Spatio-temporally Regularized 4-D Cardiovascular C-arm CT Reconstruction Using a Proximal Algorithm

Oliver Taubmann[1,2,*], Mathias Unberath[1,2,*], Guenter Lauritsch[3], Stephan Achenbach[4], Andreas Maier[1,2]

[1] Pattern Recognition Lab, Friedrich-Alexander-University Erlangen-Nuremberg, Germany
[2] Erlangen Graduate School in Advanced Optical Technologies (SAOT), Germany
[3] Siemens Healthcare GmbH, Forchheim, Germany
[4] Department of Cardiology, Friedrich-Alexander-University Erlangen-Nuremberg, Germany
* These authors contributed equally to this work

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Coronary Rotational Angiography

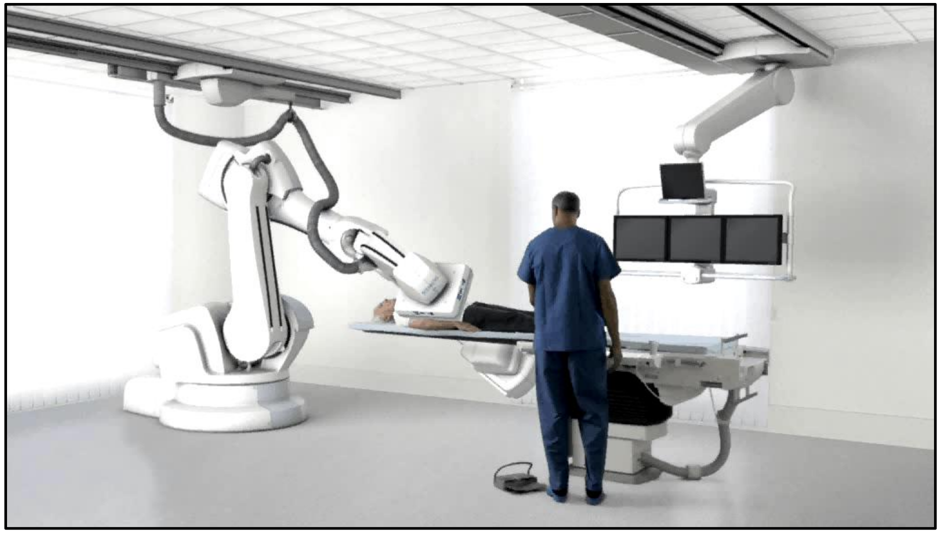
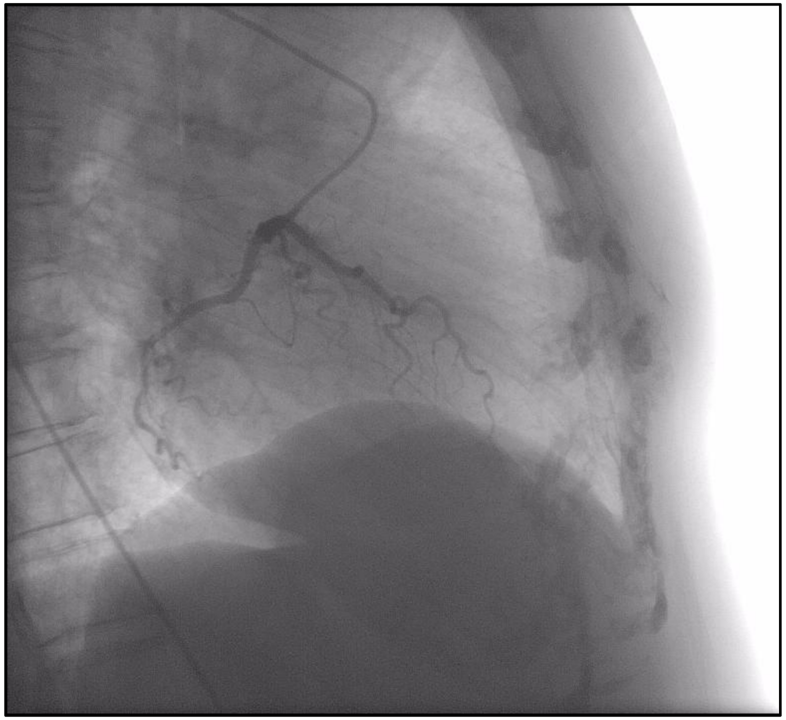


Fig.: Artis zeego multi-axis C-arm system, Siemens Healthcare GmbH, Forchheim, Germany.



