Reanimating Patients: Cardio-respiratory CT and MR motion phantoms based on clinical CT patient data

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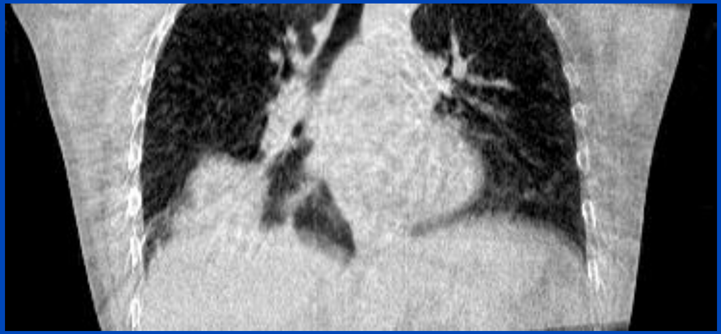
Introduction

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



3D CBCT

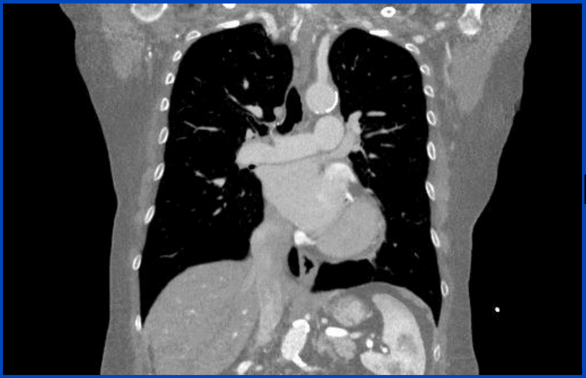
5D MoCo

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

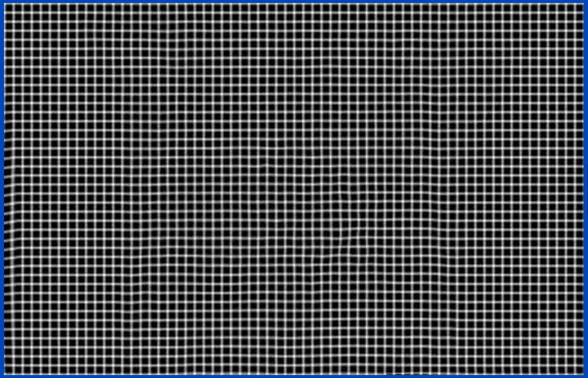
S. Sauppe, A. Hahn, M. Brehm, P. Paysan, D. Seghers, and M. Kachelrieß, "Five-dimensional motion compensation for respiratory and cardiac motion with cone-beam CT of the thorax region," in Proceeding of SPIE, D. Kontos, T. Flohr, and J. Lo, eds., p. 97830H, (San Diego), Mar. 2016.

Aim

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



High resolution patient data



Motion information

5D phantom

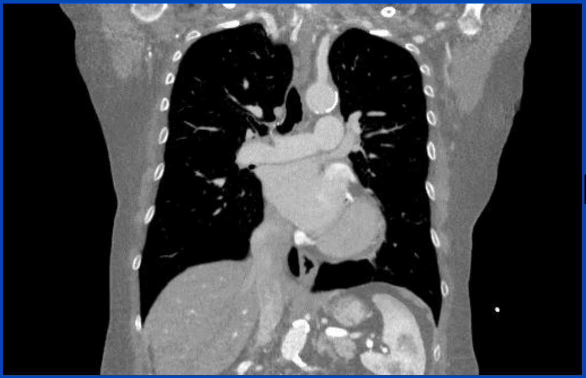
C=0 HU, W=1400 HU

Motion Transfer

4D respiratory source

Transfer motion to static destination patient anatomy

4D cardiac source



High resolution patient data

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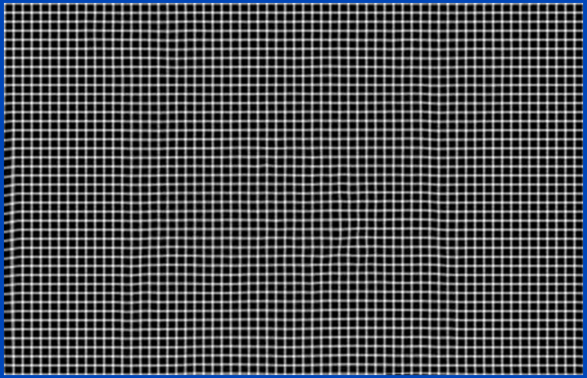

