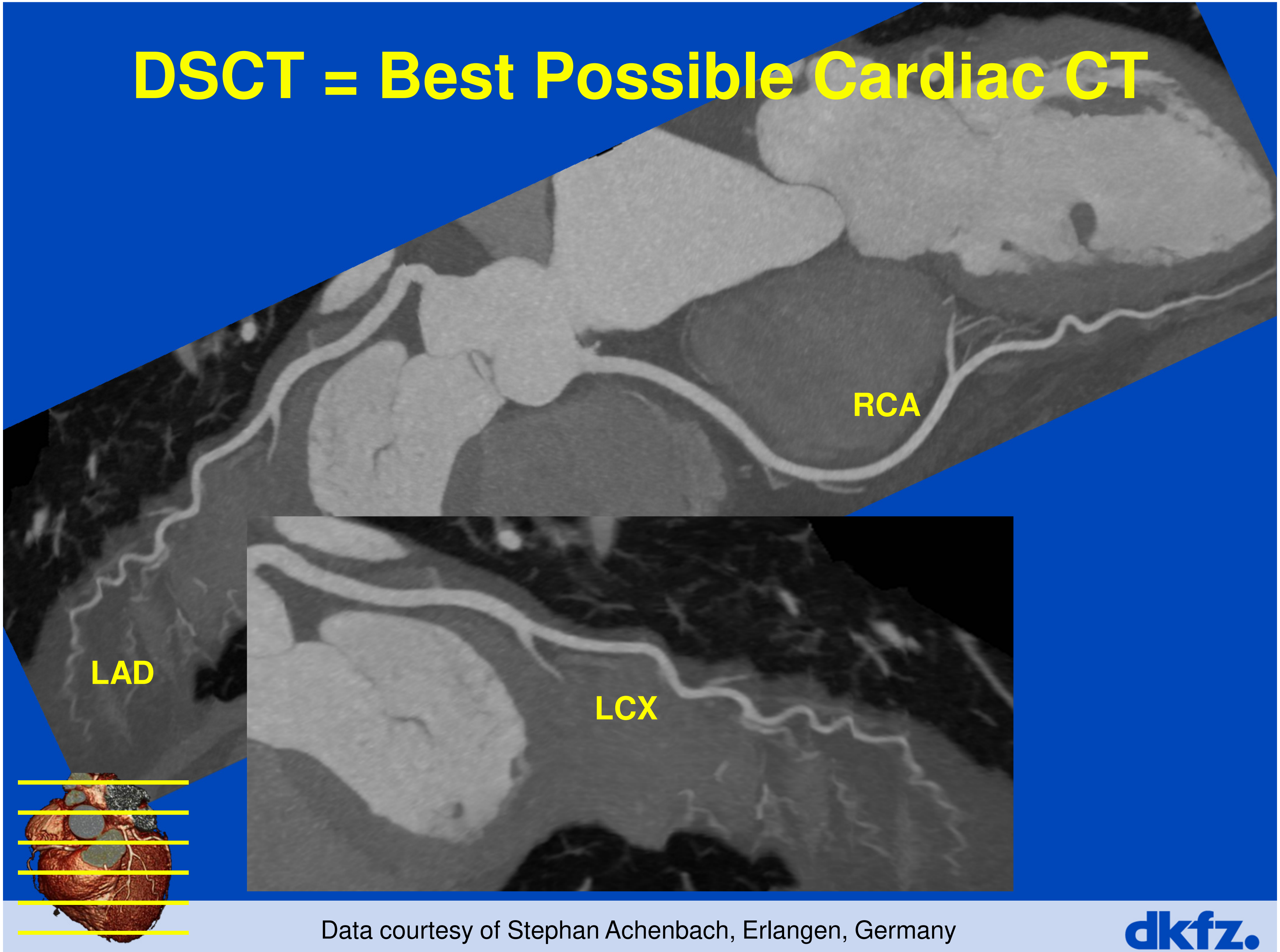
Calcified in RCA
Dual Source CT in Turbo Flash Mode
737 mm/s scan speed
143 ms scan time
63 ms temporal resolution
70 kV tube voltage
39 mGy·cm dose length product (DLP)
0.55 mSv effective dose





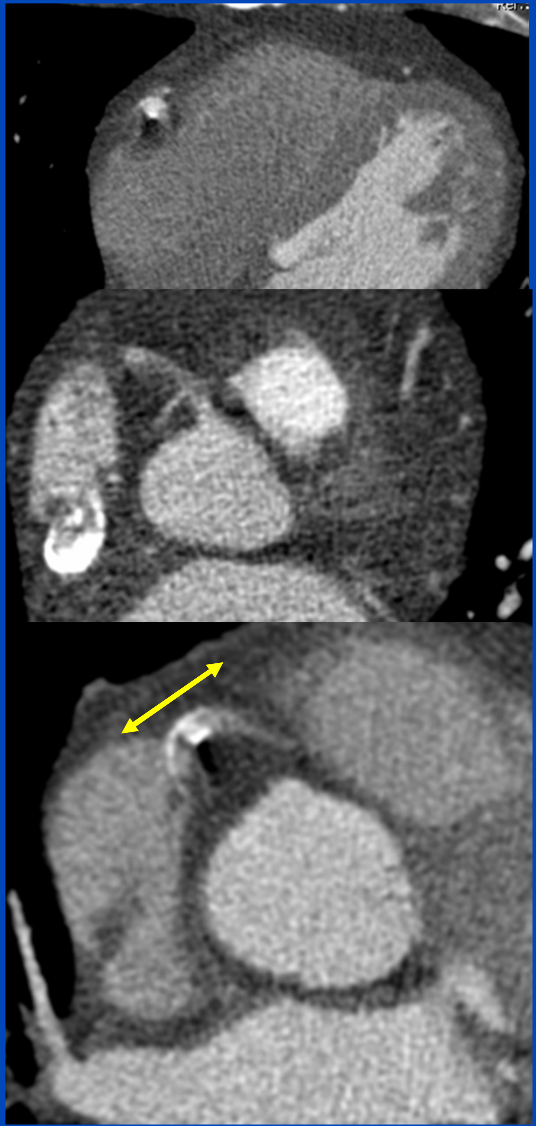
Data courtesy of Stephan Achenbach, Erlangen, Germany

DSCT = Best Possible Cardiac CT



Data courtesy of Stephan Achenbach, Erlangen, Germany

Motion Artifacts May Still be Present



- **In cardiac CT, the imaging of small and fast moving vessels places high demands on the spatial and temporal resolution of the reconstruction.**
- **Mean displacements of** $d \approx \frac{t_{rot}}{2} \bar{v} \approx \frac{250}{2} \text{ ms } 50 \frac{\text{mm}}{\text{s}} = 6.25 \text{ mm}$ **are possible (RCA mean velocity measurements[1,2,3,4]).**
- **Standard FDK- based cardiac reconstruction might have an insufficient temporal resolution introducing strong motion artifacts.**

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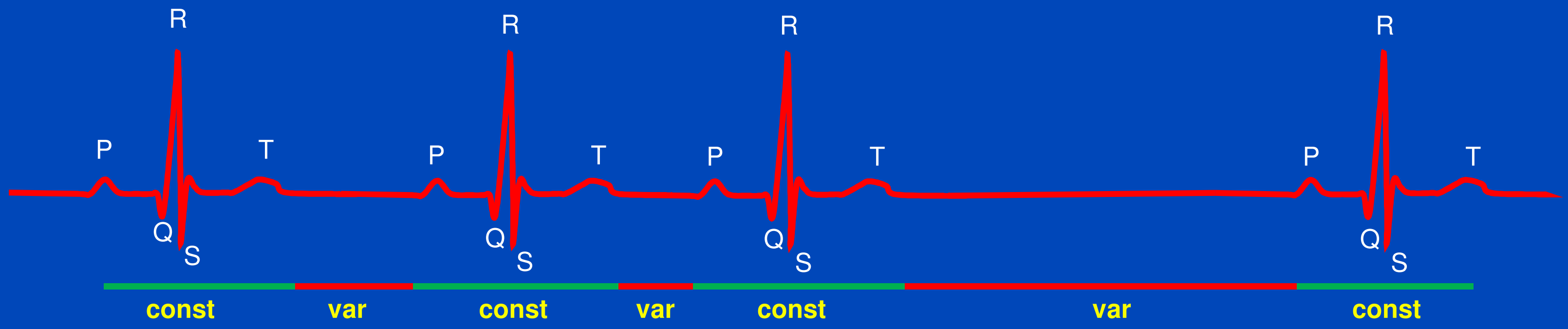
[4] Achenbach et al. In-plane coronary arterial motion velocity: measurement with electron-beam CT. Radiology, Vol. 216, Aug 2000.

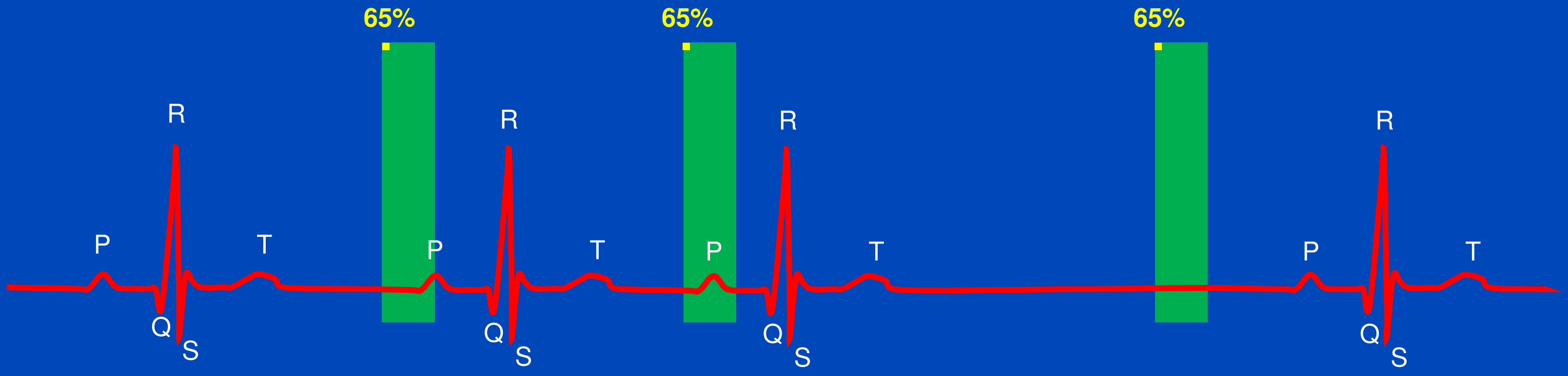
Heart Rate Variability = Diastolic Phase Variability

- Unless some pathology of the nervous connections are there, the HR variability is caused by irregular trigger from the sinoatrial (SA) node.
- The diastolic phase can be interrupted by that trigger.
- The distance between P, Q, R, S, T waves only depends on the electrical signal transmission, and is repeated as a constant pattern in absence of specific pathologies.
- Changes in heart rate typically only affect the diastolic phase duration.
- Normally, systolic phase scanning is preferred for f_H >75 bpm.



