Respiratory and Cardiac Motion-Compensated 5D Cone-Beam CT of the Thorax Region

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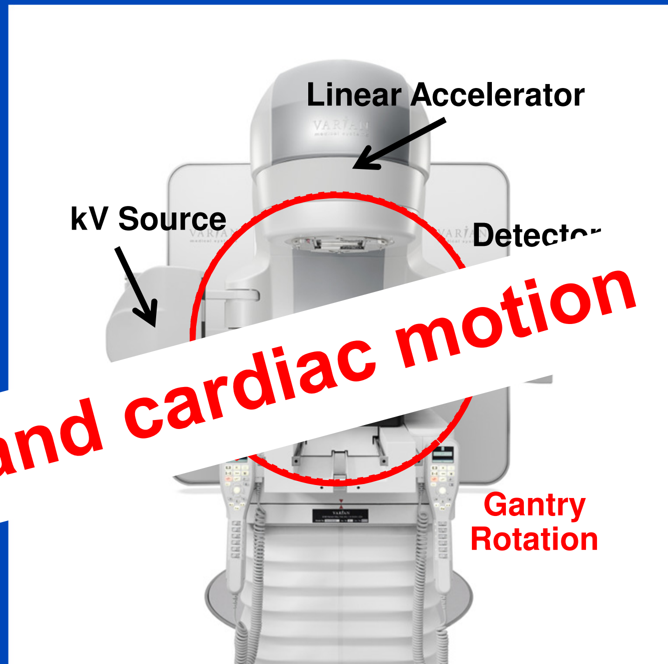
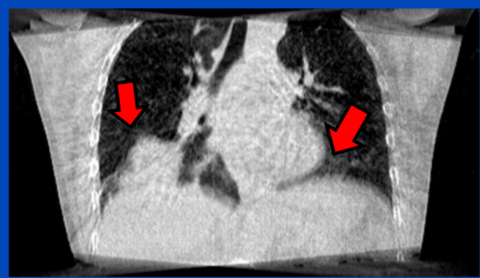
Slowly Rotating CBCT Devices

- 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 clinic…
  (0.25 s /360°)
- Breat… …30 …ycles per minute …thus per scan)
- Heartbeat about 50 to 80 times per minute

Task: Account for respiratory and cardiac motion





Motion blurring in standard 3D reconstruction

5D Motion Compensation removes almost all motion blurring

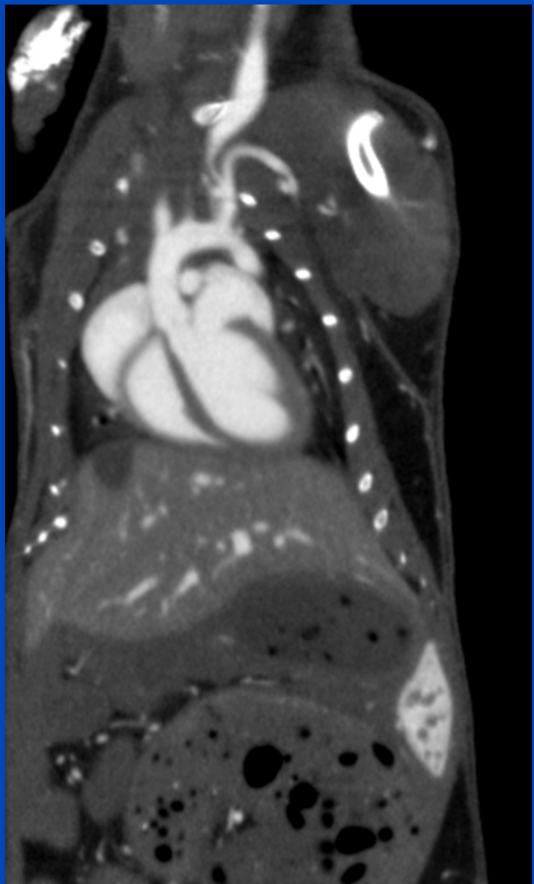
Aim

Provide high fidelity respiratory- and cardiac-correlated volumes (5D volumes) from on-board CBCT scans without using dedicated acquisition techniques or prior knowledge from planning scans.

- **Use case:**
  - Accurate patient positioning
    - Reduce irradiation of the heart (organ at risk)
  - Treatment verification
  - Online treatment adaption

5D MoCo Mouse Data[1]

Mouse with 280 bpm and 150 rpm



5D data displayed as:
Heart: 360 bpm
Lung: 180 rpm

- 20 respiratory windows with $\Delta r = 10\%$
- 10 cardiac windows with $\Delta c = 20\%$
- rpm and bpm signal for gating intrinsically determined

[1]M. Brehm, S. Sawall, J. Maier, S. Sauppe, and M. Kachelrieß. Cardiorespiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation. Med. Phys. 42(4):1948-1958, April 2015.

