Keeping the Pace

Heart Rate Informed 3-D Motion Detection for Adaptive Temporal Smoothing

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Fully4D June 4, 2015

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Clinical Setting

- Interventional 4-D (3-D+t) cardiac imaging with C-arm systems

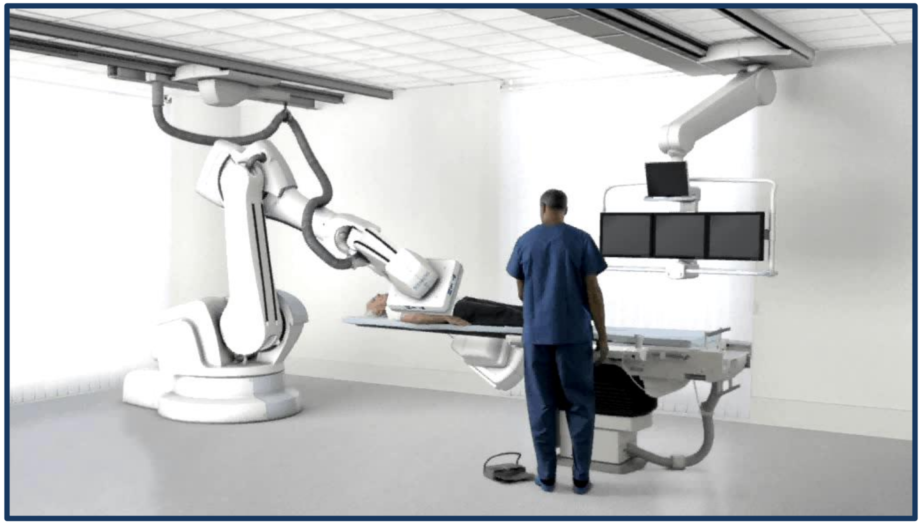


Fig.: Artis zeego multi-axis C-arm system, Siemens Healthcare GmbH, Forchheim, Germany.

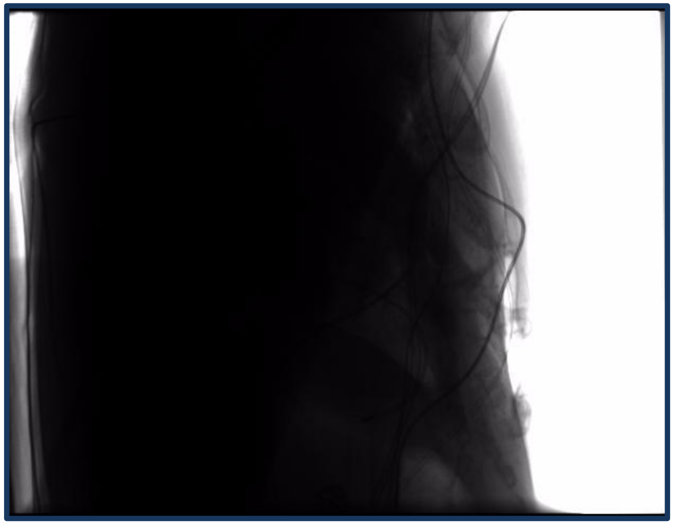


Fig.: Rotational angiogram, courtesy of Dr. Bernd Abt, Centre of Cardio-vascular Diseases, Rotenburg a.d. Fulda, Germany.

Gated Reconstruction

- Retrospective electrocardiography (ECG) gating [1]