Phase Selection: Relative vs. Absolute - % vs. ms

- Relative phase selection (in %) is not suggested if the HR has a high variability (> 5 bpm) because the data window could fall into very different cycle phases.
- When using absolute phase selection (in ms), a negative delay has to be selected for diastolic phase: it happens before the R peak.
- Caution: For relative phase selection and for absolute diastolic phase selection the scanner needs to predict the next R peak.



relative phase selection

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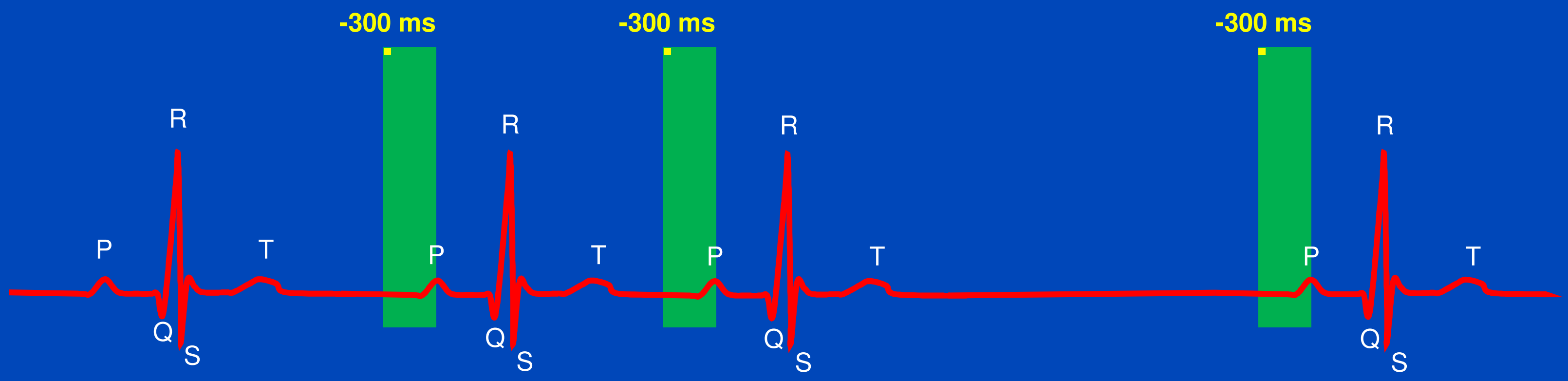

absolute phase selection (diastole)

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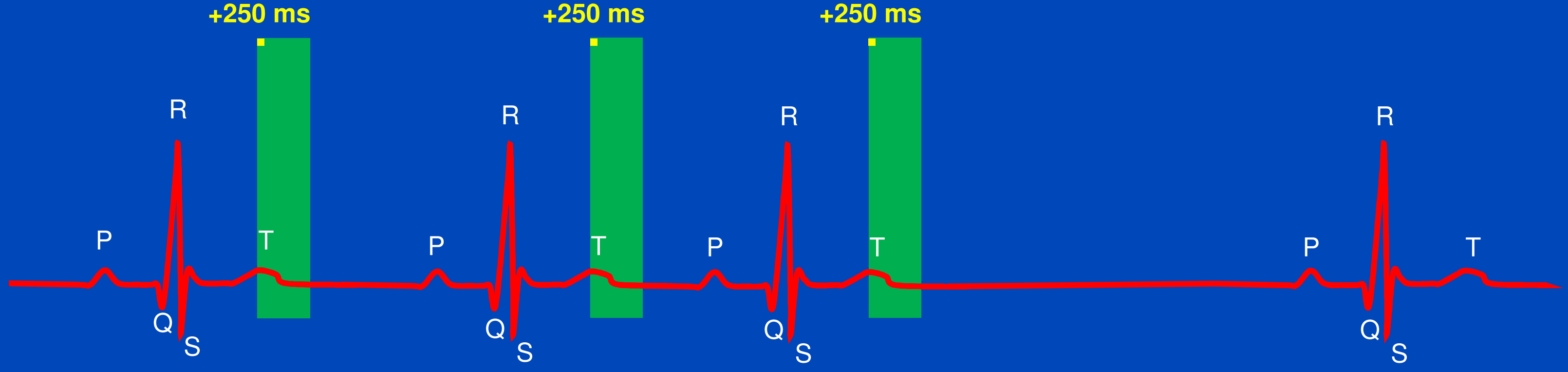
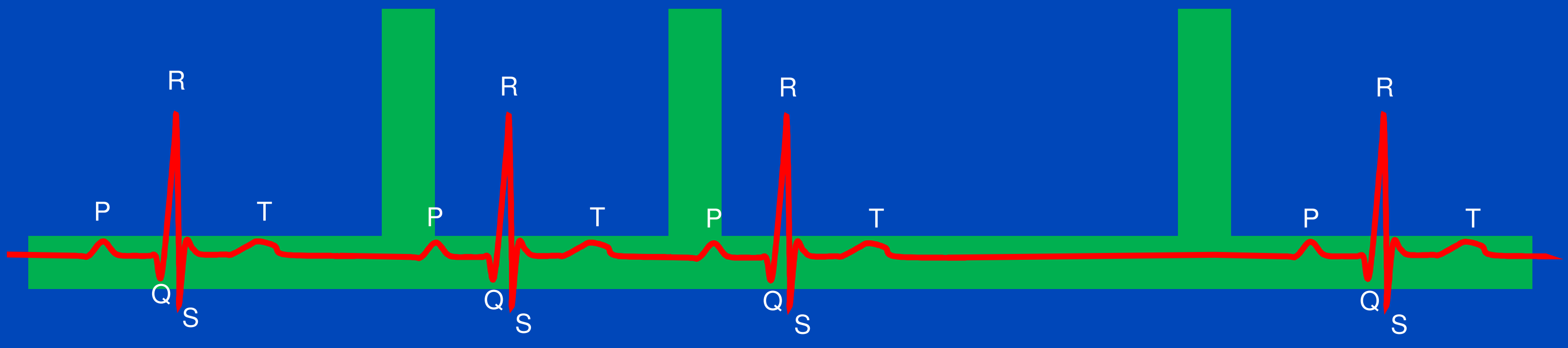


absolute phase selection (systole)

Prospective vs. Retrospective Gating

- Retrospective gating = low pitch spiral (very robust, allows retrospective ECG editing)
- Prospective gating (triggering) = sequence scan (step-and-shoot, skips 1 or 2 beats and ectopic beats) or high pitch spiral
- Unstable heart rate requires either retrospective gating or prospective gating with an adaptive window (e.g. low dose from 50% to 80% and full dose from 60% to 70%).
- For stable (variability < 4 bpm) and low (< 60 bpm) heart rates, one may perform a high pitch spiral scan (on DSCT) in diastolic phase (systolic phase is too short). One may scan caudo-cranial to have the ventricle (at higher risk to move) scanned first.



retrospective gating (low pitch spiral)

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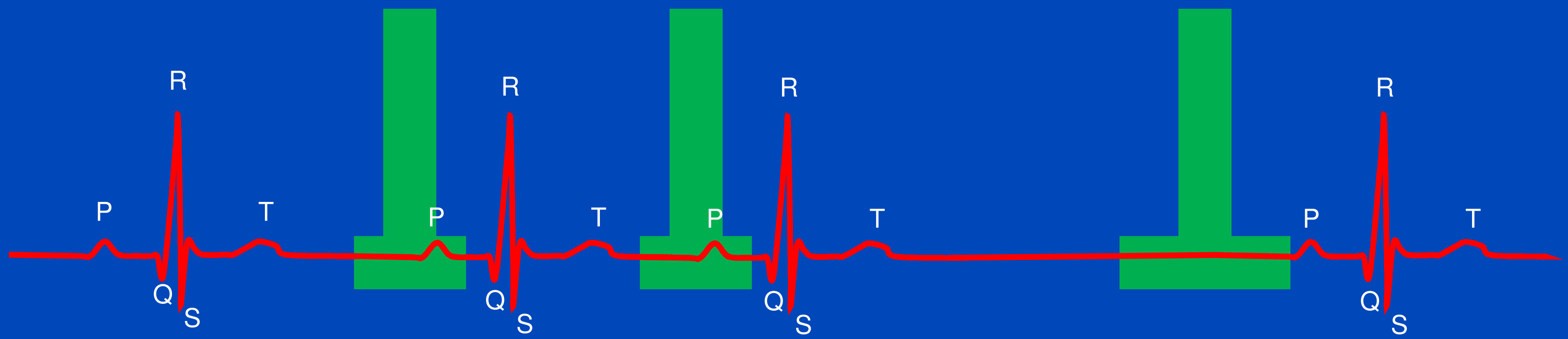

prospective gating (sequence scan)

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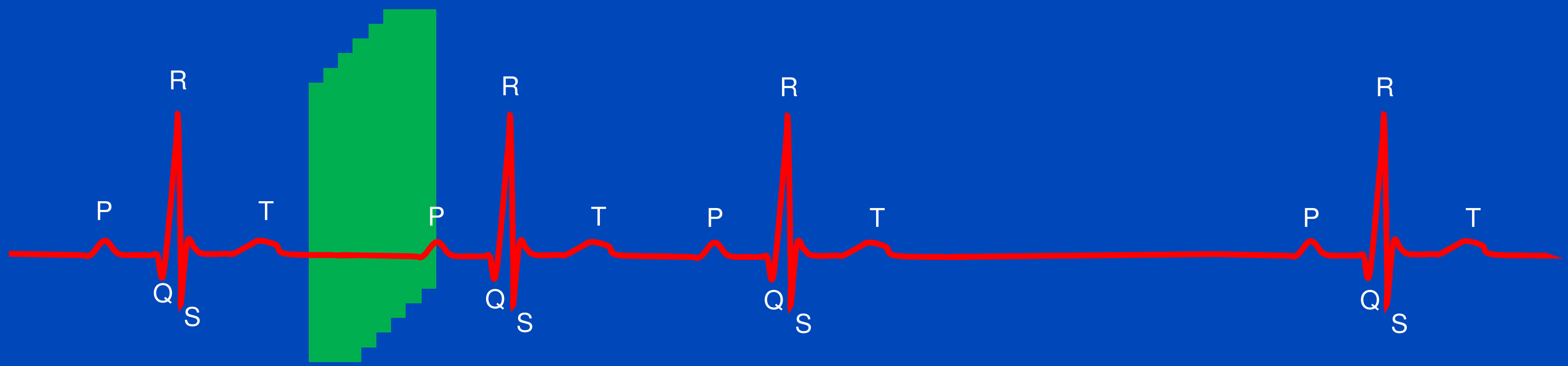
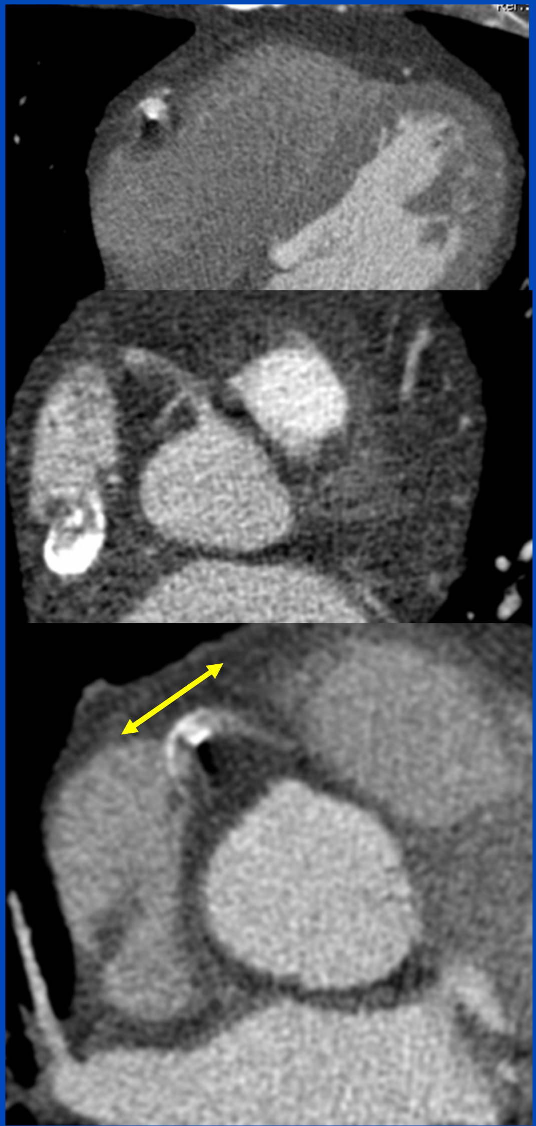


prospective gating (high pitch spiral)

Motion Artifacts May Still be Present!



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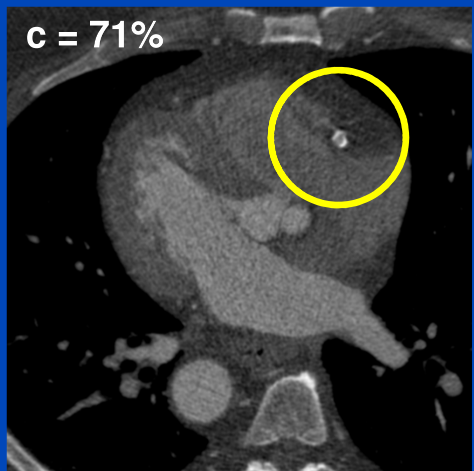
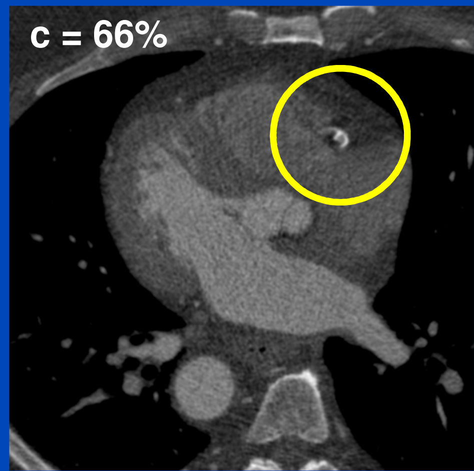
Motion Compensation is the Future!

Reducing Motion Artifacts in Cardiac CT

- For single source systems, several algorithmic motion compensation (MoCo) solutions have been developed. These may be also useful for DSCT.
- In view of dose-optimized scan protocols, we want to focus on methods, which utilize only the data needed for the reconstruction of a single cardiac phase (short scan data ≙ 180° + fan angle).
- Especially beneficial in cases of patients with high or irregular heart rates or non-optimally chosen gating positions.