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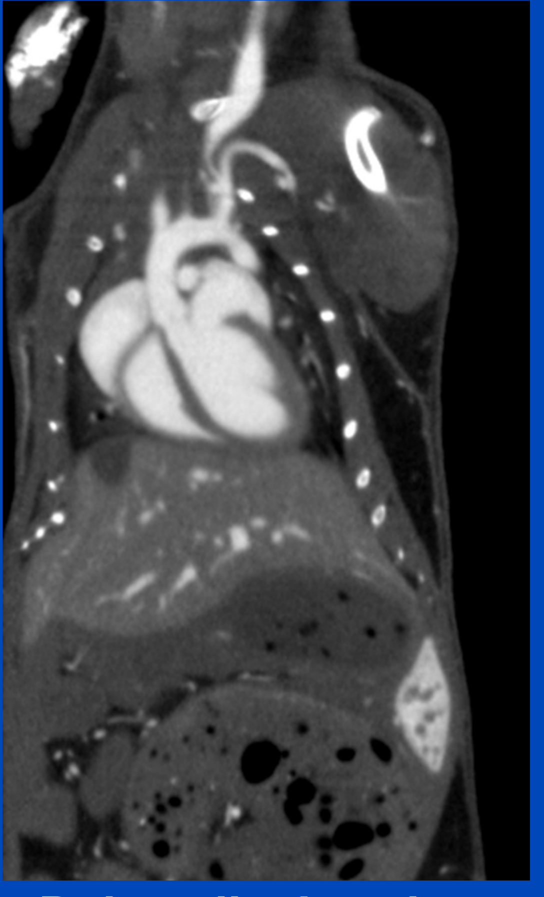

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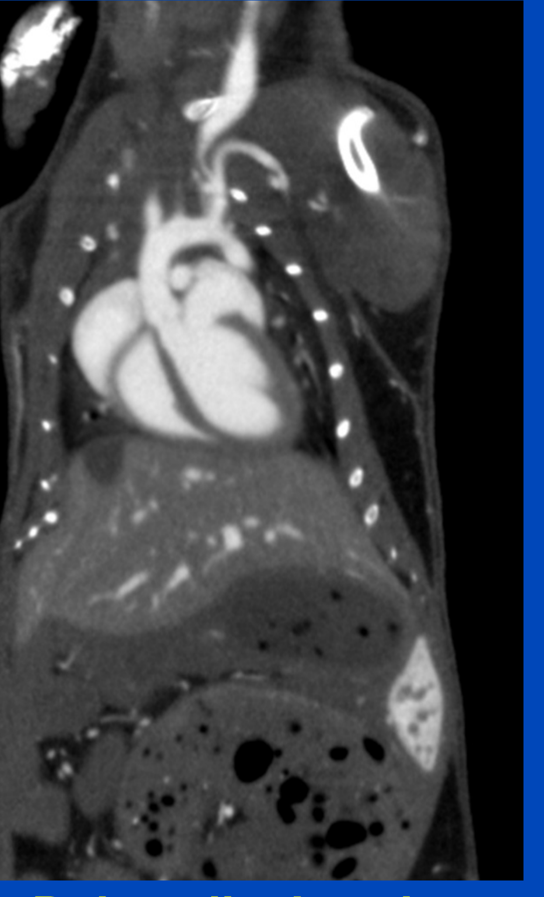
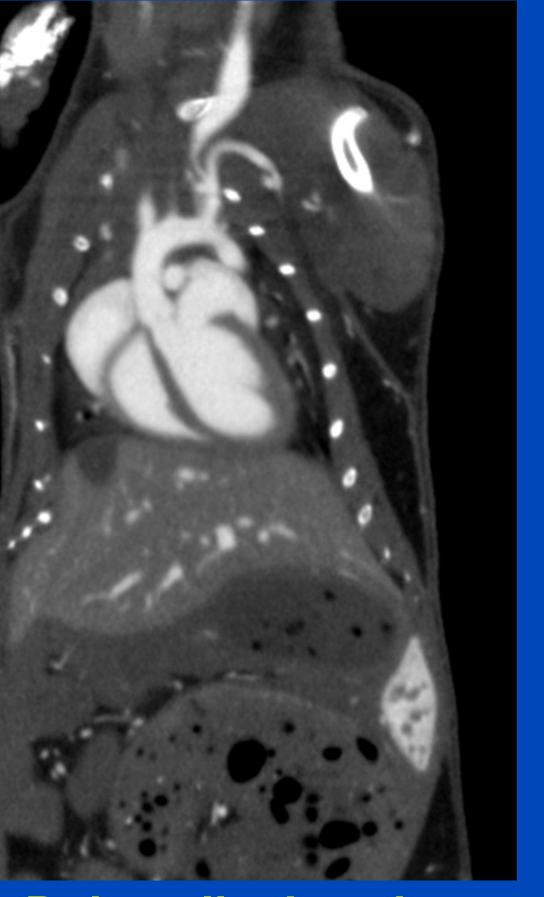


5D data displayed as:
Heart: 0 bpm
Lung: 90 rpm



5D data displayed as:
Heart: 90 bpm
Lung: 0 rpm

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[1]M. Brehm, S. Sawall, J. Maier, S. Sauppe, and M. Kachelrieß. Cardiorespiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation. Med. Phys. 42(4):1948-1958, April 2015.

