Reanimating Patients using Motion Transfer: A Cardiorespiratory Motion Ground Truth Based on Clinical CT Patient Data

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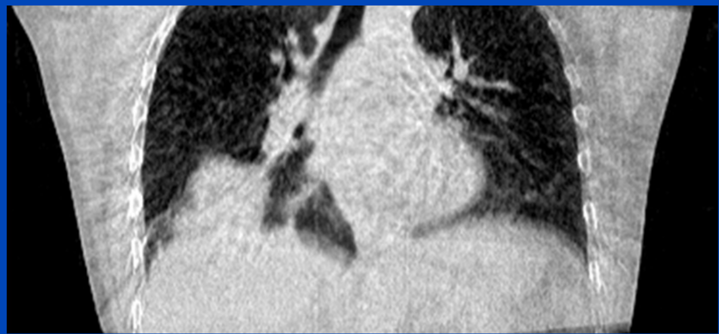
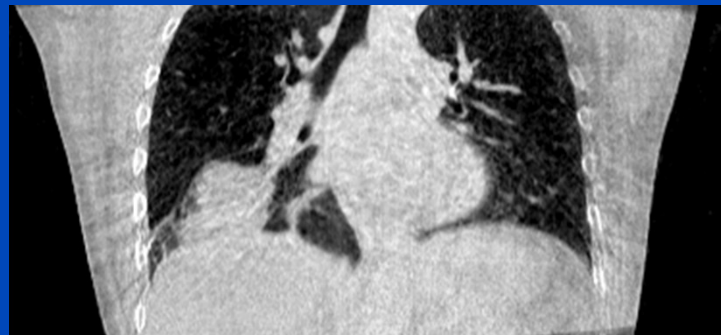
Introduction

- **Motion compensation (MoCo) is an important tool in medical imaging.**



3D CBCT



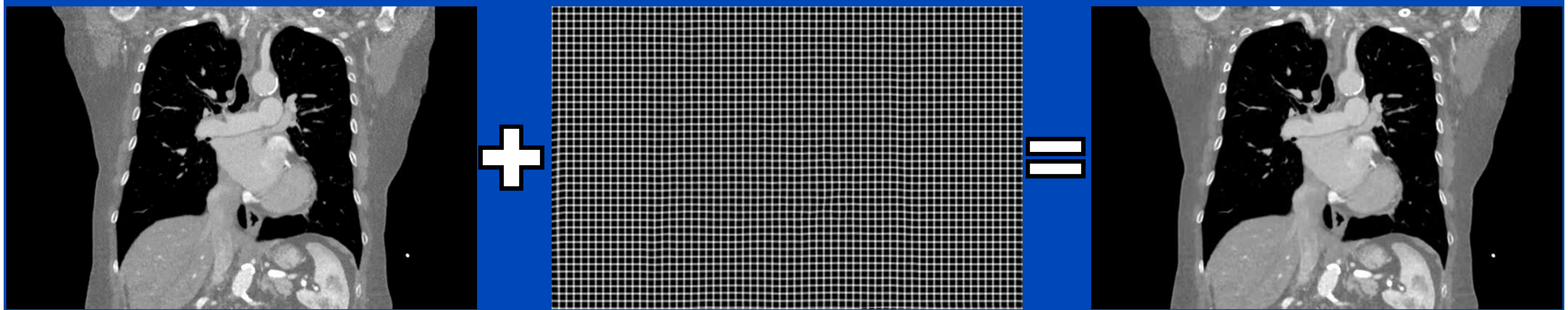
5D MoCo

- **Hard to assess algorithms quantitatively as there is no motion ground truth available.**

S. Sauppe, A. Hahn, M. Brehm, P. Paysan, D. Seghers, and M. Kachelrieß, "Five-dimensional motion compensation for respiratory and cardiac motion with cone-beam CT of the thorax region," SPIE Medical Imaging Conference Record 97830H:1-9, March 2016

Aims

- Generate motion phantoms based on voxelized patient data.
- Provide 4D and 5D motion ground truth (GT) patient data including motion information.