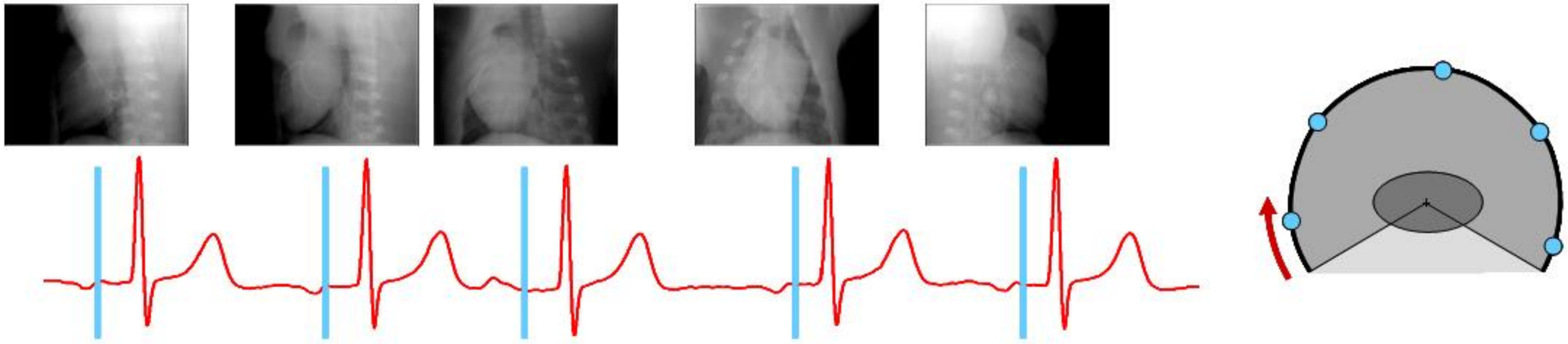


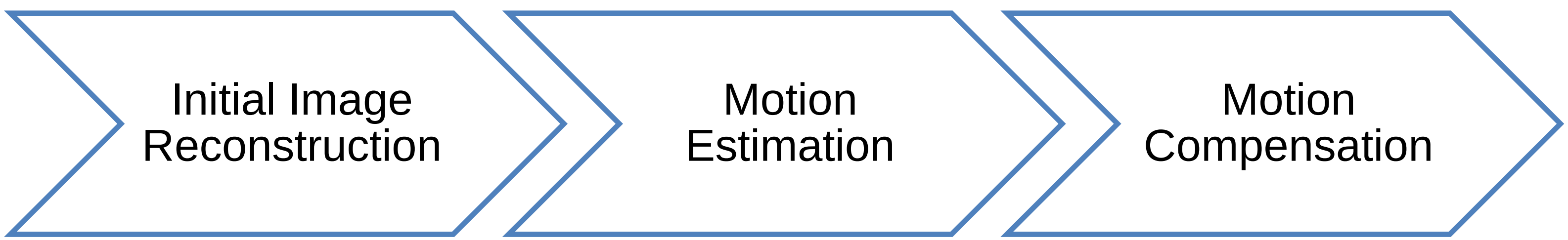
Fig.: Projection images from a C-arm sweep belonging to the same relative heart phase.

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

State-of-the-Art: Motion Compensation

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

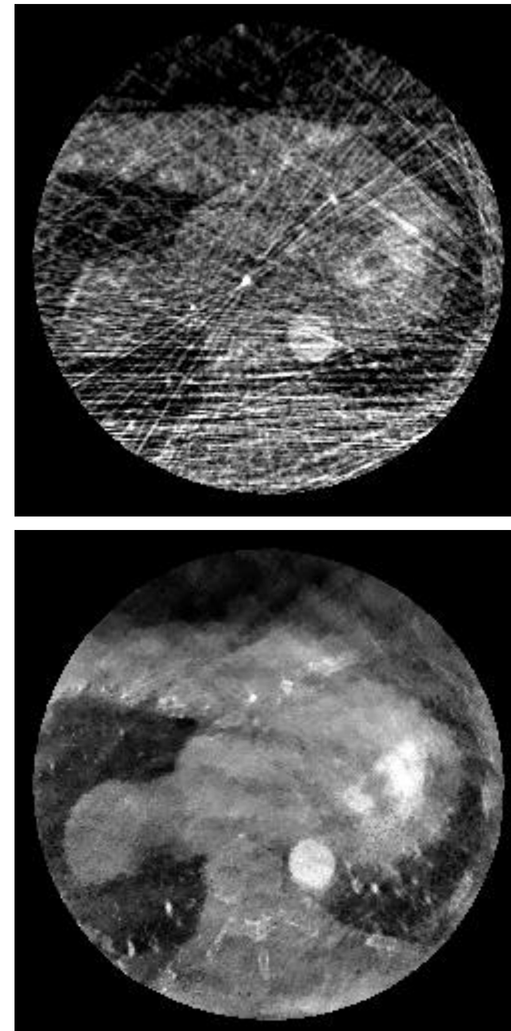
- Approach: Motion compensated reconstruction [1]
  - Estimate motion from initial reconstruction
  - Final reconstruction from all data



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

Initial Image Reconstruction

- Severe artifacts in clinical patient data
- Reduced significantly by several steps:
  - Catheter removal [1]
  - Thresholding of filtered projections
  - McKinnon-Bates artifact suppression [2]
  - Joint bilateral filtering