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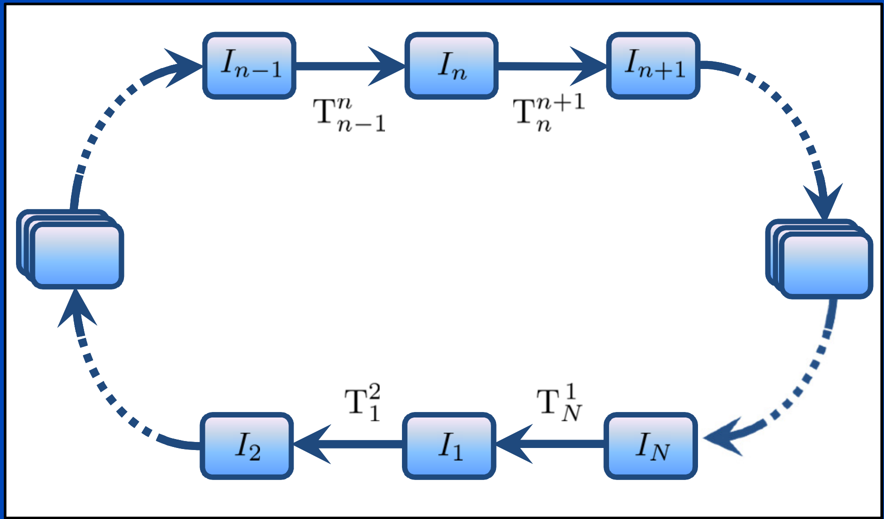
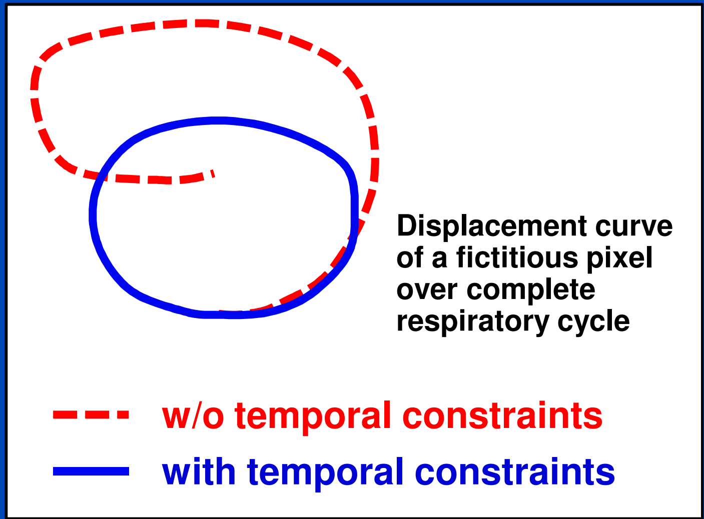
5D Motion Compensation on Patient Data

- Different geometry as micro CT scanner
  - Varian True Beam KV imaging system
- Patients without contrast agent
  - Lower contrast in the region of the heart
  - Makes intrinsic cardiac motion signal detection more difficult
- Some patients have an irregular or slow breathing frequency

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 periodic breathing and heartbeat 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 Compensation (MoCo)

- **3D Reconstruction**

$$f = \mathsf{X}^{-1}\, p$$

- **4D MoCo**

$$f_{\mathrm{r}} = \sum_{\rho} \mathsf{D}_{\rho}^{r}\, \mathsf{X}^{-1}\, \mathsf{G}_{\rho}\, p$$

$$\mathsf{D}_{\rho}^{r} = \prod_{J=\rho}^{r-1} \mathsf{T}_{J}^{J+1} = \mathsf{T}_{r-1}^{r} \circ \ldots \circ \mathsf{T}_{\rho+1}^{\rho+2} \circ \mathsf{T}_{\rho}^{\rho+1}$$

