Estimate, Compensate, Iterate

Joint Motion Estimation and Compensation in 4-D Cardiac C-arm Computed Tomography

Oliver Taubmann[1,2], Günter Lauritsch[3], Andreas Maier[1,2], Rebecca Fahrig[3,4], and Joachim Hornegger[1,2]

[1] Pattern Recognition Lab, FAU Erlangen-Nuremberg, Germany
[2] Graduate School in Advanced Optical Technologies (SAOT), Erlangen, Germany
[3] Siemens Healthcare GmbH, Forchheim, Germany
[4] Radiological Sciences Laboratory, Stanford University, California, USA

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SIEMENS SAOT

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

Outline

1. **Introduction:** Clinical Setting
2. **State-of-the-Art:** 4-D Cardiac C-arm CT
3. **Method**: Iterative Motion Estimation and Compensation
4. **Experiments:** Data, Quantitative and Visual Results
5. **Summary and Outlook:** Trade-off, Functional Analysis

Clinical Setting

- Interventional 4-D (3-D+t) C-arm CT of the left ventricle
- Goal: Functional analysis of cardiac motion

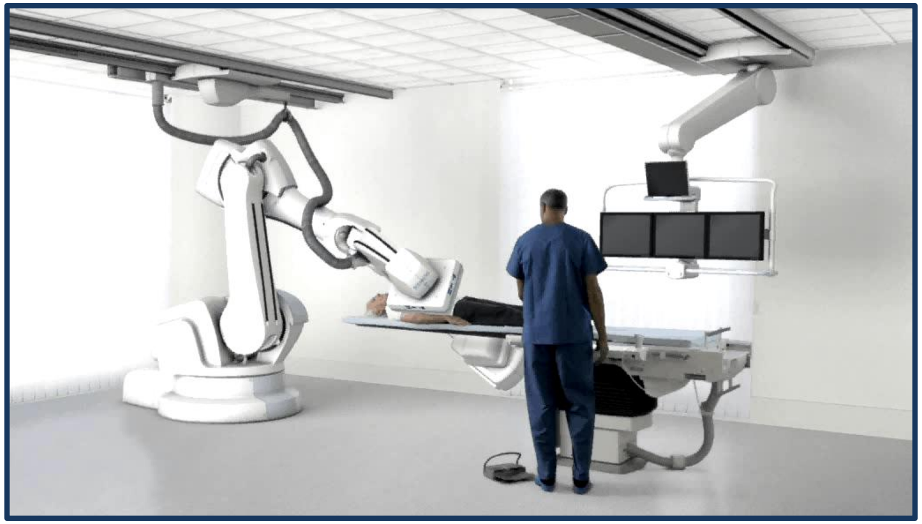


Fig.: Artis zeego multi-axis C-arm system, Siemens Healthcare GmbH, Forchheim, Germany.

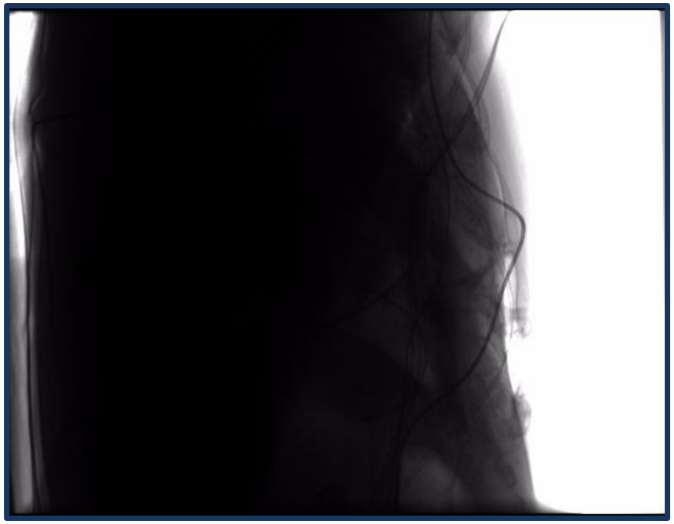


Fig.: Rotational angiogram, courtesy of Dr. Bernd Abt, Centre of Cardio-vascular Diseases, Rotenburg a.d. Fulda, Germany.