Coronary Rotational Angiography

- 3-D anatomy of vascular trees considered beneficial [1]
  - Diagnostic assessment
  - Interventional guidance
- Requires cardiac motion management
  - Slow gantry rotation
  - ECG gating yields very few views

[1] Çimen et al.: **Reconstruction of Coronary Arteries from X-ray Angiography: A Review**, Med Image Anal 2016

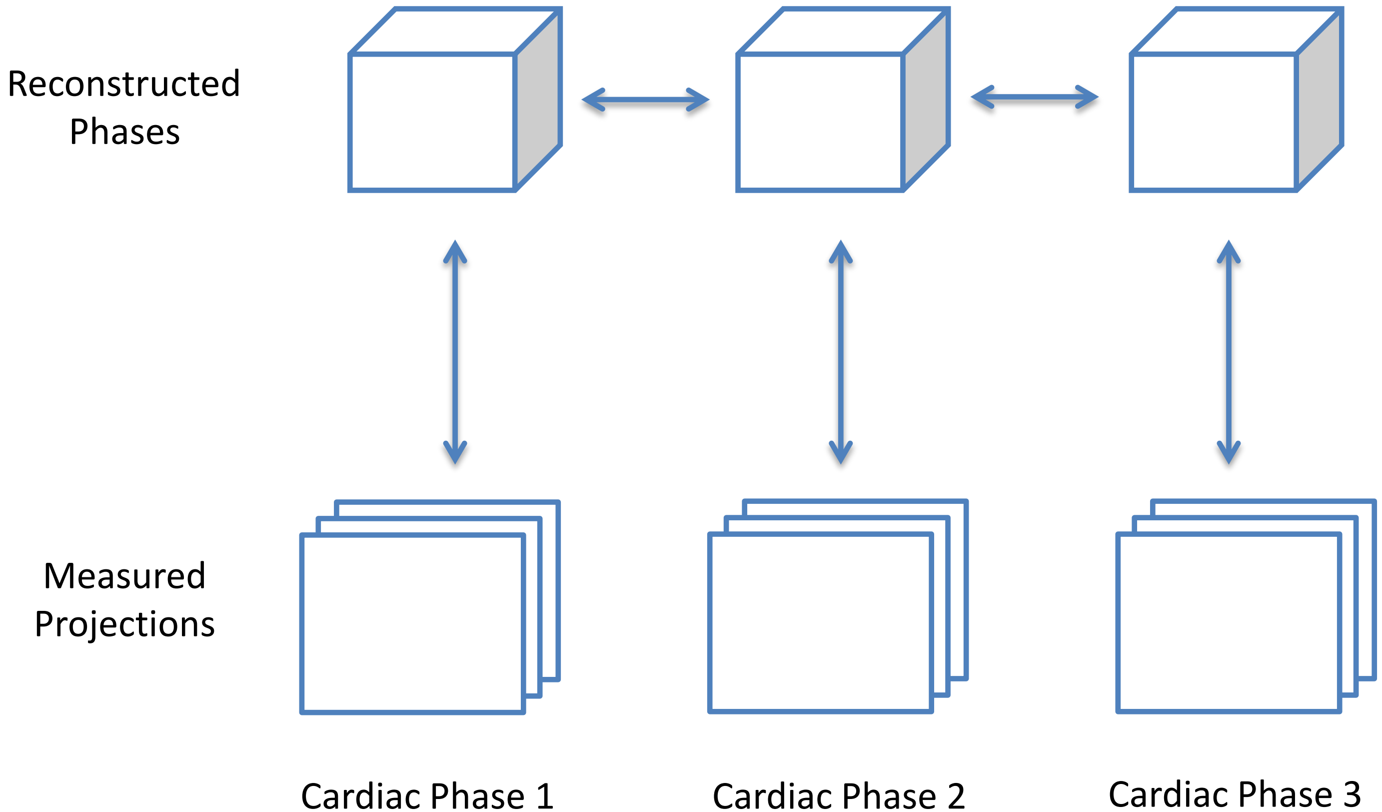
Coronary Rotational Angiography

- Volumetric (tomographic) reconstruction
  - Usually requires more (consistent) data
- Compressed sensing exploits image properties
  - Total variation: Ideal images are sparse in gradient domain [1]
  - Temporal regularization addresses insufficient data more effectively [2]