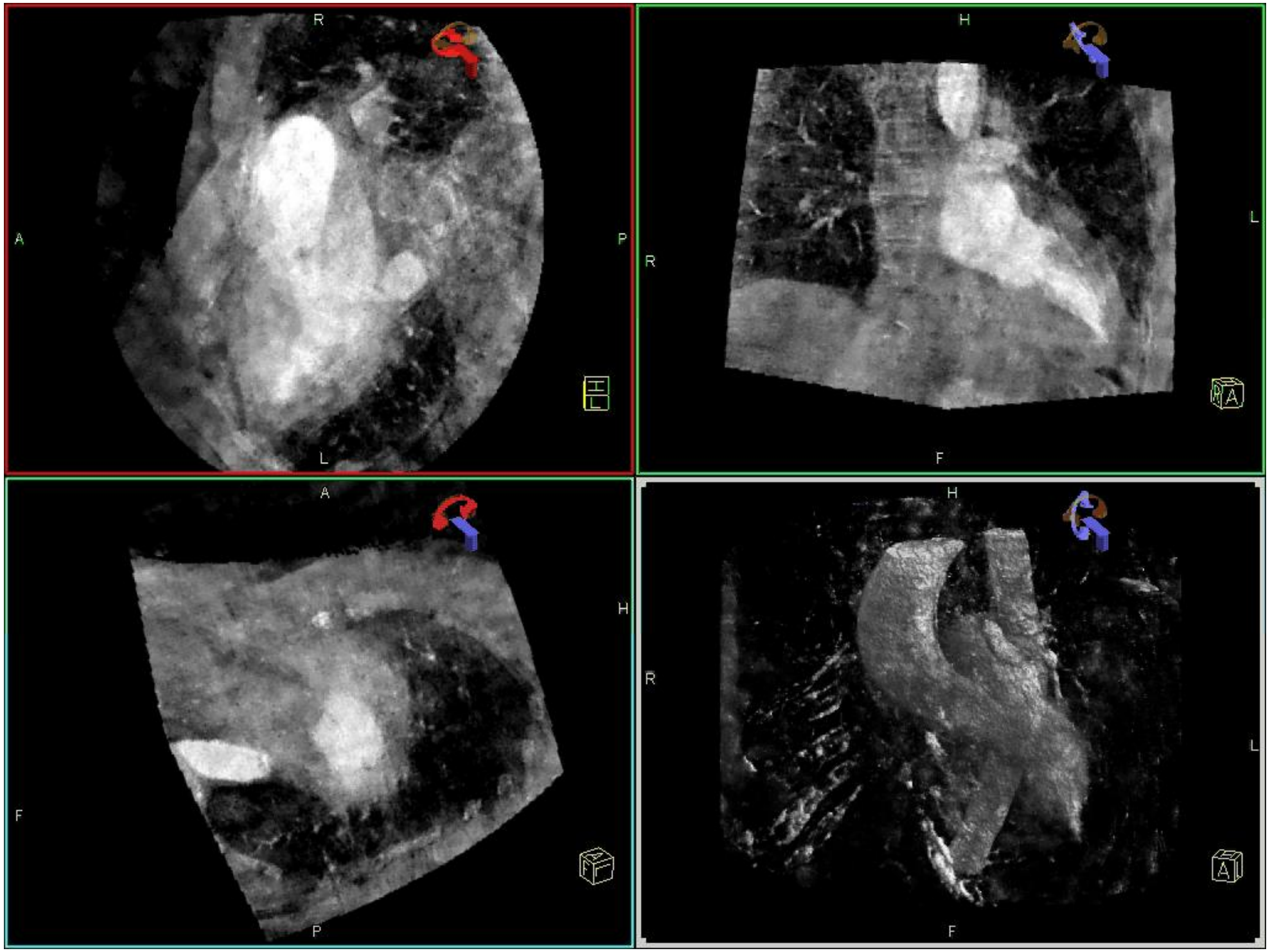


[1] Müller et al.: **Catheter artifact reduction (CAR) in dynamic cardiac chamber imaging with interventional C-arm CT,** *Proc. 3rd international conference on image formation in X-ray CT*, pp. 418-421, 2014

[2] Mc Kinnon and Bates: **Towards imaging the beating heart usefully with a conventional CT scanner**, *IEEE Trans. Biomed. Eng.*, 1981

Fig.: Axial views of ECG-gated reconstructions from clinical data, with (bottom) and without (top) artifact reduction. Data courtesy of Dr. Abt, Centre of Cardiovascular Diseases, Rotenburg a.d. Fulda.