Gated Reconstruction

Retrospective electrocardiography (ECG) gating [1]:

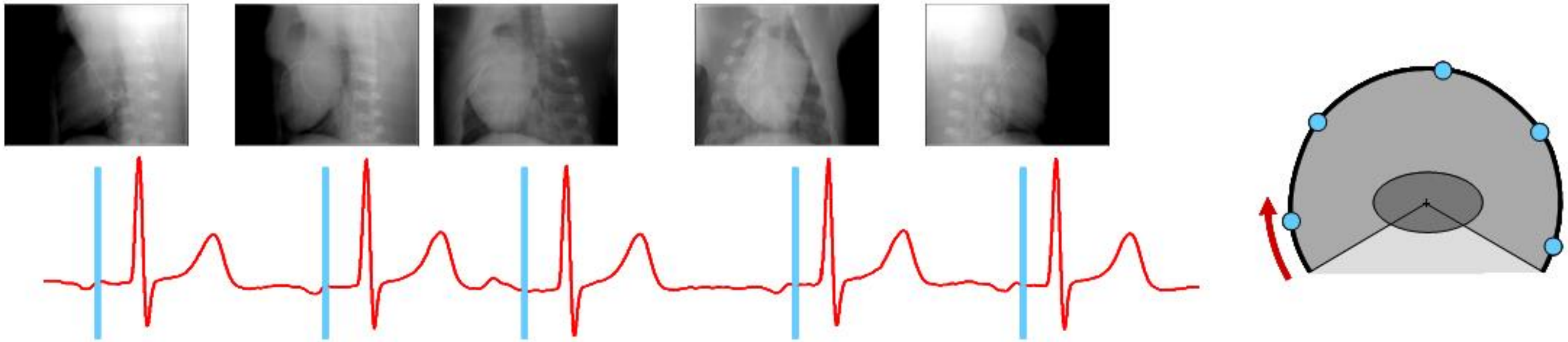


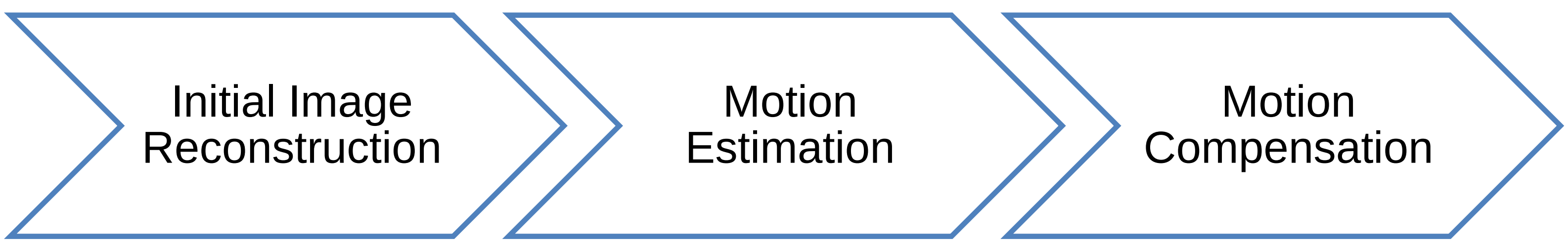
Fig.: Projection images from a C-arm sweep belonging to the same relative heart phase.