[1] Wu et al.: **Total Variation Regularization Method for 3-D Rotational Coronary Angiography**, Bildverarbeitung für die Medizin 2011

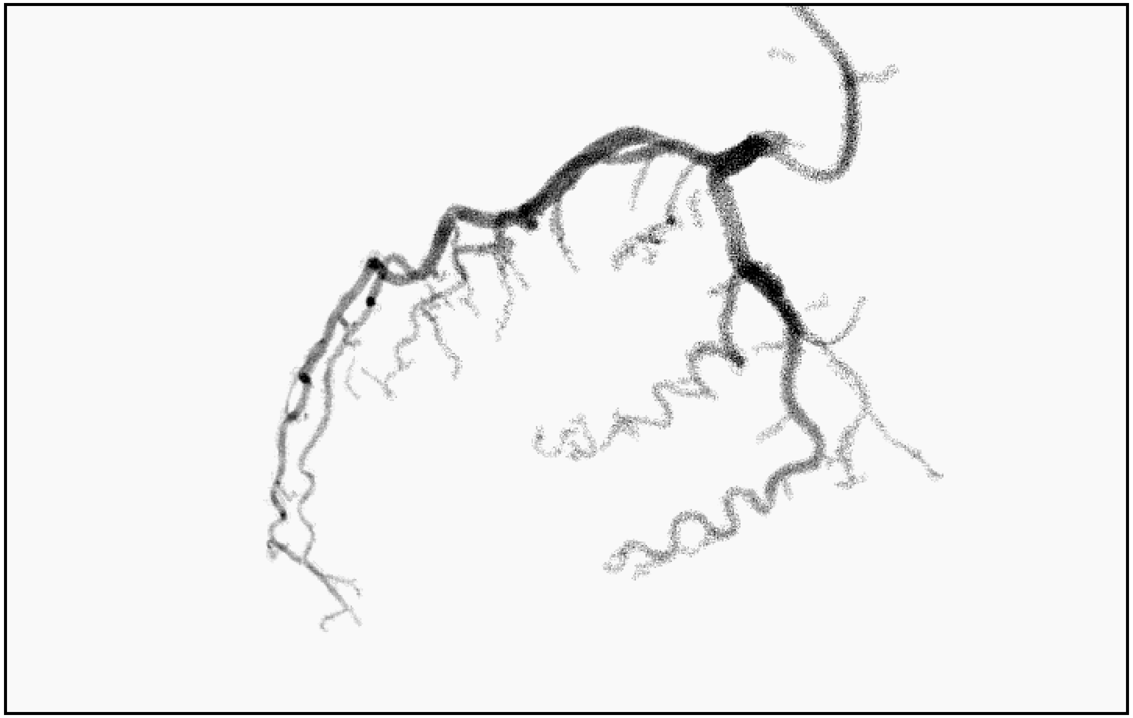
[2] Taubmann et al.: **Convex temporal regularizers in cardiac C-arm CT**, CT Meeting 2016

Temporal Regularization vs. Undersampling



Vessel Extraction [1]

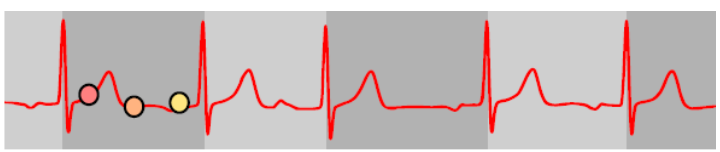
- Thorax is truncated, arteries are not
- Truncation can cause artifacts in tomographic reconstruction
- Perform single-frame background subtraction [1]