Motion information

=

5D phantom

C=0 HU, W=1400 HU

Motion Transfer with Deformable Image Registration

Motion extraction

$f_t(\boldsymbol{r})$	Motion data in source anatomy
$\boldsymbol{m}_t(\boldsymbol{r})$	Motion information stored in motion vector fields (MVFs)
t	Motion phase

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

Anatomy matching

$g(\boldsymbol{r})$	Static patient data in destination anatomy
$\boldsymbol{d}(\boldsymbol{r})$	Anatomy map relating both anatomies

$$\rightarrow g(\boldsymbol{r}) \doteq f_0(\boldsymbol{d}(\boldsymbol{r}))$$

MVF transfer

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

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

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Interpatient Registration

- The anatomy map $d(r)$ is estimated based on the following cost function:

$$\mathcal{C}(\boldsymbol{d}) = \mathrm{MI}(f_0, g, \boldsymbol{d}) + \lambda\, \mathcal{R}(\boldsymbol{d}) + \mathcal{L}$$

- Mutual information (MI) is used as a similarity criterion.
- $\mathcal{R}(d)$ is a penalty term necessary to conserve the behavior of the transferred motion.
- Corresponding anatomic regions are forced to be mapped upon each other by a landmark term $\mathcal{L}$.

Contribution of Anatomy Map to Transformed Motion

- **Local change of volume generated by a coordinate transform is given by the Jacobian determinant.**
- **The same expansion motion in both anatomies means the same determinant at corresponding positions:**

$$\det\left[\frac{\partial \tilde{\boldsymbol{m}}}{\partial \boldsymbol{r}}(\boldsymbol{r})\right] \stackrel{!}{=} \det\left[\frac{\partial \boldsymbol{m}}{\partial \boldsymbol{r}}(\boldsymbol{d}(\boldsymbol{r}))\right]$$

- **Plugging in** $\tilde{\boldsymbol{m}}_t(\boldsymbol{r}) = \boldsymbol{d}^{-1}(\boldsymbol{m}_t(\boldsymbol{d}(\boldsymbol{r})))$ **yields:**

$$\det\left[\frac{\partial \boldsymbol{d}^{-1}}{\partial \boldsymbol{r}}(\boldsymbol{m}(\boldsymbol{d}(\boldsymbol{r})))\right] \cdot \det\left[\frac{\partial \boldsymbol{d}}{\partial \boldsymbol{r}}(\boldsymbol{r})\right] \stackrel{!}{=} 1$$

Motivation for Regularization Penalty

- View anatomy map components as series in $\boldsymbol{r}$:

$$\boldsymbol{d}(\boldsymbol{r}) = \boldsymbol{c} + \boldsymbol{A}\boldsymbol{r} + \mathcal{O}(|\boldsymbol{r}|^2)$$

$$\boldsymbol{d}^{-1}(\boldsymbol{r}) = \widehat{\boldsymbol{c}} + \widehat{\boldsymbol{A}}\boldsymbol{r} + \mathcal{O}(|\boldsymbol{r}|^2)$$

- If higher-than-linear order coefficients vanish:

$$\Rightarrow \widehat{\boldsymbol{A}} = \boldsymbol{A}^{-1}$$

$$\rightarrow \det\left[\frac{\partial \boldsymbol{d}^{-1}}{\partial \boldsymbol{r}}\right] \cdot \det\left[\frac{\partial \boldsymbol{d}}{\partial \boldsymbol{r}}\right] = \det[\boldsymbol{A}^{-1}] \cdot \det[\boldsymbol{A}] = 1$$

Affine Regularization Penalty

- **Higher order in this series need to be suppressed:**

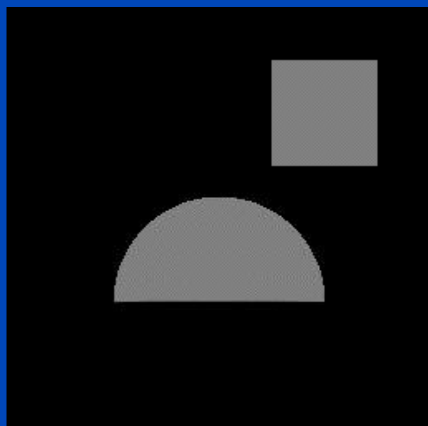
$$\boldsymbol{d}(\boldsymbol{r}) = \boldsymbol{c} + \boldsymbol{A}\boldsymbol{r} + \mathcal{O}(|\boldsymbol{r}|^2)$$

