Managing Motion in CT: Conventional Approaches and Motion Compensating Techniques

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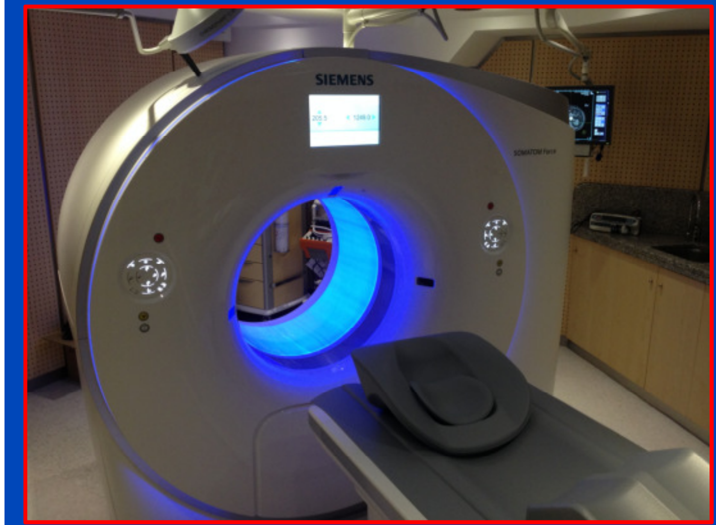
DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

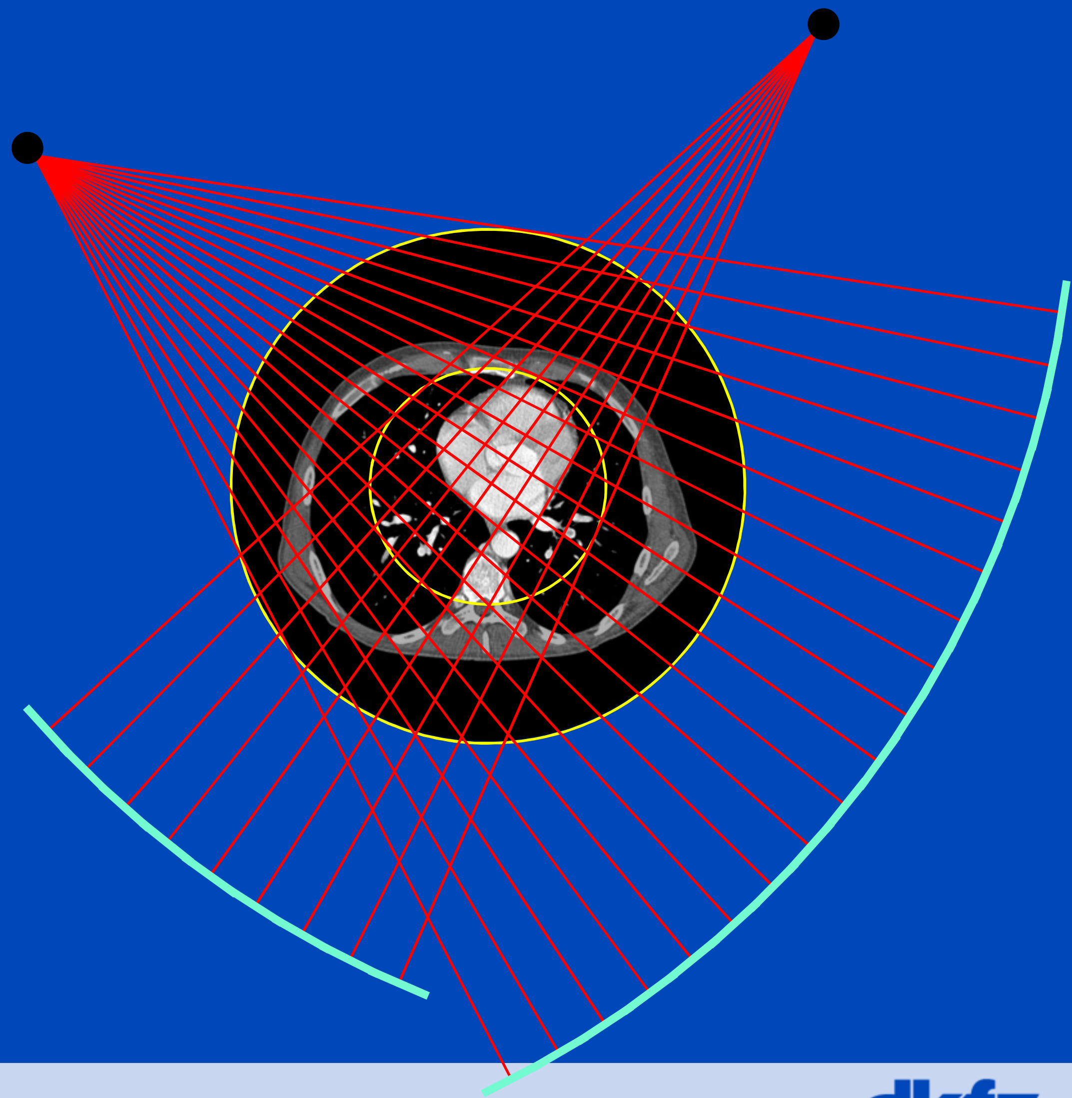
CT

CT is much faster than one motion cycle!

(this presentation)



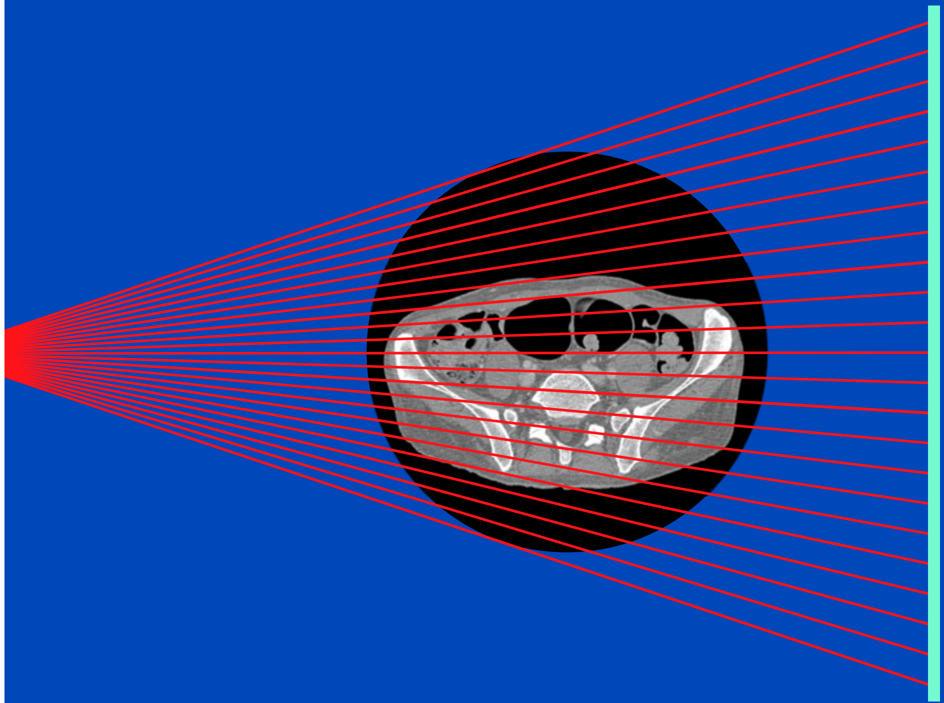
Siemens SOMATOM Force
dual source cone-beam spiral CT

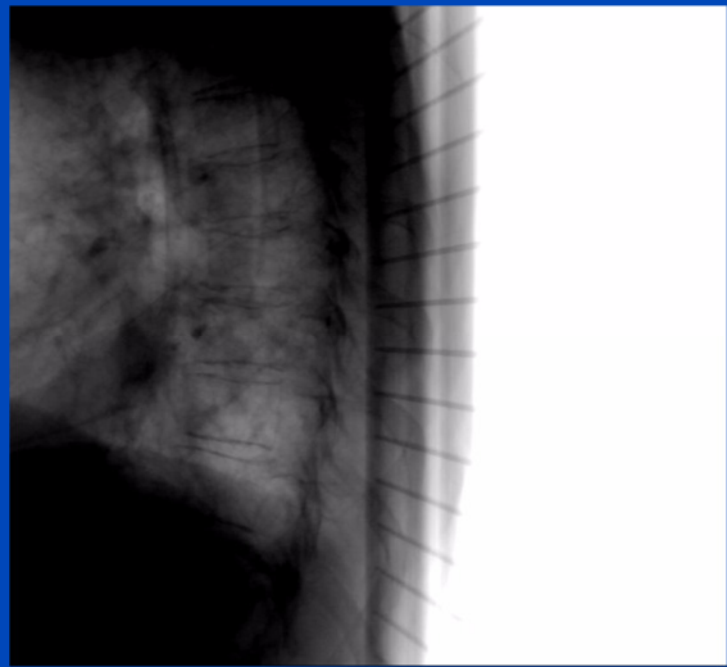


CBCT

CBCT is much slower than one motion cycle!

(next presentation)





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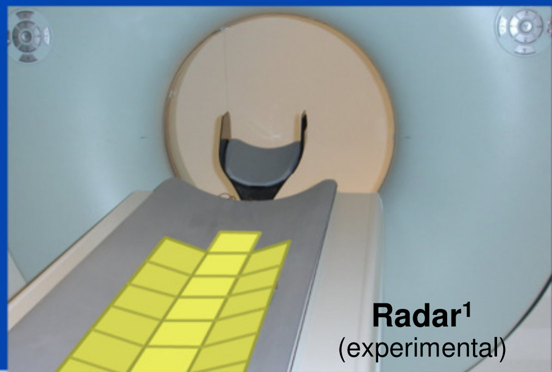
External Gating Signals

Respiratory

Aktina respiratory belt

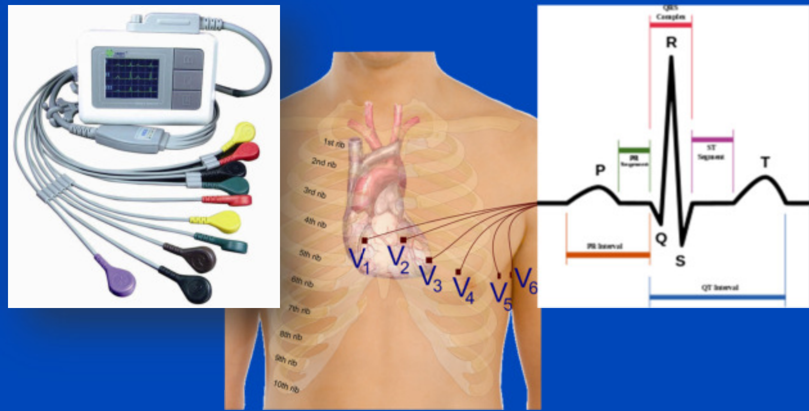
Anzai respiratory belt

Varian respiratory monitoring (RPM)



Radar[1] (experimental)

Cardiac



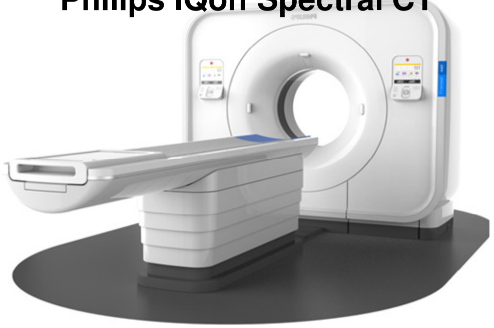
Electrocardiogram (ECG)

Pulse oximeter

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

GE Revolution CT

Philips IQon Spectral CT



Siemens Somatom Force

Toshiba Aquilion ONE Vision

In-plane resolution: 0.4 … 0.7 mm

Nominal slice thickness: S = 0.5 … 1.5 mm

Tube (max. values): 120 kW, 150 kV, 1300 mA

Effective tube current: mAs_{eff} = 10 mAs … 1000 mAs

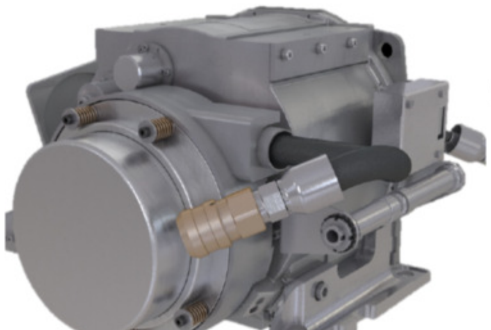
Rotation time: T_{rot} = 0.25 … 0.5 s

Simultaneously acquired slices: M = 16 … 320

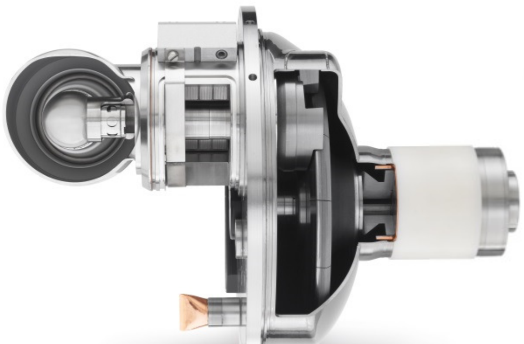
Table increment per rotation: d = 1 … 183 mm

Scan speed: up to 73 cm/s

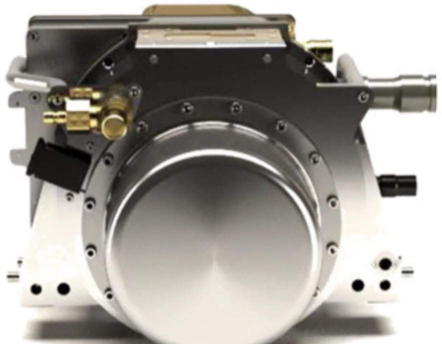
Temporal resolution: 50 … 250 ms



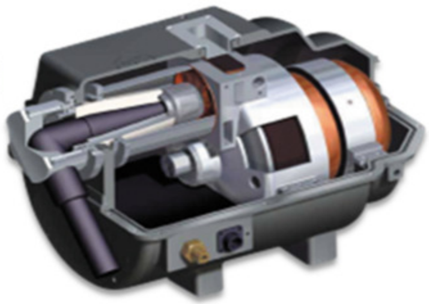
GE Performix HDw



Philips iMRC



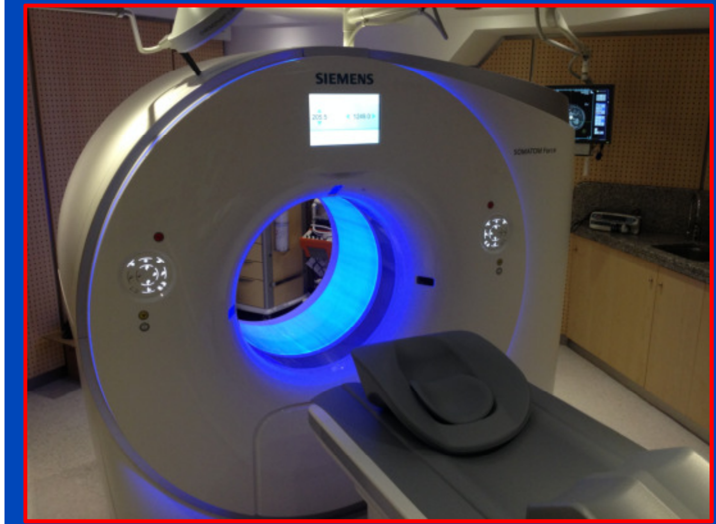
Siemens Vectron



Toshiba Megacool Vi

Cardiac CT

Cardiac CT



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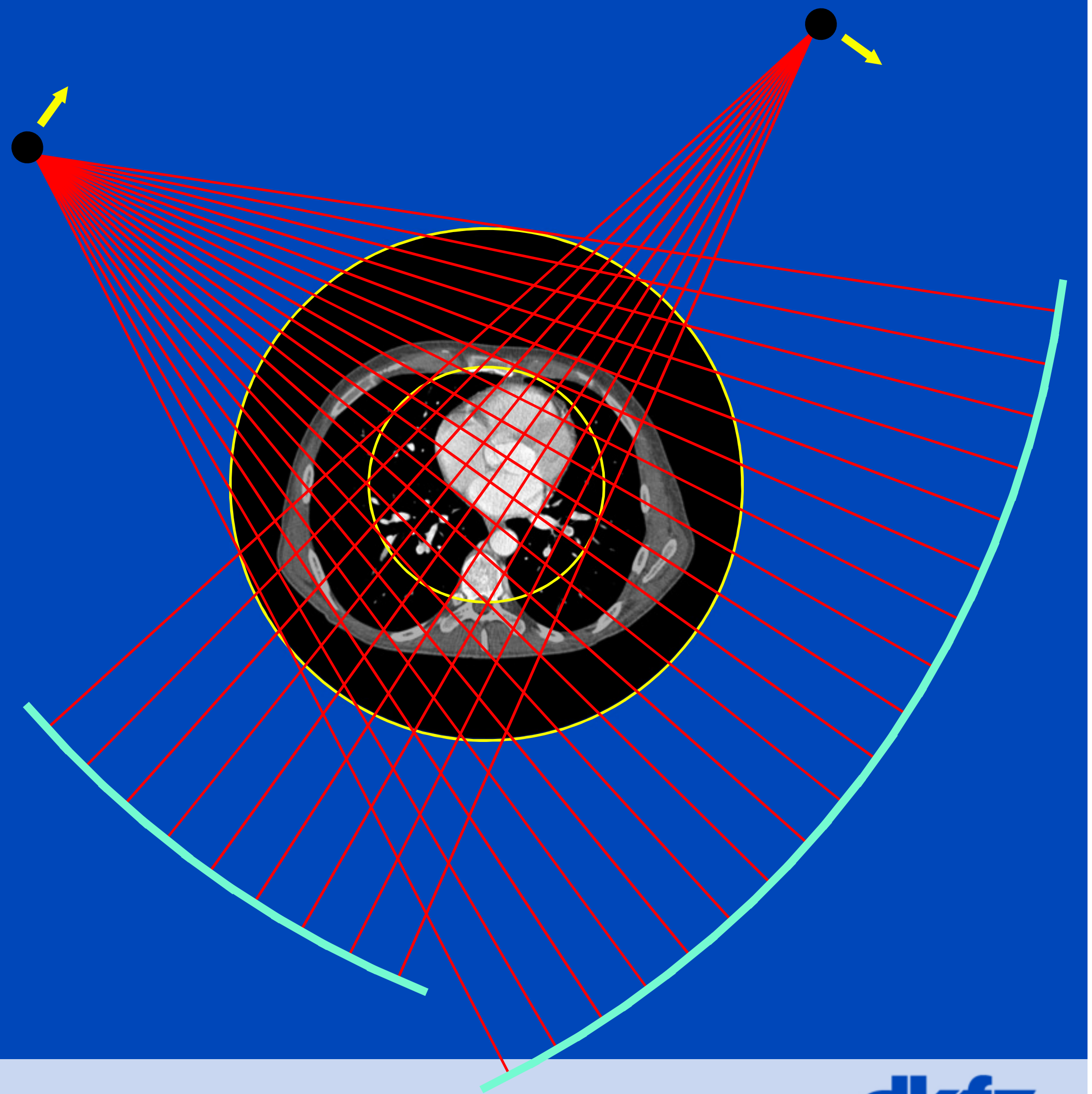