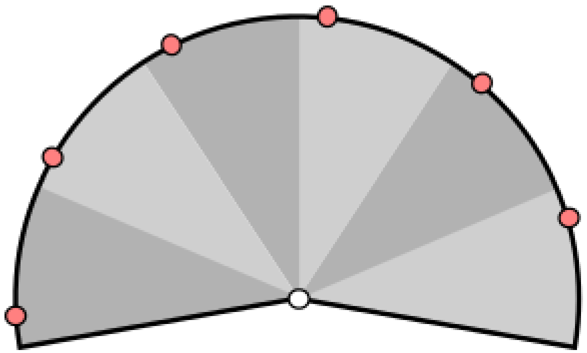


[1] Unberath et al.: **Virtual Single-frame Subtraction Imaging**, CT Meeting 2016

Electrocardiogram Gating

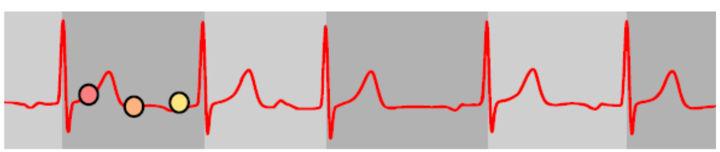
- Vessel images grouped into subsets (gates) based on ECG
- **Trade-off:**
  - Wider windows $\rightarrow$ More data per gate, higher inconsistency
  - Narrower windows $\rightarrow$ Less inconsistency, strongly undersampled

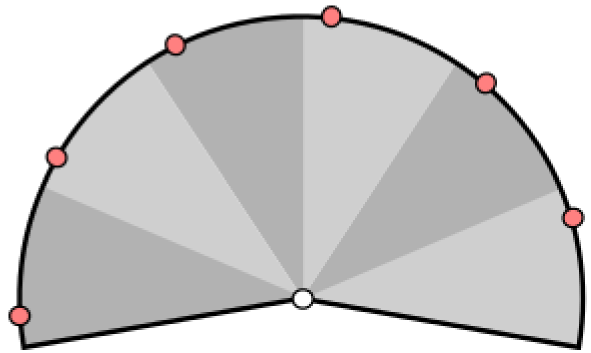




Electrocardiogram Gating

- **Our approach:**
  - Minimize residual motion (select only best fit from each cycle)
  - Choose the total number of gates such that all data is used
  - Compensate for undersampling by temporal regularization





Tomographic 4-D Reconstruction

$$\arg\min_{\boldsymbol{i}} \; r(\boldsymbol{i}) + \lambda_{\mathrm{s}} \cdot \|\boldsymbol{i}\|_{\mathrm{sTV}} + \lambda_{\mathrm{t}} \cdot \|\boldsymbol{i}\|_{\mathrm{tTV}} + \iota_{\mathbb{R}_+}(\boldsymbol{i})$$

Global convex objective function comprised of…

- Data fidelity
- Sparsity in spatial gradient domain
- Sparsity in temporal gradient domain

Objective Function – Data Fidelity

$$\arg\min_{\boldsymbol{i}} \; r(\boldsymbol{i}) + \lambda_\mathrm{s} \cdot \|\boldsymbol{i}\|_\mathrm{sTV} + \lambda_\mathrm{t} \cdot \|\boldsymbol{i}\|_\mathrm{tTV} + \iota_{\mathbb{R}_+}(\boldsymbol{i})$$

$r(\boldsymbol{i}) = \frac{1}{2}\|\boldsymbol{A}\boldsymbol{i} - \boldsymbol{p}\|_2^2$	Squared residual norm
$\boldsymbol{i} \in \mathbb{R}^{N_\mathrm{ph} \cdot N_\mathrm{vox}}$	Voxels to reconstruct (vectorized 4-D image)
$\boldsymbol{p} \in \mathbb{R}^{N_\mathrm{proj} \cdot N_\mathrm{pix}}$	Measured line integrals after gating
$\boldsymbol{A} \in \mathbb{R}^{(N_\mathrm{proj} \cdot N_\mathrm{pix}) \times (N_\mathrm{ph} \cdot N_\mathrm{vox})}$	X-ray projection operator
$\iota_{\mathbb{R}_+}$	Characteristic function for non-negativity