High resolution patient data | Motion vector field (MVF) | 5D phantom

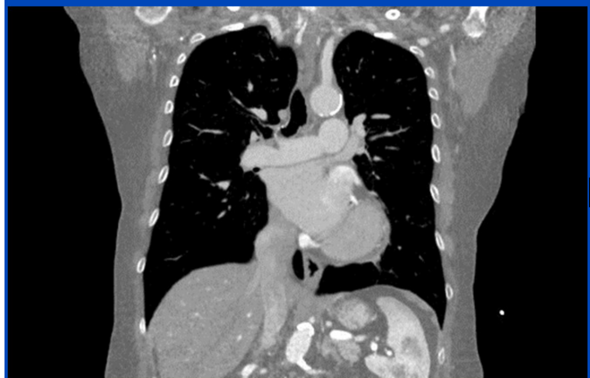
C = 0 HU, *W* = 1400 HU

Motion Transfer

4D respiratory source

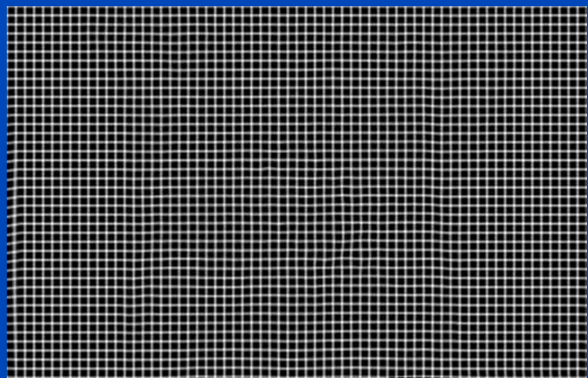
Transfer motion to static destination patient anatomy

4D cardiac source



High resolution patient data

+



Motion vector field (MVF)

=

5D phantom

C = 0 HU, *W* = 1400 HU

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Motion Transfer with Deformable Image Registration

1. Motion extraction

$f_t(\boldsymbol{r})$ Motion data (phase *t*) in source anatomy

$\boldsymbol{m}_t(\boldsymbol{r})$ Motion vector fields (MVFs)

$$f_t(\boldsymbol{r}) = f_0(\boldsymbol{m}_t(\boldsymbol{r}))$$

2. Anatomy matching

$g_0(\boldsymbol{r})$ Static patient data in destination anatomy

$\boldsymbol{d}(\boldsymbol{r})$ Anatomy map relating both anatomies

$$g_0(\boldsymbol{r}) \doteq f_0(\boldsymbol{d}(\boldsymbol{r}))$$

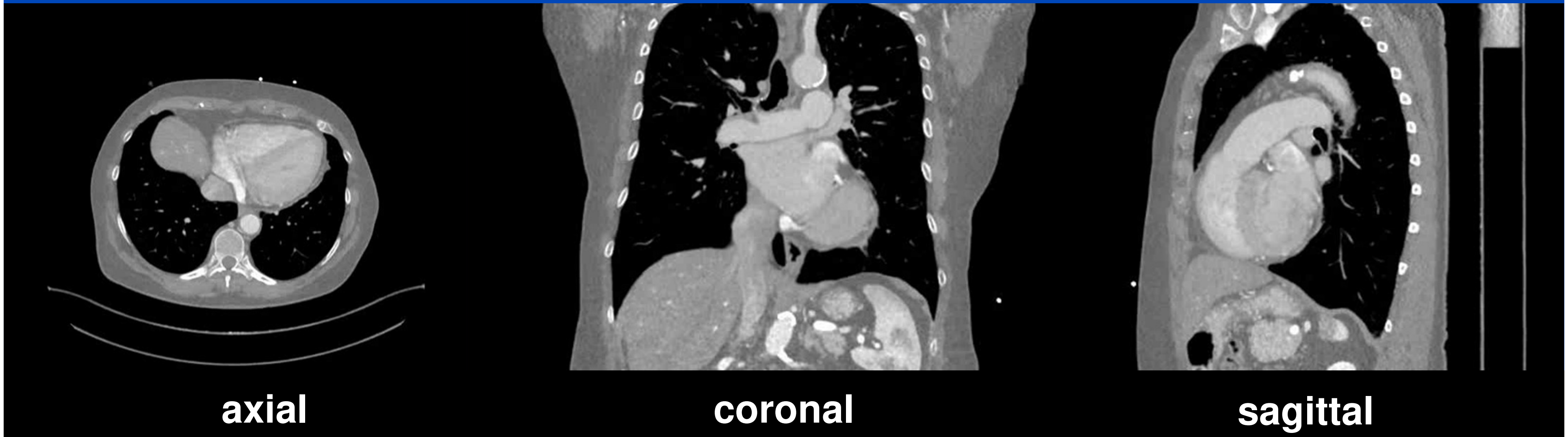
3. MVF transfer

$$\tilde{\boldsymbol{m}}_t(\boldsymbol{r}) = \boldsymbol{d}^{-1}(\boldsymbol{m}_t(\boldsymbol{d}(\boldsymbol{r})))$$

$$g_t(\boldsymbol{r}) = g_0(\tilde{\boldsymbol{m}}_t(\boldsymbol{r}))$$

Cardiac Reanimated Destination Patient

- We successfully applied the approach to cardiac motion.
- A well-regularized anatomy map leads to realistic cardiac motion transfer.