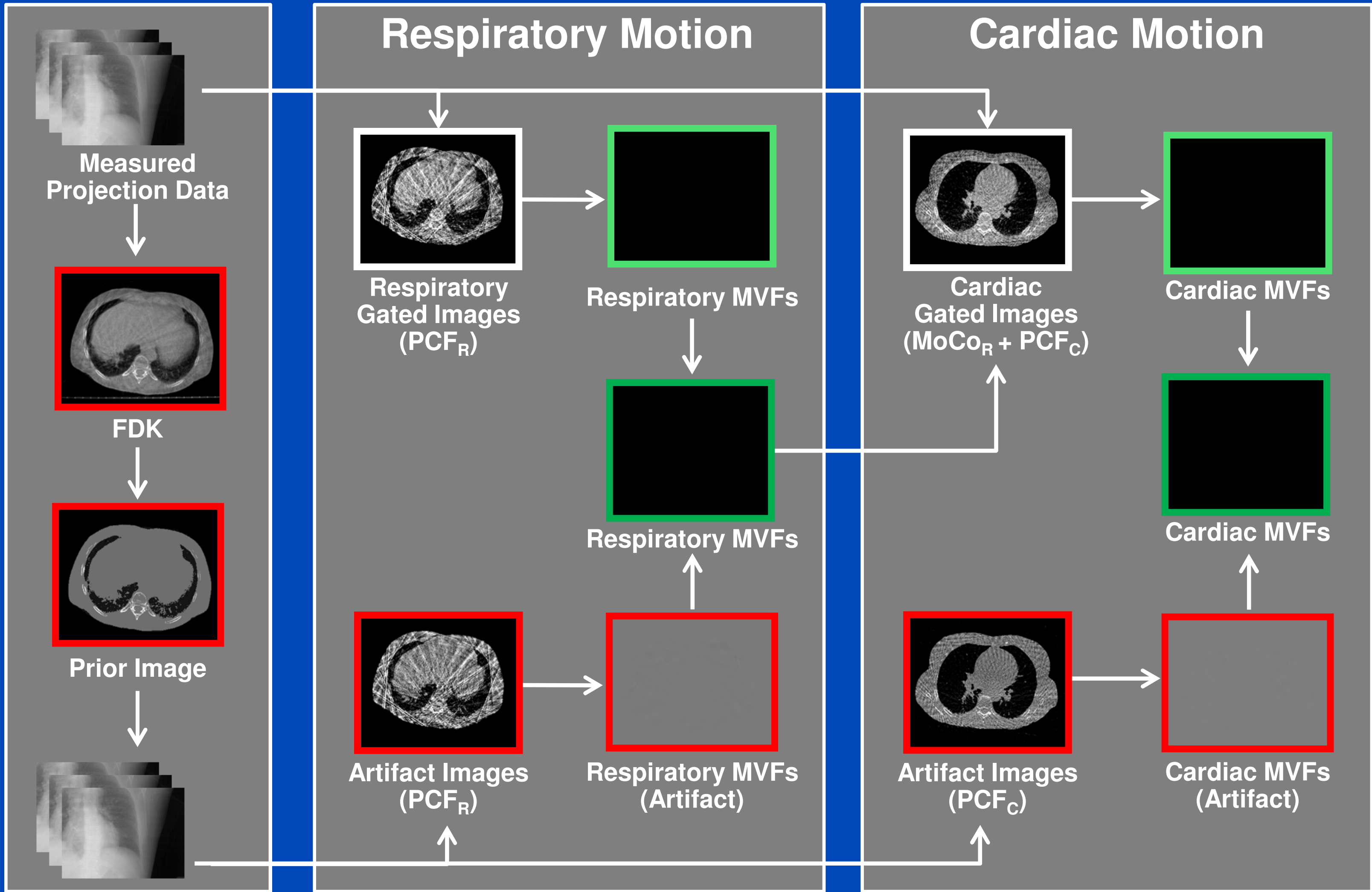
- **5D MoCo**

$$f_{\mathrm{r,c}} = \sum_{\rho,\gamma} \mathsf{D}_{\rho,\gamma}^{r,c}\, \mathsf{X}^{-1}\, \mathsf{G}_{\rho}\, \mathsf{G}_{\gamma}\, p$$

f	**Image**
X	**X-ray transform** (forward projection)
X^{-1}	**Backprojection (FDK)**
p	**Rawdata**
D_{ρ}^{r}	**Deformation operator**
G_{ρ}	**Gating operator**
T	**Transformation operator** (between 2 motion phases)
$\circ$	**Concatenation**