Objective Function – TV Regularization

$$\arg\min_{\boldsymbol{i}} \; r(\boldsymbol{i}) + \lambda_{\mathrm{s}} \cdot \|\boldsymbol{i}\|_{\mathrm{sTV}} + \lambda_{\mathrm{t}} \cdot \|\boldsymbol{i}\|_{\mathrm{tTV}} + \iota_{\mathbb{R}_+}(\boldsymbol{i})$$

$\|\boldsymbol{i}\|_{\mathrm{sTV}} = \|\boldsymbol{D}_{\mathrm{s}}\boldsymbol{i}\|_{1,2}$	Spatial TV norm (sum of spatial gradient magnitudes)
$\|\boldsymbol{i}\|_{\mathrm{tTV}} = \|\boldsymbol{D}_{\mathrm{t}}\boldsymbol{i}\|_{1}$	Temporal TV norm (sum of temporal gradients)
$\boldsymbol{D}_{\mathrm{s}}$	Spatial forward-difference operator (zero boundary)
$\boldsymbol{D}_{\mathrm{t}}$	Temporal forward-difference operator (periodic)
$\lambda_{\mathrm{s}}, \lambda_{\mathrm{t}}$	Regularizer weights

Optimization – Proximal Algorithm by Condat [1]

$$
\begin{aligned}
&\boldsymbol{i}_{\mathrm{prev}} \leftarrow \boldsymbol{i} \\
&\boldsymbol{i} \leftarrow \left(\boldsymbol{i} - \tau(\nabla r(\boldsymbol{i}) + \boldsymbol{D}_{\mathrm{s}}^{\top}\boldsymbol{g}_{\mathrm{s}} + \boldsymbol{D}_{\mathrm{t}}^{\top}\boldsymbol{g}_{\mathrm{t}})\right)_{+} \\
&\boldsymbol{g}_{\mathrm{s}} \leftarrow \mathrm{prox}_{(\lambda_{\mathrm{s}}\|\cdot\|_{1,2})^*}(\boldsymbol{g}_{\mathrm{s}} + \sigma\boldsymbol{D}_{\mathrm{s}}(2\boldsymbol{i} - \boldsymbol{i}_{\mathrm{prev}})) \\
&\boldsymbol{g}_{\mathrm{t}} \leftarrow \mathrm{prox}_{(\lambda_{\mathrm{t}}\|\cdot\|_{1})^*}(\boldsymbol{g}_{\mathrm{t}} + \sigma\boldsymbol{D}_{\mathrm{t}}(2\boldsymbol{i} - \boldsymbol{i}_{\mathrm{prev}}))
\end{aligned}
$$

Updates given by full primal-dual splitting

- TV proximal operator (no closed-form solution) replaced by linear transforms and L^1 / $L^{1,2}$ proximal operators (analytic solution)
- Therefore: “simple” operations only, no nested loops

[1] Condat: **A Generic Proximal Algorithm for Convex Optimization – Application to Total Variation Minimization**, *IEEE Signal Processing Letters,* 2014

Experiments

- CAVAREV [1]
  - Overview
    - Platform for evaluating cardiac vasculature reconstruction
    - Dynamic numerical phantom derived from patient data
    - Projections simulated using acquisition geometry of a real C-arm
  - Specifics
    - **7 heart cycles**, 133 projection images
    - Variant without respiratory motion (breathhold assumption)
    - 19 (= 133/7) gates, 256^3 voxels of isotropic size 0.5 mm