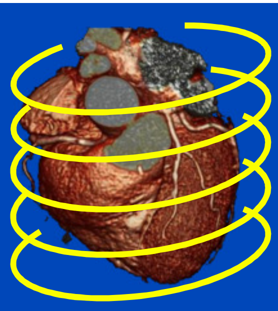
Coronary Motion

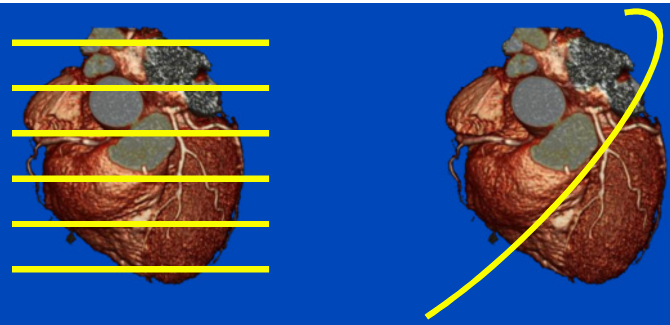
Publication	Mean Velocity		
	RCA	LAD	LCX
Achenbach et al.	69.5 mm/s	22.4 mm/s	48.4 mm/s
Vembar et al.	47.0 mm/s	30.0 mm/s	31.0 mm/s
Husmann et al.	35.8 mm/s	20.2 mm/s	24.9 mm/s

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.





Retrospective Gating	Prospective Gating
=	=
Standard scan + ECG-correlated recon	ECG-triggered scan + standard recon
Standard spiral scan with low pitch value ($p \leq f_H \cdot t_{rot}$)	ECG-triggered sequence- or spiral scan with high pitch value
Phase-correlated reconstruction	Standard image reconstruction
$p \cdot T_{rot} / 2 \leq$ Temp. resolution $\leq T_{rot} / 2$	Temporal resolution = $T_{rot} / 2$
Works also at high heart rates	Good at low heart rates
Dose management: ECG-based TCM	Dose management: inherent
Full phase selectivity	No phase selectivity
Highly robust (also with arrhythmia)	Sufficiently robust (not with arrythmia)
Good dose usage	Very good dose usage

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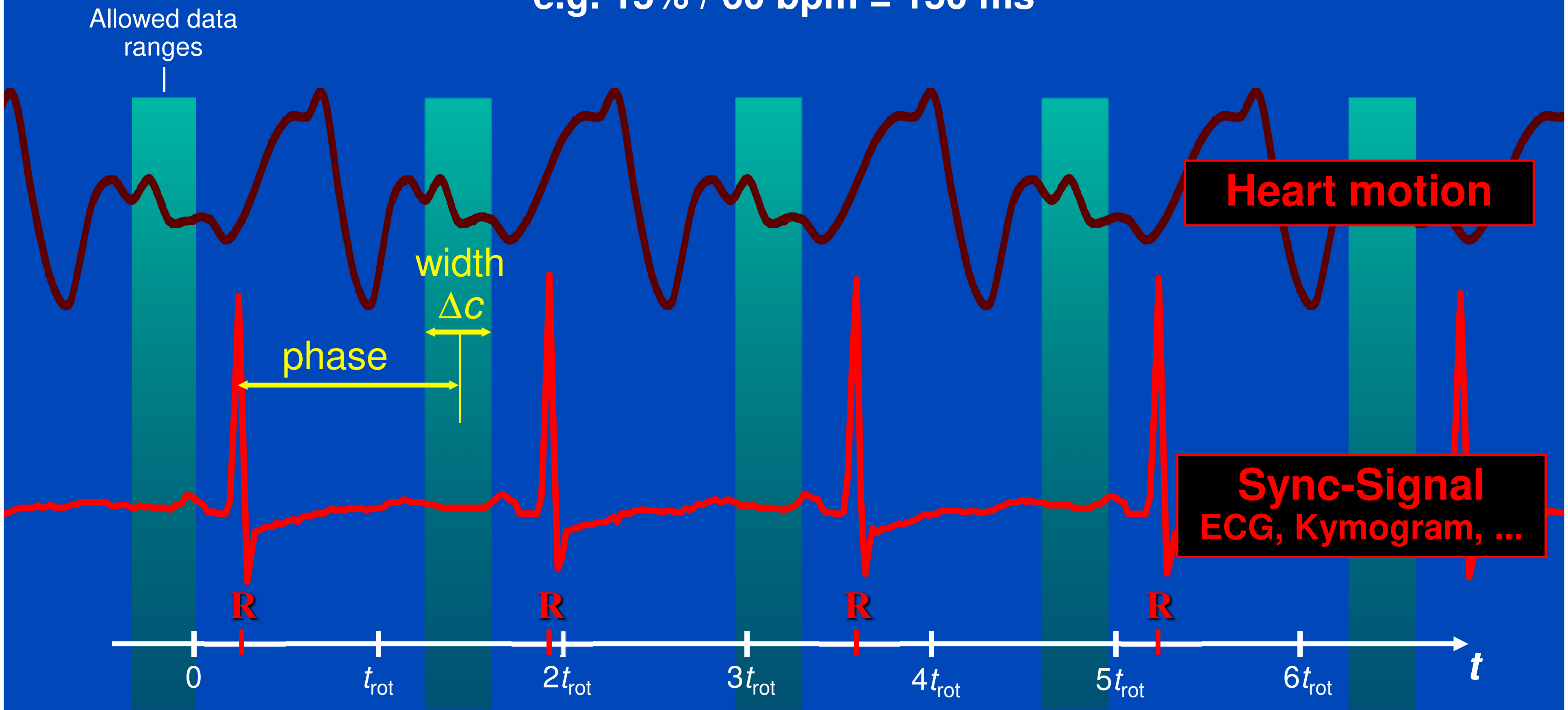
Synchronization with the Heart Phase

t_{eff} = width / heart rate

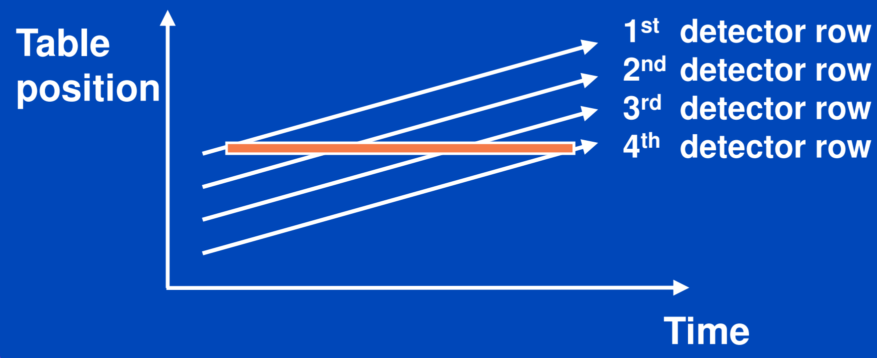
e.g. 15% / 60 bpm = 150 ms

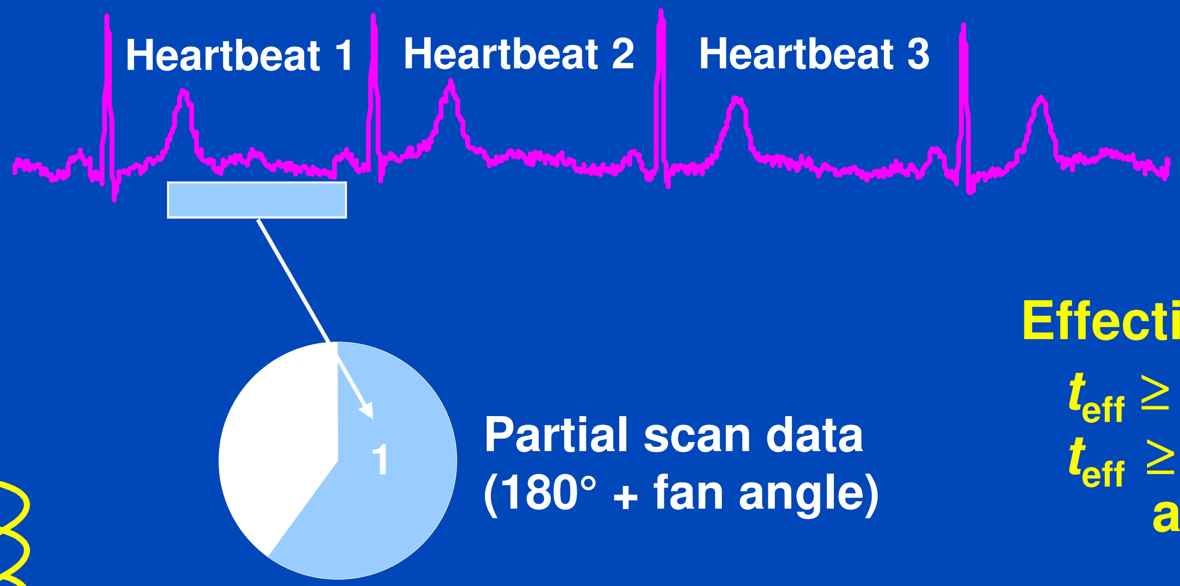


Width, and thus t_{eff}, corresponds to the FWTM of the phase contribution profile.

Partial Scan Reconstruction

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



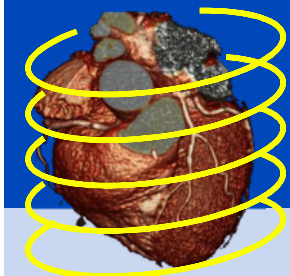


Effective scan time

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

$t_{eff} \geq 200$ ms

at $t_{rot} = 0.4$ s



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

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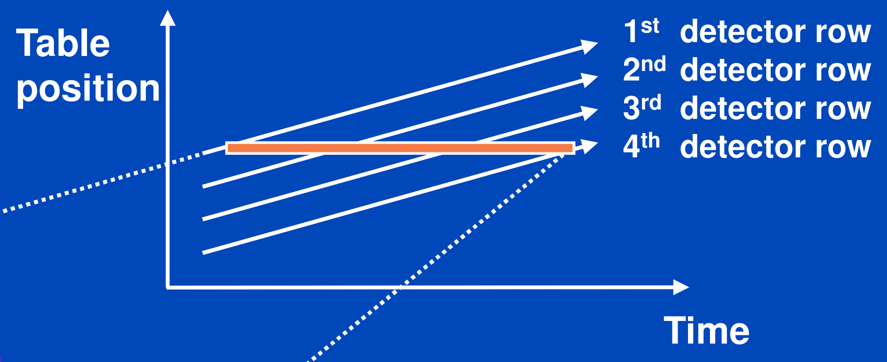
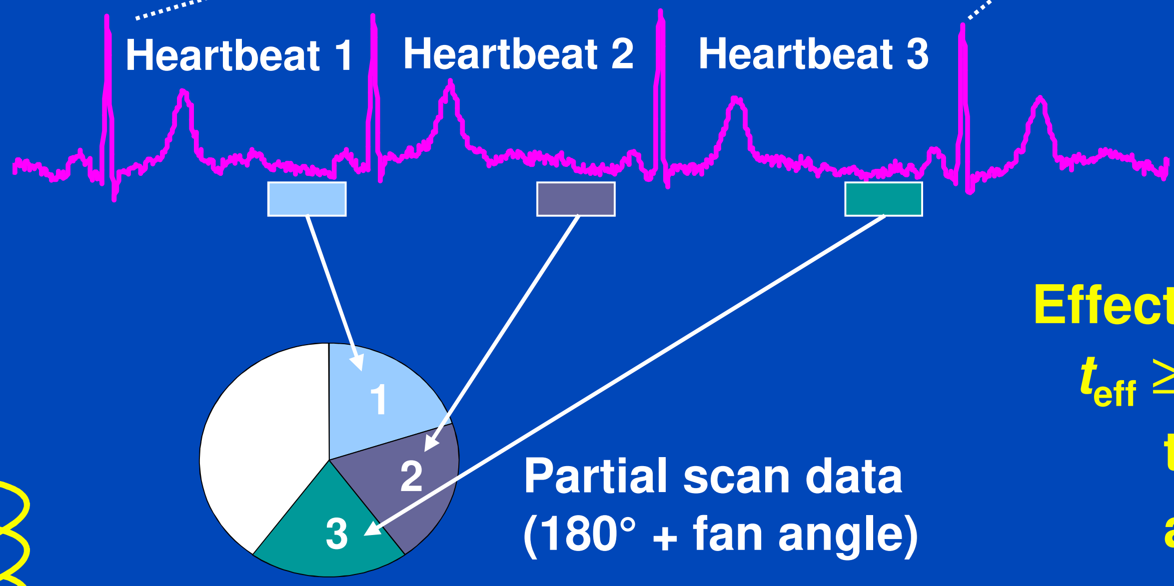
Multi-Segment Reconstruction

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



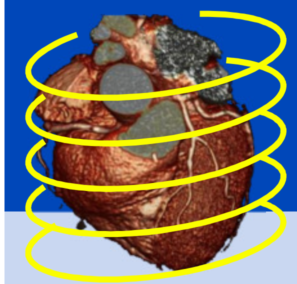


Effective scan time

$t_{eff} \geq$ **48 ms**

typ. 75-150 ms

at t_{rot} = 0.4 s



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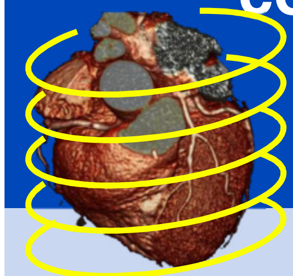
Pitch Value and Full Phase Selectivity

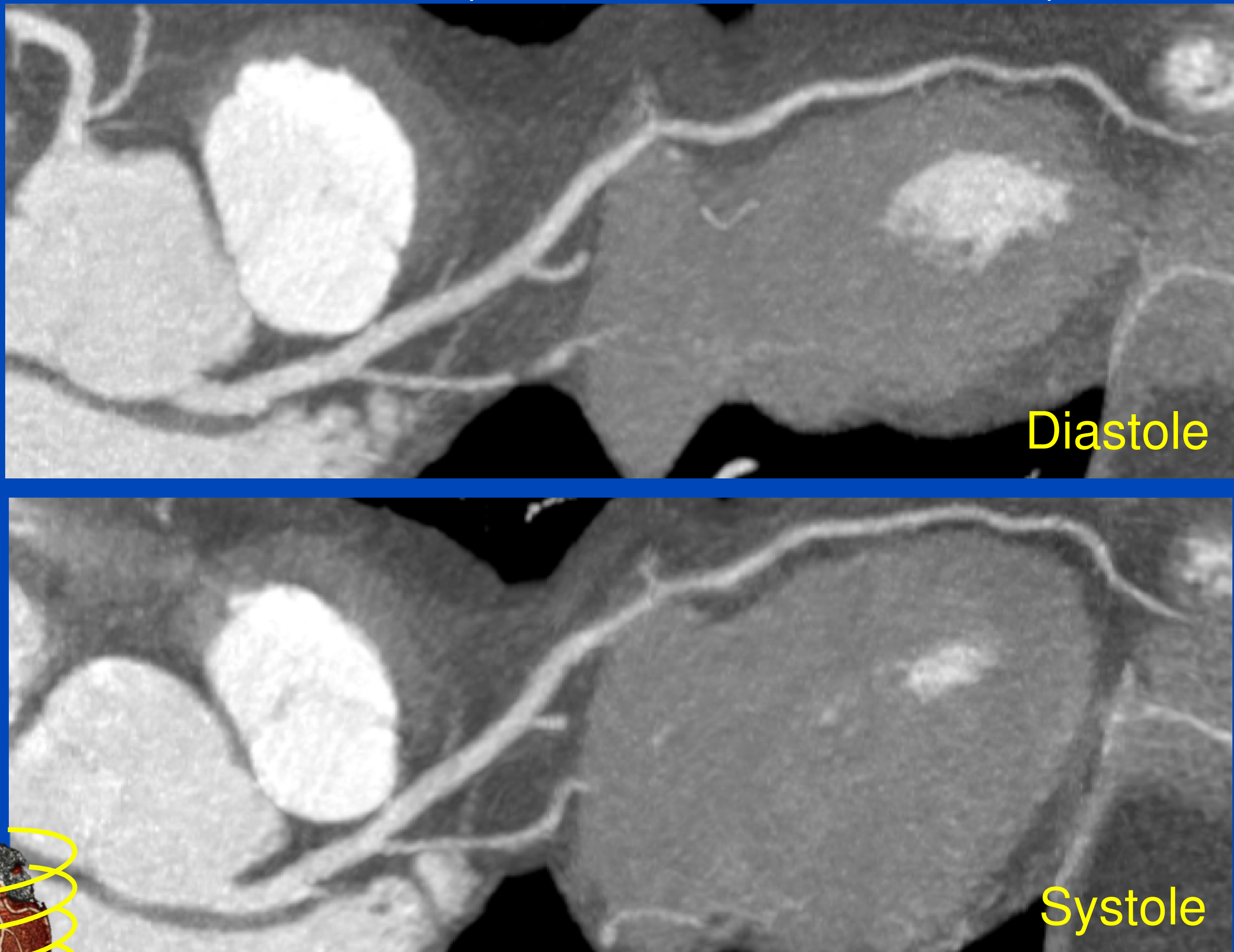
- Each voxel must be illuminated by the x-rays at least as long as one motion cycle of the heart takes
- The table increment per motion cycle must not be larger than the collimation of the scanner

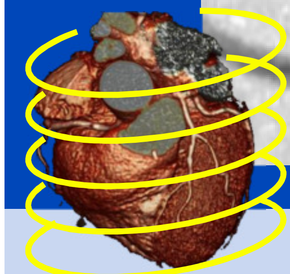
$$p \le f_{\mathrm{H}} t_{\mathrm{rot}}$$

- 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.