Temporal Inconsistency



Heart Rate Informed 3-D Motion Detection for Adaptive Temporal Smoothing

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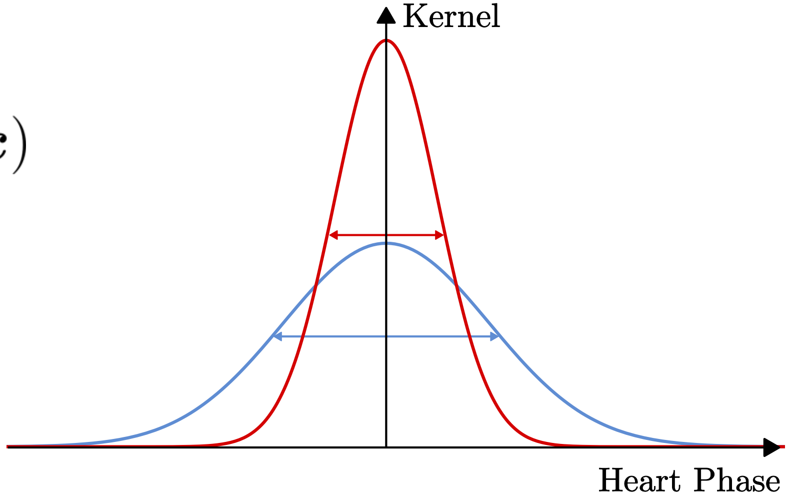
Adaptive Temporal Smoothing

- Perform Gaussian smoothing in temporal domain:

$$\boldsymbol{I}_s^t(\boldsymbol{x}) = \sum_{t'=0}^{N_{\text{phases}}} \boldsymbol{I}^{t'}(\boldsymbol{x}) \cdot \frac{1}{\sigma(\boldsymbol{x})\sqrt{2\pi}} \exp\left(-\frac{\text{dist}^2(t,t')}{2\sigma^2(\boldsymbol{x})}\right)$$

- Choose $\sigma(\boldsymbol{x})$ dependent on the amount of cardiac motion $\boldsymbol{M}_{\text{w}}(\boldsymbol{x})$



$$\sigma(\boldsymbol{x}_i) \leq \sigma(\boldsymbol{x}_j) \Leftrightarrow \boldsymbol{M}_{\text{w}}(\boldsymbol{x}_i) \geq \boldsymbol{M}_{\text{w}}(\boldsymbol{x}_j)$$

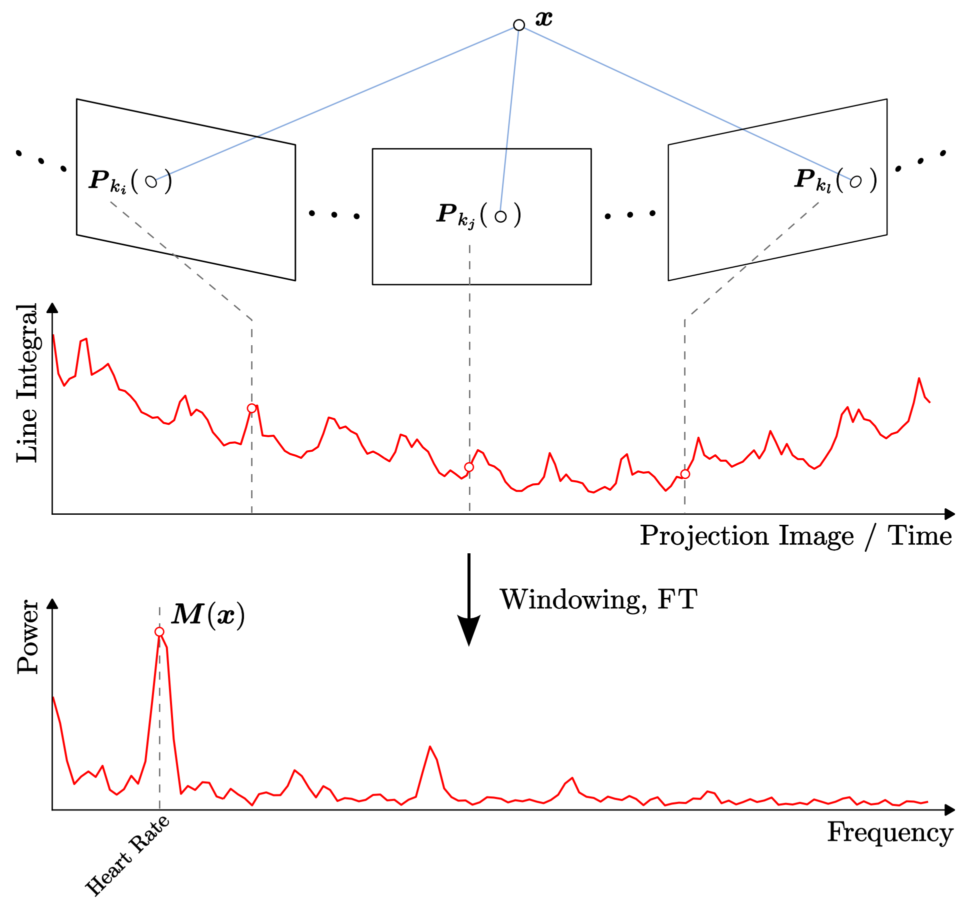
Heart Rate Informed 3-D Motion Detection