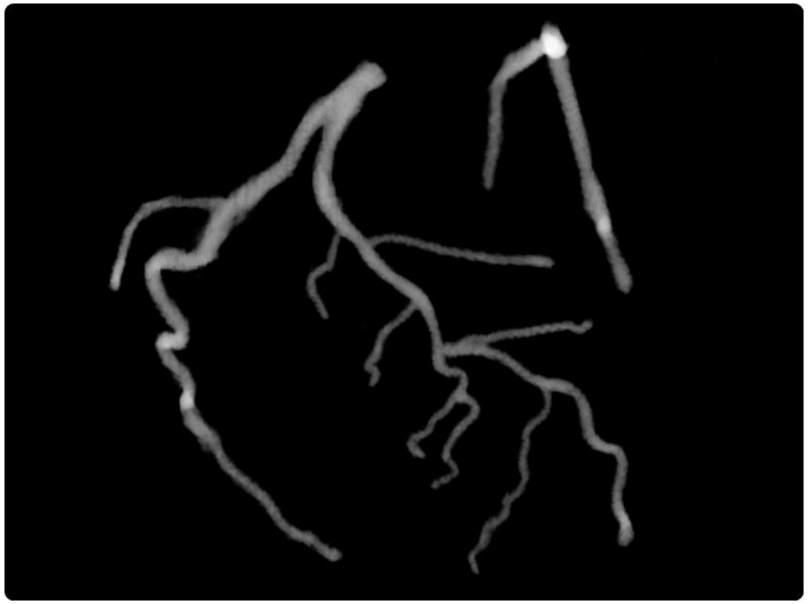
[1] Rohkohl et al.: **CAVAREV – An Open Platform for Evaluating 3D and 4D Cardiac Vasculature Reconstruction**, Phys Med Biol 2010

Experiments

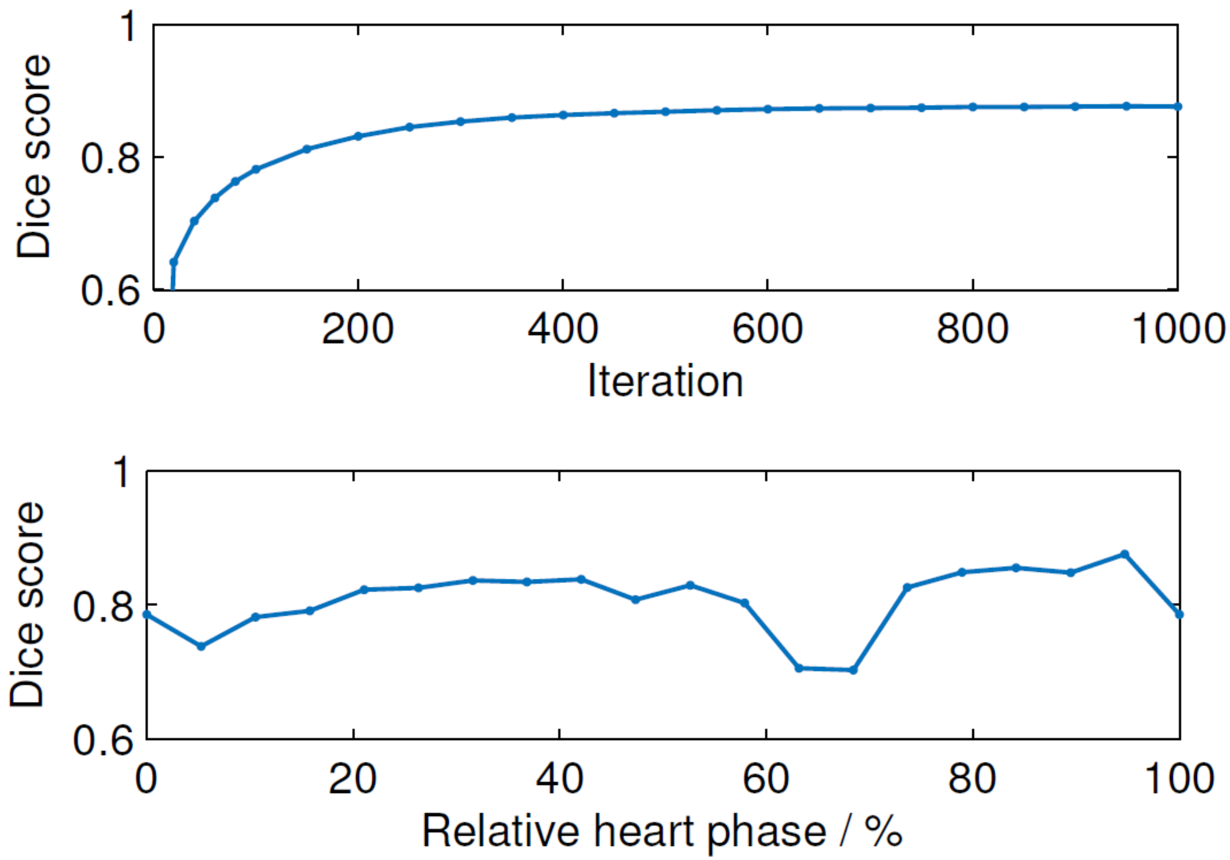
- Exemplary clinical patient data set
  - Device: Artis one (Siemens Healthcare GmbH, Forchheim, Germany)
  - **5 heart cycles**, 133 projections (4s rotation)
  - 27 (≈133/5) gates, 256^3 voxels of isotropic size 0.5 mm
  - Qualitative evaluation (visual inspection)