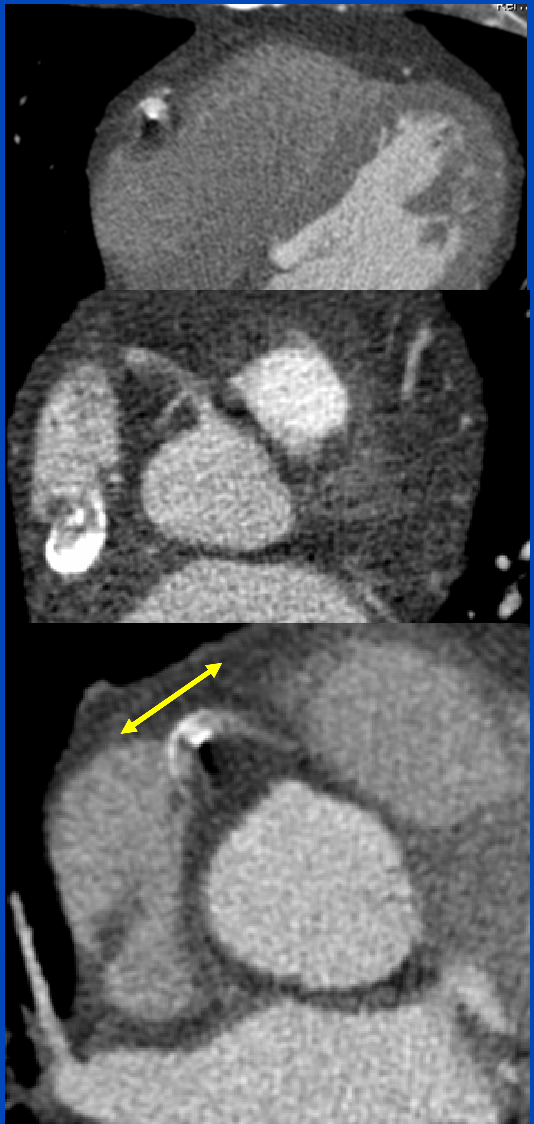
Dual-source-CT, 330 ms rotation, partial scan reconstruction, 83 ms temporal resolution





Data courtesy of Stephan Achenbach, Erlangen, Germany

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** $d \approx \frac{t_{rot}}{2}\bar{v} \approx \frac{250}{2}\,\mathrm{ms}\; 50\,\frac{\mathrm{mm}}{\mathrm{s}} = 6.25\,\mathrm{mm}$ **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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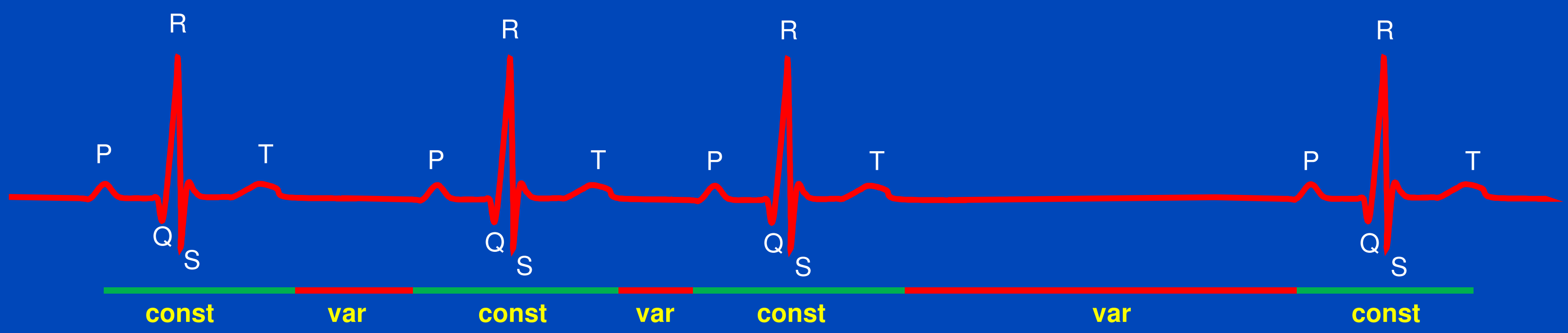
Heart Rate Variability = Diastolic Phase Variability

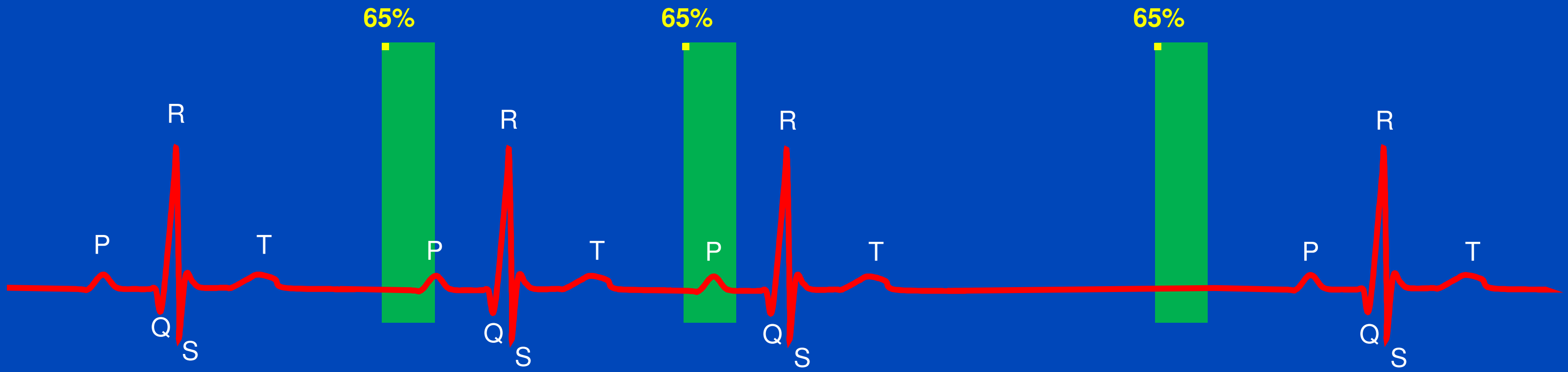
- Unless some pathology of the nervous connections are there, the HR variability is caused by irregular trigger from the sinoatrial (SA) node.
- The diastolic phase can be interrupted by that trigger.
- The distance between P, Q, R, S, T waves only depends on the electrical signal transmission, and is 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.



dkfz.

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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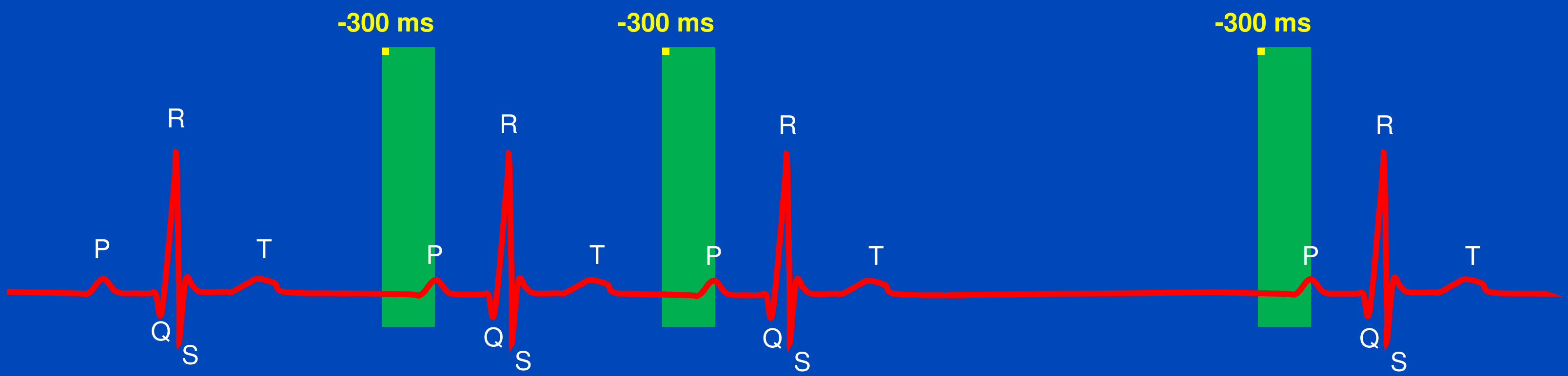

absolute phase selection (diastole)

dkfz.

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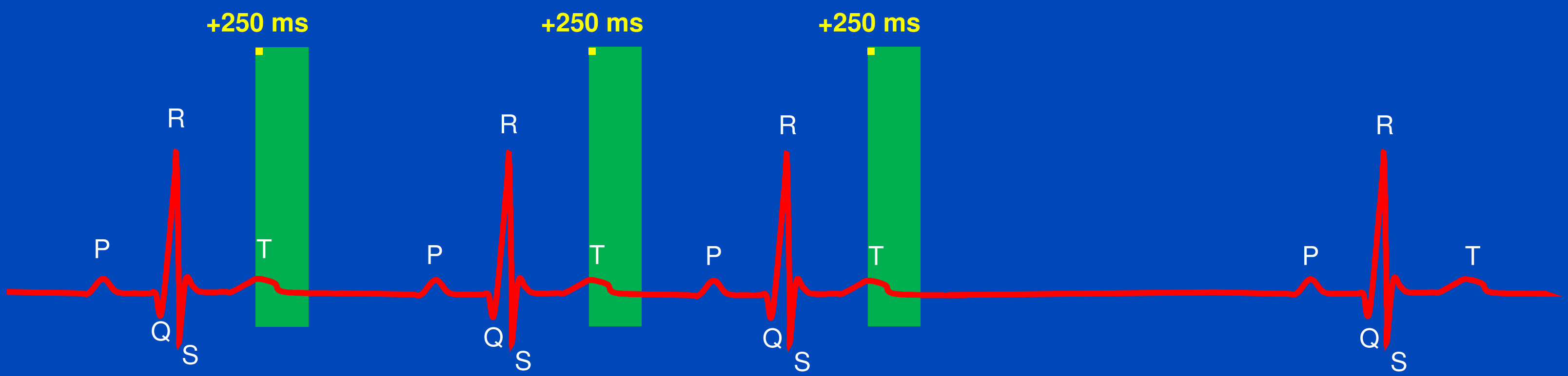
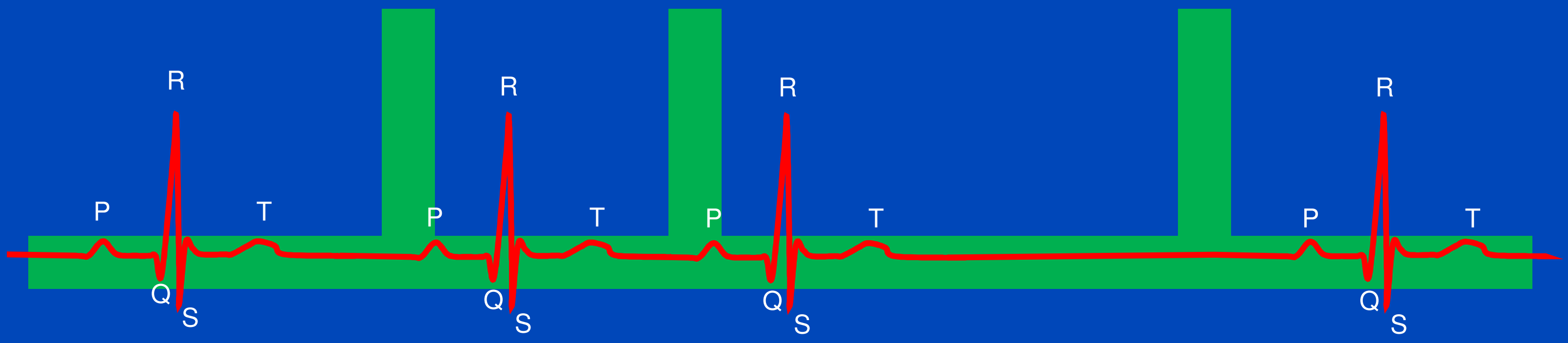


absolute phase selection (systole)

dkfz.

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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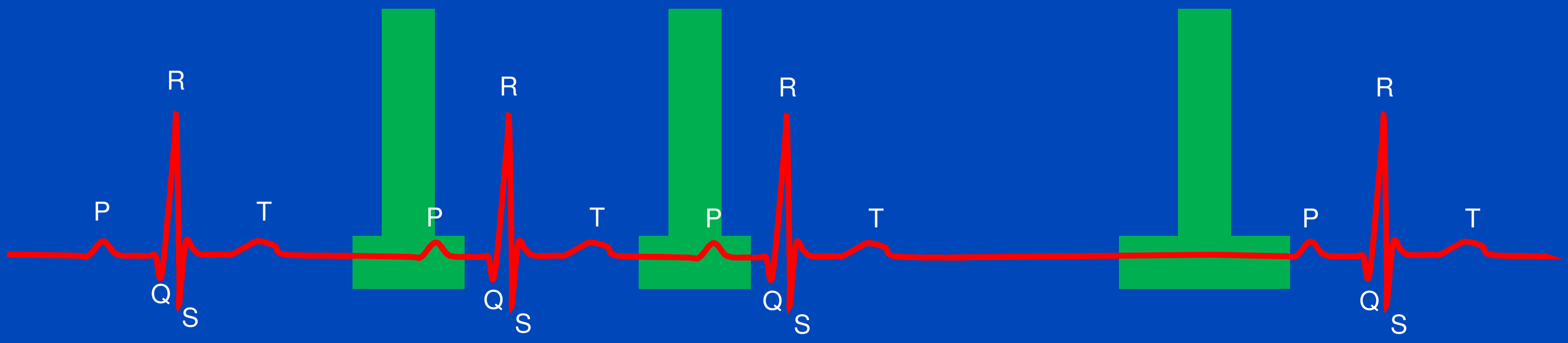

prospective gating (sequence scan)