Best phase



Non-optimally chosen gating position

Algorithms to Improve Temporal Resolution in Cardiac CT

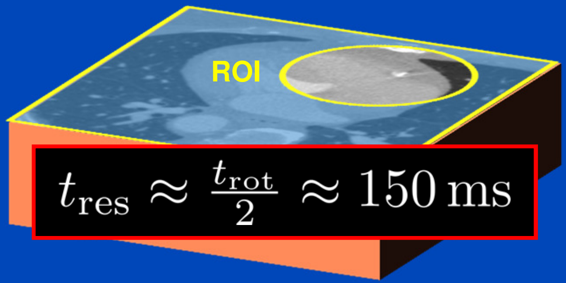
	Data Range	Anatomical Landmarks	Dose Usage	MVFs
Taguchi et al. (Johns Hopkins)	1 heart cycle	no	100%	yes
SSF, Bhaglia et al. (GE)	>> 180°	arteries	<< 100%	yes
SSF+MEAD, Nett et al. (GE)	>> 180°	arteries	<< 100%	yes
Tang et al. (Toshiba)	>> 180°	arteries	<< 100%	yes
Kim et al. (KAIST)	> 180°	no	< 100%	yes
TRI-PICCS, Chen et al. (UW)	180°	no	< 100%	no
TRIM, Schöndube et al. (Siemens)	180°	arteries	< 100%	no
MAM, Rohkohl et al. (Siemens)	180°	arteries	100%	yes
PAMoCo, Hahn et al. (DKFZ)	180°	arteries	100%	yes

All algorithms can potentially also be applied to DSCT. However, this has not been done, yet.

PAMoCo

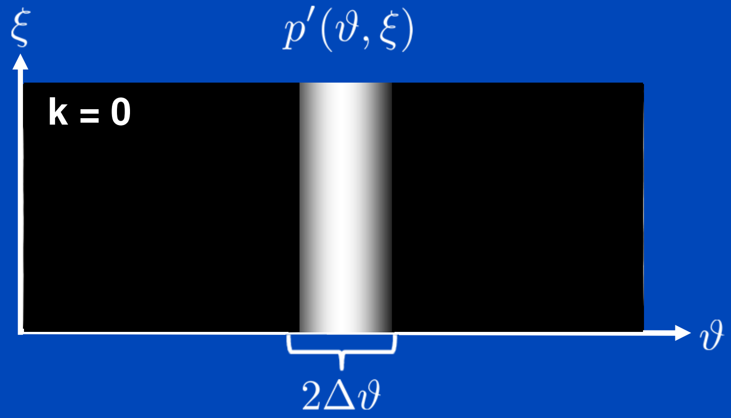
Generation of 2K+1 PARs

Initial segmented stack volume



$$t_{\mathrm{res}} \approx \frac{t_{\mathrm{rot}}}{2} \approx 150\,\mathrm{ms}$$

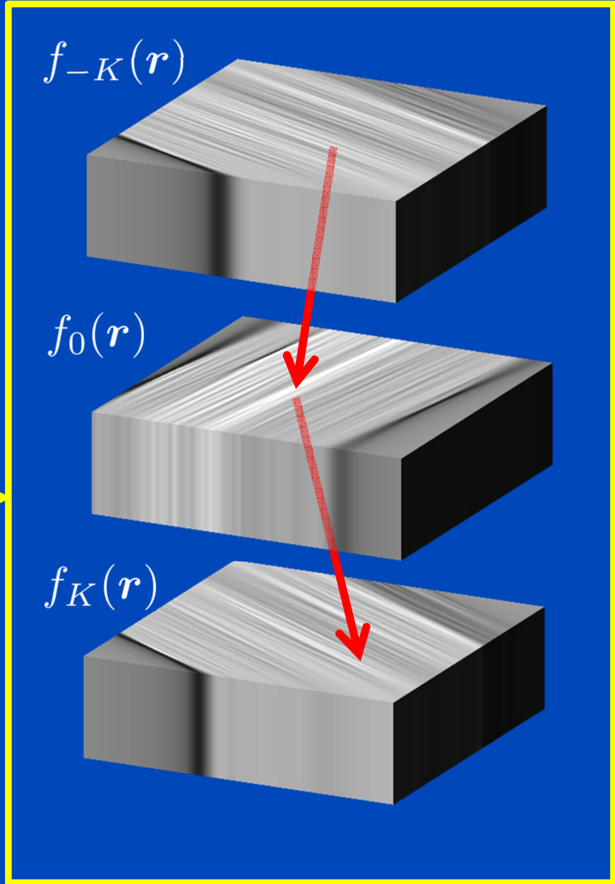
Subdivide the projection data $p'(\vartheta,\xi)$ into 2K + 1 overlapping sectors



$$p_k(\vartheta,\xi) = w_k(\vartheta)p'(\vartheta,\xi)$$

$$w_k(\vartheta) = \Lambda((\vartheta-\vartheta_k)/2\Delta\vartheta)$$

Partial angle reconstructions $f_k(\boldsymbol{r})$



$$t_{\mathrm{res}} \approx \frac{t_{\mathrm{rot}}/2}{(2K+1)/2} \approx 10\,\mathrm{ms}$$

FWHM = $\Delta\vartheta$ **K = 15**

SIEMENS

J. Hahn, M. Kachelrieß et al. Reduction of motion artifacts in cardiac CT based on partial angle reconstructions from short scan data. SPIE Medical Imaging Conference Record 97831A:1-9, March 2016.

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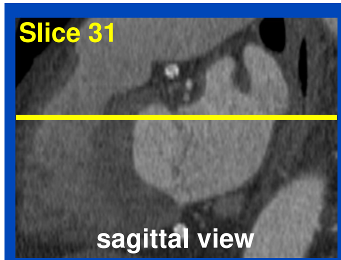
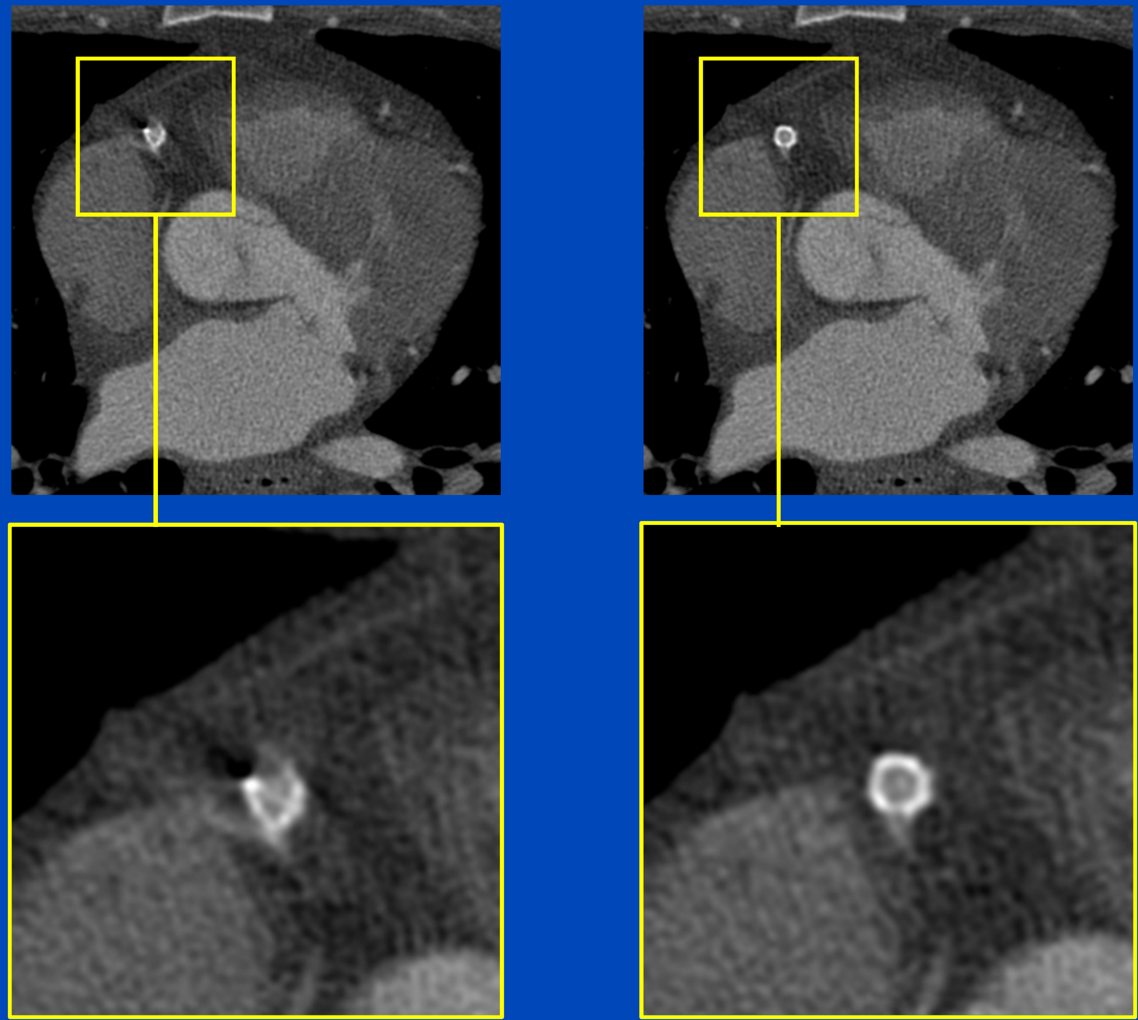


Patient 1

FBP

PAMoCo

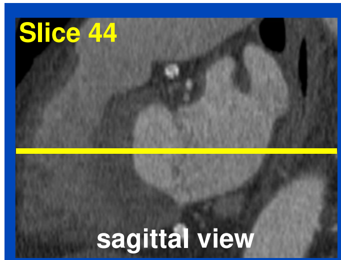


SIEMENS

$\overline{HR}$ = 74 bpm, c = 30%,
C = 400 HU, W = 1500 HU

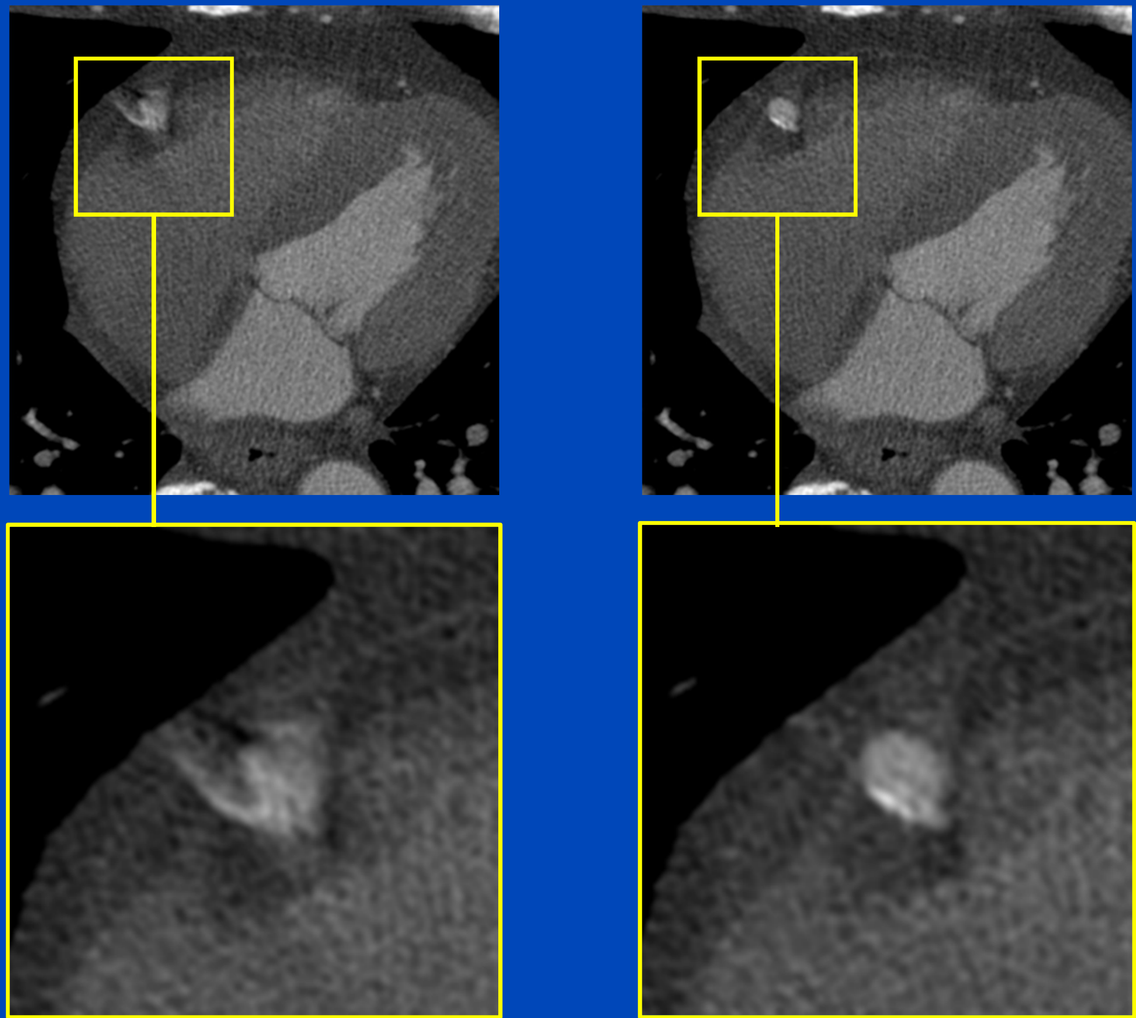
PAMoCo with $N_t \times N_\lambda \times 3 = 3 \times 3 \times 3 = 27$
parameter each stack

dkfz.