Reanimated destination patient

C = 0 HU, *W* = 1400 HU

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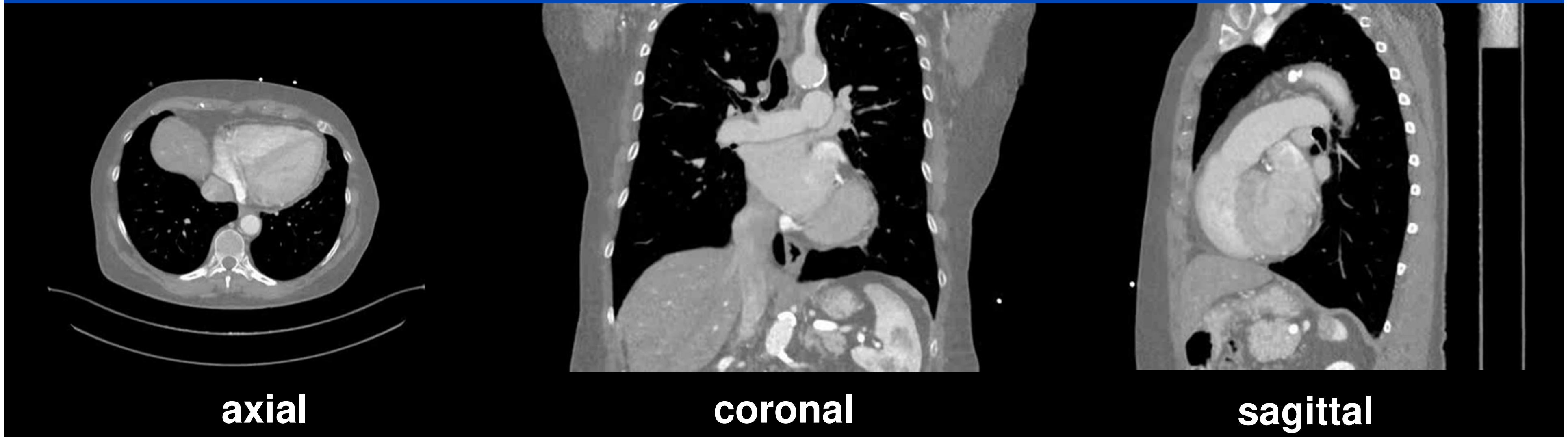
Cardio-Respiratory Motion Phantom

- Composition of cardiac and respiratory MVFs leads to 5D motion



Reanimated destination patient

C = 0 HU, *W* = 1400 HU

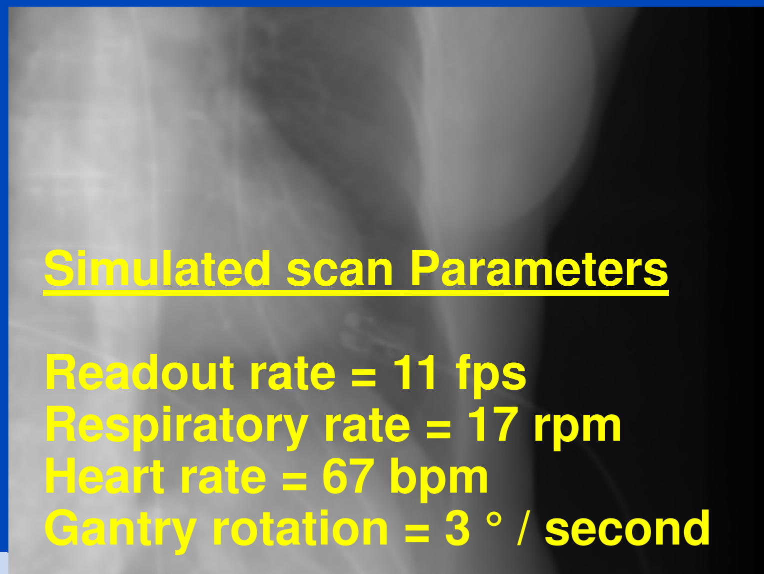
CBCT Simulations of Phantom

- The motion phantom was used to simulate rawdata corresponding to a Varian True Beam scan.
- Cardio-respiratory motion was simulated by forward projecting the motion phantom according to each projection's cardiac and respiratory phase.
- Phase-correlated Feldkamp (PCF) and artifact-specific cyclic motion compensation (acMoCo[1,2,3]) performed for reconstruction.