[1] Desjardin et al.: **ECG-gated Cardiac CT**, *Am J Roentgenol*, 2004

Motion Compensation

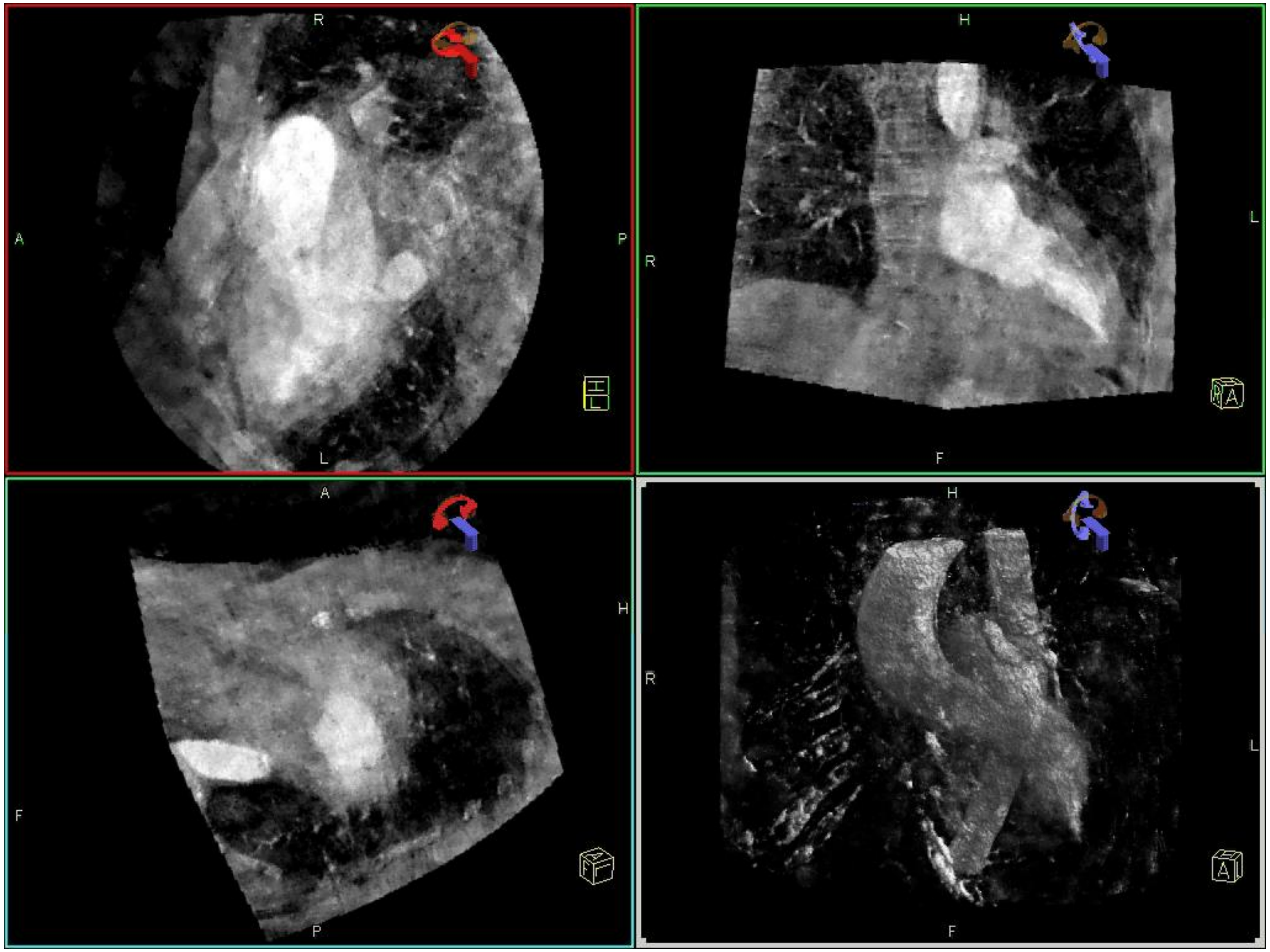
- Image quality of gated reconstructions insufficient
  - Artifacts due to angular undersampling

- Approach: Motion compensated reconstruction [1]
  - Estimate motion from initial reconstruction
  - Final reconstruction from all data



[1] Müller et al.: **Image artefact propagation in motion estimation and reconstruction in interventional cardiac C-arm CT**, *Physics in Medicine and Biology*, 2014

Temporal Inconsistency



Temporal Inconsistency – How to Deal with It?

- Artifacts appear to “jump” over time
  - Undesired flickering impression
  - Tough challenge for non-rigid motion estimation

- Temporal regularization / smoothing
  - Temporal TV regularization in algebraic reconstruction [1]
  - Motion estimation using 4-D B-Splines (implicit smoothing) [2]
  - Adaptive Gaussian smoothing based on a motion map [3]