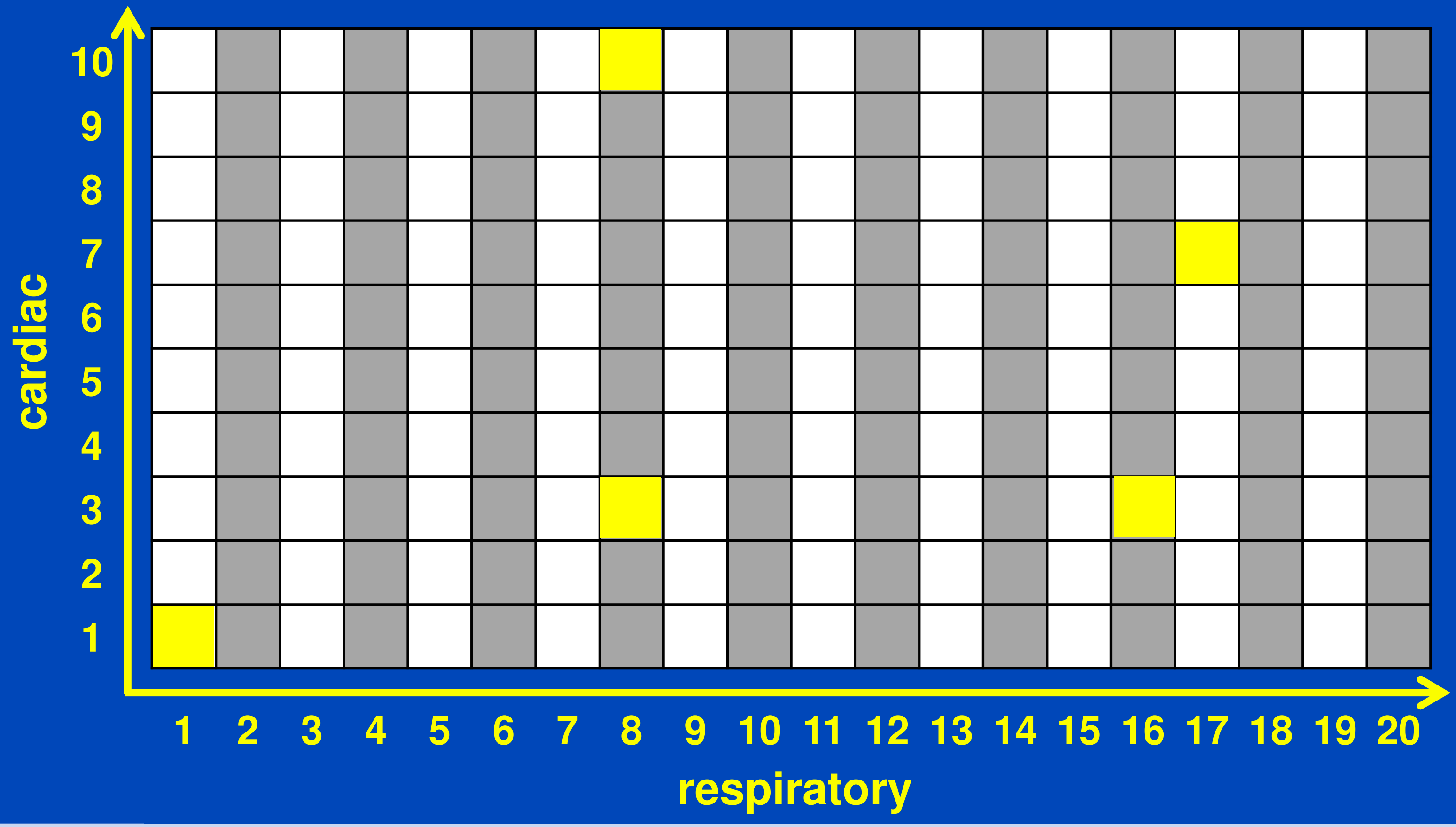
5D Motion Compensation

Simplified Illustration of Workflow[1]



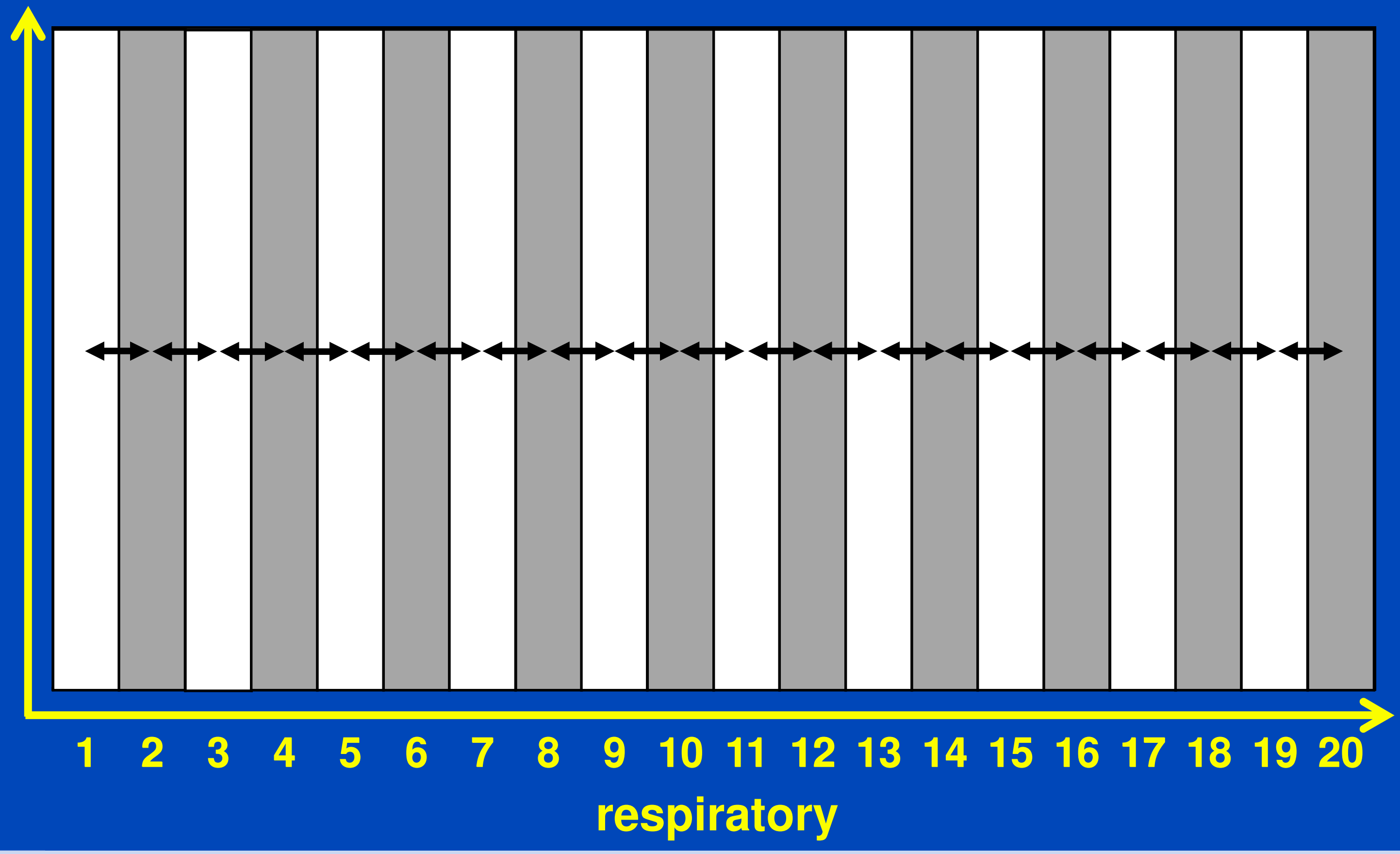
5D Motion Compensation
Double Gating

- Matrix represents all rawdata, sorted into different cardiac and respiratory bins (double gating)