[1] 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.

[2] 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.

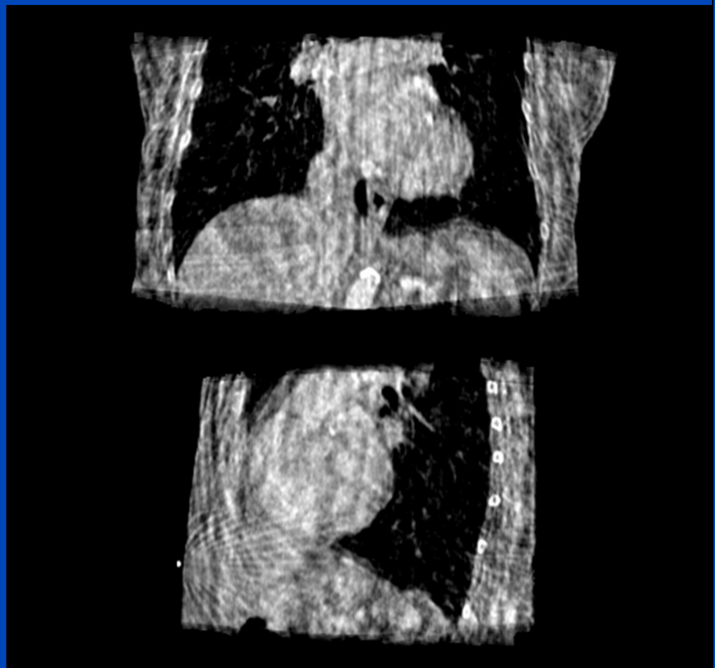
[3] Brehm, Sawall, Maier, and Kachelrieß, "Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation" Med. Phys. 42(4):1948-1958, 2015.



acMoCo of Respiratory Motion

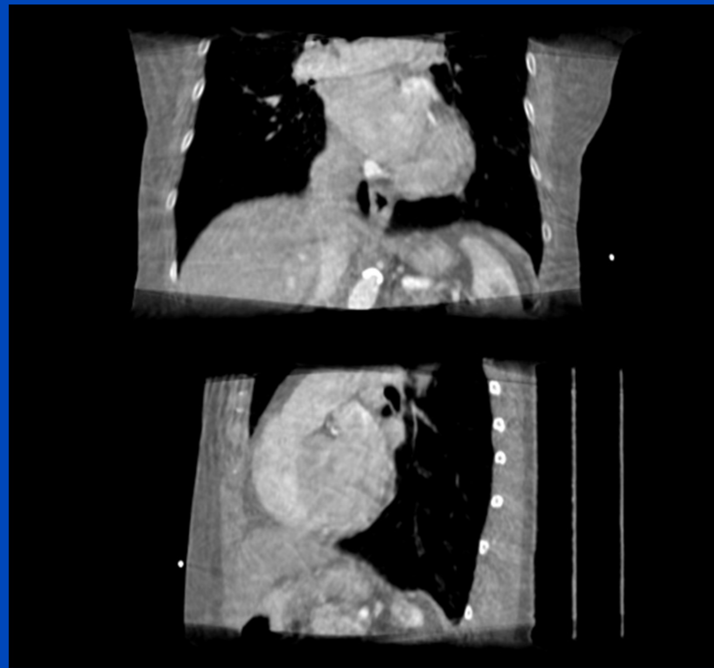
Phase-correlated FDK reconstructions (PCF)

- 20% dose usage
- significant artifacts



Motion-Compensated reconstructions (acMoCo)