Patient 1

FBP **PAMoCo**



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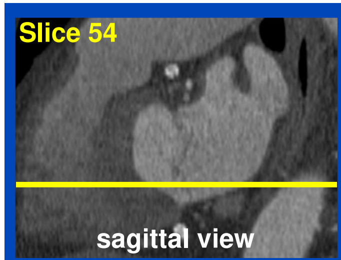
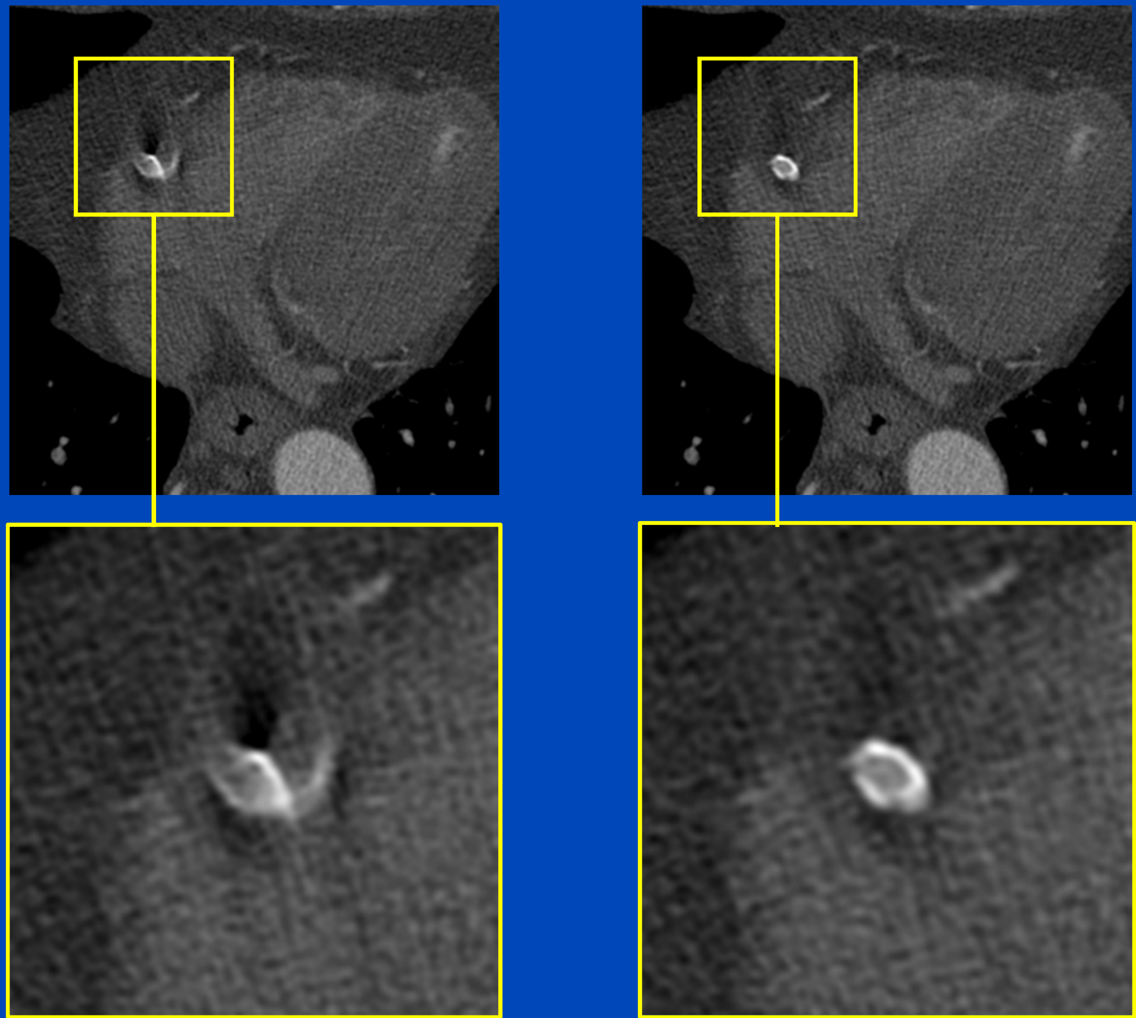


Patient 1

FBP | **PAMoCo**



$\overline{HR}$ = 74 bpm, c = 30%,
C = 400 HU, W = 1500 HU

PAMoCo with $N_t \times N_\lambda \times 3 = 3 \times 3 \times 3 = 27$
parameter each stack

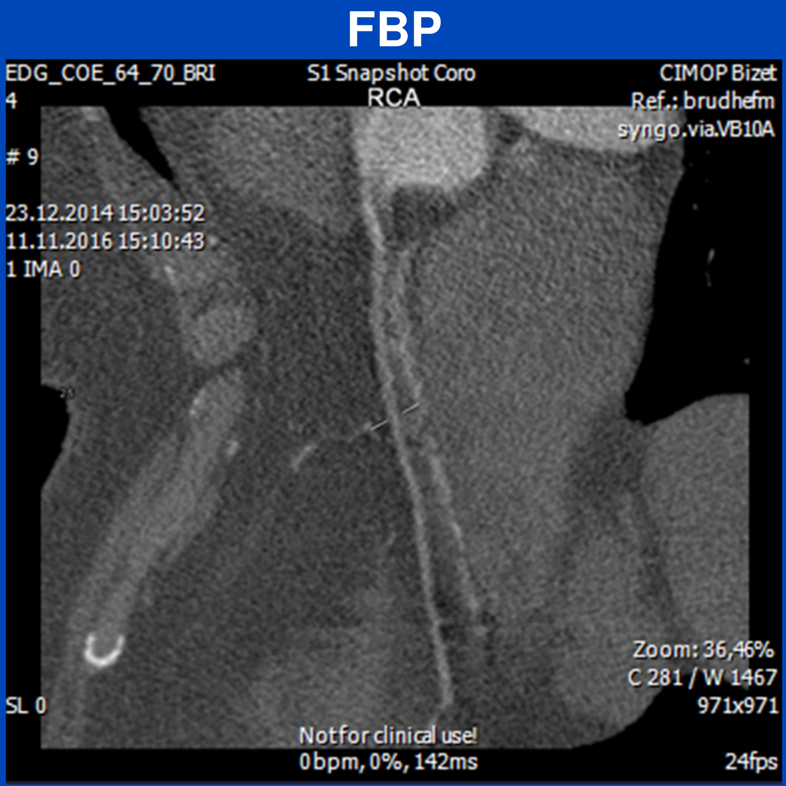
Patient 1

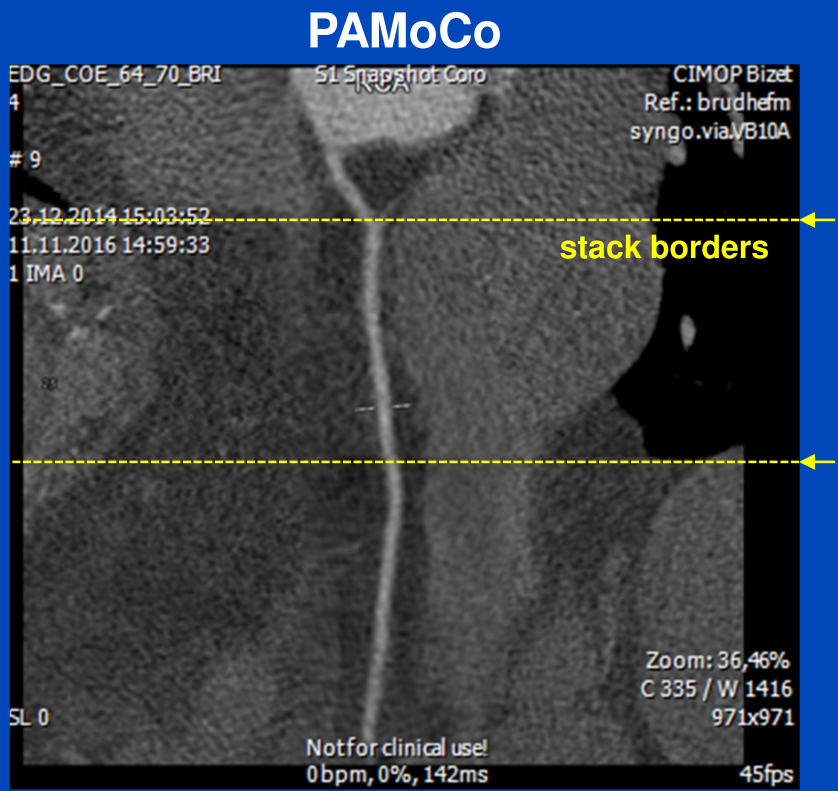
FBP

PAMoCo

curved MPRs of the RCA

Patient 2

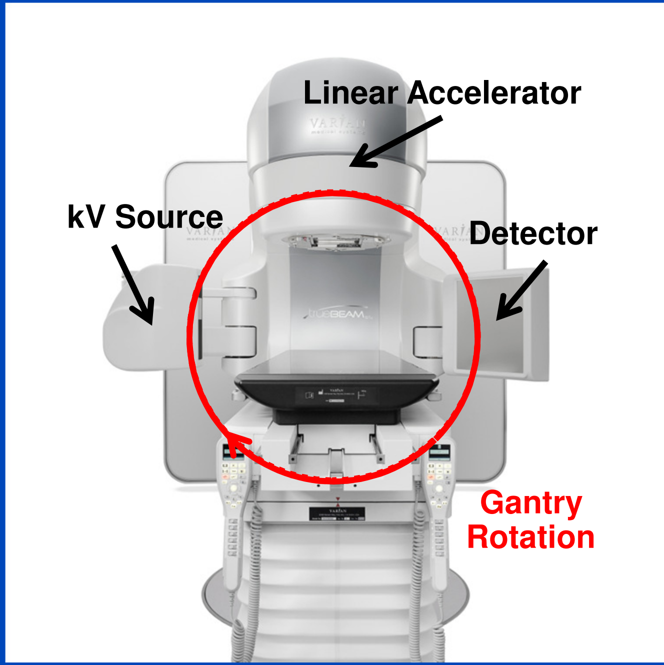


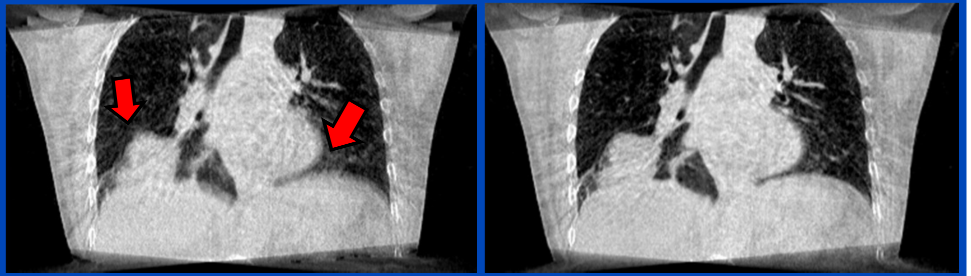


curved MPRs created with syngo.via

Slowly Rotating CBCT Devices

- Image-guided radiation therapy (IGRT)
  - Cone-beam CT (CBCT) imaging unit mounted on gantry of a LINAC treatment system
  - Accurate information about patient motion required for radiation therapy
- Slow gantry rotation speed of 6° per second (60 s/360°)
  - Much slower than clinical CT devices
- Breathing about 10 to 30 respiration cycles per minute (and thus per scan)
- Heartbeat about 50 to 80 beats per minute





Motion blurring in standard 3D reconstruction

5D* Motion Compensation removes almost all motion blurring

Account for patient motion!

*Brehm, Sawall, Maier, and Kachelrieß, "Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation" Med. Phys. 42(4):1948-1958, 2015.