- **Penalizing a non-vanishing second derivative will suppress non-linear behavior.**
- **Choose the regularization:**

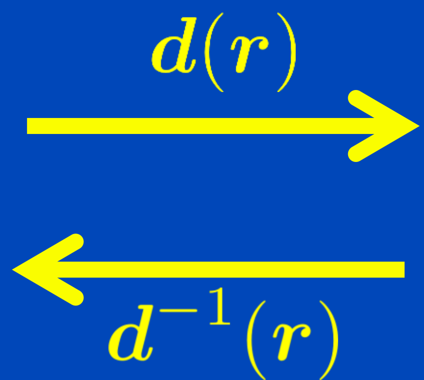
$$\mathcal{R}(\boldsymbol{d}) = \sum_{i,j,k} \left(\frac{\partial^2 \boldsymbol{d}_i(\boldsymbol{r})}{\partial \boldsymbol{r}_j \partial \boldsymbol{r}_k} \right)^2$$

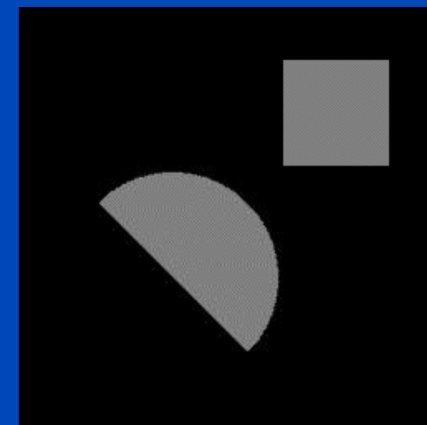
- **This term is well-known in image registration but was not used in the context of transferring motion yet.**

Generic Example

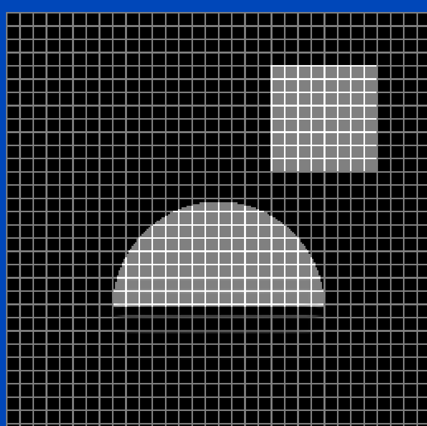


Source anatomy $f_0(\boldsymbol{r})$





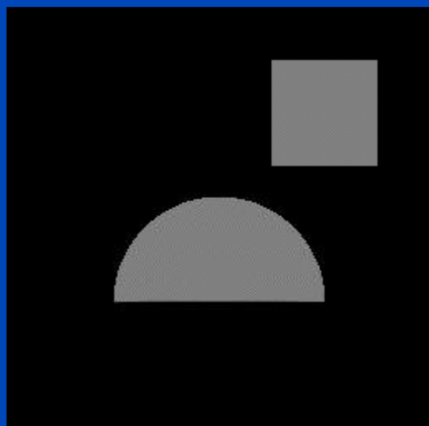
Destination anatomy $g(\boldsymbol{r})$



Source motion $f_0(\boldsymbol{m}_t(\boldsymbol{r}))$

The success of the transfer of motion strongly depends on the regularization of the anatomy map!