- 100% dose usage
- nearly artifact-free



***C* = 0 HU, *W* = 1400 HU**

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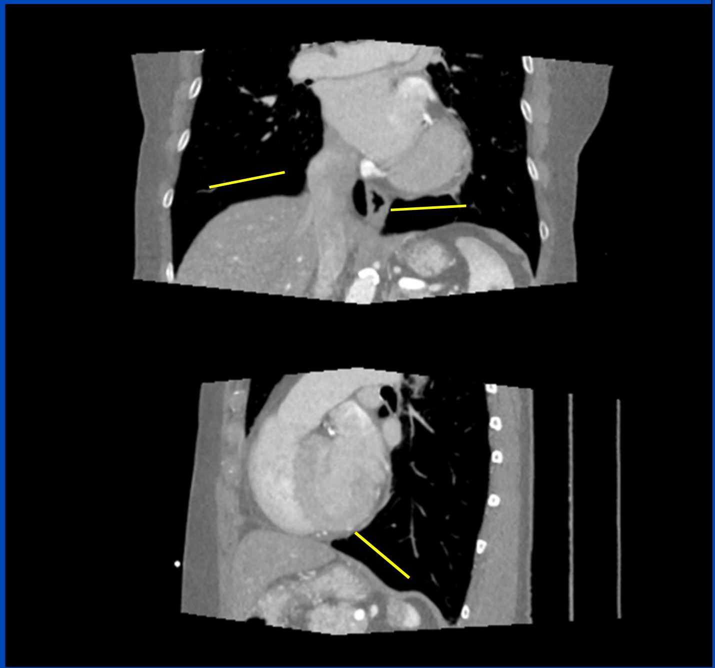
Comparison of GT and acMoCo

Ground truth respiratory motion

- ideal image
- no artifacts



Motion-Compensated reconstructions (acMoCo)

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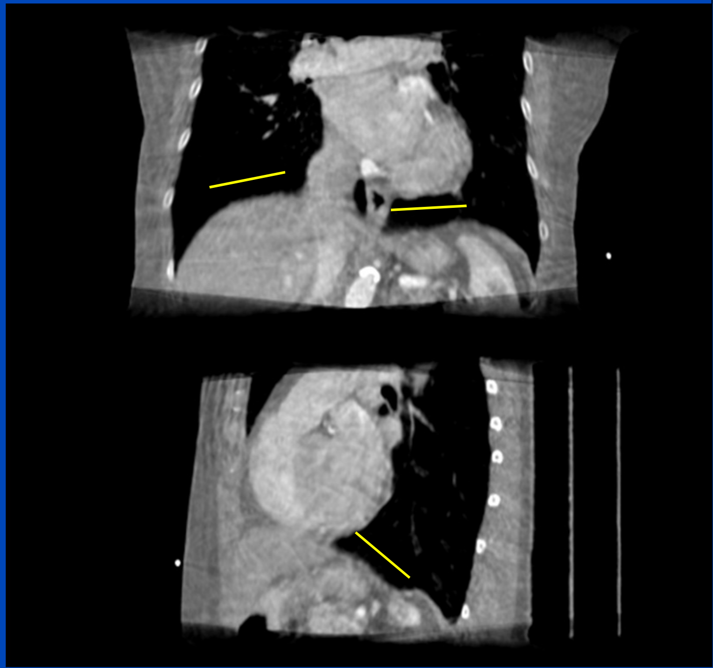


One can detect a slight motion underestimation in the acMoCo images.

Evaluation of MVF Deviation

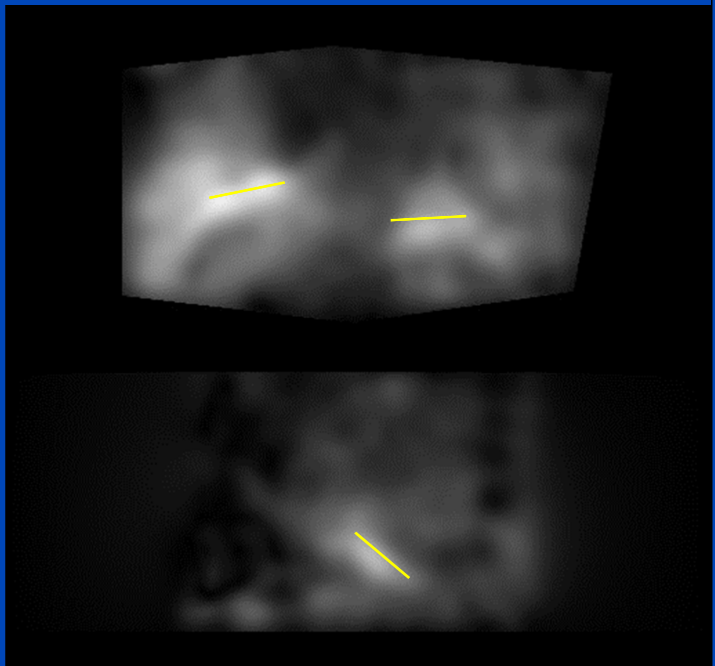
- Each ground truth voxel position $\boldsymbol{m}_t^{\mathrm{GT}}(\boldsymbol{r})$ is known at each time point. A direct comparison to the estimated motion $\boldsymbol{m}_t^{\mathrm{acMoCo}}(\boldsymbol{r})$ is performed.
- The acMoCo algorithm takes all phase-correlated images into account during motion compensation to achieve 100% dose usage.
- Hence to quantify the deviation between the estimated MVFs and the ground truth one needs to evaluate the deviation average over all phases:

$$\Delta(\boldsymbol{r}) = \left\| \langle \boldsymbol{m}_t^{\mathrm{GT}}(\boldsymbol{r}) - \boldsymbol{m}_t^{\mathrm{acMoCo}}(\boldsymbol{r}) \rangle_t \right\|$$

Motion Vector Field Deviation

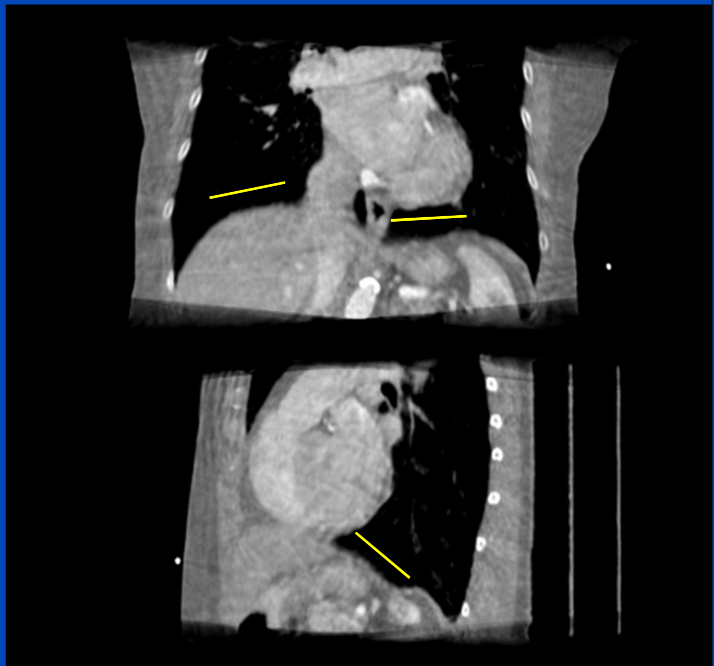
MVF deviation

$$\Delta(\boldsymbol{r}) = \left\| \langle \boldsymbol{m}_t^{\mathrm{GT}}(\boldsymbol{r}) - \boldsymbol{m}_t^{\mathrm{acMoCo}}(\boldsymbol{r}) \rangle_t \right\|$$



Motion-compensated reconstructions (acMoCo)

- 100% dose usage
- nearly artifact-free



Largest deviation in maximum-amplitude phase.
Motion underestimation appears at the diaphragm.

***C* = 3 mm, *W* = 6 mm**

***C* = 0 HU, *W* = 1400 HU**

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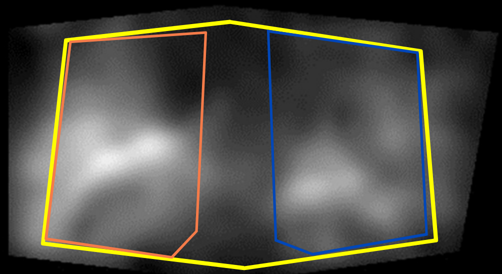
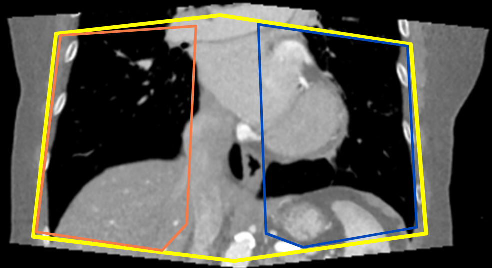
Respiratory MVF Accuracy