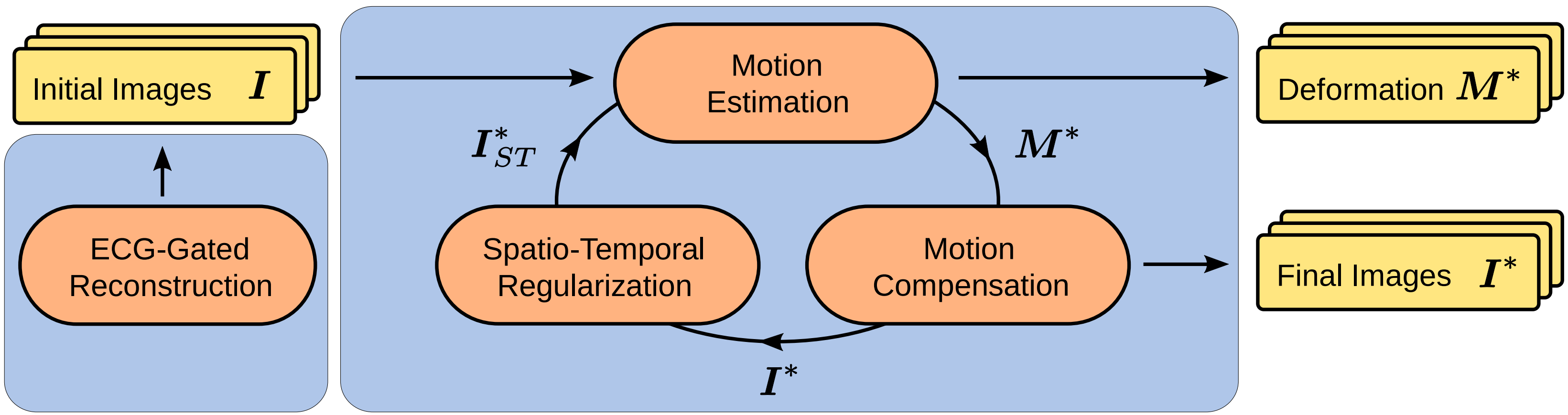
[1] Mory et al.: **Cardiac C-arm computed tomography using a 3D + time ROI reconstruction method with spatial and temporal regularization**, *Med Phys*, 2014

[2] Metz et al.: **Nonrigid registration of dynamic medical imaging data using nD + t B-splines and a groupwise optimization approach**, *Med IA*, 2011

[3] Taubmann et al.: **Keeping the Pace: Heart Rate Informed 3-D Motion Detection for Adaptive Temporal Smoothing**, *Fully3D*, 2015

Iterative Motion Estimation and Compensation

Method Overview



Motion Estimation

Pair-wise 3-D/3-D image registration [1] of all cardiac phases:

$$\boldsymbol{M}^* = \left\{ \underset{\boldsymbol{M}_{t\to t'}}{\operatorname{argmin}} \left[\mathcal{D}\left(\boldsymbol{I}^{t'}, \boldsymbol{M}_{t\to t'} \boldsymbol{I}^{t} \right) \right] : t, t' \in \mathcal{N}_{\mathrm{ph}},\ t \neq t' \right\}$$

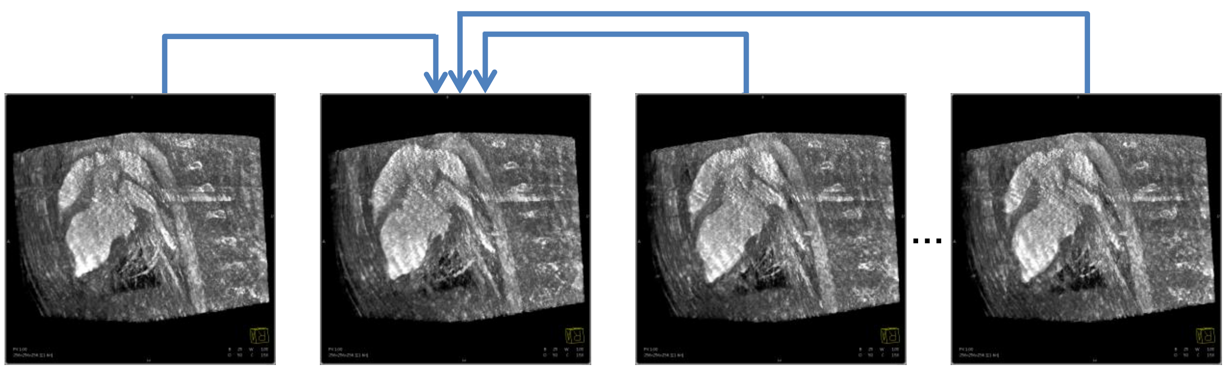


Fig.: Registration of each phase to one reference.

[1] Klein et al.: **elastix: a toolbox for intensity based medical image registration**, *IEEE Trans Med Imaging*, 2010

Motion Estimation

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- $\boldsymbol{I} = \{\boldsymbol{I}^t : t \in \mathcal{N}_{\text{ph}}\}$ 3-D images for all cardiac phases
- $\boldsymbol{M} = \{\boldsymbol{M}_{t\to t'} : t, t' \in \mathcal{N}_{\text{ph}}\}$ Deformation operators for all phase pairs
- $\mathcal{D}(\cdot, \cdot)$ Dissimilarity metric (negative NCC)

[1] Klein et al.: **elastix: a toolbox for intensity based medical image registration**, *IEEE Trans Med Imaging*, 2010