- Center piece of our method

- Key ideas:
  1. Projections show heart motion, but no artifacts correlated with it
  2. High temporal resolution (many individual heart beats)
  3. Frequency (heart rate!) is known from the ECG

Heart Rate Informed 3-D Motion Detection

- Approach:
  1. "Follow" $\boldsymbol{x}$ over the whole sweep
  2. Consider line integrals as temporal profile
  3. Perform frequency analysis, compute power spectrum
  4. Obtain energy $M(\boldsymbol{x})$ assoc. with heart rate



Motion Maps

Spatial distribution of heart rate energy visualized:

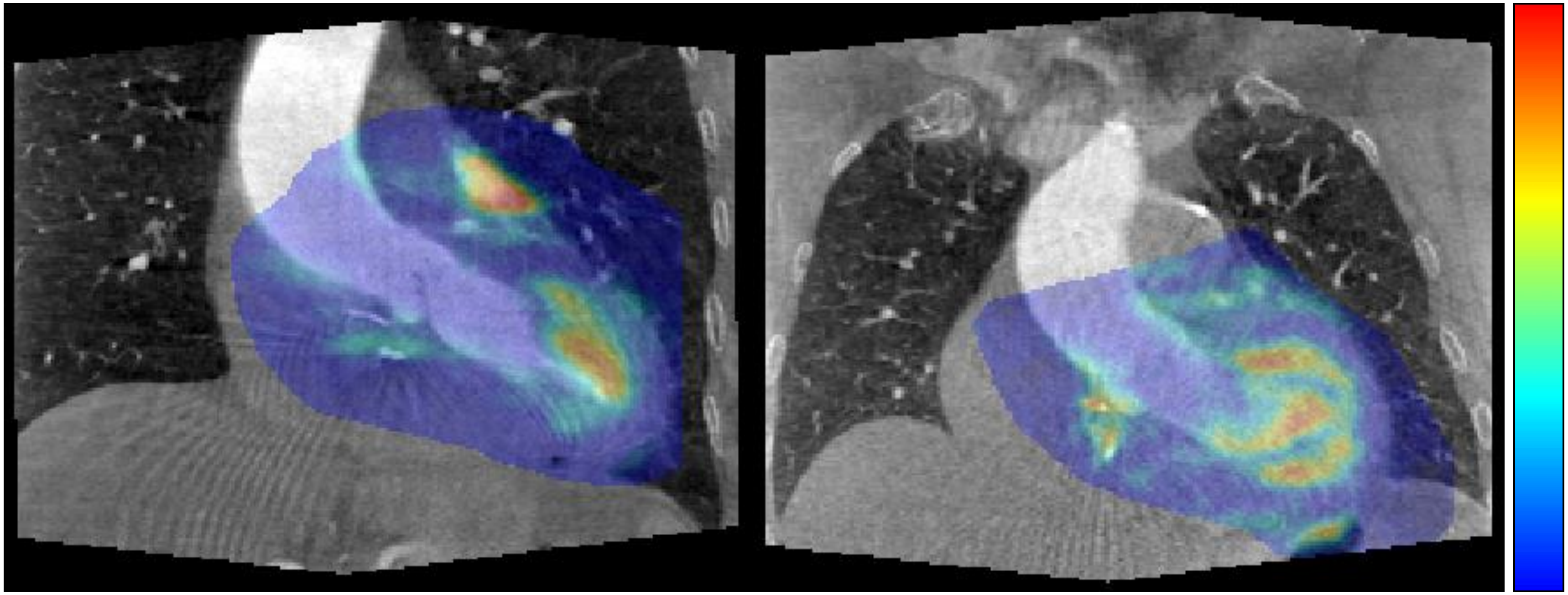
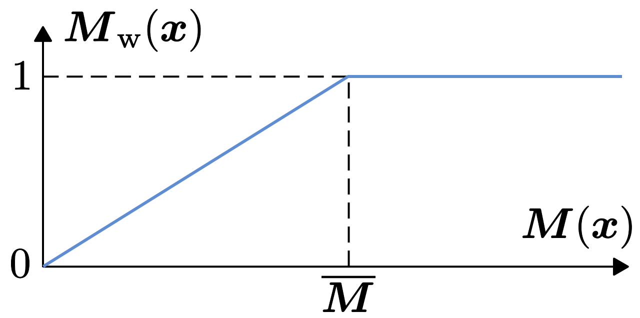