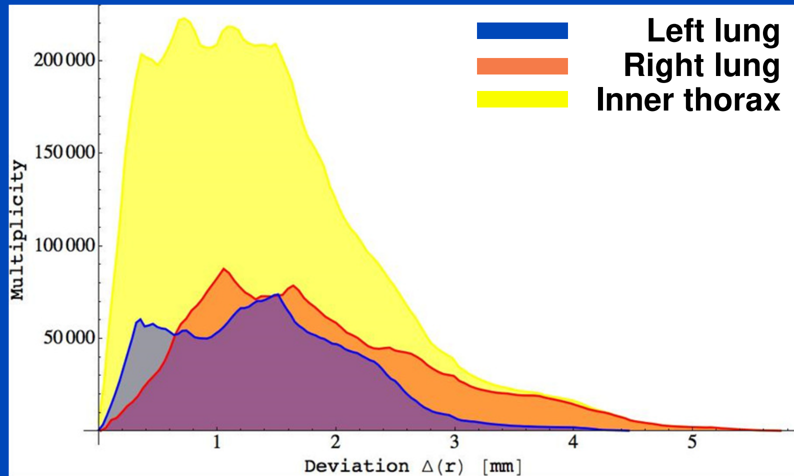
MVF deviation $\Delta(r)$



C = 3 mm, W = 6 mm

GT respiratory motion





Distribution of Deviation in ROI

ROI	Deviation
Left lung	(1.42 ± 0.77) mm
Right lung	(1.91 ± 1.02) mm
Inner thorax	(1.46 ± 0.92) mm

***C* = 0 HU, *W* = 1400 HU**

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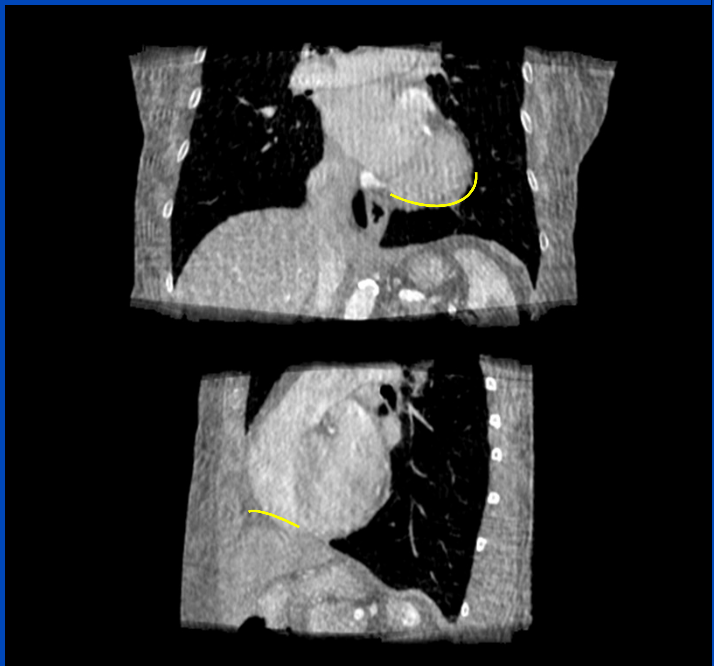
acMoCo of Cardiac Motion

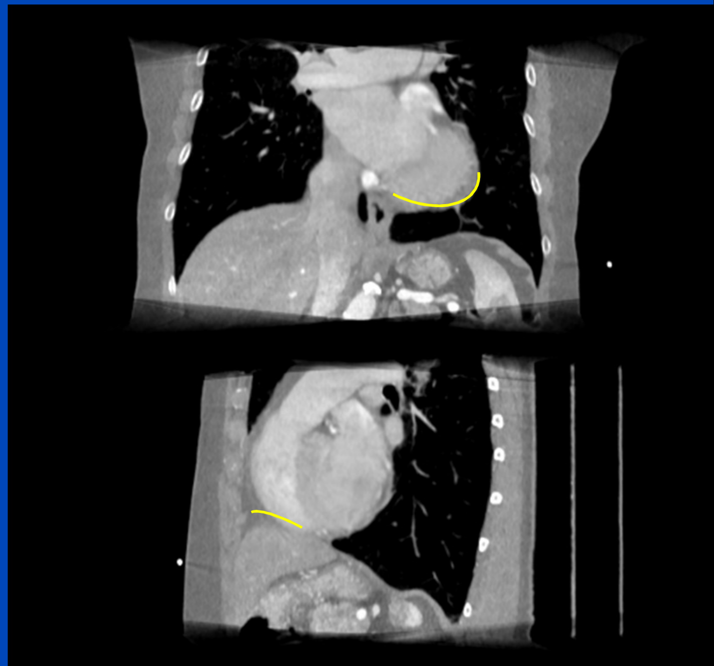
Phase-correlated FDK reconstructions (PCF)

- 20% dose usage
- significant artifacts



Motion-compensated reconstructions (acMoCo)