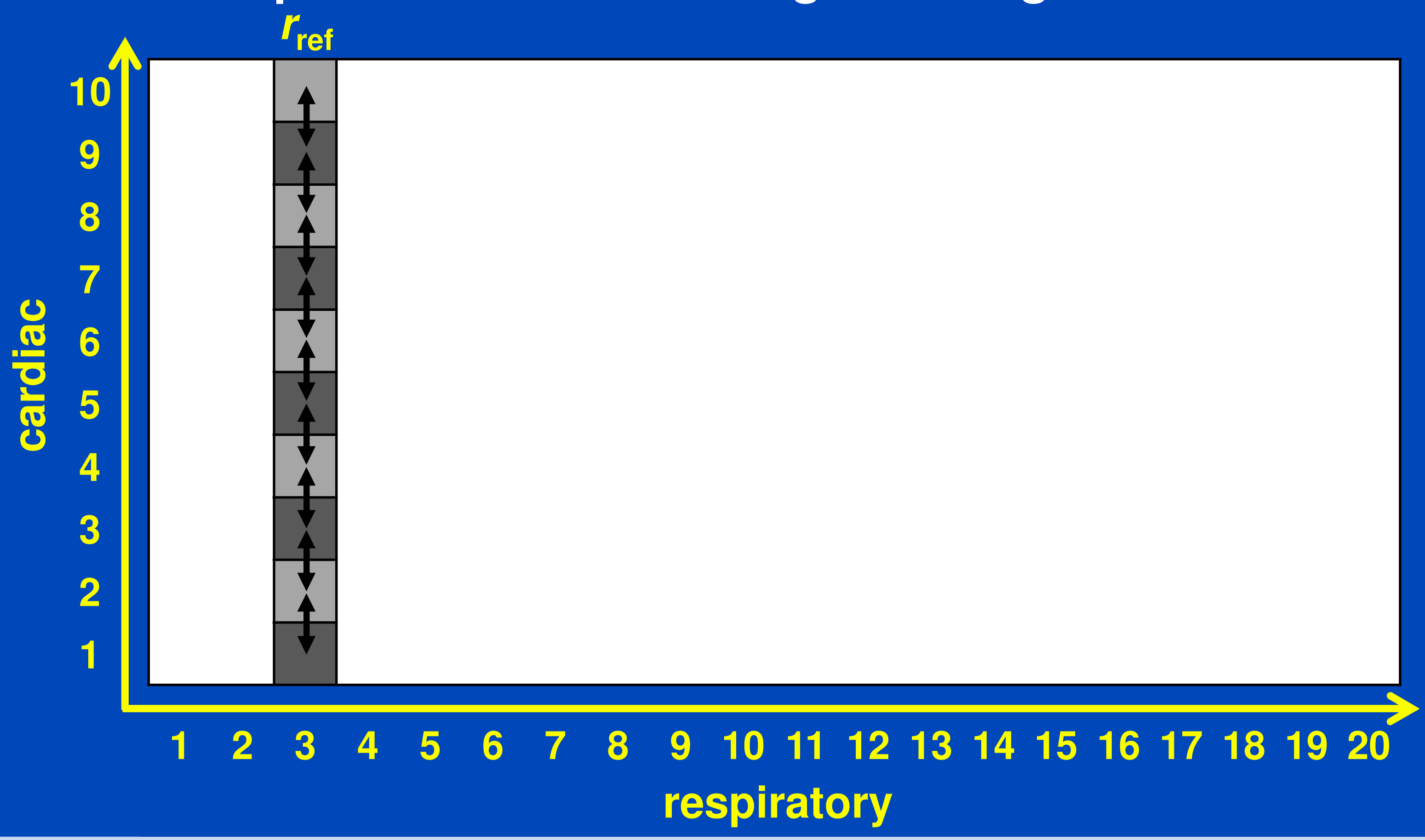
5D Motion Compensation
Respiratory Motion Estimation