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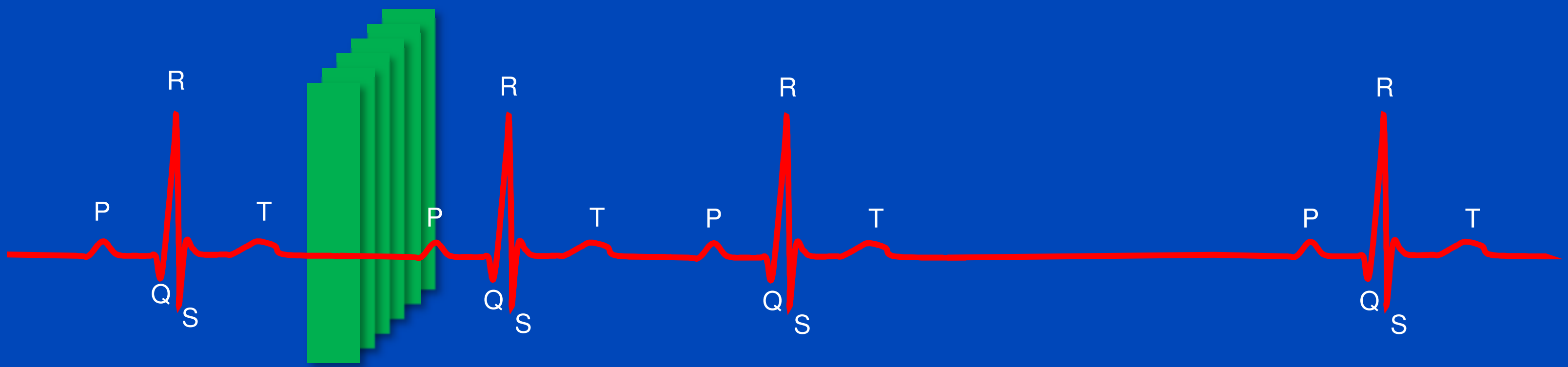
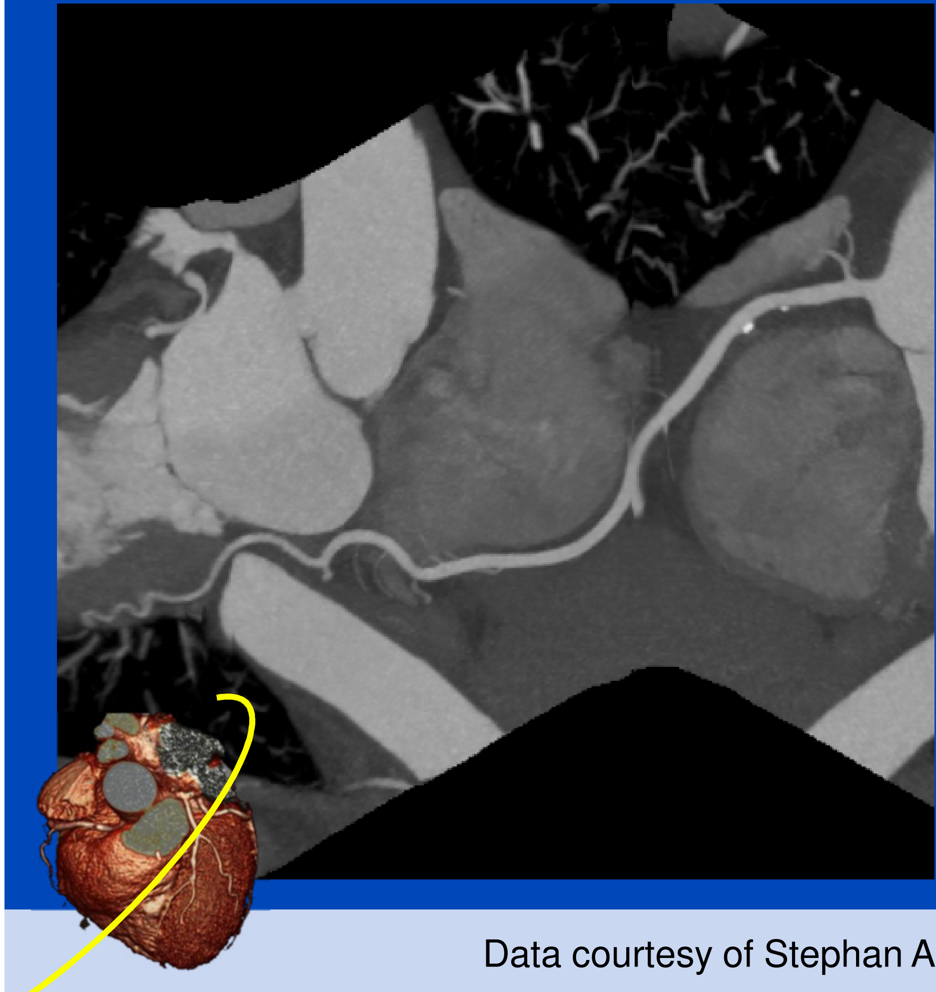
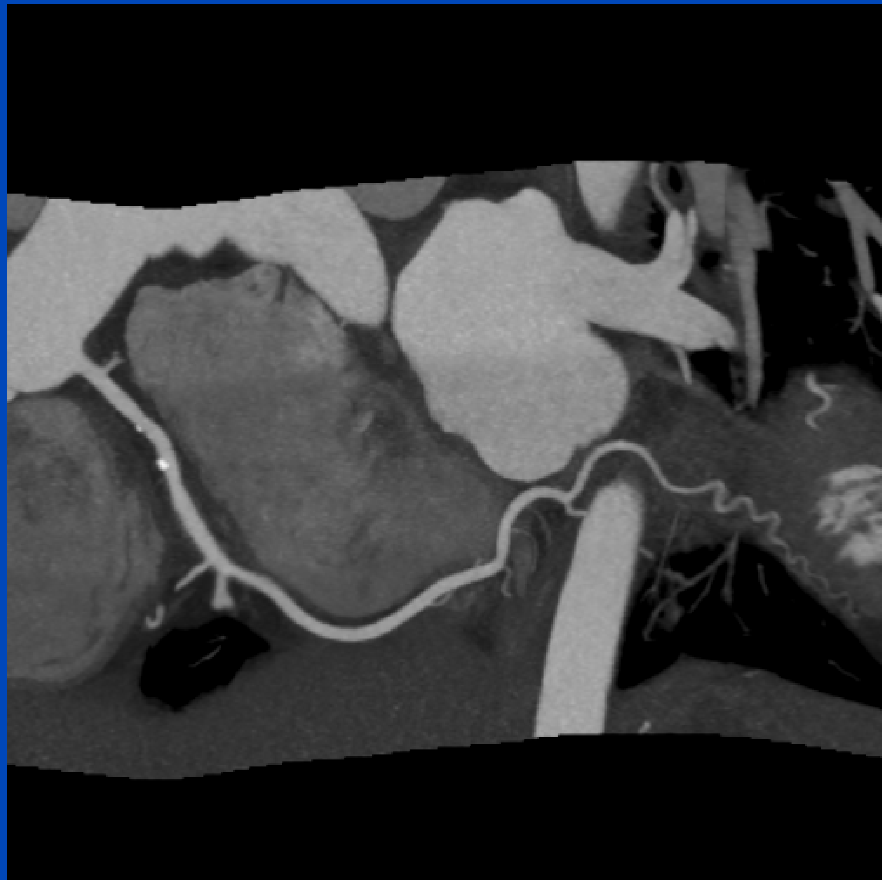


prospective gating (high pitch spiral)

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





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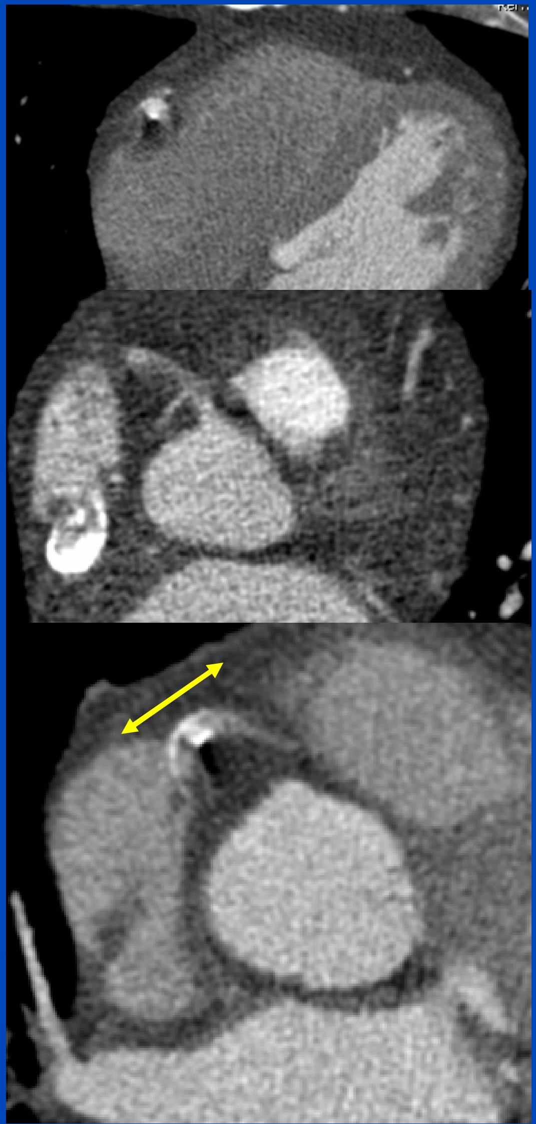

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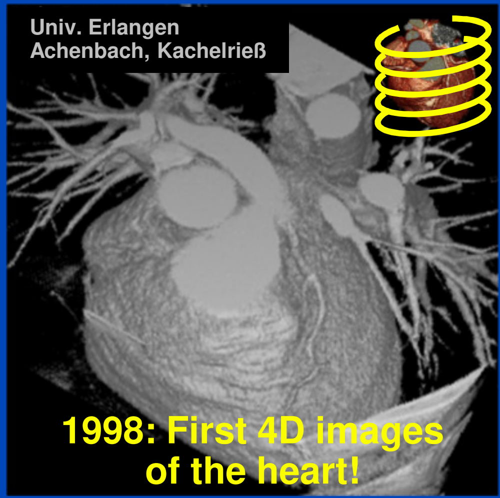
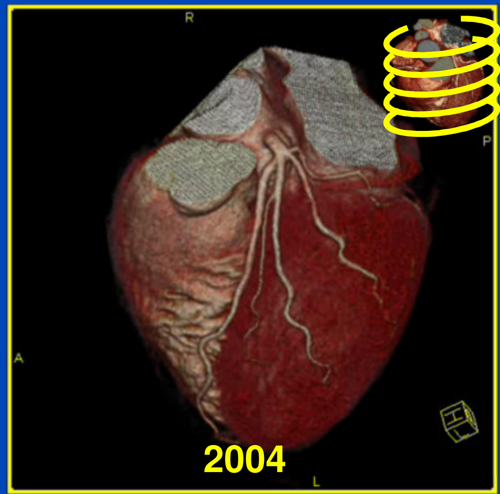
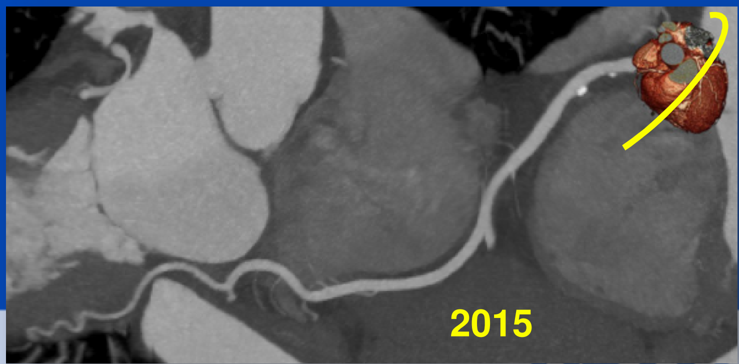
Motion Compensation is the Future!

Cardiac CT MoCo Strategies

- Acquire and reconstruct all phases
  - determine the MVFs (quite difficult)
  - either map all phases into a target phase
  - or improve on each phase separately
- Acquire and reconstruct some adjacent phases
  - determine the MVFs (quite difficult)
  - either map all phases into a target phase
  - or improve on each phase separately
- Acquire and reconstruct a single phase
  - determine the MVFs (extremely difficult because there are no redundancies)
  - improve on the single phase image







Data courtesy of University of Erlangen, Germany

Algorithms to Improve Temporal Resolution in Cardiac CT

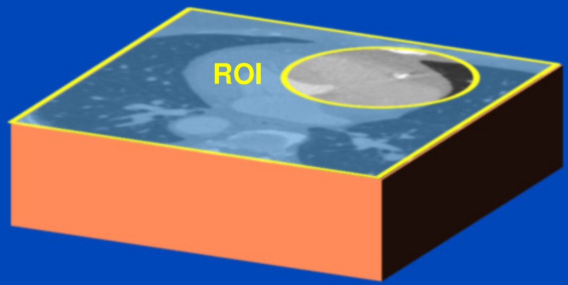
	Data Range	Anatomical Landmarks	Dose Usage	MVFs
Taguchi et al. (Johns Hopkins)	1 heart cycle	no	100%	yes
SSF, Bhaglia et al. (GE)	>> 180°	arteries	<< 100%	yes
SSF+MEAD, Nett et al. (GE)	>> 180°	arteries	<< 100%	yes
Tang et al. (Toshiba)	>> 180°	arteries	<< 100%	yes
Kim et al. (KAIST)	> 180°	no	< 100%	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.

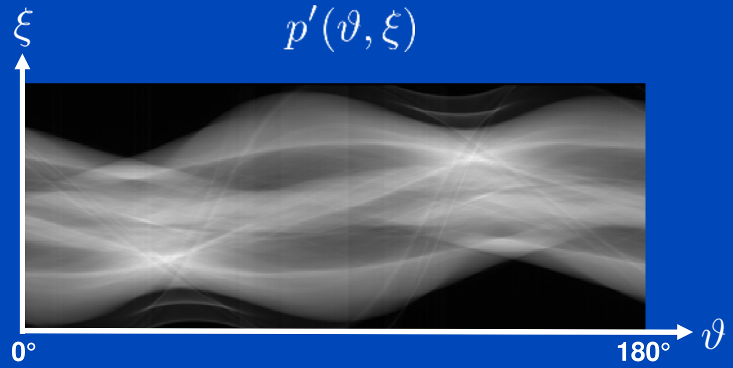
PAMoCo

Generate 2K+1 Partial Angle Reconstructions

Initial segmented stack volume



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



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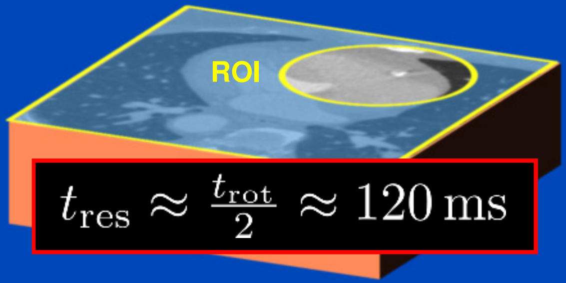
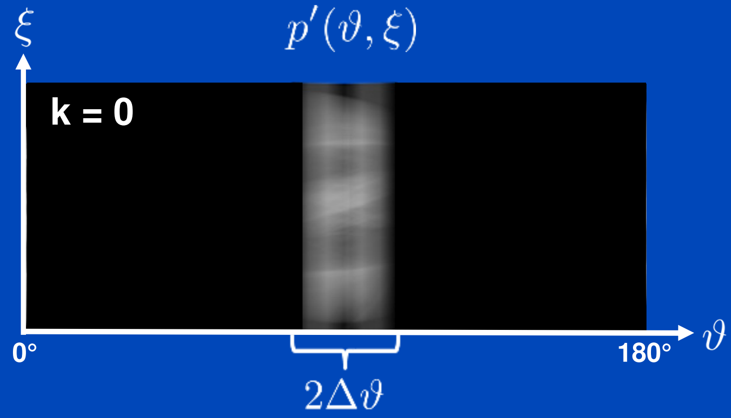
Initial segmented stack volume



$$t_{\text{res}} \approx \frac{t_{\text{rot}}}{2} \approx 120\,\text{ms}$$

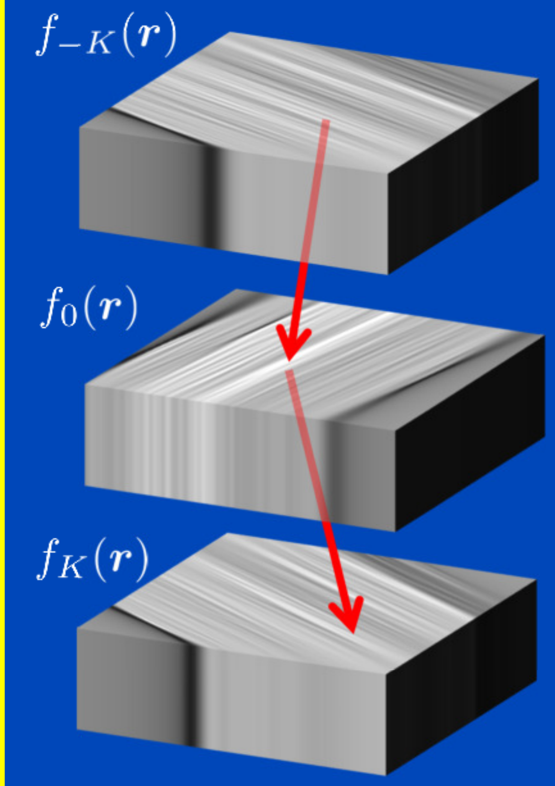
Subdivide the projection data $p'(\vartheta, \xi)$ into 2K + 1 overlapping sectors



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

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

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



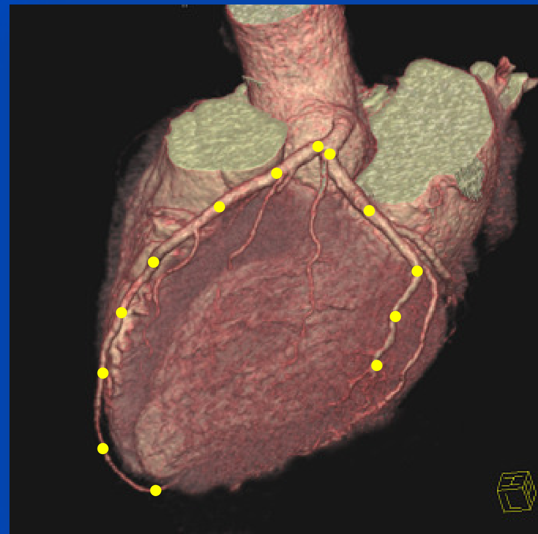
$$t_{\text{res}} \approx \frac{t_{\text{rot}}/2}{(2K+1)/2} \approx 10\,\text{ms}$$

FWHM = $\Delta\vartheta$ **K = 12**

PAMoCo Motion Model

- Control points along coronary arteries

$$\boldsymbol{r} = \boldsymbol{r}(\lambda_n)$$



- Polynomial around each control point

$$\boldsymbol{d}(\boldsymbol{s}, \lambda, t) = \sum_{p,l} \boldsymbol{s}_{lp}(\lambda - \lambda_0)^l (t - t_0)^p$$