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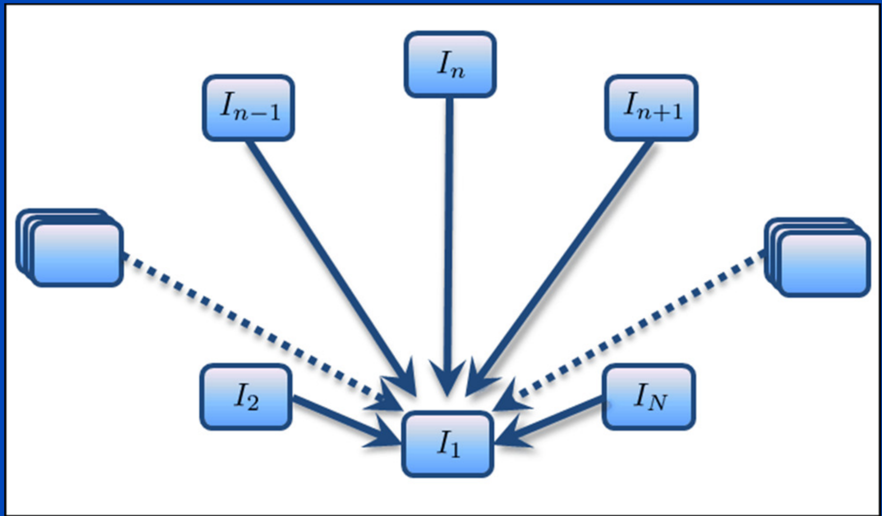
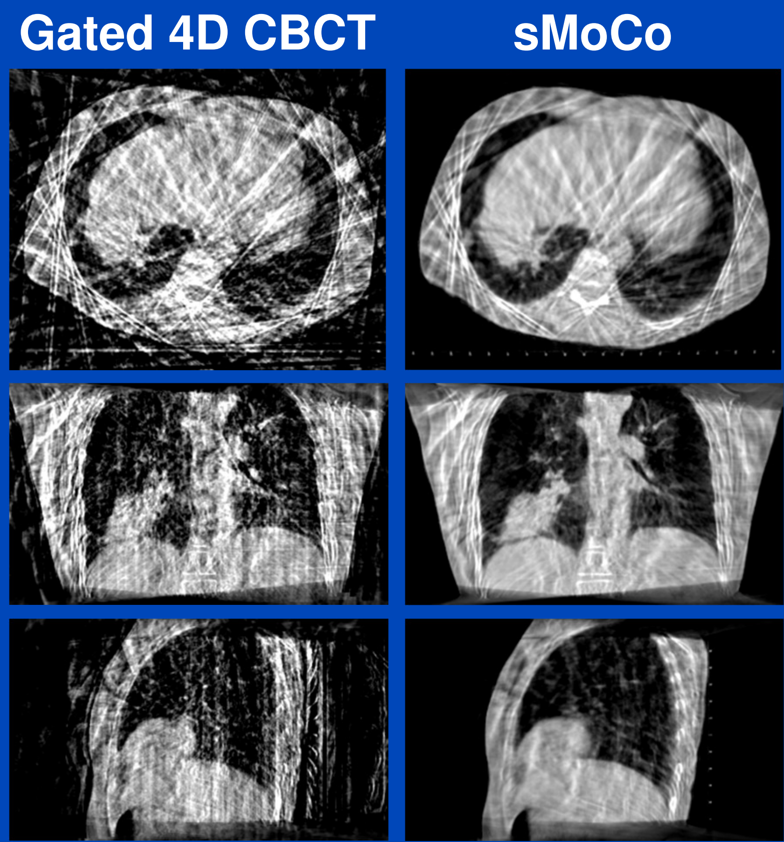
A Standard Motion Estimation and Compensation Approach (sMoCo)

- Motion estimation via standard 3D-3D registration



- Has to be repeated for each reconstructed phase

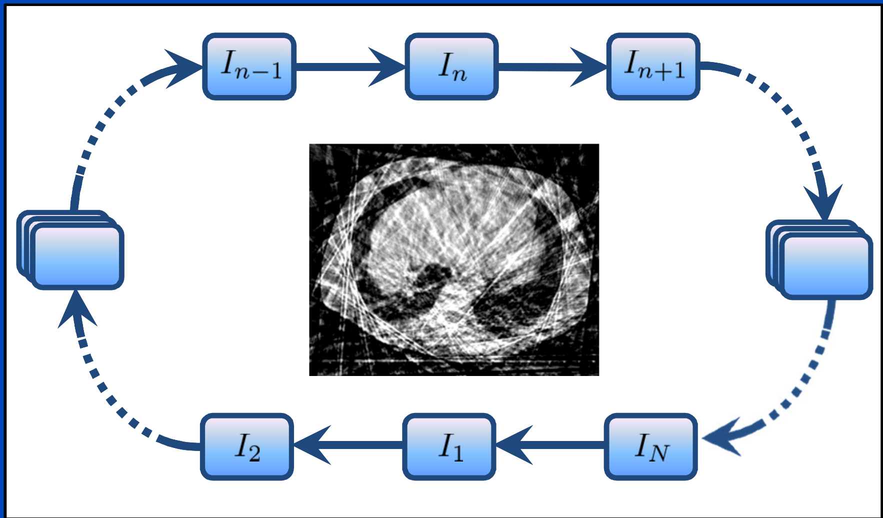


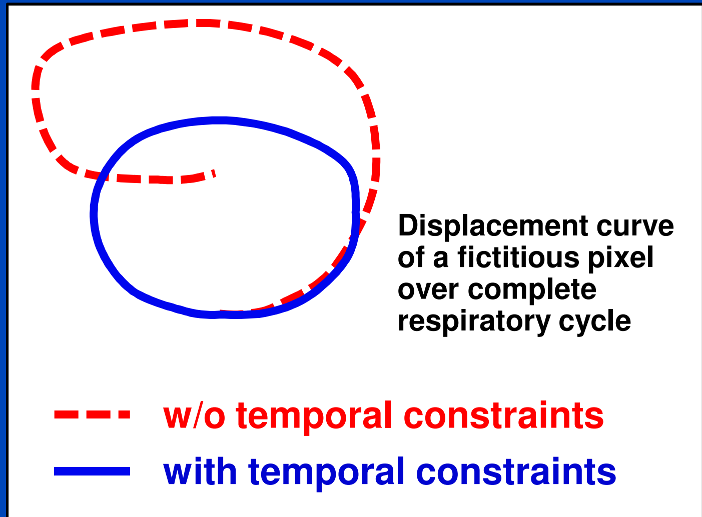
- Streak artifacts from gated reconstructions propagate into sMoCo results

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

Motion Estimation
with Cyclic Regularization (cMoCo)

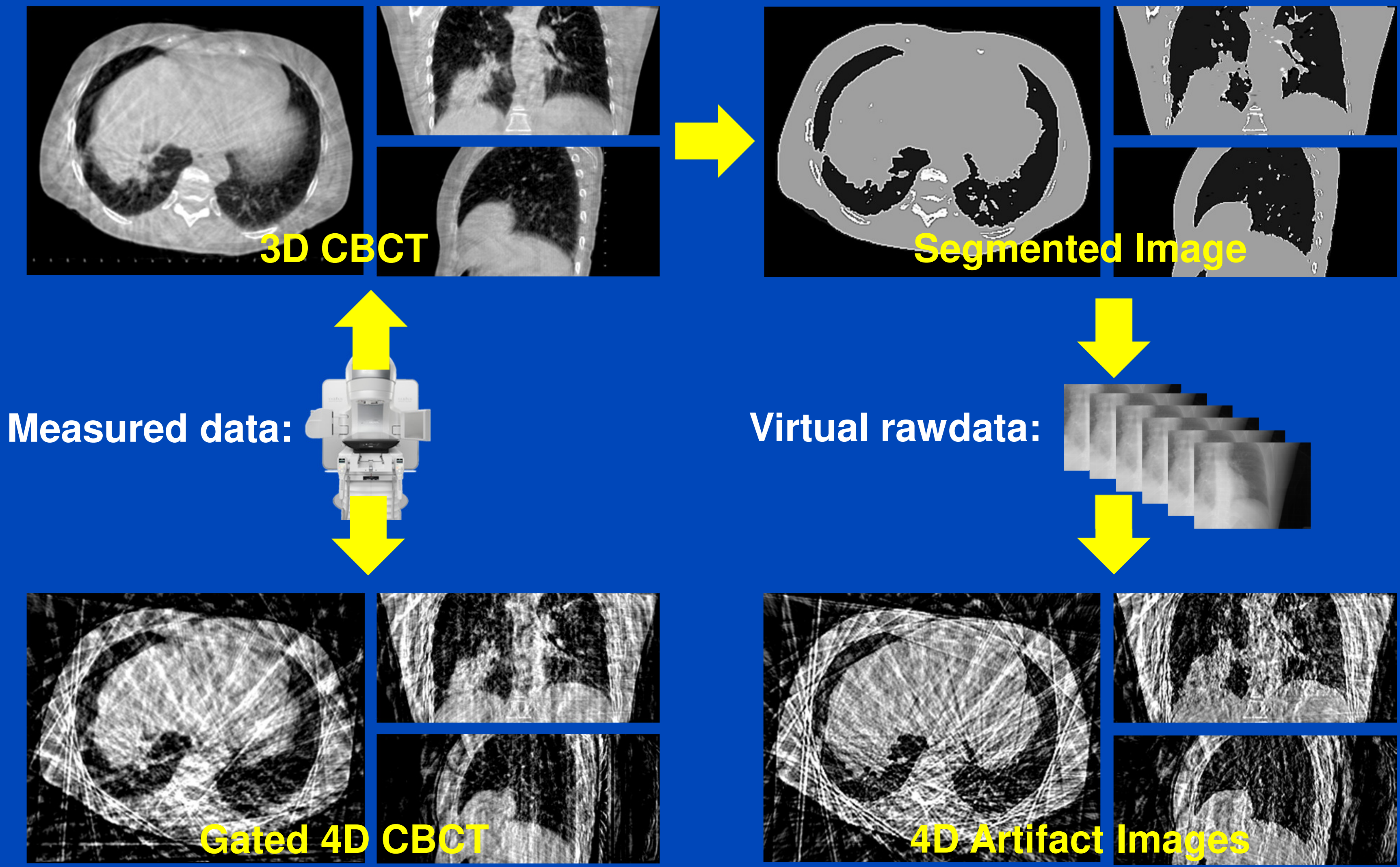
- Motion estimation only between adjacent phases
- Incorporate additional knowledge
  - A priori knowledge of quasi periodic breathing pattern
  - Non-cyclic motion is penalized
  - Error propagation due to concatenation is reduced





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.

Motion Estimation
with Artifact-Model-Based Regularization (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.

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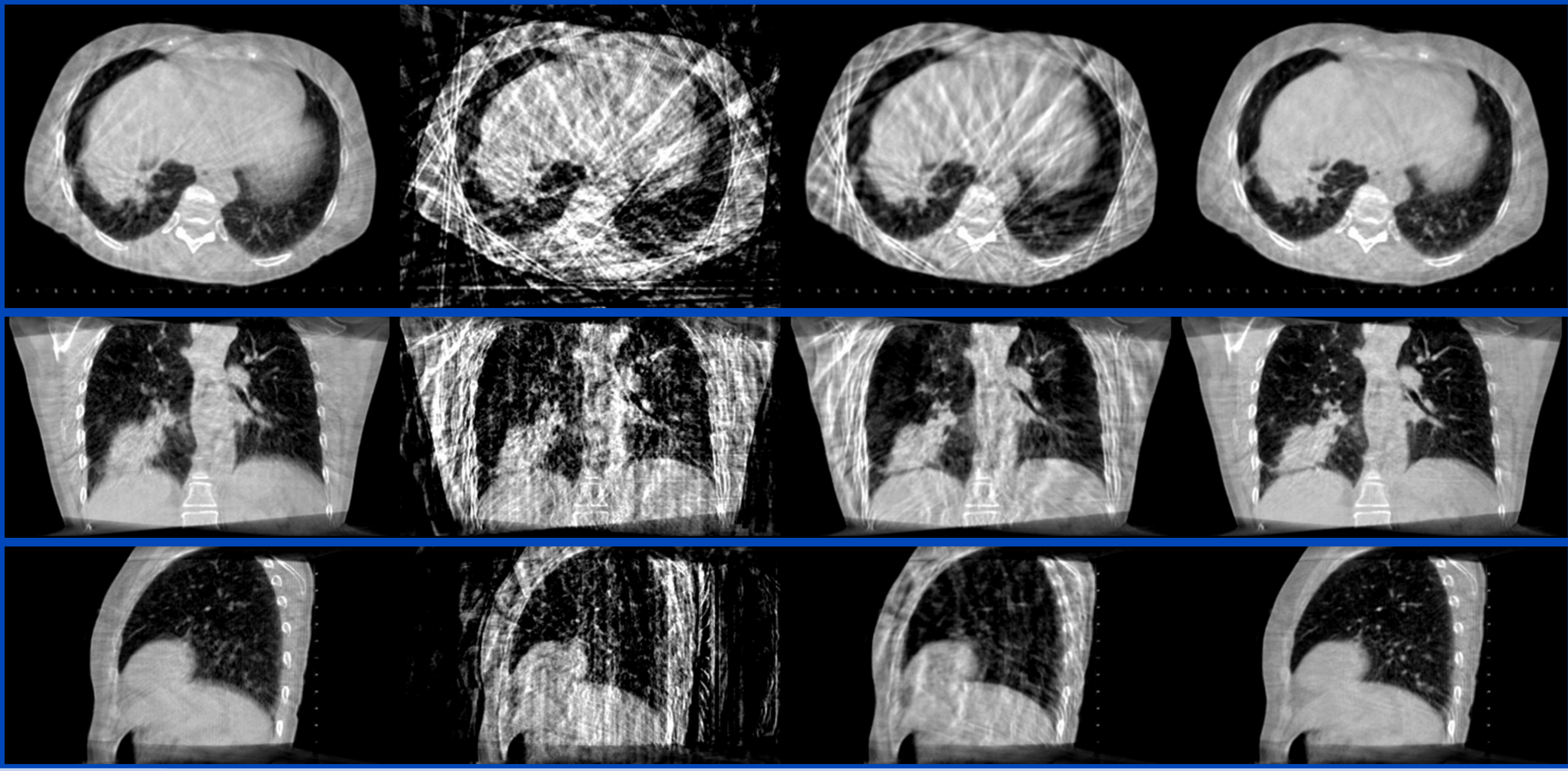
Patient Data – Results

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



VARIAN medical systems

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

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What about the Heart?