Fig.: Color-coded visualizations of detected cardiac motion inside considered ROI for patients 1 and 2. Overlayed on reconstruction from all data for orientation. Warmer hues correspond to larger motion.

Heart Rate Informed 3-D Motion Detection

- Remove outliers and denoise:
  - Median filter (3 x 3)
  - Blur filter (1.5 mm std. dev.)

- Normalization:



- Linear interpolation of $\sigma(\boldsymbol{x})$:

$$\sigma(\boldsymbol{x}) = \sigma_{\min} \cdot \boldsymbol{M}_{\mathrm{w}}(\boldsymbol{x}) + \sigma_{\max} \cdot (1 - \boldsymbol{M}_{\mathrm{w}}(\boldsymbol{x}))$$

Experiments and Results

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Data

- 2 clinical patient data sets (Rotenburg a. d. Fulda):
  - Acquisition duration 14.5 s, 381 projection images
  - Right ventricular pacing to 115 bpm (~27 heart beats)
  - Systemic contrast injection (91 ml total, pulmonary artery)

- Dynamic heart phantom data set [1,2]
  - Projections simulated using polychromatic X-ray spectrum
  - 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

Experimental Setup

1. Generate initial images with and without temporal smoothing
2. Perform motion estimation and compensation on both
3. Compare final images (same projections, different motion)

Temporal Inconsistency Measured

- Static (uncontrasted, yellow) vs. dynamic (contrasted, red) regions
  - Uncontrasted blood / tissue should barely vary over time
  - Temporal variation in LV blood pool due to motion should be preserved