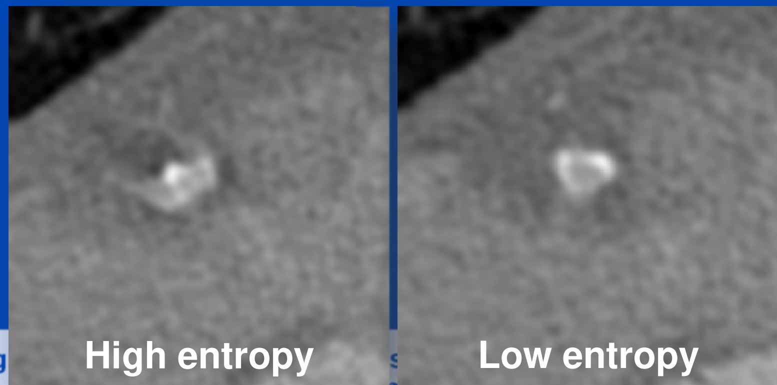
- DVFs continued onto all voxels

$$\boldsymbol{d} = \boldsymbol{d}(\boldsymbol{s}, \boldsymbol{r}, t)$$

- Sum up partial angle images

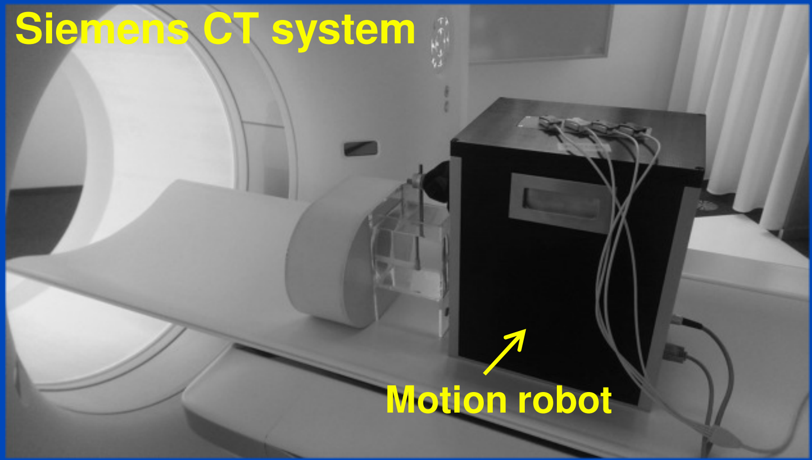
$$f_{\mathrm{MoCo}}(\boldsymbol{r}) = \sum_{k=-K}^{K} f_k\big(\boldsymbol{r} + \boldsymbol{d}(\boldsymbol{s}, \boldsymbol{r}, t_k)\big)$$

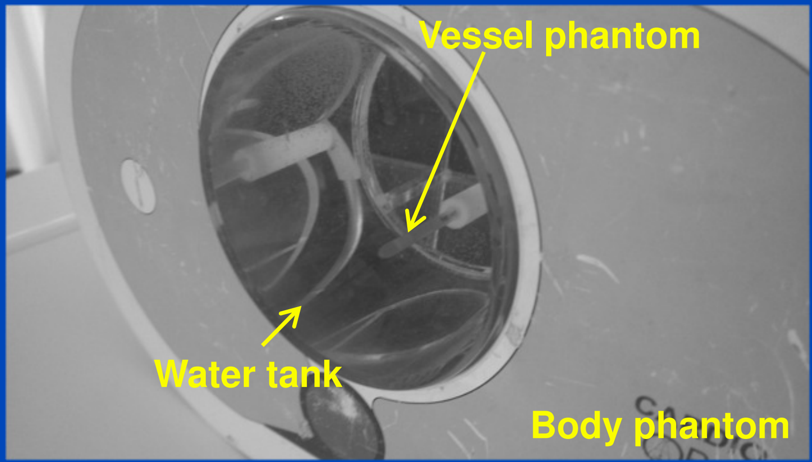
- Open DVF parameters chosen to minimize the image entropy



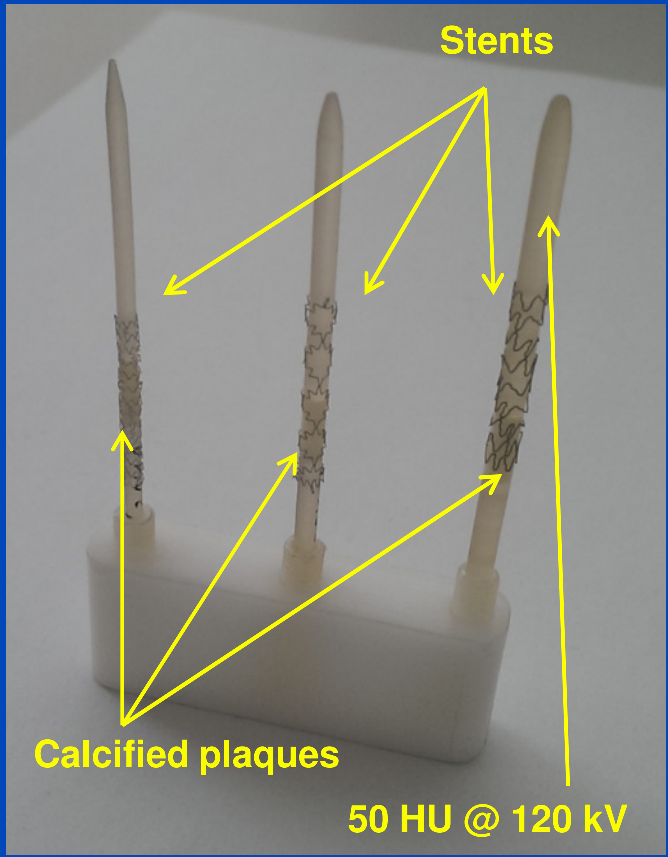
J. Hahn, M. Kachelrieß et al. Motion compensation in the reg
partial angle reconstructions from short scan CT data. Med. Phys. 44(11):5795-5813, September 2017.

Phantom Measurement





d = 1.5 mm 2.5 mm 3 mm

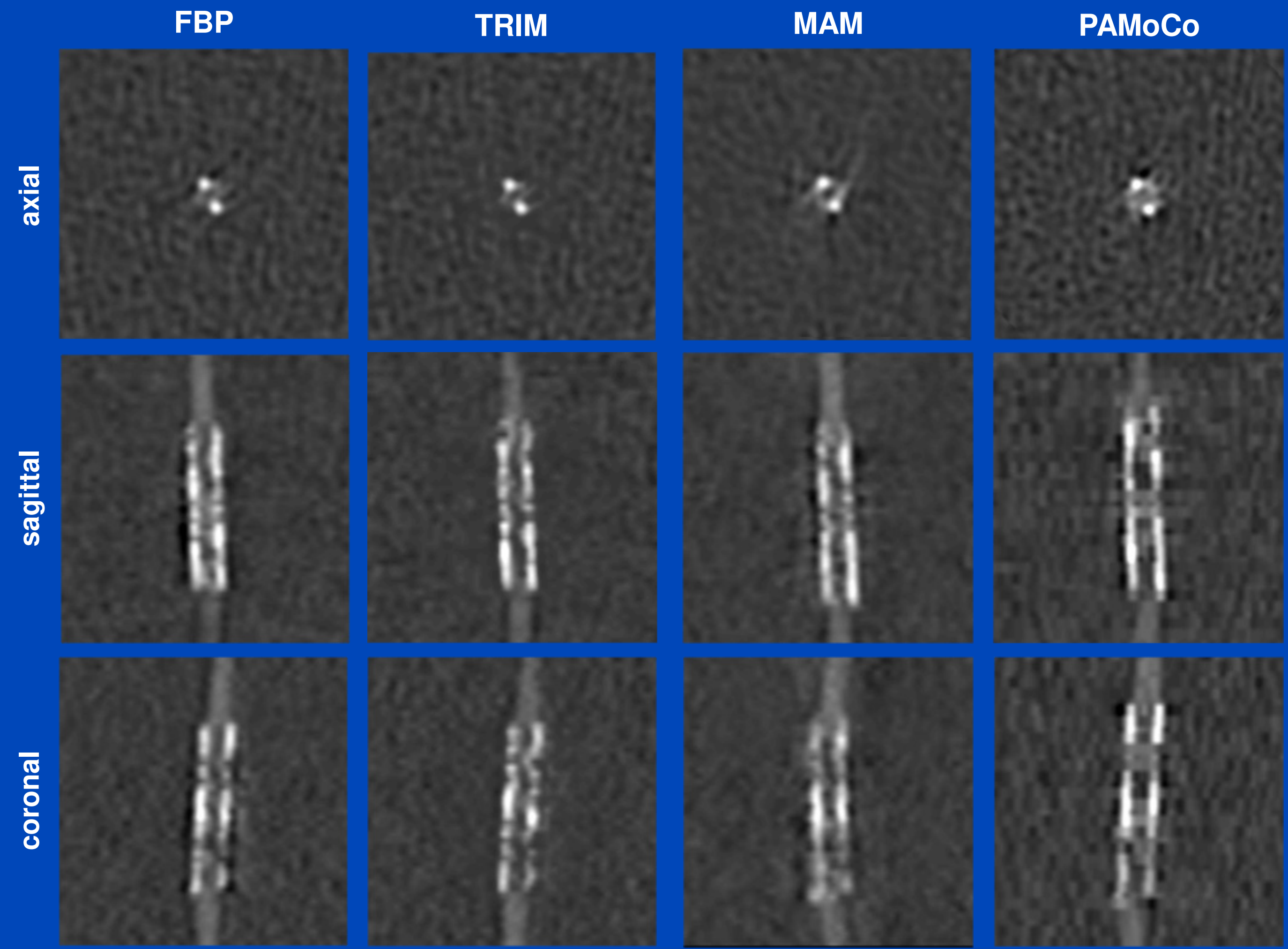


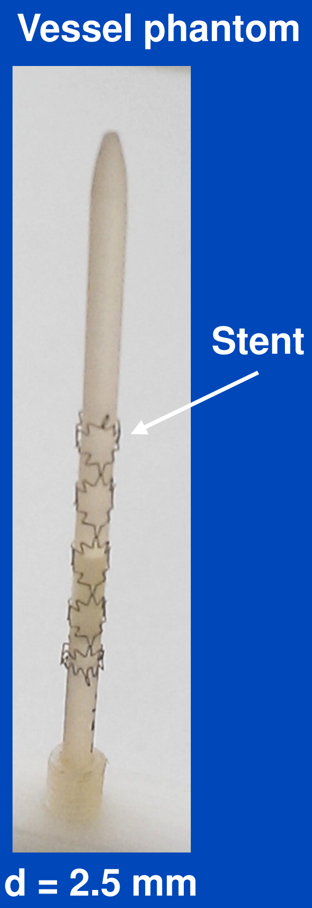
SIEMENS

dkfz.

Phantom

Best Phase





SIEMENS

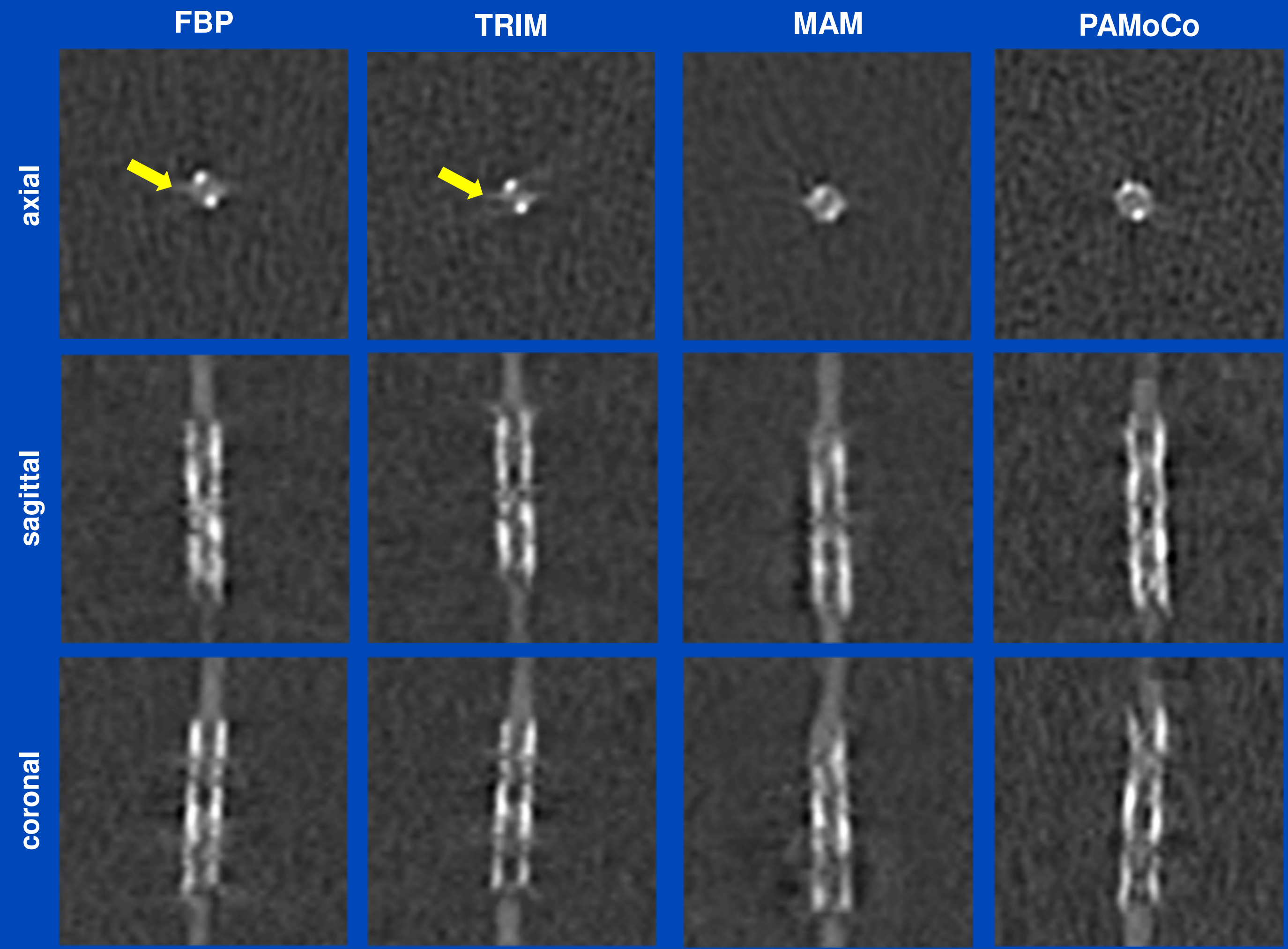
$\overline{HR}$ = 74 bpm, c = 74%,
C = 400 HU, W = 1500 HU

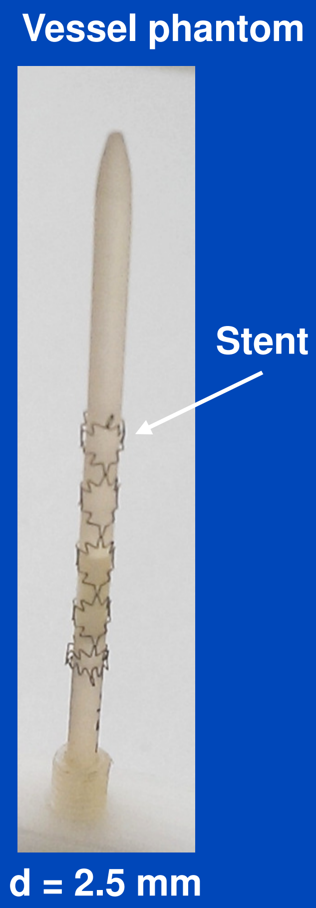
PAMoCo with $N_t \times N_\lambda \times 3 = 3 \times 3 \times 3 = 27$ parameter each stack

dkfz.