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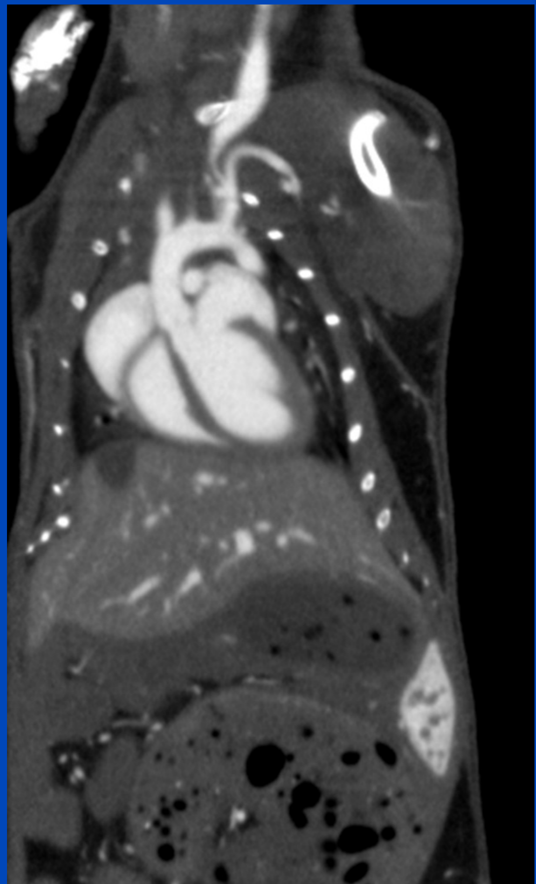
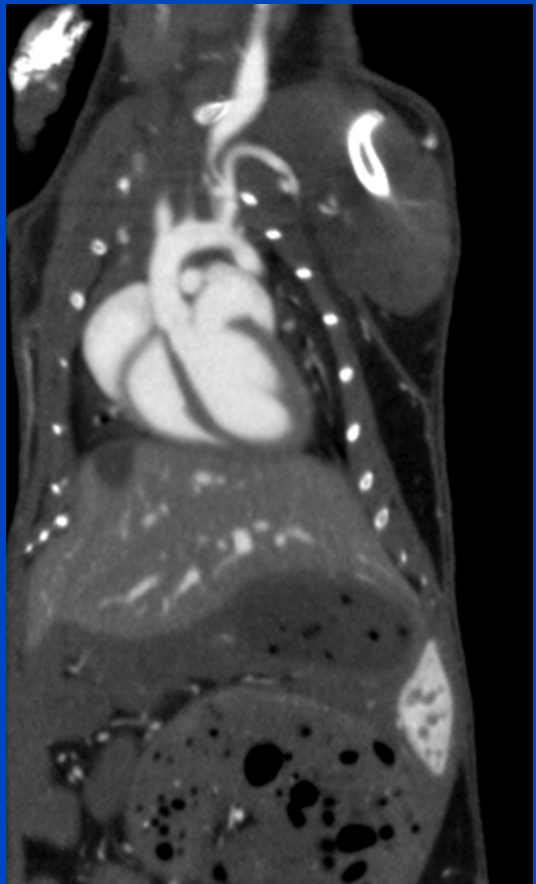


Data displayed as:

Heart: 280 bpm

Lung: 150 rpm

Mouse with 150 rpm and 280 bpm.

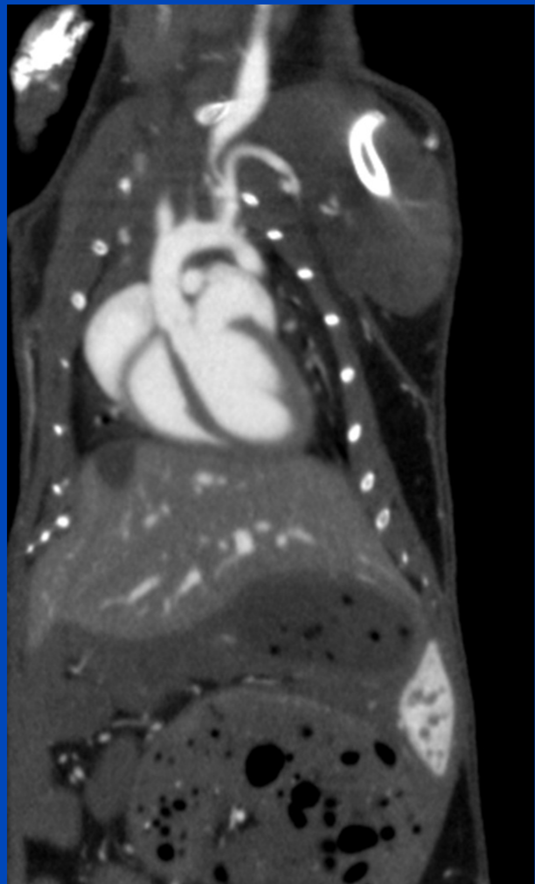


Data displayed as:

Heart: 90 bpm

Lung: 90 rpm

Mouse with 180 rpm and 240 bpm.

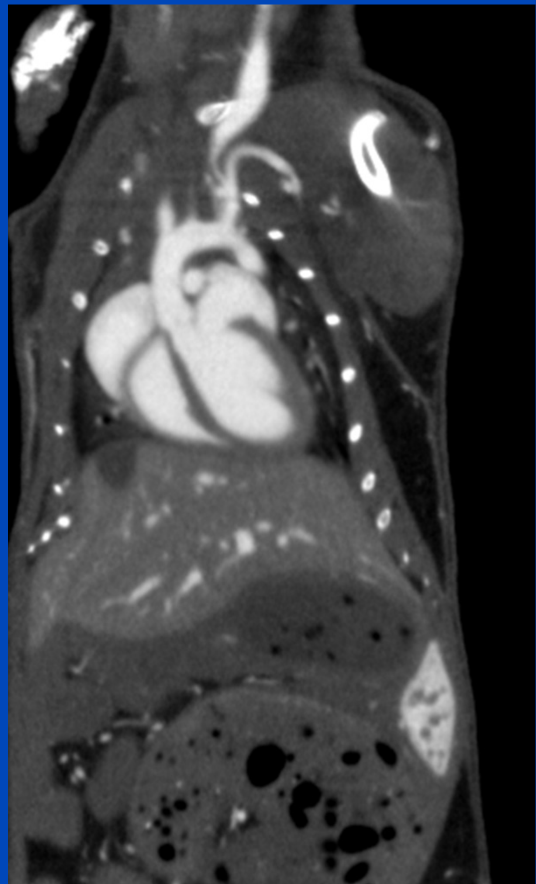


Data displayed as:

Heart: 0 bpm

Lung: 90 rpm

Mouse with 180 rpm and 240 bpm.



Data displayed as:

Heart: 90 bpm

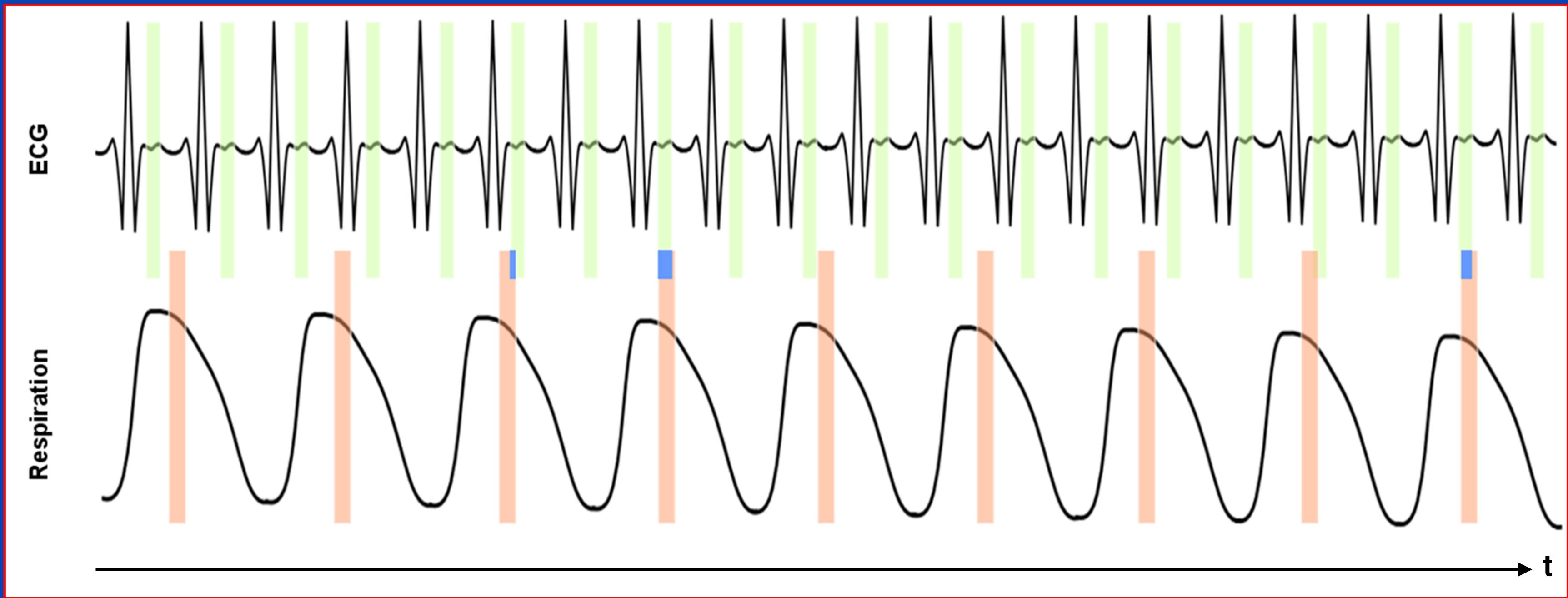
Lung: 0 rpm

Mouse with 180 rpm and 240 bpm.