Motion Estimation

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- Cubic B-Spline motion model
- Multi-resolution scheme with 3-level pyramid
- Optimization with L-BFGS and random image sampling
- Restricted to ROI $\boldsymbol{\Omega}$ around the heart

[1] Klein et al.: **elastix: a toolbox for intensity based medical image registration**, *IEEE Trans Med Imaging*, 2010

Motion Compensation

Motion-compensated (filtered backprojection) reconstruction [1]:

$$\boldsymbol{I}^* = \left\{ \boldsymbol{I}^t : \boldsymbol{A}^{t'} \boldsymbol{M}_{t \to t'} \boldsymbol{I}^t = \boldsymbol{P}^{t'};\ t, t' \in \mathcal{N}_{\text{ph}} \right\}$$

- $\boldsymbol{A}^t$ X-ray projection operator corresponding to $\boldsymbol{P}^t$
- $\boldsymbol{P}^t$ Measured projections assigned to phase t

[1] Schäfer et al.: **Motion-compensated and gated cone beam filtered back-projection for 3-D rotational x-ray angiography**, *IEEE Trans Med Imaging*, 2006

Motion Compensation

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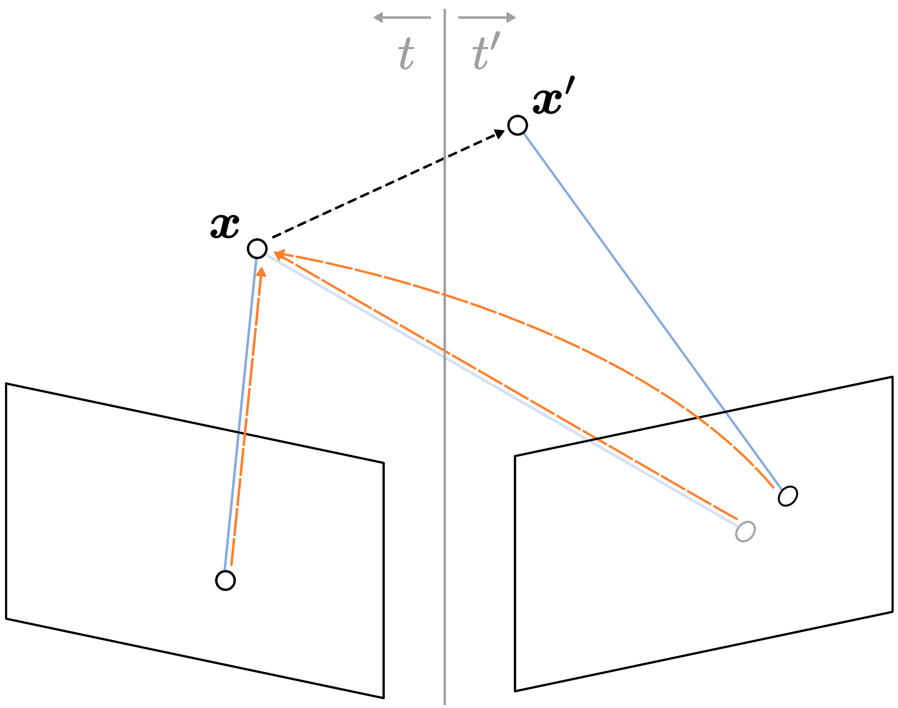

[1] Schäfer et al.: **Motion-compensated and gated cone beam filtered back-projection for 3-D rotational x-ray angiography**, *IEEE Trans Med Imaging*, 2006

Spatio-temporal Regularization

Spatial and temporal bilateral filtering:

$$\boldsymbol{I}_S^t(\boldsymbol{x}) = \sum_{\boldsymbol{x}' \in N(\boldsymbol{x})} \frac{\boldsymbol{I}^t(\boldsymbol{x}')}{w_S} \cdot \exp\left(-\frac{\|\boldsymbol{x}-\boldsymbol{x}'\|_2^2}{2\sigma_S^2} - \frac{(\boldsymbol{I}^t(\boldsymbol{x}) - \boldsymbol{I}^t(\boldsymbol{x}'))^2}{2\sigma_I^2}\right)$$

$$\boldsymbol{I}_{ST}^t(\boldsymbol{x}) = \sum_{t' \in \mathcal{N}_{\text{ph}}} \frac{\boldsymbol{I}_S^{t'}(\boldsymbol{x})}{w_T} \cdot \exp\left(-\frac{\text{dist}^2(t,t')}{2\sigma_T^2} - \frac{(\boldsymbol{I}^t(\boldsymbol{x}) - \boldsymbol{I}^{t'}(\boldsymbol{x}))^2}{2\sigma_I^2}\right)$$