Phantom

5% off Best Phase





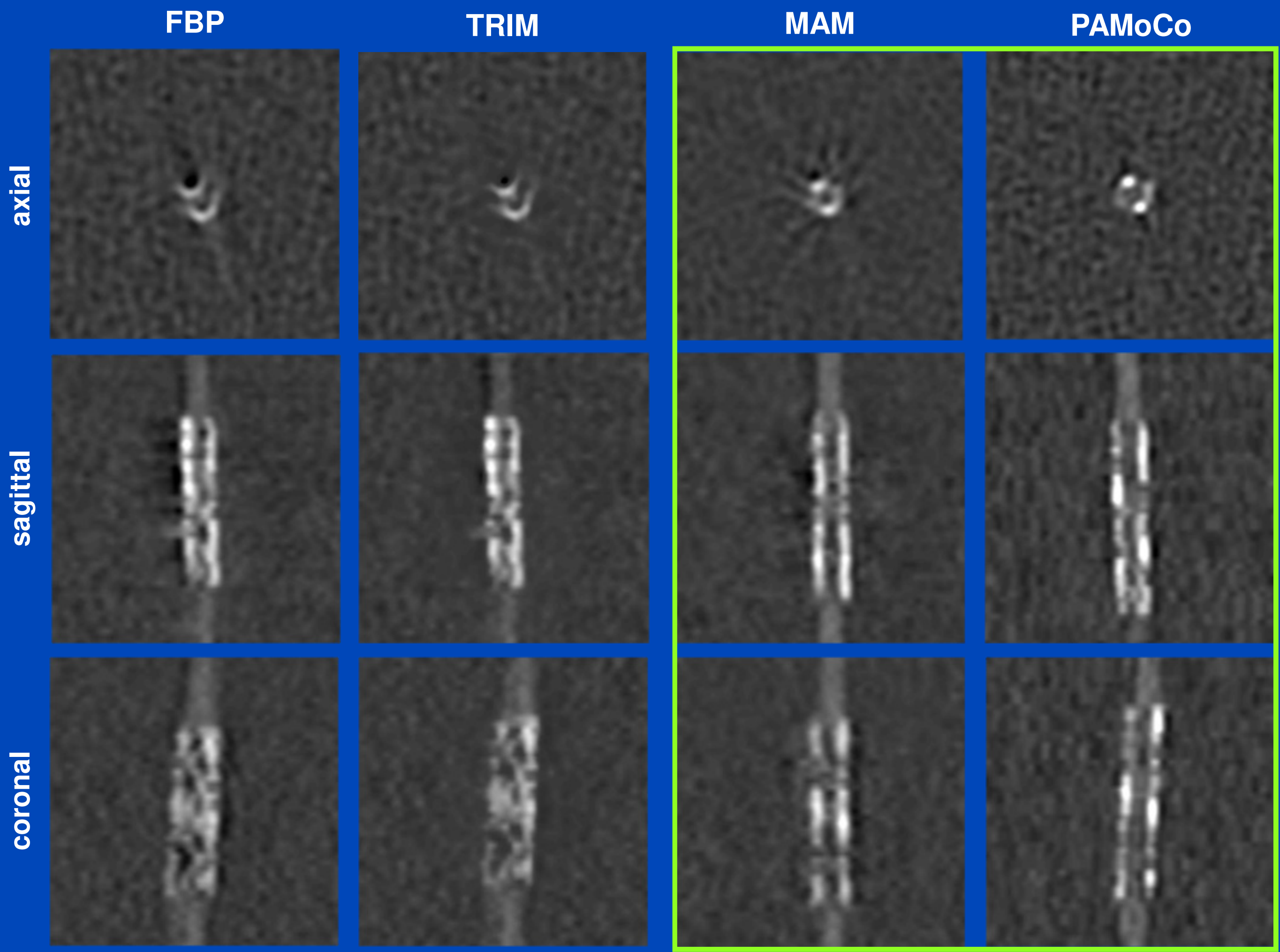
SIEMENS $\overline{HR}$ = 74 bpm, c = 74%,
C = 400 HU, W = 1500 HU

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

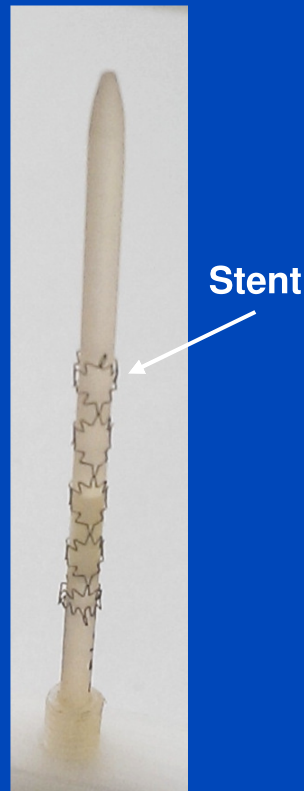
dkfz.

Phantom

10% off Best Phase



Vessel phantom



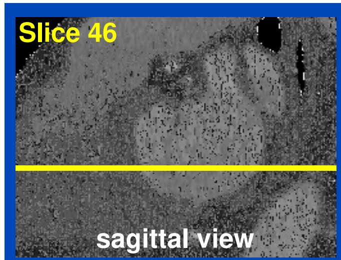
d = 2.5 mm

SIEMENS

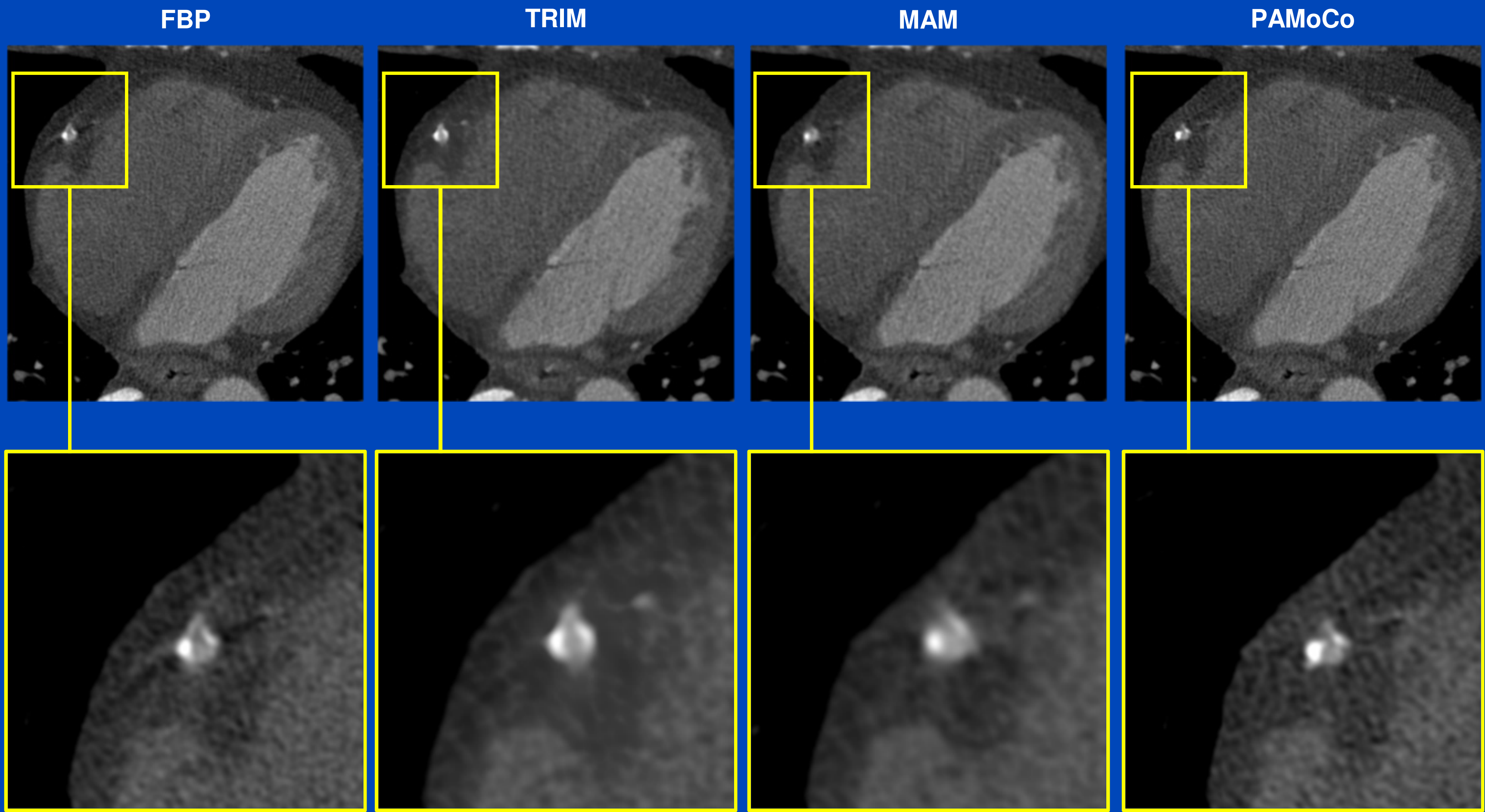
$\overline{HR}$ = 74 bpm, c = 74%,
C = 400 HU, W = 1500 HU

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

dkfz.

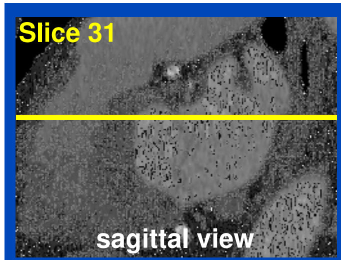


Patient 1



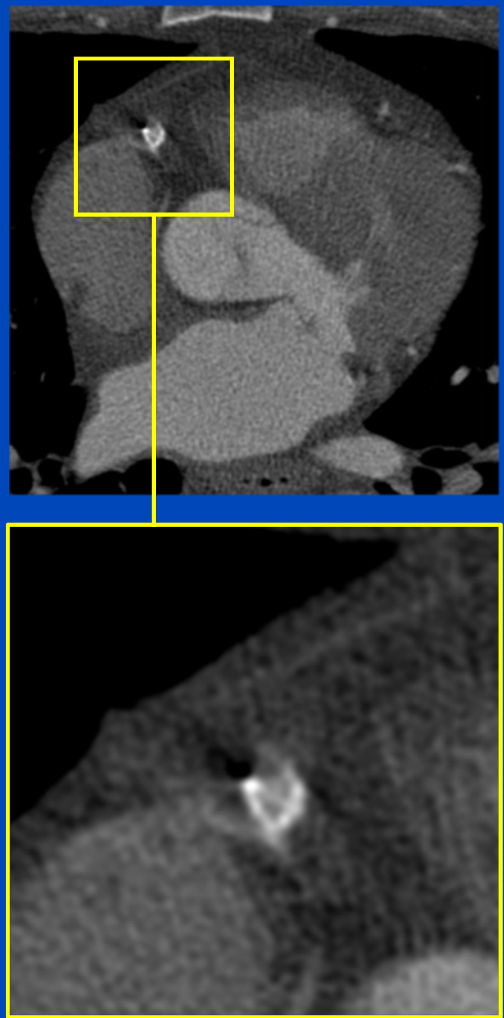
$\overline{HR}$ = 74 bpm, c = 74%,
C = 400 HU, W = 1500 HU

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

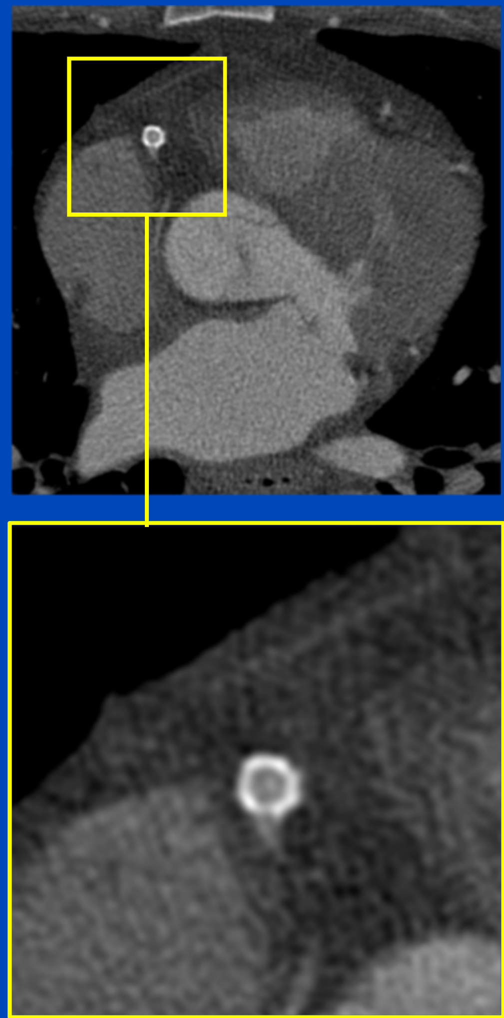


Patient 1

FBP



PAMoCo

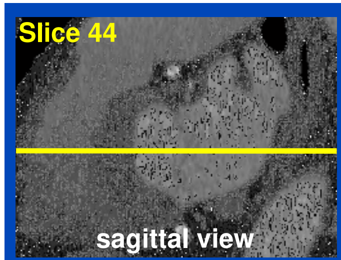


SIEMENS

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

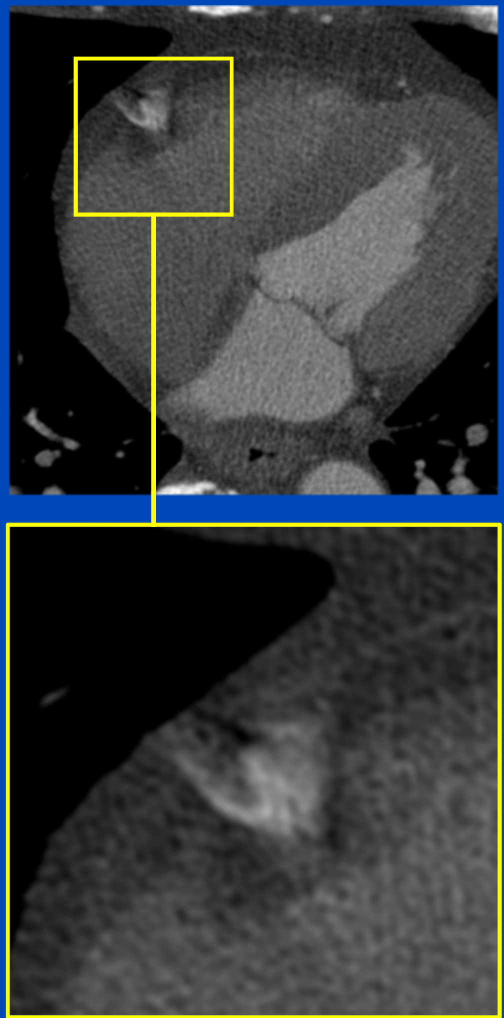
PAMoCo with $N_t \times N_\lambda \times 3 = 3 \times 3 \times 3 = 27$
parameter each stack

dkfz.

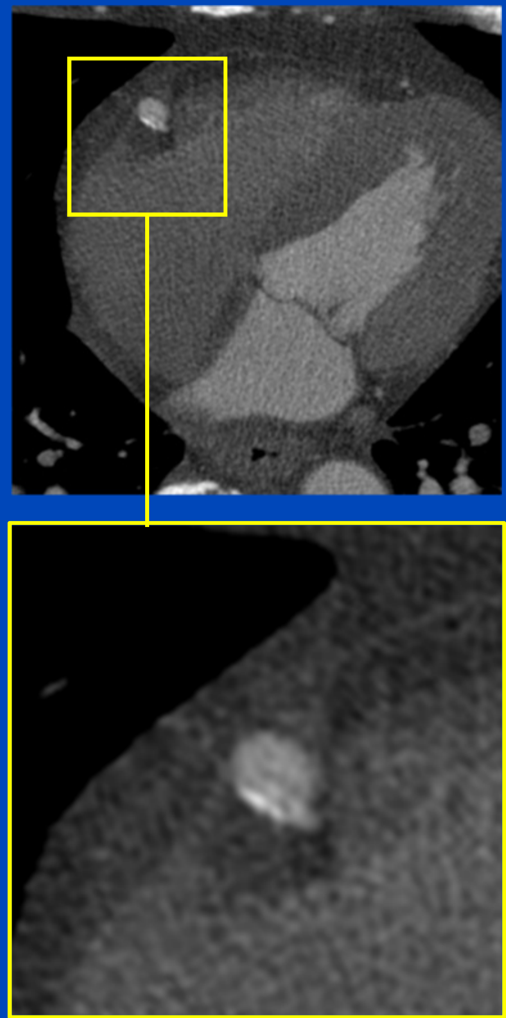


Patient 1

FBP



PAMoCo

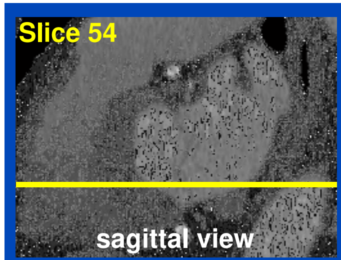


SIEMENS

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

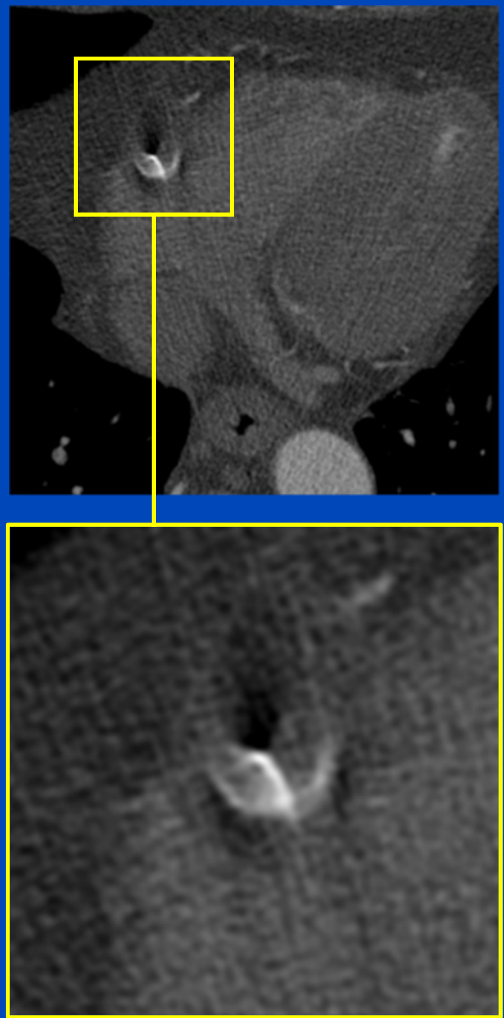
PAMoCo with $N_t \times N_\lambda \times 3 = 3 \times 3 \times 3 = 27$
parameter each stack

dkfz.