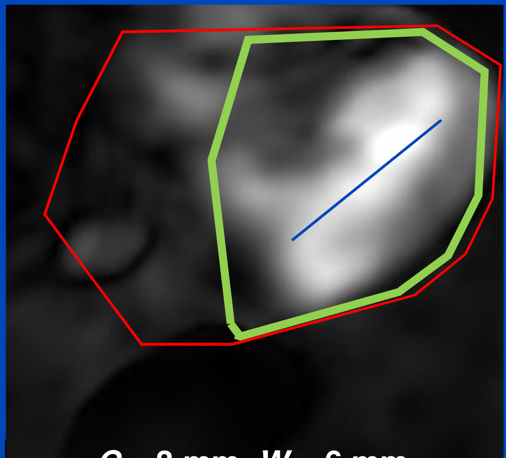
- 100% dose usage
- nearly artifact-free



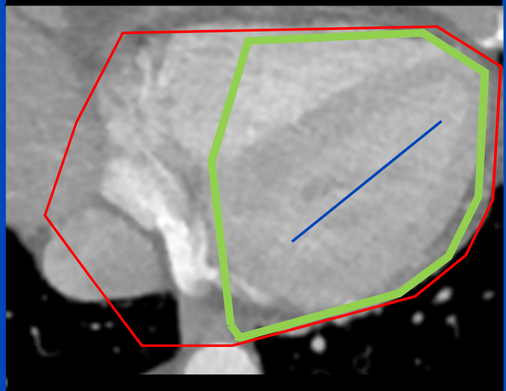
One can detect a slight motion underestimation in the acMoCo images.

Cardiac MVF Accuracy

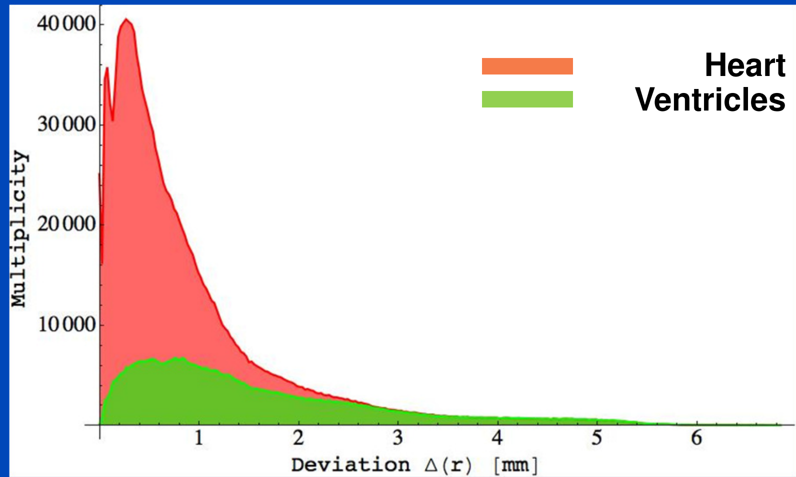
MVF deviation $\Delta(r)$



C = 3 mm, W = 6 mm



GT cardiac Motion



Distribution of Deviation in ROI

ROI	Deviation
Heart	(0.92 ± 0.95) mm
Ventricles	(1.60 ± 1.24) mm

***C* = 0 HU, *W* = 1400 HU**

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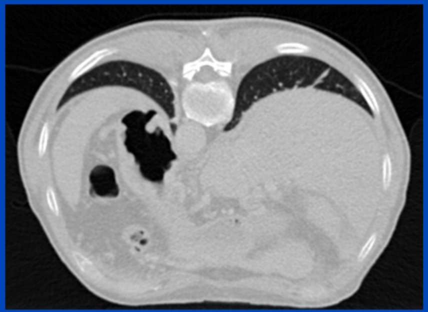
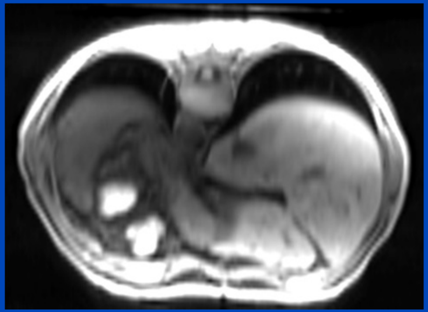
Conclusion

- Successfully simulated a 5D cardiorespiratory motion phantom on patient data. (A careful regularization of the anatomy map is needed for a reasonable motion transfer.)
- Evaluation of the acMoCo algorithm shows an accuracy of about 1.5 mm.
- Motion transfer also works between different modalities:

4D CT



Animated 3D MR



Thank You!

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