- $\sigma_S, \sigma_T, \sigma_I$ std. devs. in spatial, temporal and intensity domain
- w_S, w_T normalization factors
- $\text{dist}(t, t')$ distance of phases in the cardiac cycle

Spatio-temporal Regularization

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$$\boldsymbol{I}_{ST}^t(\boldsymbol{x}) = \sum_{t' \in \mathcal{N}_{\text{ph}}} \frac{\boldsymbol{I}_S^{t'}(\boldsymbol{x})}{w_T} \cdot \exp\left(\underbrace{-\frac{\operatorname{dist}^2(t, t')}{2\sigma_T^2}}_{\text{temporal proximity}} - \frac{(\boldsymbol{I}^t(\boldsymbol{x}) - \boldsymbol{I}^{t'}(\boldsymbol{x}))^2}{2\sigma_I^2} \right)$$

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Experiments and Results

Experimental Setup

- Images compared:
  - Proposed: $\boldsymbol{I}_3^t(\boldsymbol{x})$, result after three iterations
  - Reference: $\boldsymbol{I}_1^t(\boldsymbol{x})$, result after first compensation step

- Data:
  - 3 clinical patient data sets
    - Acquisition duration 14.5 s
    - RV pacing to 115 bpm
    - Systemic contrast injection (91 ml total, pulmonary artery)
  - Dynamic heart phantom [1,2]
    - Scan protocol identical to clinical data sets
    - Ground truth reconstruction from projections of static phantom

[1] Segars et al.: **4D XCAT phantom for multimodality imaging research**, *Medical Physics*, vol. 37, 2010.

[2] Maier et al.: **CONRAD - A software framework for cone-beam imaging in radiology**, *Medical Physics*, vol. 40(11), 2013

Quantitative Results (Phantom)

Quality measures w. r. t. ground truth calculated over Ω:

- RMSE 86.3 HU $\rightarrow$ 73.6 HU (**-14.7 %**)
- UQI [1] 0.80 $\rightarrow$ **0.95**
- Motion estimation error 2.08 $\pm$ 1.92 mm $\rightarrow$ 1.52 $\pm$ 1.91 mm

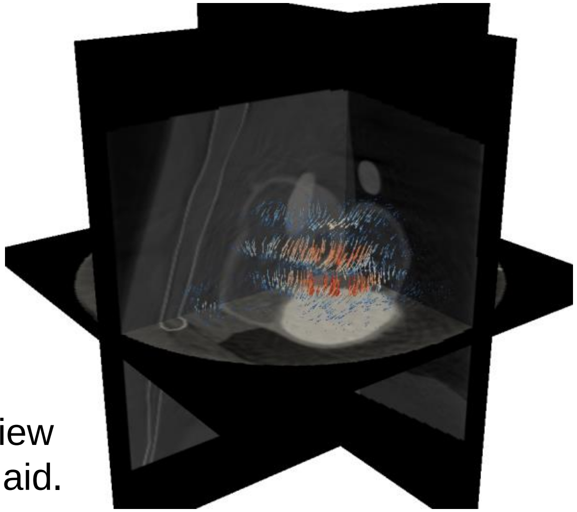


Fig.: Orthogonal slices view with motion vectors overlaid.

[1] Wang et al.: **A Universal Image Quality Index**, *Signal Processing Letters, IEEE*, vol. 9, 2002.

Quantitative Results (All Data Sets)

- Quantify reduction of artificial motion
  - Measured in ideally static region $\Omega_s \subset \Omega$
  - Decrease of temporal intensity variance

- Assess (motion) blur
  - Sharpness of left ventricular blood pool boundary preserved or increased