Results: CAVAREV

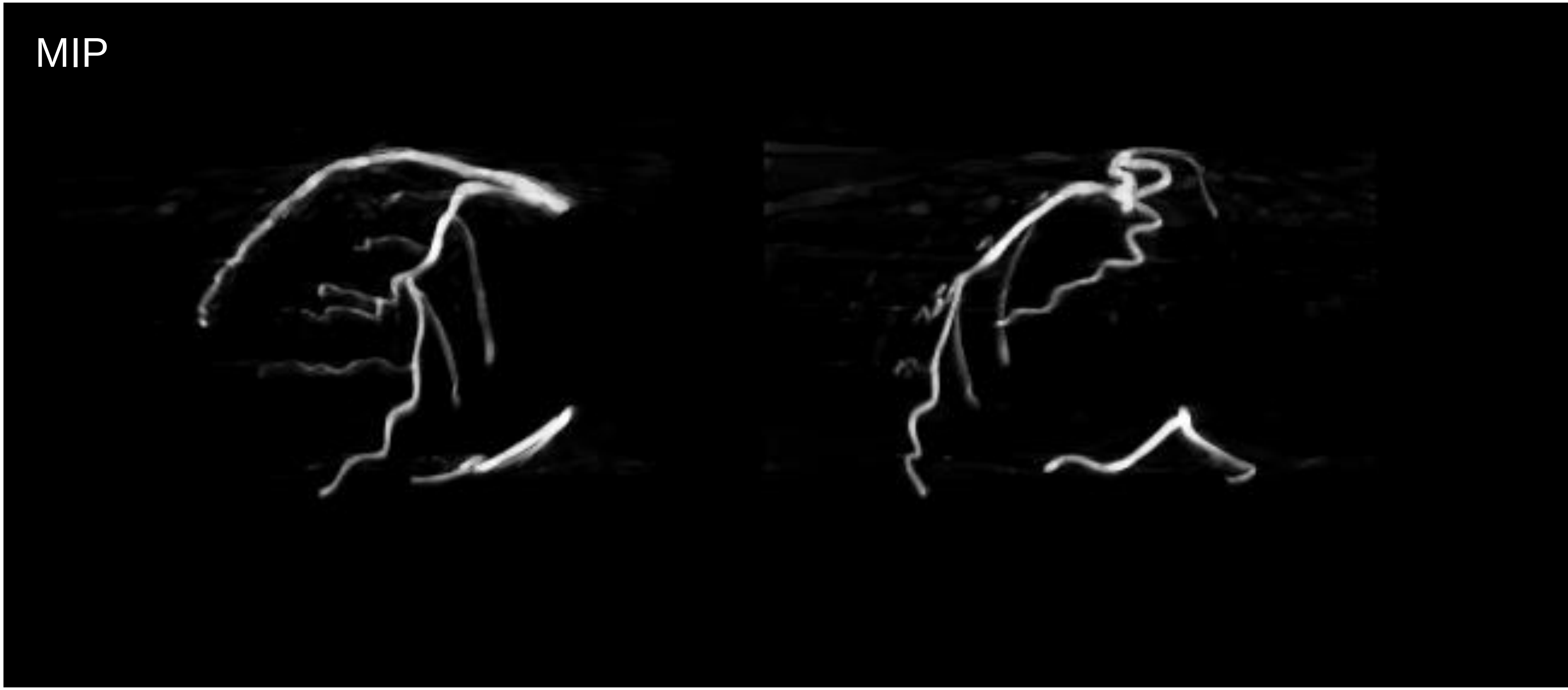
Method	Dice
Standard FDK	0.431
ECG-Gated FDK	0.595
Dynamic Level Sets [Keil 2009]	0.692
PICCS [Wu 2011, Chen 2012]	0.726
L1 minimization [Wu 2011, Li 2004]	0.730
Streak-Red. Gated FDK [Rohkohl 2008]	0.744
Resid. Motion Comp. [Schwemmer 2013a]	0.776
Spatial Total Variation [Wu 2011]	0.785
Motion Compensation [Schwemmer 2013b]	0.823
Spatio-temporal TV (proposed)	**0.876**