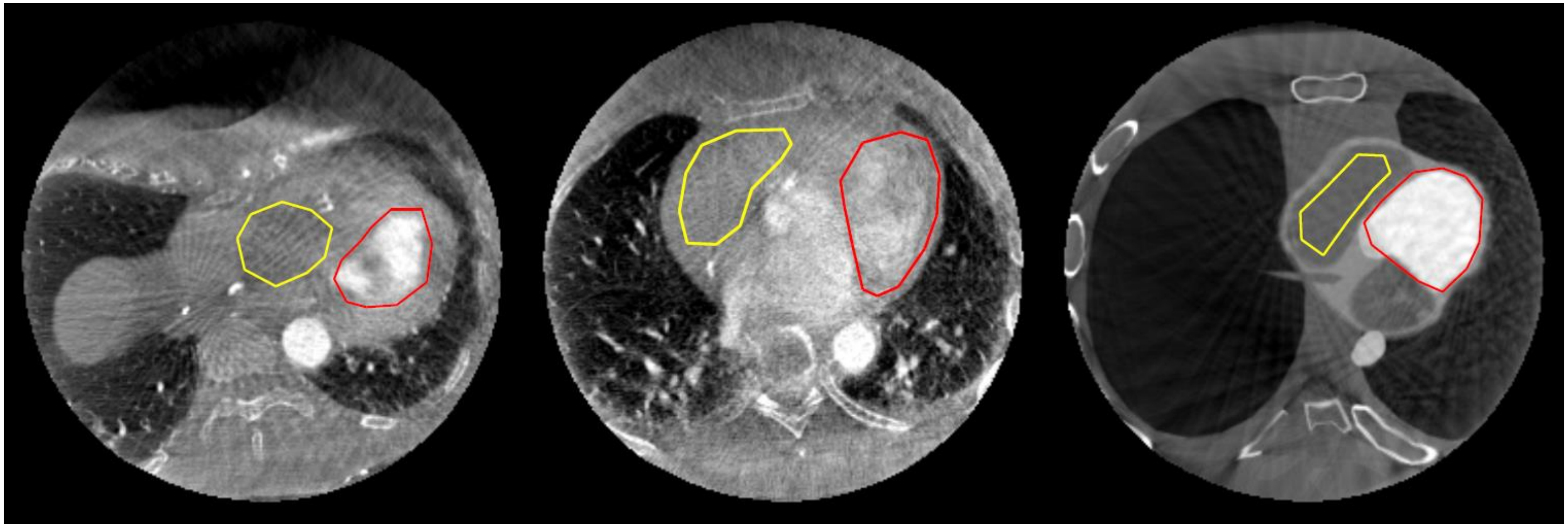


Fig.: Regions chosen for quantitative evaluation in patient 1, patient 2, and the phantom.

Temporal Inconsistency Measured

- Temporal statistics (mean $\pm$ **std**), averaged over regions:

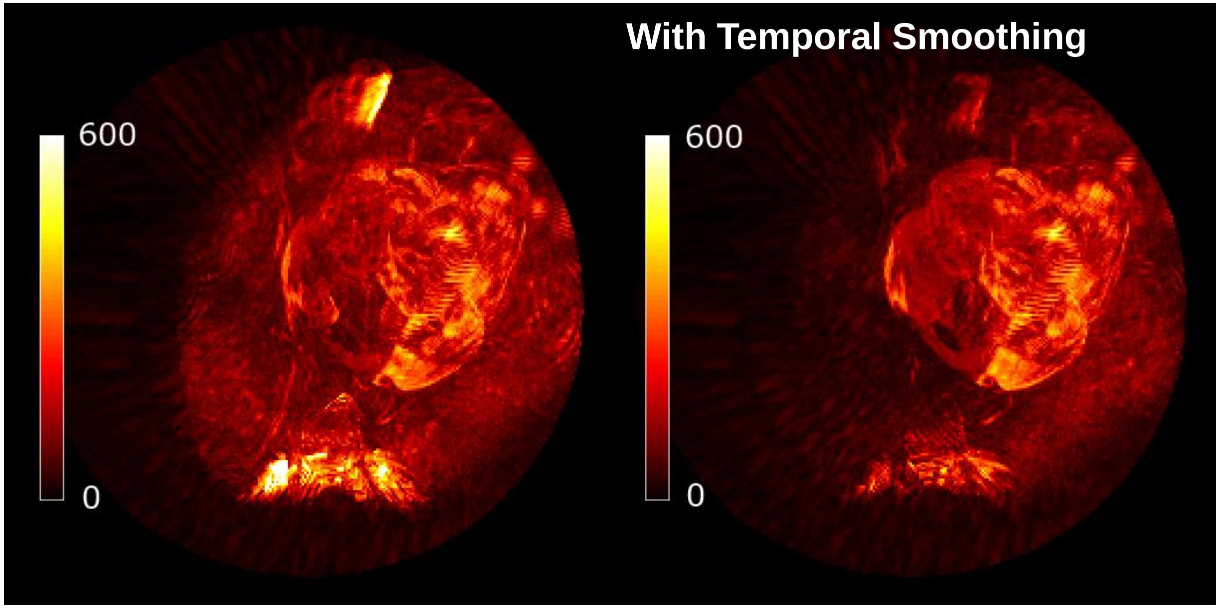
Data set	TS	Static	Dynamic
Patient 1	-	$634 \pm \mathbf{70}$	$964 \pm \mathbf{154}$
	✓	$635 \pm \mathbf{32}$	$959 \pm \mathbf{148}$
Patient 2	-	$776 \pm \mathbf{49}$	$870 \pm \mathbf{83}$
	✓	$776 \pm \mathbf{23}$	$866 \pm \mathbf{78}$
Phantom	-	$593 \pm \mathbf{33}$	$1232 \pm \mathbf{110}$
	✓	$594 \pm \mathbf{12}$	$1230 \pm \mathbf{107}$

- Static: Std. dev. reduced by more than 50%
- Dynamic: Almost no change (despite higher means)

Phantom: Reduced Error

- RMSE reduced by about 9%
  - Not as dramatic as decrease in temporal variance
  - Improved temporal consistency reduces artifacts in spatial domain

Fig.: Phantom model re-constructions. Motion estimated from initial images processed with (right) and without (left) temporal smoothing. Color-coded error images: Absolute difference, MIP along z.