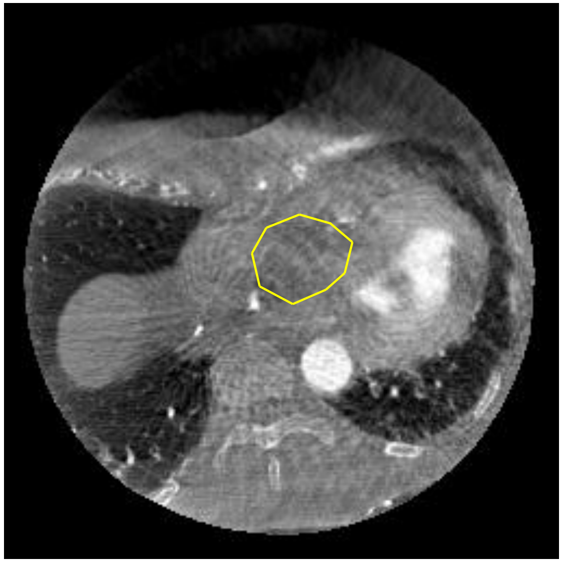
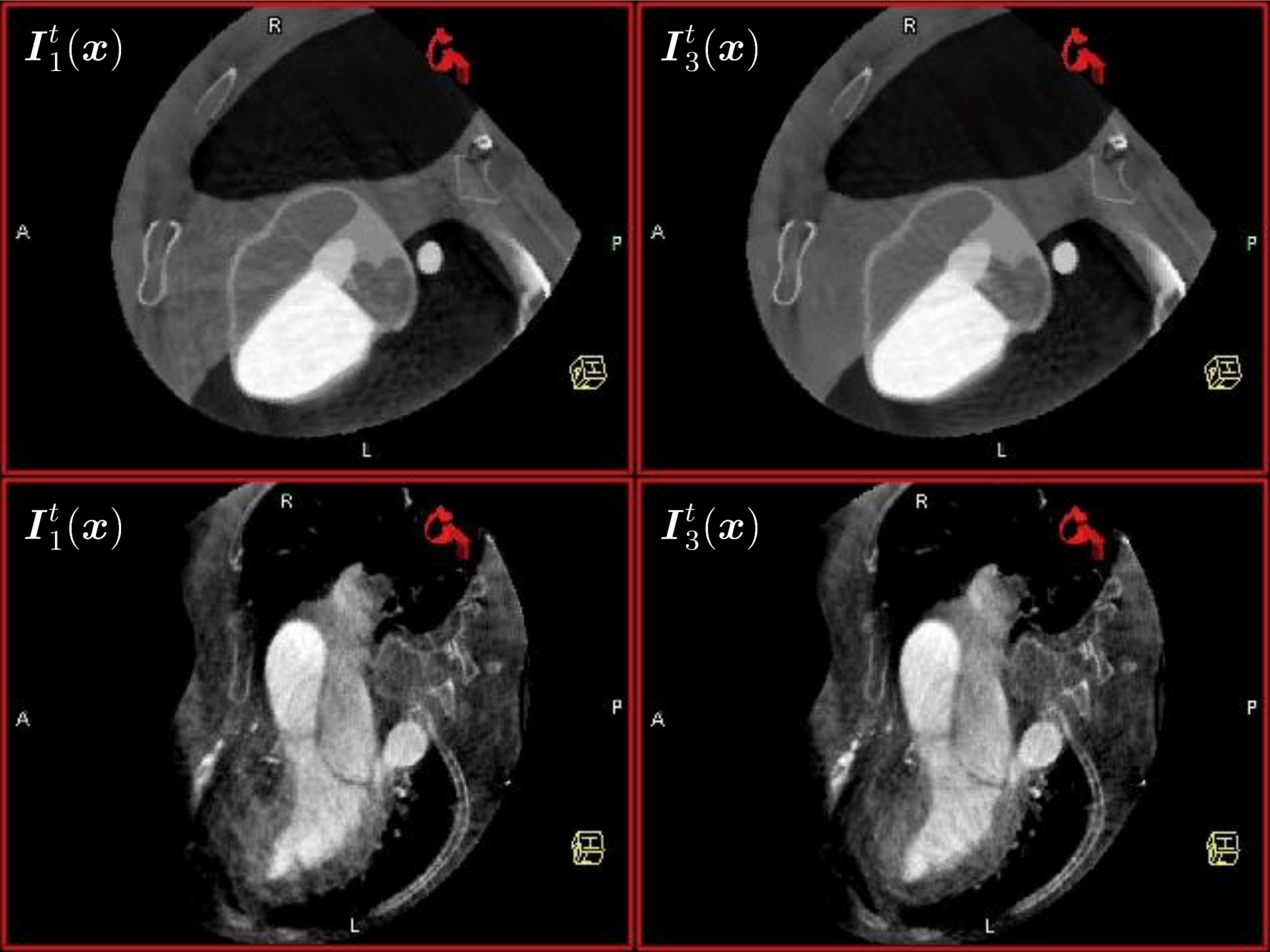


Fig.: Selected ideally static region in patient 1 (yellow).