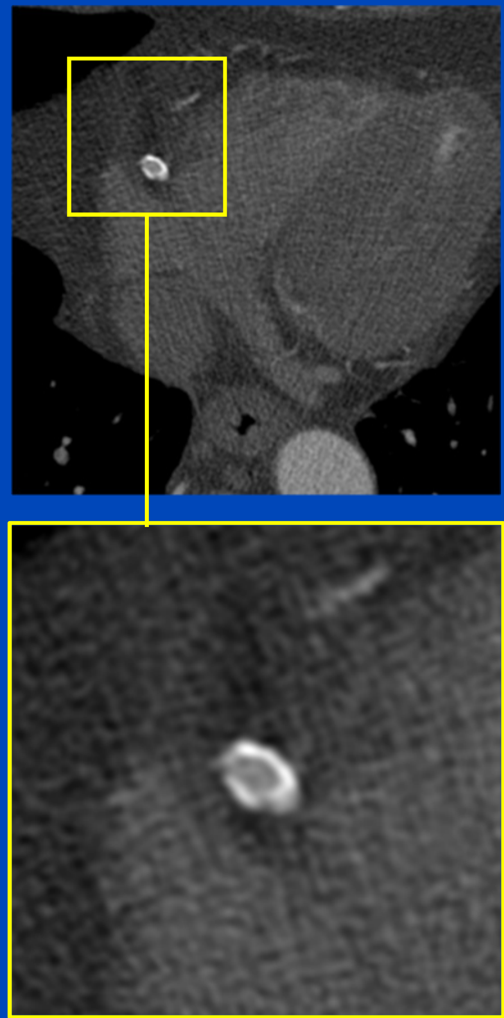


Patient 1

FBP



PAMoCo



$\overline{HR}$ = 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

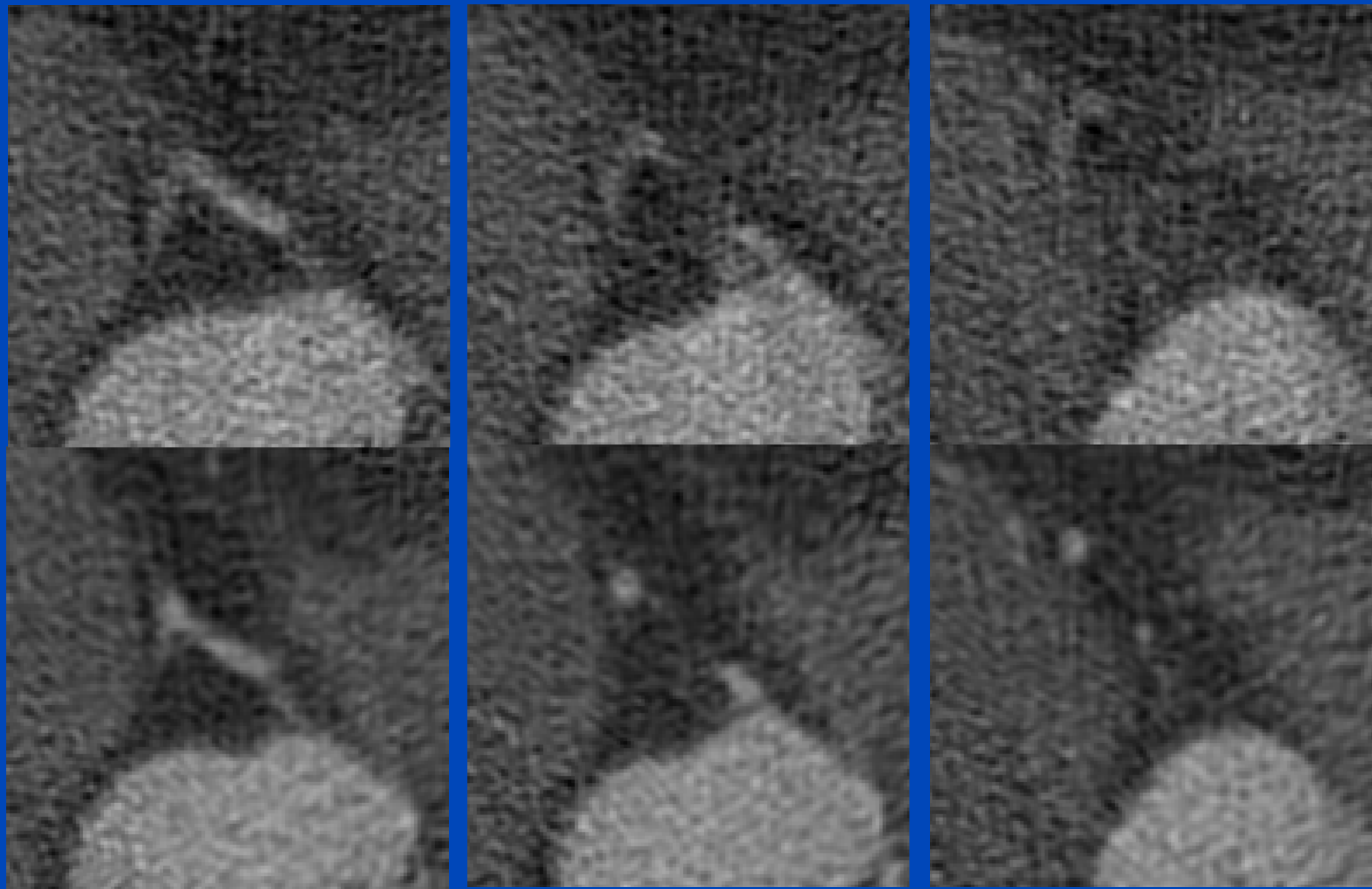
Stack 1

Patient 2

Slice 27 | Slice 34 | Slice 154

FBP

PAMoCo



$\overline{HR}$ = 70 bpm, c = 50%,
C = 400 HU, W = 1500 HU

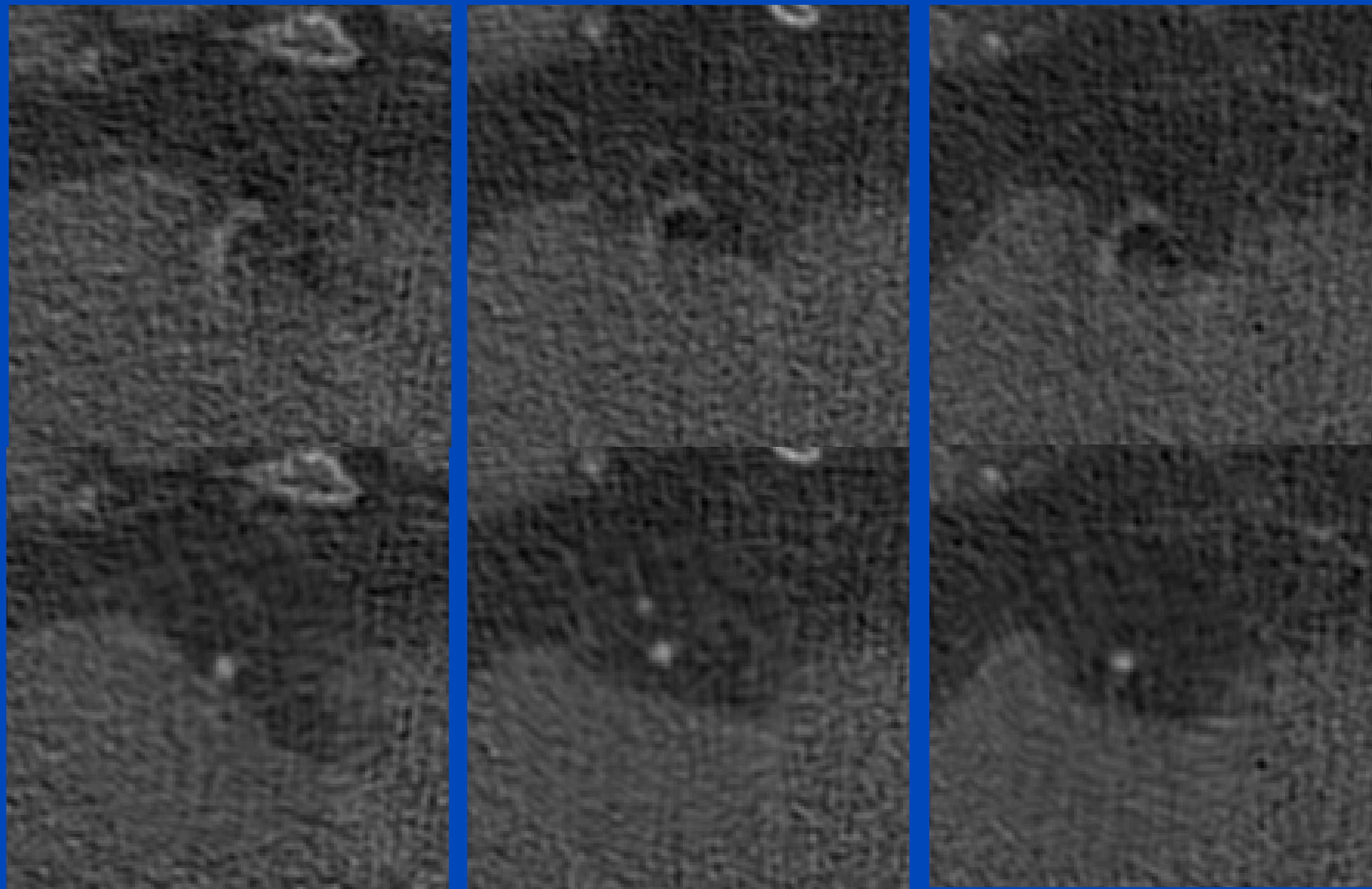
Stack 2

Patient 2

Slice 6 | Slice 37 | Slice 154

FBP

PAMoCo



SIEMENS

$\overline{HR}$ = 70 bpm, c = 50%,
C = 400 HU, W = 1500 HU

dkfz.

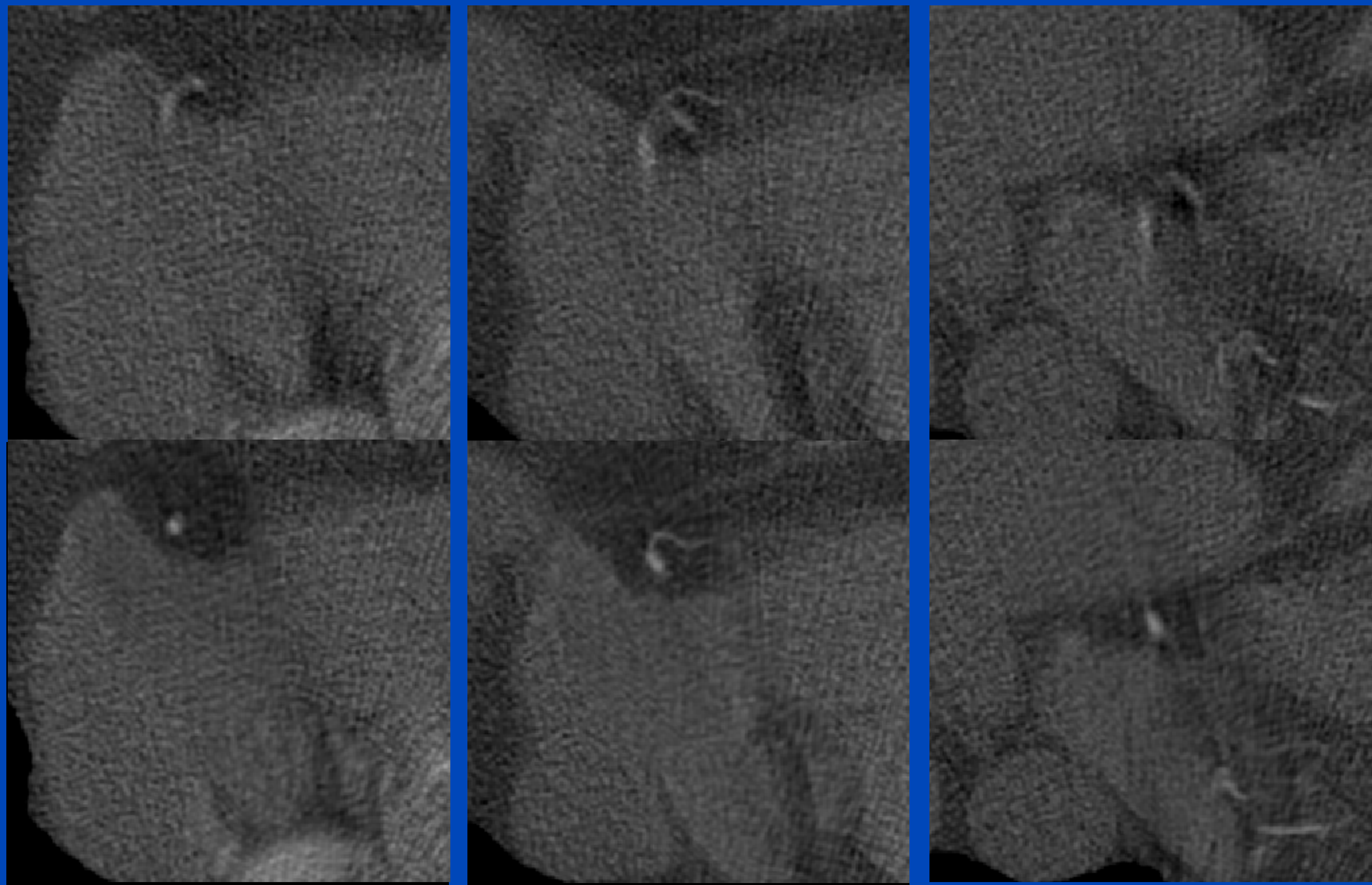
Stack 3

Patient 2

Slice 6 | Slice 37 | Slice 154

FBP

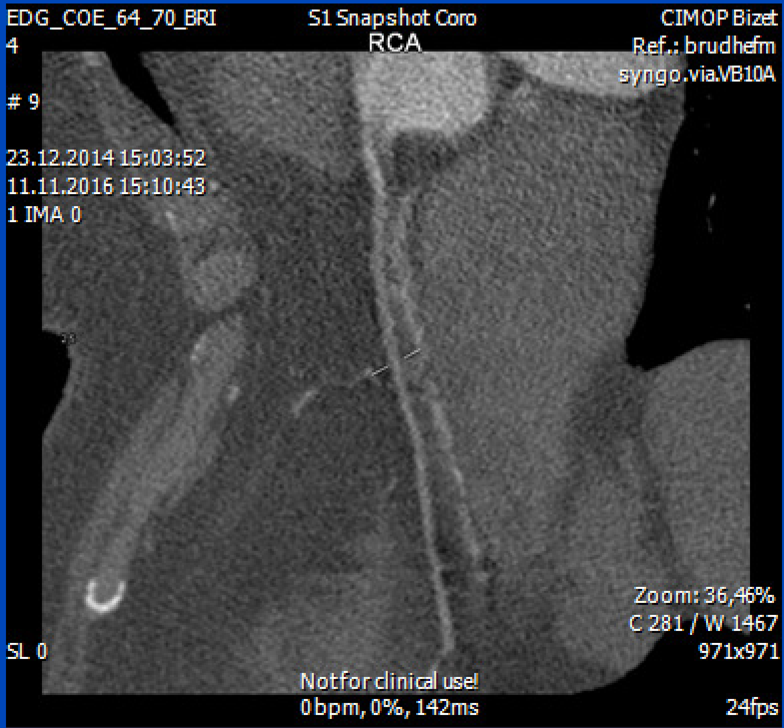
PAMoCo



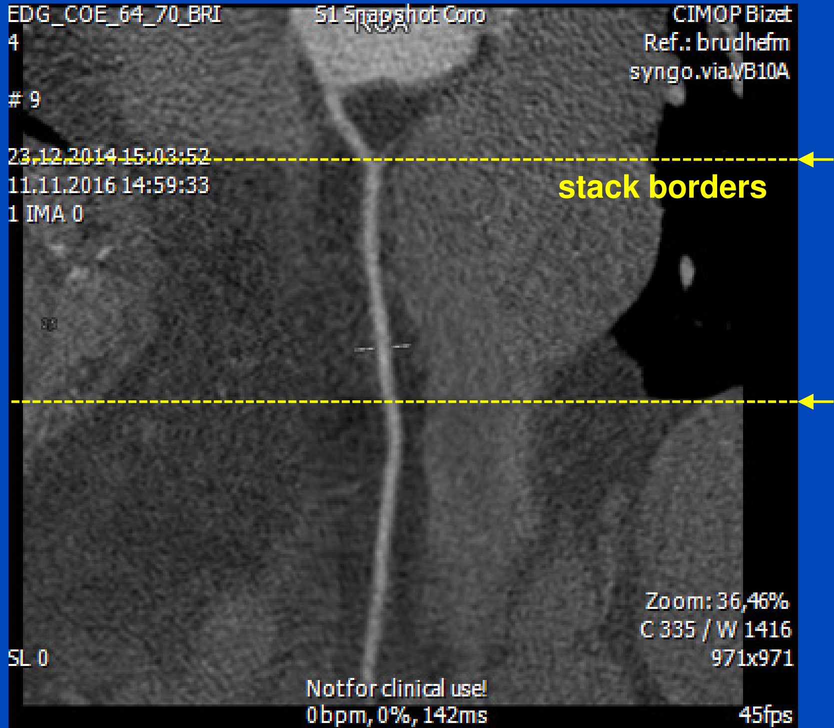
$\overline{HR}$ = 70 bpm, c = 50%,
C = 400 HU, W = 1500 HU