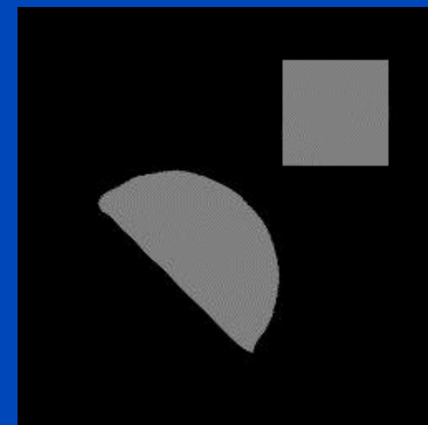
Estimation of Anatomy Map



Source anatomy $f_0(\boldsymbol{r})$

$\boldsymbol{d}(\boldsymbol{r})$ uncon-strained

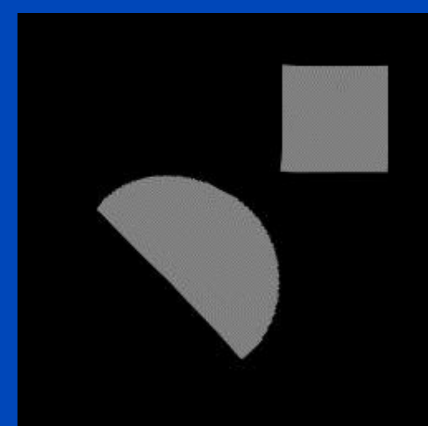
$\lambda = 0$



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

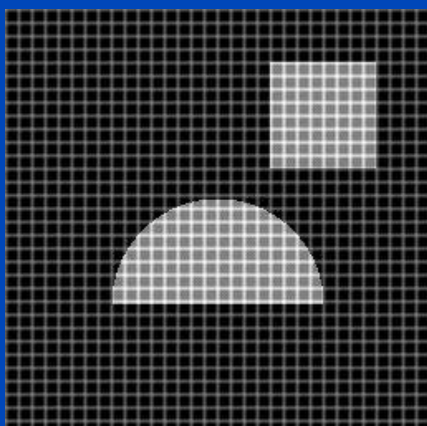
$\boldsymbol{d}(\boldsymbol{r})$ affinely constrained

$\lambda > 0$



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

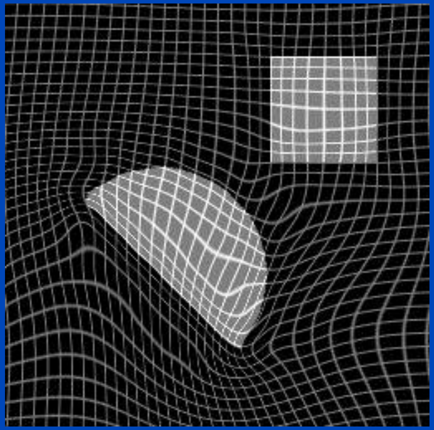
Properties of Anatomy Map



Source anatomy $f_0(\boldsymbol{r})$

$\boldsymbol{d}(\boldsymbol{r})$ uncon-strained

$\lambda = 0$



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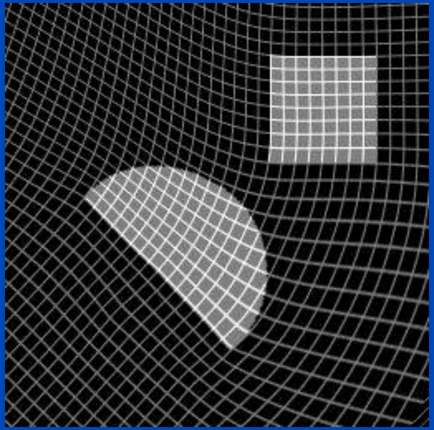
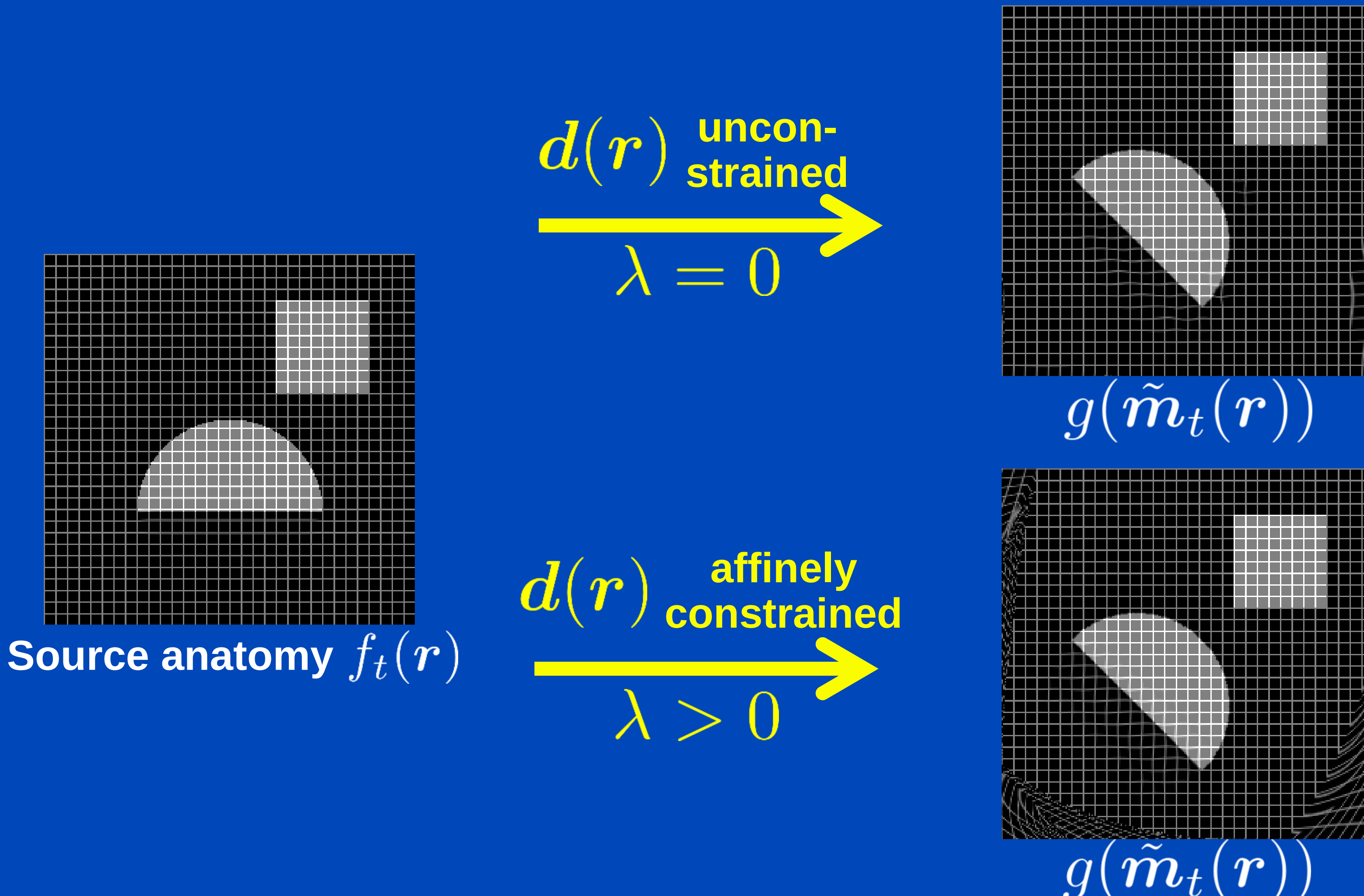