Details at our poster or in the paper!


$I_1^t(x)$
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Human Observer Study

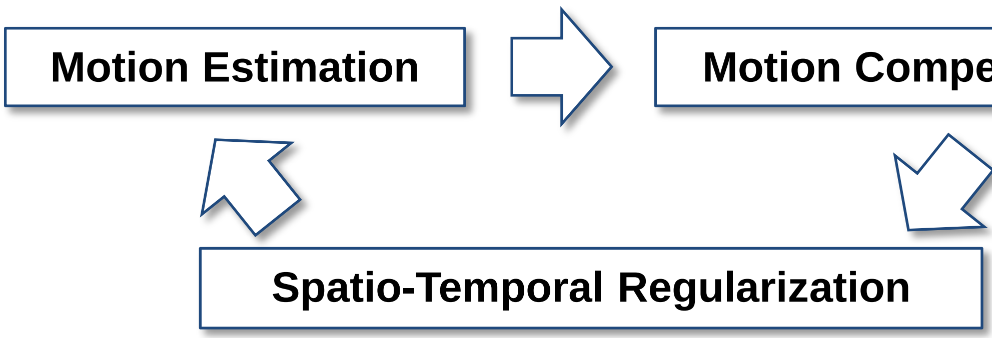
Visual image quality rated by human observers

- 9 technical experts blinded to the method
- Scale: 0 (“unacceptable”) through 4 (“very good”)

Data set	$\boldsymbol{I}_1^t$	$\boldsymbol{I}_3^t$
Patient 1	$\mathbf{2.1} \pm 0.60$	$\mathbf{3.7} \pm 0.50$
Patient 2	$\mathbf{1.4} \pm 0.73$	$\mathbf{2.4} \pm 0.88$
Patient 3	$\mathbf{1.4} \pm 0.53$	$\mathbf{3.4} \pm 0.73$
Phantom	$\mathbf{1.9} \pm 0.78$	$\mathbf{3.7} \pm 0.50$

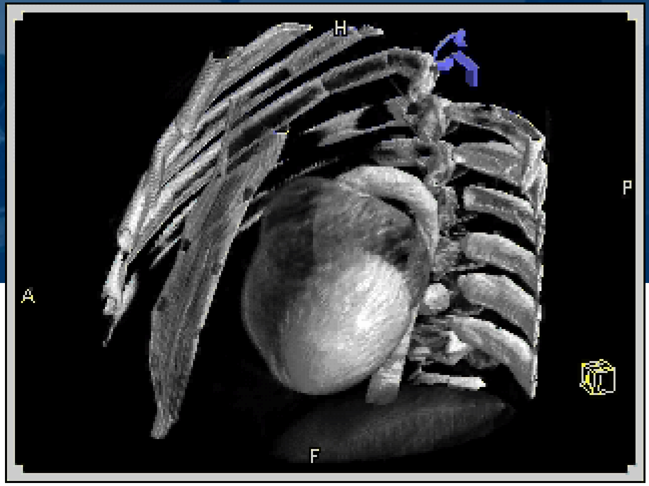
Summary and Outlook

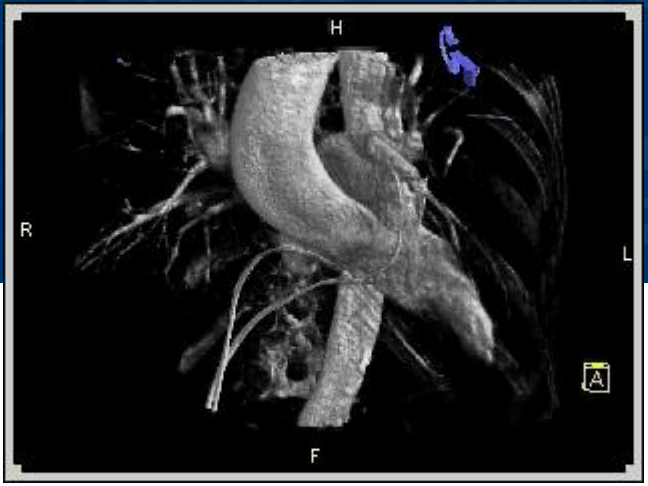
- Iterative scheme for improved image quality / motion accuracy:



- Reduced artificial motion patterns ⇔ Increased computational effort

- Future work:
  - Experiments with 4-D iterative reconstruction methods
  - Advancing functional analysis in the interventional suite





Thanks for your attention!
Any questions?

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