- Respiratory MVFs are estimated neglecting the effect of cardiac motion



5D Motion Compensation
Cardiac Motion Estimation

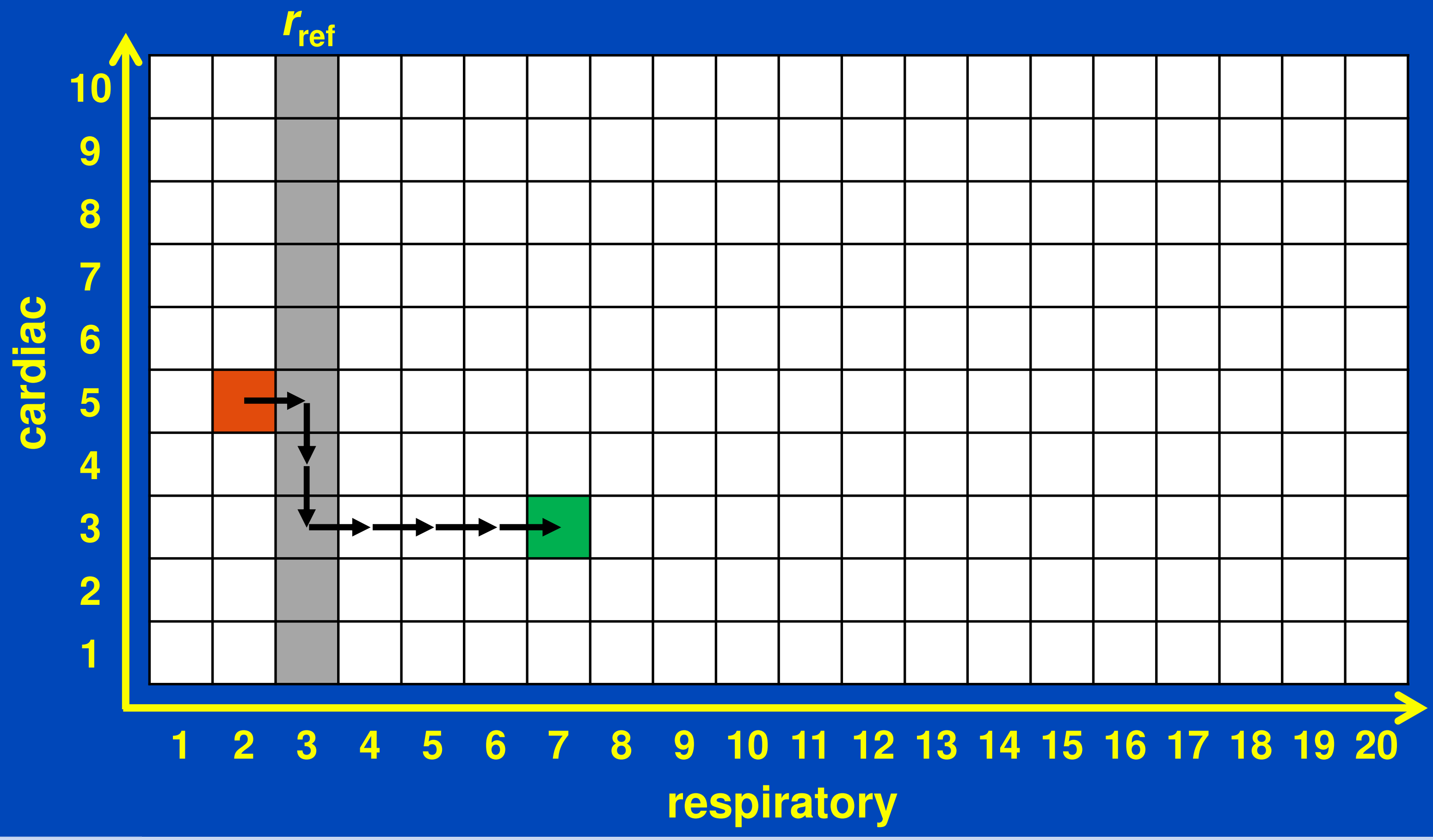
- **Cardiac MVFs are estimated employing respiratory motion-compensated and cardiac-gated images.**



5D Motion Compensation

MoCo Reconstruction

- Employing 5D double gated images, any arbitrary combination of respiratory and cardiac phase can be reconstructed.



5D Motion Compensation

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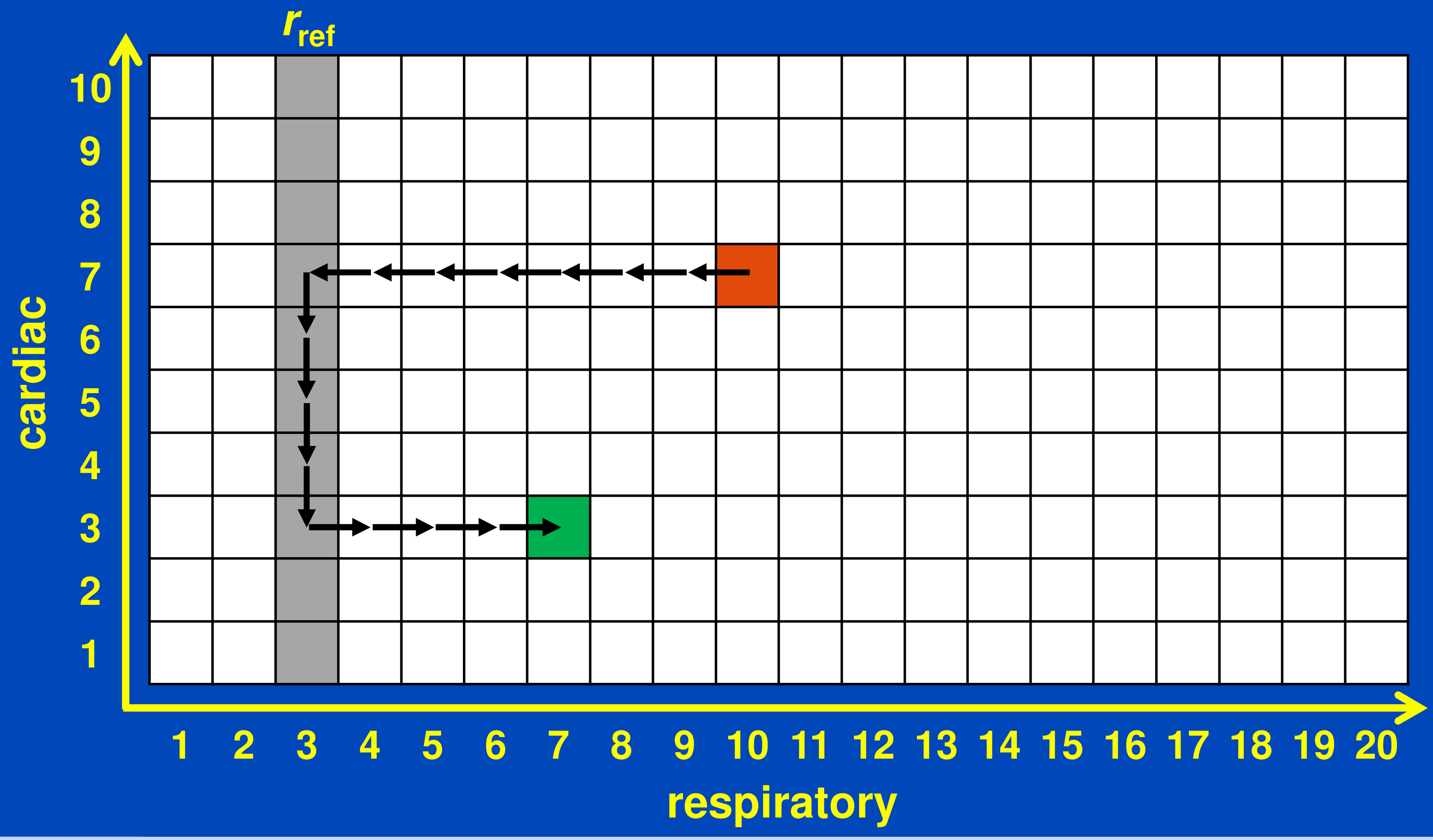