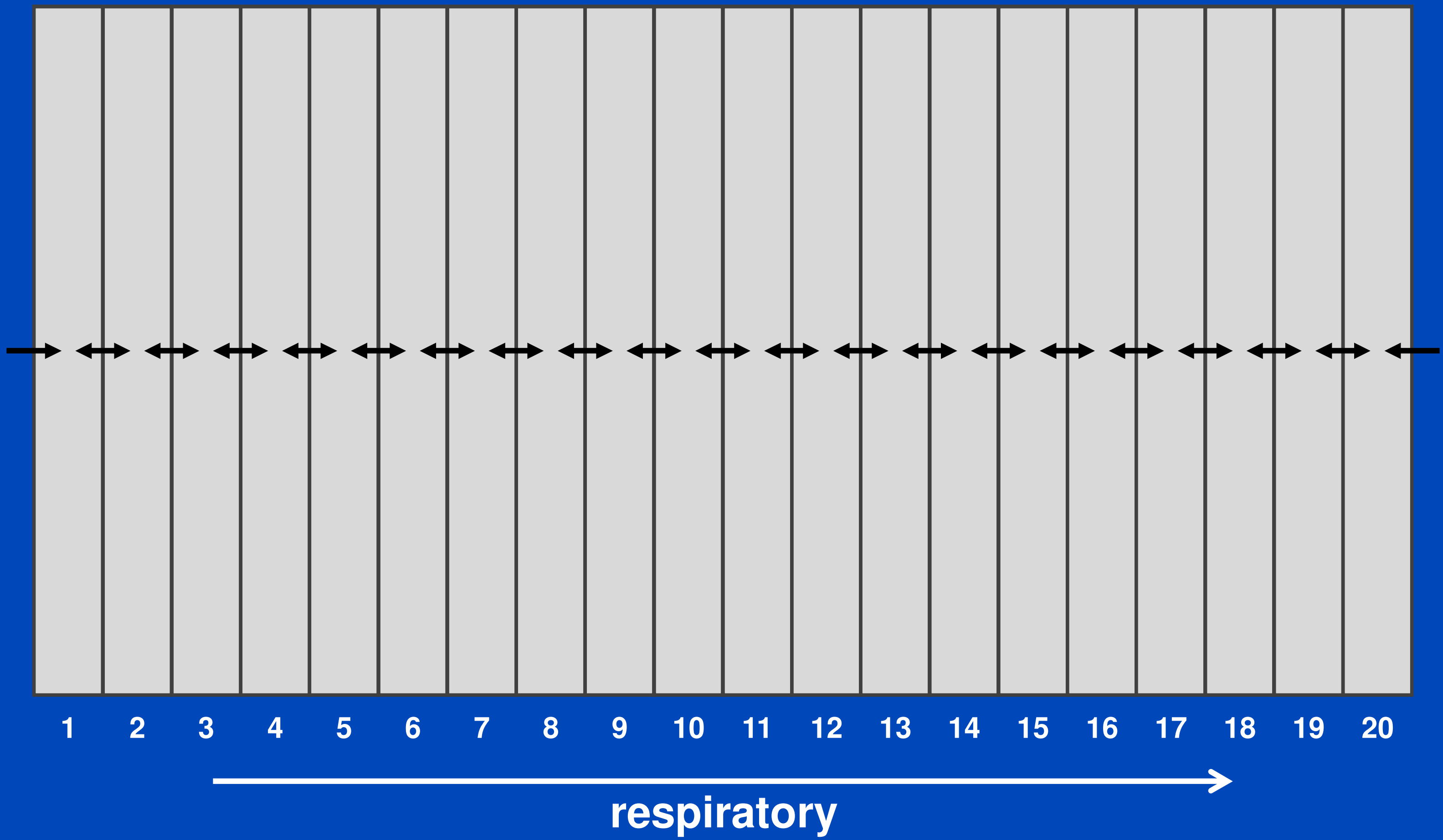
5D with Double Gating?

Double gating example:

- Cardiac window width: 20%
- Respiratory window width: 10%
- Only 2% of all projections per reconstructed volume

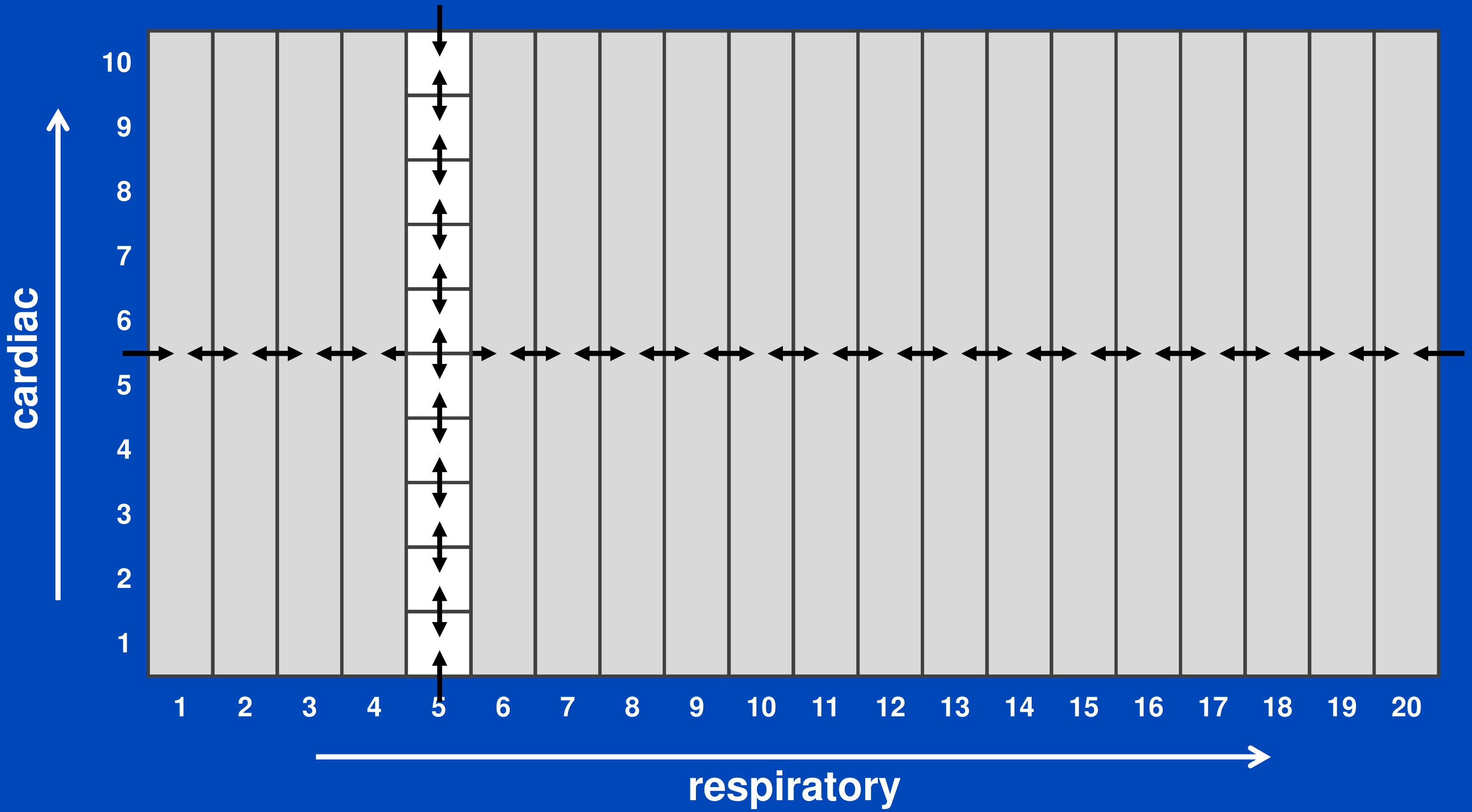


5D Motion Compensation



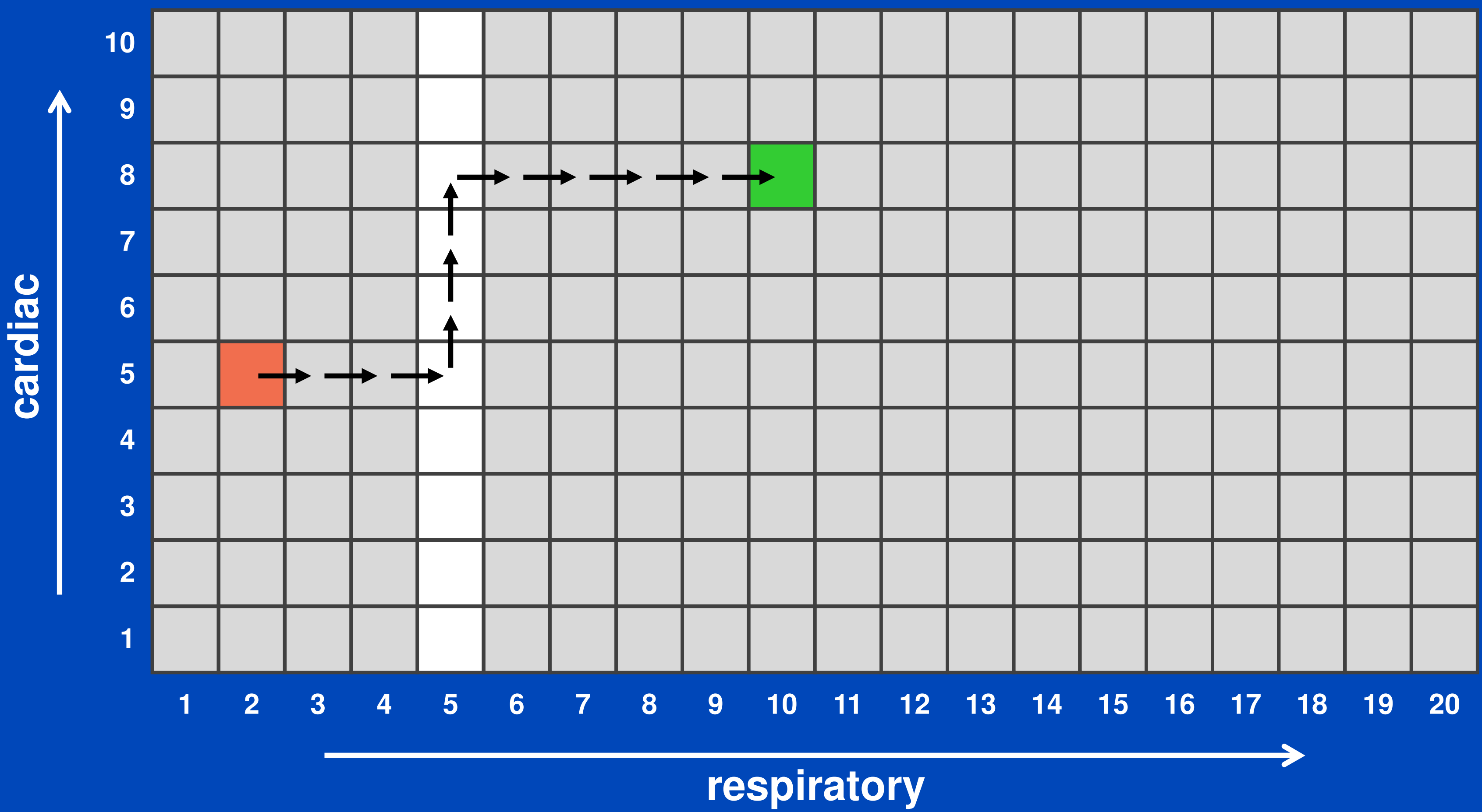
Brehm, Sawall, Maier, and Kachelrieß, “Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation” Med. Phys. 42(4):1948-1958, 2015.

5D Motion Compensation

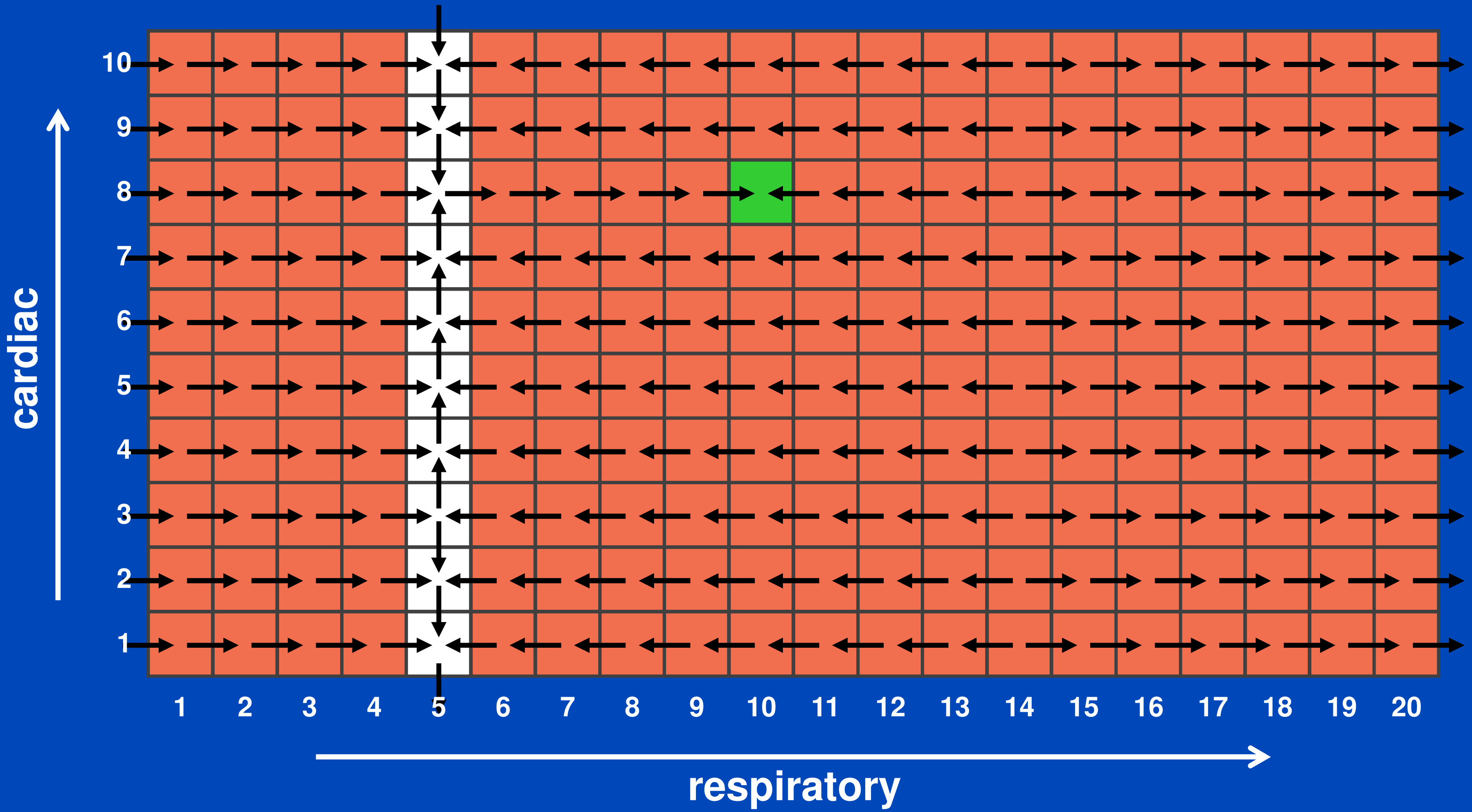


Brehm, Sawall, Maier, and Kachelrieß, "Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation" Med. Phys. 42(4):1948-1958, 2015.