Patient 2

FBP



PAMoCo

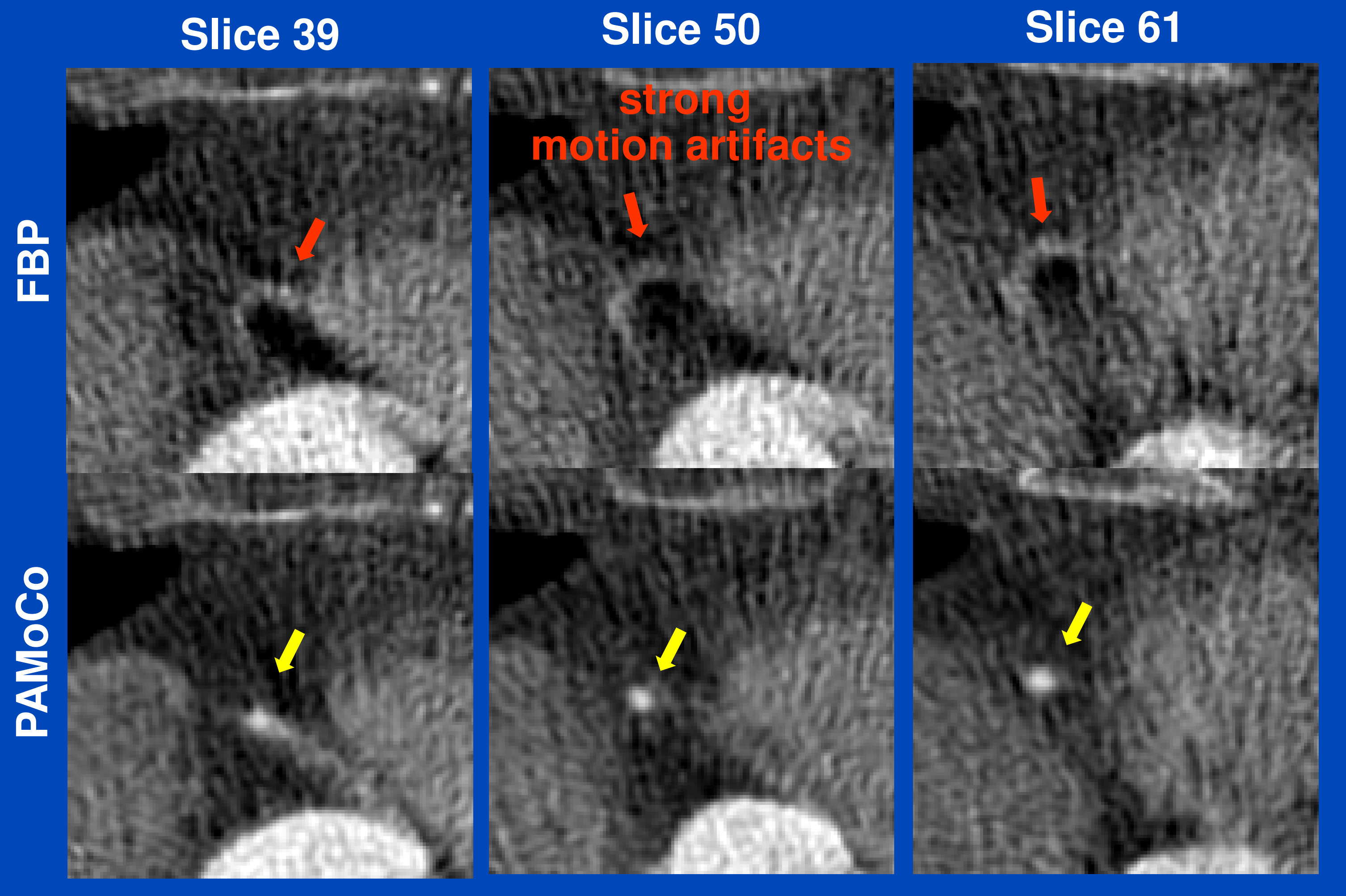


curved MPRs created with syngo.via

$\overline{HR}$ = 70 bpm, c = 50%,
C = 400 HU, W = 1500 HU

Stack 1

Patient 3



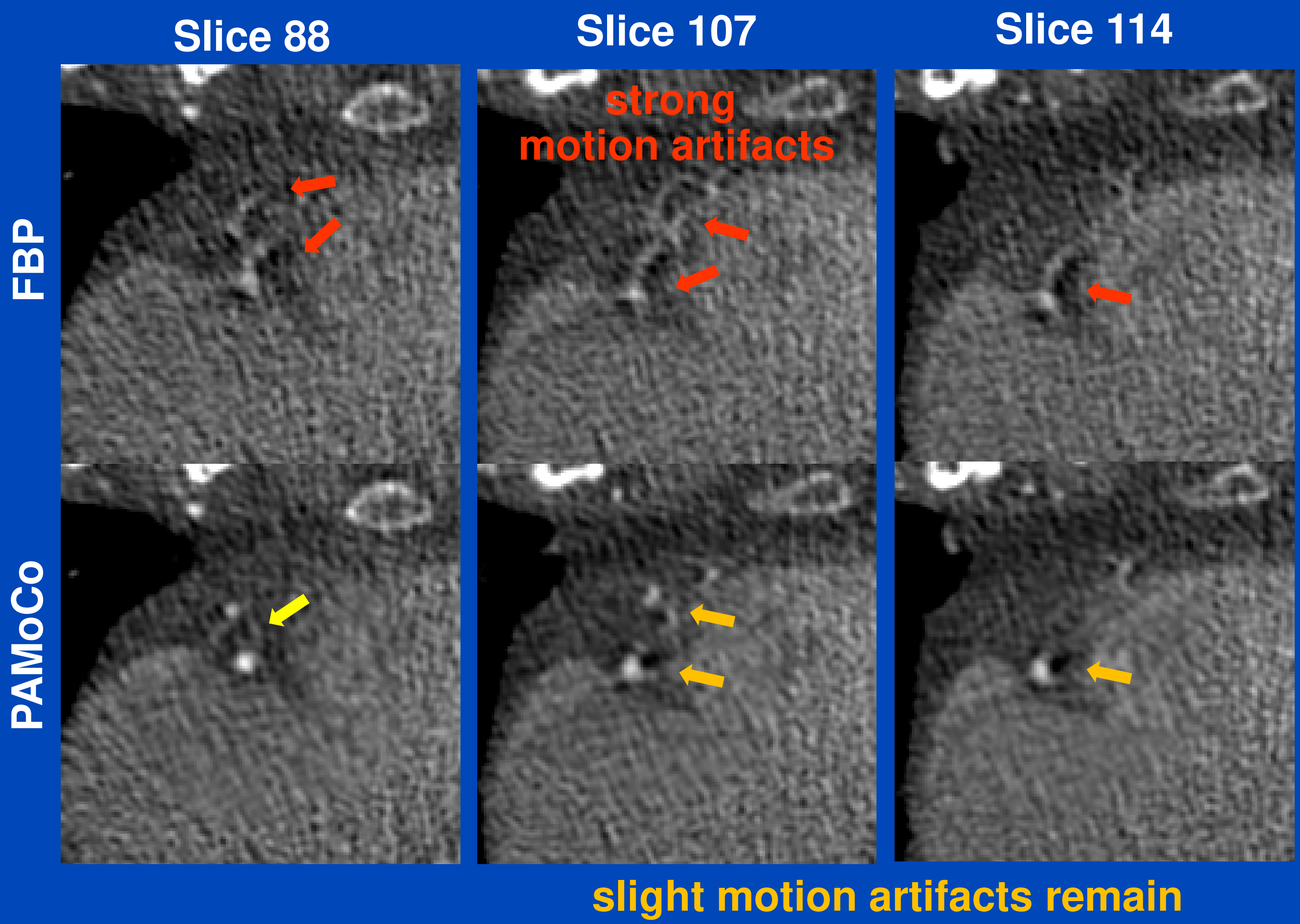
$\overline{HR}$ = 69 bpm, c = 50%,
C = 400 HU, W = 1500 HU

SIEMENS

dkfz.

Stack 2

Patient 3



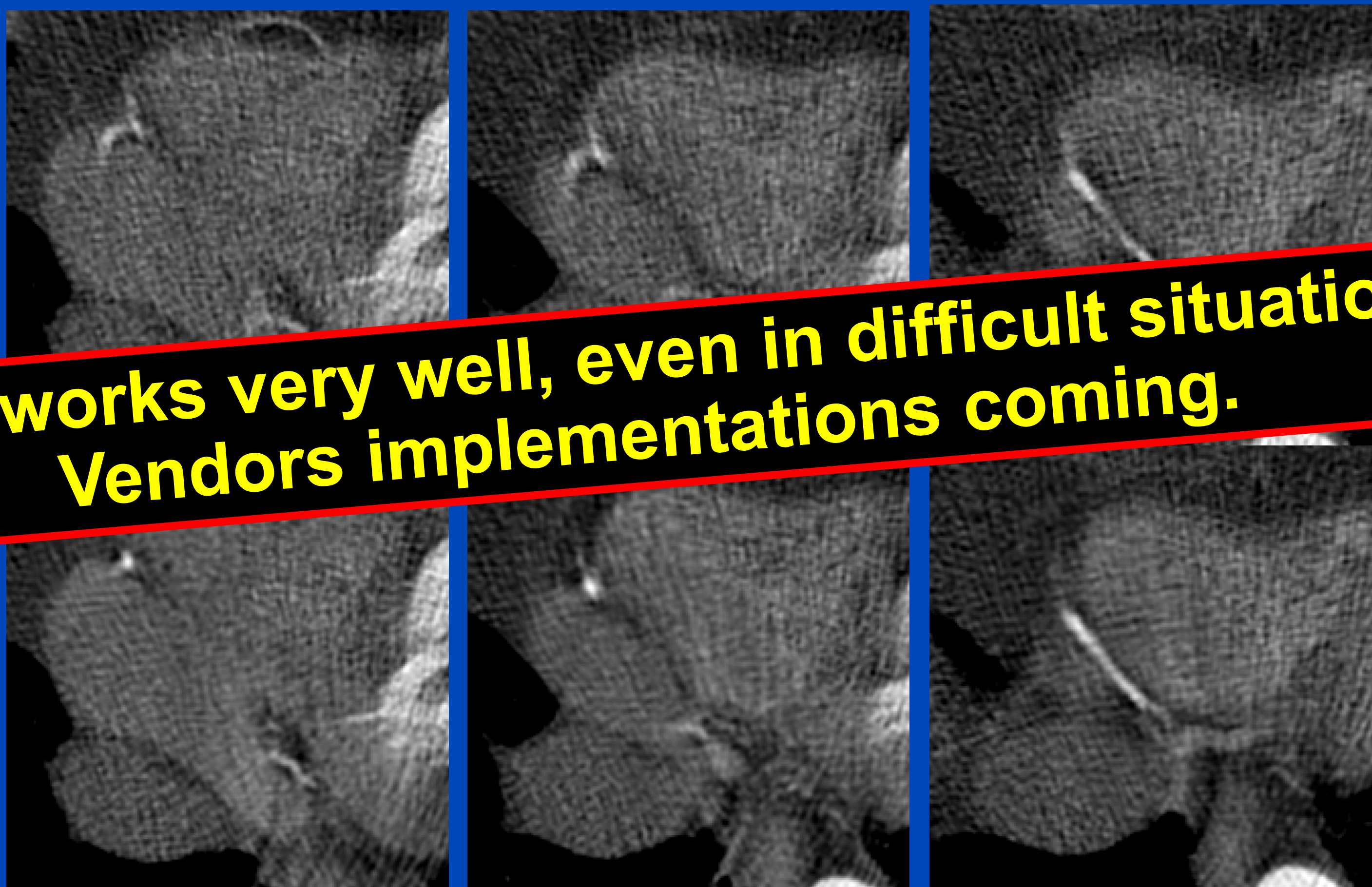
Stack 3

Patient 3

Slice 130 | Slice 142 | Slice 150

FBP

PAMoCo



MoCo works very well, even in difficult situations. Vendors implementations coming.

SIEMENS

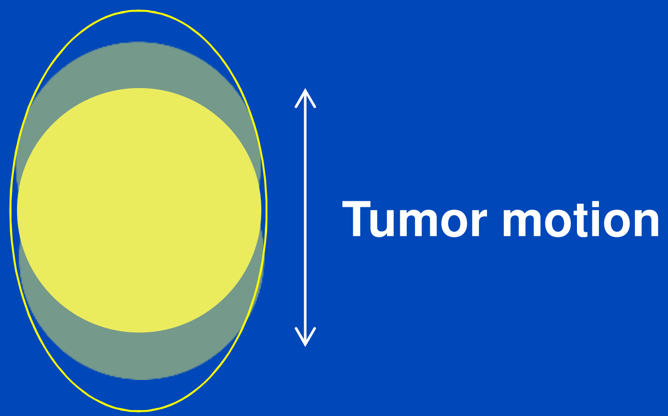
$\overline{HR}$ = 69 bpm, c = 50%,
C = 400 HU, W = 1500 HU

dkfz.

Respiratory-Correlated CT
(mainly for IGRT)

IGRT Problem: Target Motion

- **During radiation treatment the patient's tumor will move due to respiratory (and cardiac) motion**
- **Tumor motion can be up to several centimeters for diaphragm, liver, kidney, pankreas, thorax, …**
- **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**

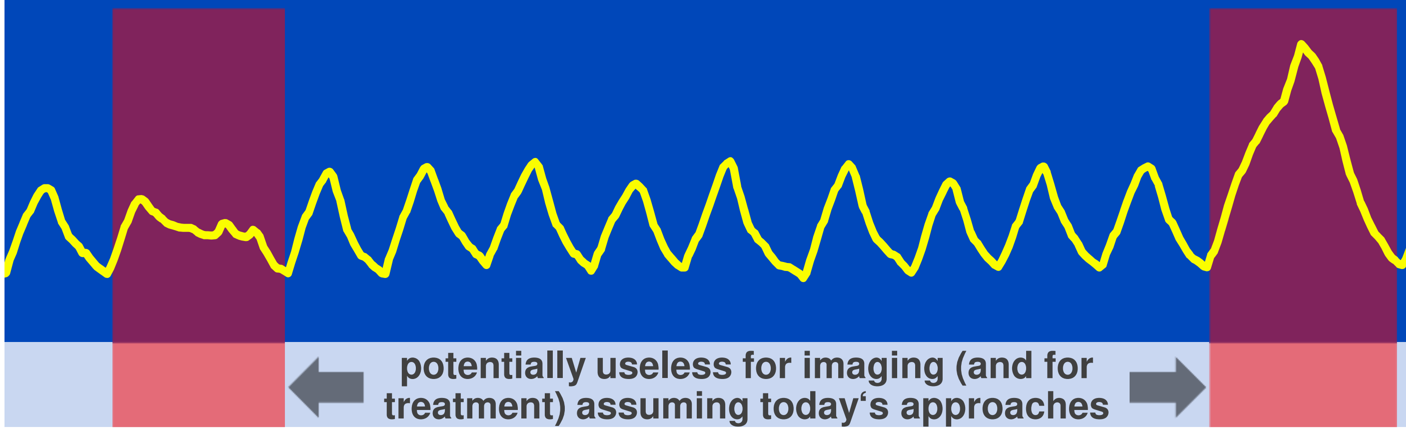


IGRT Motion Management

- Record motion surrogate signals
  - Motion belts (Anzai, Mayo, …)
  - Optical signal (RPM, …)
  - Intrinsic rawdata-based signals (kymogram, radar, …)
- Quantifying motion due to respiration
  - 4D planning CT scan (low pitch spiral or multiple rotation sequence)
  - Several CT scans
  - 4D CBCT scan (slow circle, preferrably with motion compensation)
  - Oblique x-ray image pairs (fiducial markers may be required)
- Accounting for motion during treatment
  - Breath-hold (with patient coaching, no 4D CT required)
  - Gating (4D CT or 4D CBCT advantageous)
  - Tracking (4D CT or 4D CBCT required)

4D Planning CT

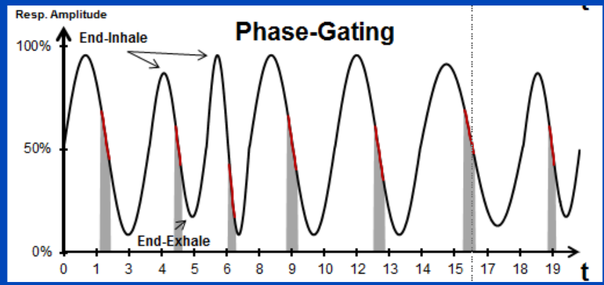
- Either conduct a very low pitch spiral CT $p \leq f_{\mathrm{R}} t_{\mathrm{rot}}$
- or a sequence scan (several circle scans).
- Scan needs to be slow enough to cover a full motion cycle at each z-position.
- Phase-correlated image reconstruction.
- Problems, such as data gaps, may occur with irregular breathers.



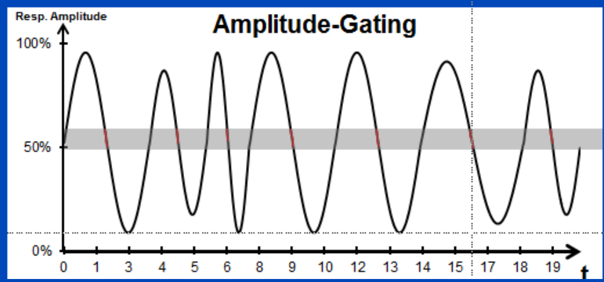
dkfz.

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 Planning CT = Low Pitch Spiral

C = 0 HU, W = 1000 HU

Problems with 4D Respiratory-Correlated CT

- Pitch value must be low enough $p \leq f_{\mathrm{R}} t_{\mathrm{rot}}$
- Irregular respiration may yield data gaps
  - these are typically filled by interpolating adjacent images
  - and not by advanced reconstruction techniques

MoCo could help to fill in the missing data. However: Vendors show no interest!

CT image taken from Low et al., PMB 58:L31-L36, 2013.

Summary

- Cardiac motion management works very well.
- Cardiac CT requires careful protocol selection.
- Some cardiac patients may benefit from MoCo.
- Respiratory motion management works well.
- MoCo may be useful for respiratory CT, but is not provided by the vendors.

Thank You!

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