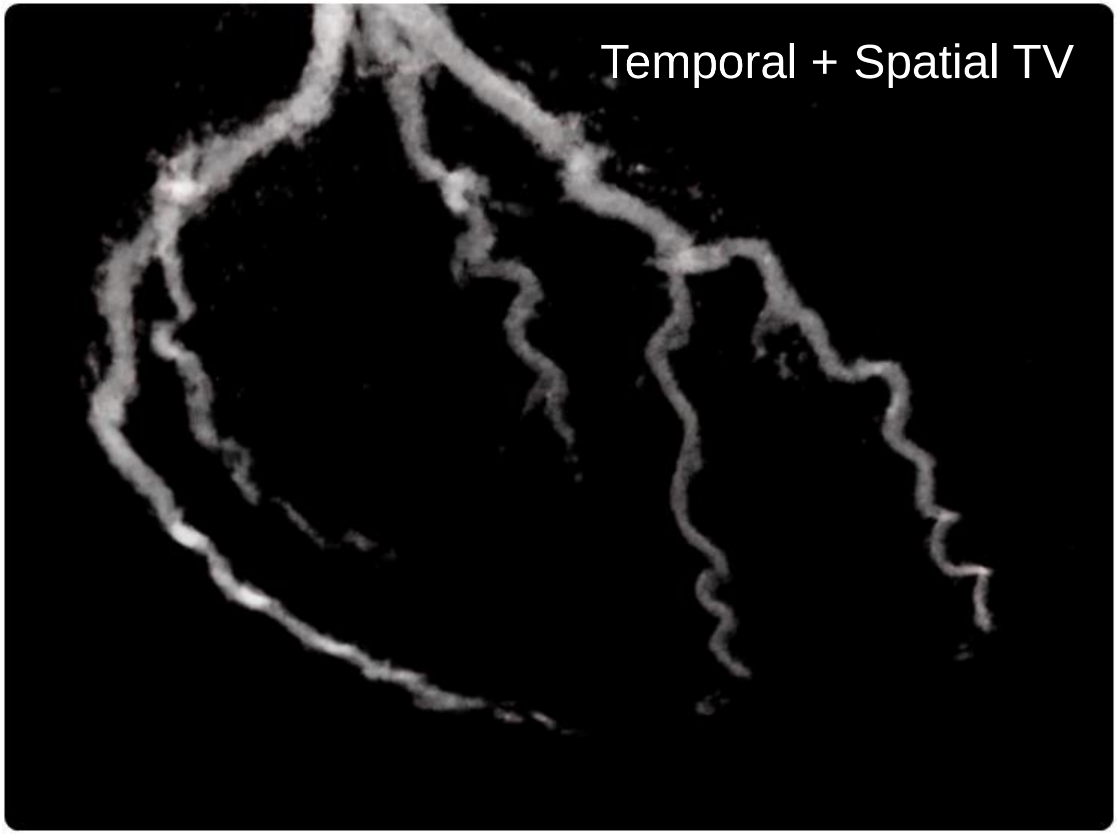
Results: CAVAREV



Results: CAVAREV



Results: Clinical Data



Summary and Outlook

- Key idea:
  - Minimize residual motion within each gate
  - Exploit all data by spatio-temporal regularization

Potential extensions:

- Temporal regularization for background subtraction
  - Reduce inconsistency due to segmentation errors
- Respiratory motion compensation
  - E.g. based on Fourier-domain or epipolar consistency conditions
  - Applicable since extracted vessel images are not truncated

Thanks for your attention!

Questions?