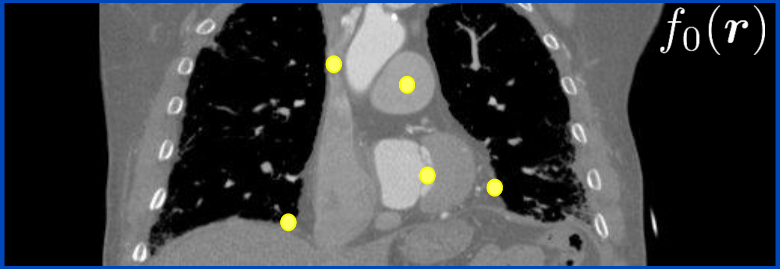
$f_0(\boldsymbol{d}(\boldsymbol{r}))$

Transformed Motion Vector Fields

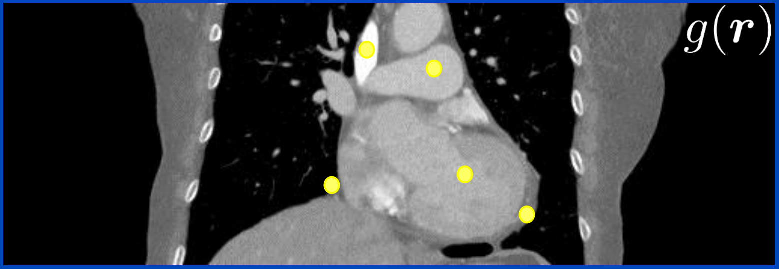


Landmarks for Interpatient Registration

Reference phase of source patient

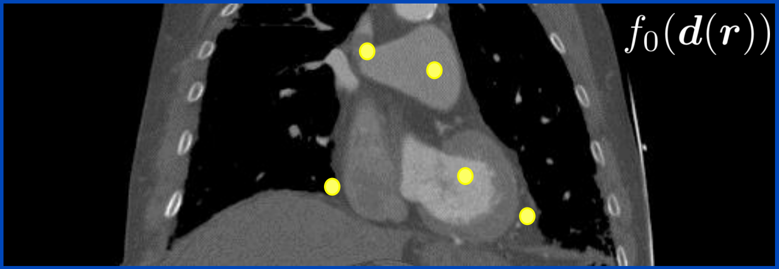


Destination patient



A small set of fiducials (●) was marked in source and destination anatomy to guide the registration algorithm.