5D MoCo Results

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

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

2% dose usage	**20% dose usage**	**100% dose usage**	**100% dose usage**

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

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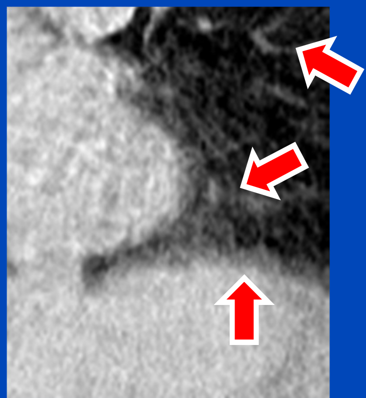
5D MoCo Results

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

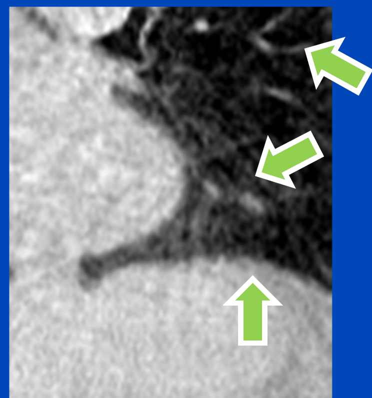
3D Reconstruction
Standard
3D Feldkamp

5D MoCo
Respiratory & Cardiac
Compensated
***r-loop*, *c*-loop**

3D Reconstruction
Region of interest



5D MoCo
Region of interest



Displayed with
real motion speed
28 rpm and 83 bpm

Summary

- **True 5D imaging in IGRT**
  - Same noise level and spatial resolution as 3D CBCT
  - 100% dose usage
- **Two-step motion estimation**
- **Method applicable for other modalities**
  - E.g. C-arm systems, MR, PET-MR
- **To do:**
  - There is a slight underestimation of motion in 5D MoCo images
  - Handle sliding organ (esp. lung) motion

- **There is more on MoCo from our group at this SPIE meeting:**
  - Hahn, Kachelrieß. Reduction of motion artifacts in cardiac CT based on partial angle reconstructions from short scan data.
    Tuesday, March 1, 11:50 AM

Thank You!

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

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

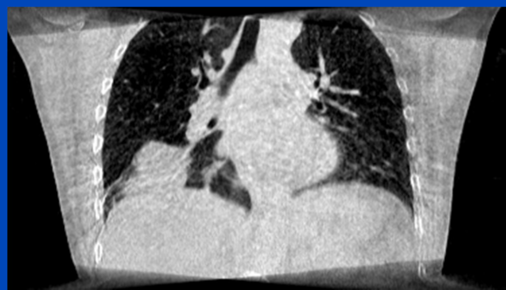
MoCo 5D Results

Respiratory Reference Phase Comparison

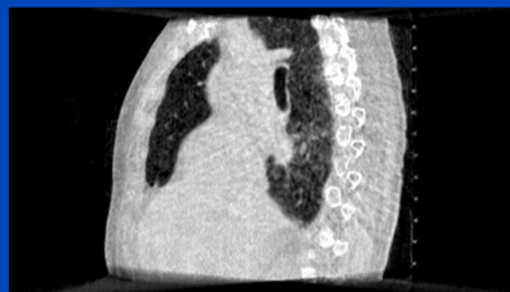
- **Test: Repeat reconstruction of an arbitrary respiratory and cardiac phase (e.g. *r* = 5, *c* = 7) with different respiratory reference phases**
- $r_{\mathrm{ref}} \in \{0, \ldots, N-1\}$, with $N = 20$
- **Only grayscale differences visible**
- **No motion in difference images**

Axial

Coronal



Sagittal



Loop over all reference phases

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

MoCo 5D Results

Respiratory Reference Phase Comparison

- **Test: Repeat reconstruction of an arbitrary respiratory and cardiac phase (e.g. *r* = 5, *c* = 7) with different respiratory reference phases**
- $r_{\mathrm{ref}} \in \{0, ..., N-1\}$, with $N = 20$
- **Only grayscale differences visible**
- **No motion in difference images**

Respiratory reference phase appears to have no relevant impact.

Axial	Coronal	Sagittal
		

$$I_n = I_{r5,c7,r_{ref}0} - I_{r5,c7,r_{ref}n}$$

***C*=0 HU, *W*=100 HU**