5D Motion Compensation



5D Motion Compensation



Brehm, Sawall, Maier, and Kachelrieß, "Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation" Med. Phys. 42(4):1948-1958, 2015.

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MoCo 5D Results

20 respiratory phases of 10% width, 10 cardiac phases of 20% width

PCF 5D	**PCF 5D**	**acMoCo 5D**	**acMoCo 5D**
Respiratory & Cardiac Gated	Respiratory Compensated & Cardiac Gated	Respiratory & Cardiac Compensated r-loop, *c* = 0%	Respiratory & Cardiac Compensated *r* = 0%, *c*-loop

C=-250 HU, *W*=1400 HU

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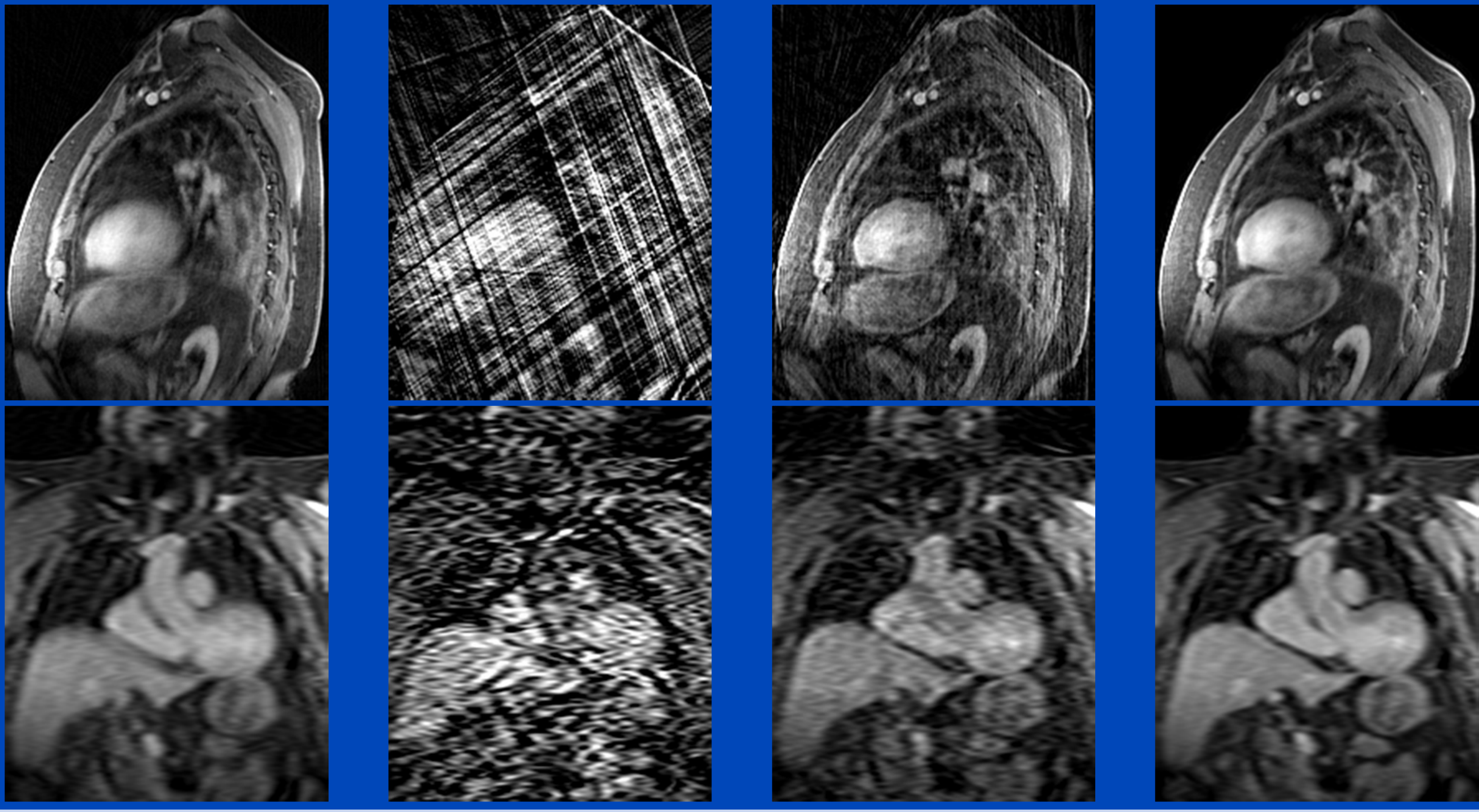
Spin-Off Effects?

5D MR Motion Compensation

Results Patient c12

3D reconstruction	5D reconstruction	5D reconstruction	5D MoCo
motion average	resp & card gated *r* = 1, *c*-loop	resp MoCo & card gated *r* = 1, *c*-loop	resp & card MoCo *r* = 1, *c*-loop



total acquisition time: 1 min 55 s, radial undersampling = 36

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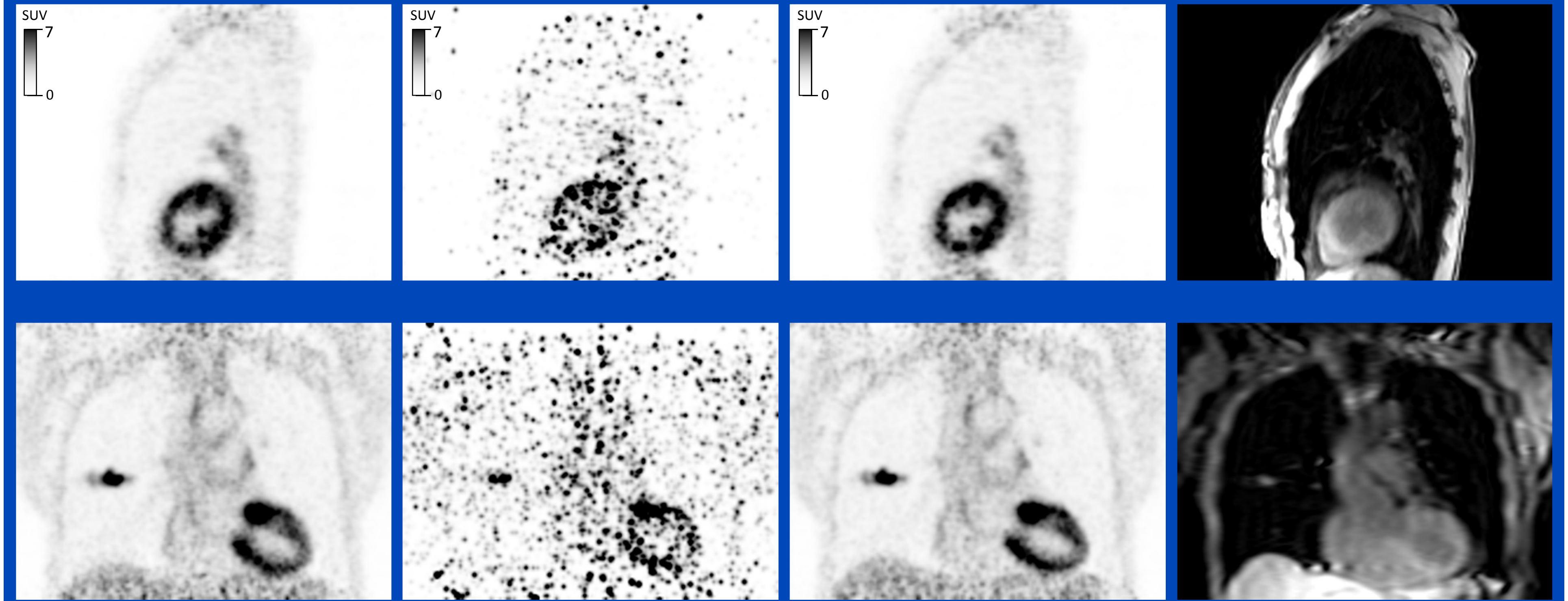
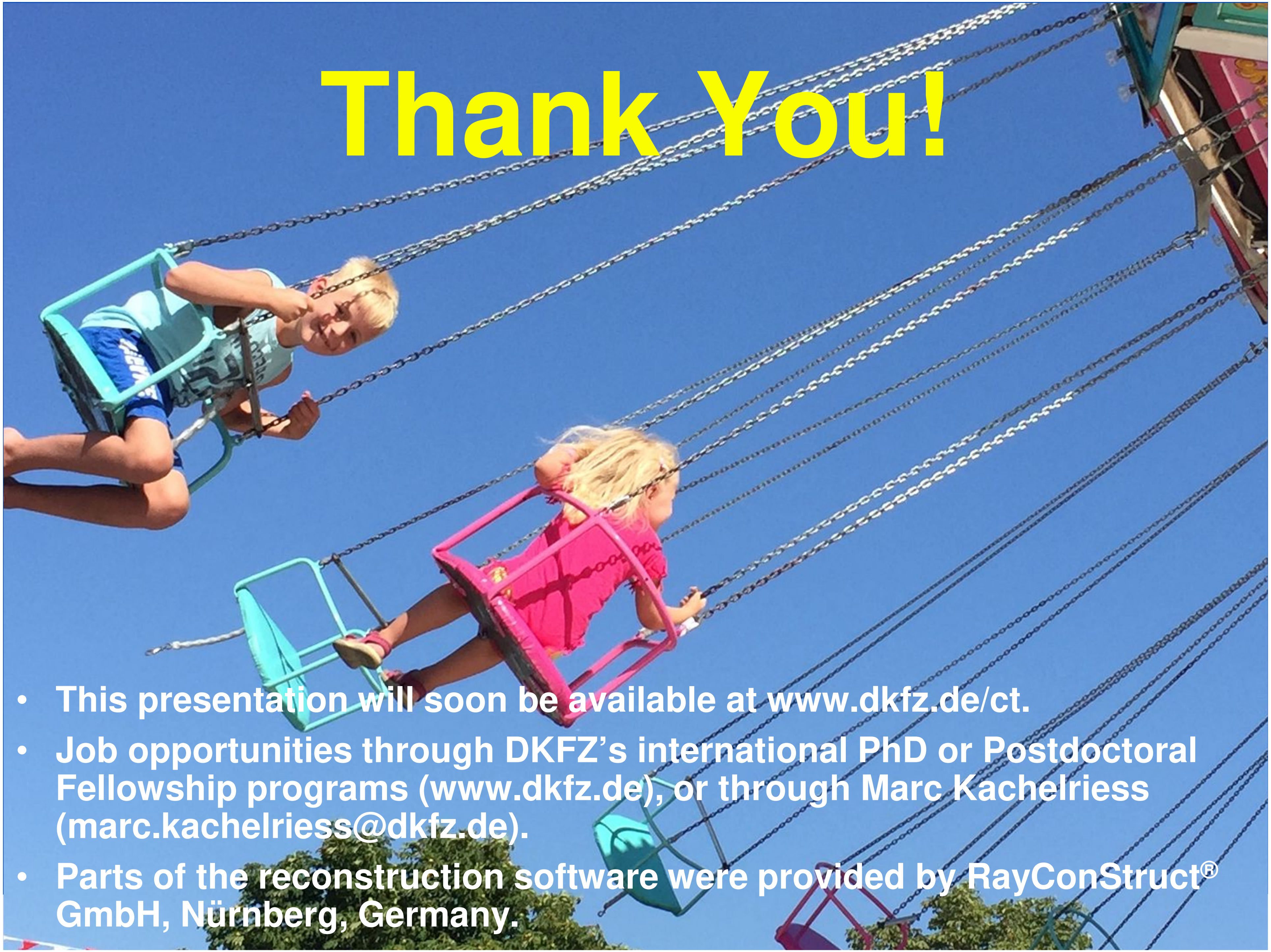
5D PET/MR Motion Compensation

Results Patient s04

3D PET motion average	5D double-gated PET *r* = 1, *c*-loop	5D MoCo PET *r* = 1, *c*-loop	5D MoCo MR *r* = 1, *c*-loop





Thank You!

- This presentation will soon be available at www.dkfz.de/ct.
- Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs (www.dkfz.de), or through Marc Kachelriess (marc.kachelriess@dkfz.de).
- Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.