Transformed source patient

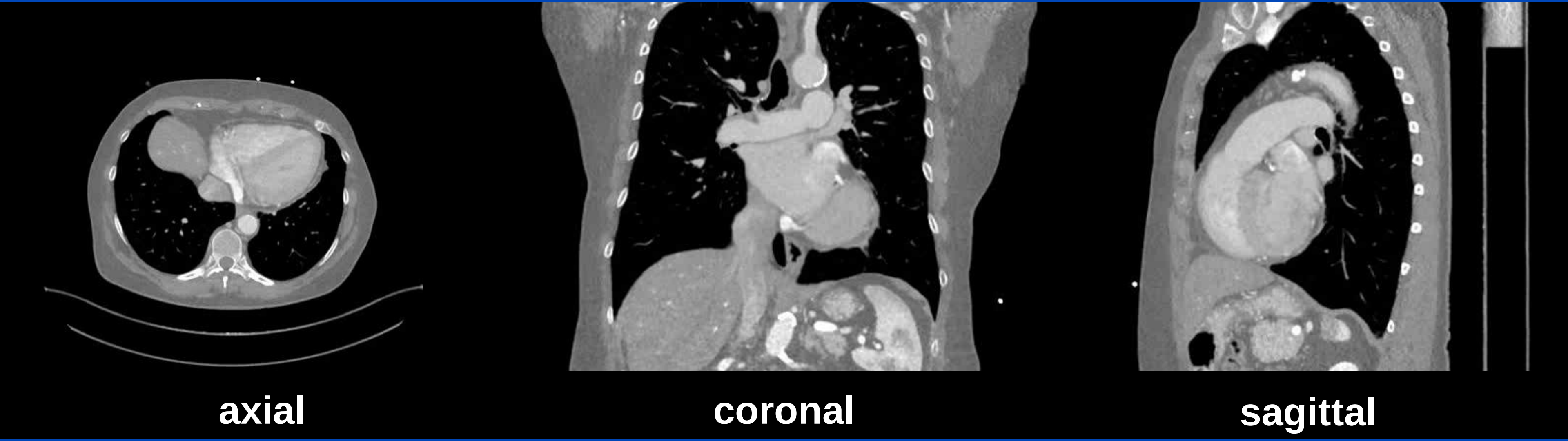


- **Local shearing necessary to match anatomy of heart.**
- **Affine constraints can be seen outside the heart.**

C=0 HU, W=1400 HU

Cardio- 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

Cardio-Respiratory Motion Phantom

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

Reanimated destination patient

C=0 HU, W=1400 HU

dkfz.

Multi-Modality Motion Transfer

- As long as an anatomy map can be computed the motion transfer is not modality-restricted.

4D CT Source patient

3D MR destination patient

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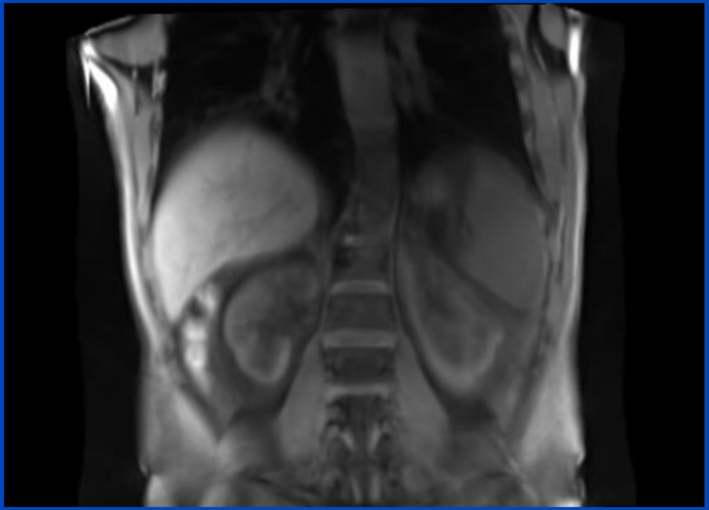
4D CT Source patient



4D MR destination patient

Conclusion

- A careful regularization of anatomy map is needed for a reasonable motion transfer.
- Successfully simulated 5D cardiorespiratory motion on patient data.
- These high-quality 4D and 5D data sets, with the motion information perfectly known, will be used to assess motion compensation algorithms.

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 directly through Marc Kachelriess (marc.kachelriess@dkfz.de).

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