In Motion (Axial)

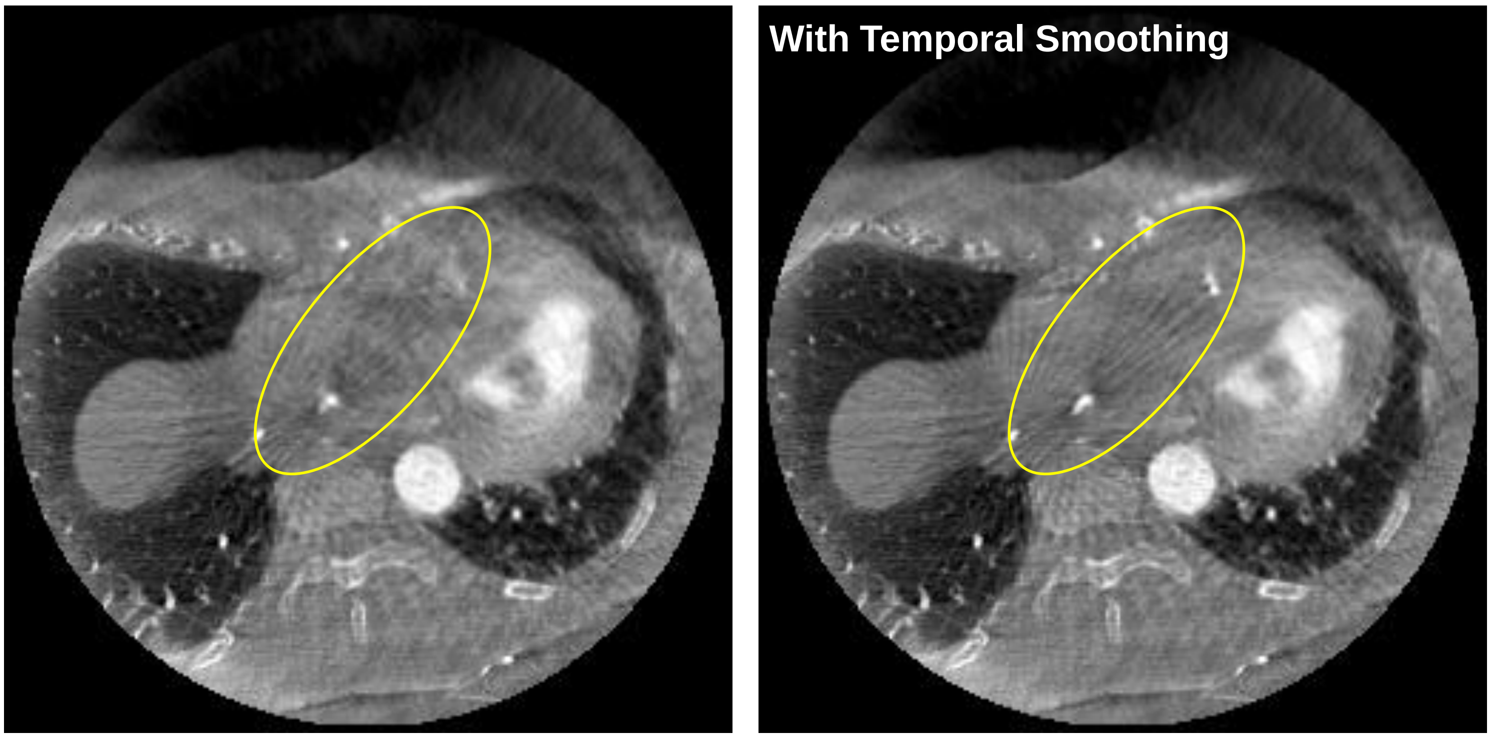


Fig.: Reconstructions for patient 1, animation of 10 phases in the cardiac cycle.

In Motion (Long Axis)

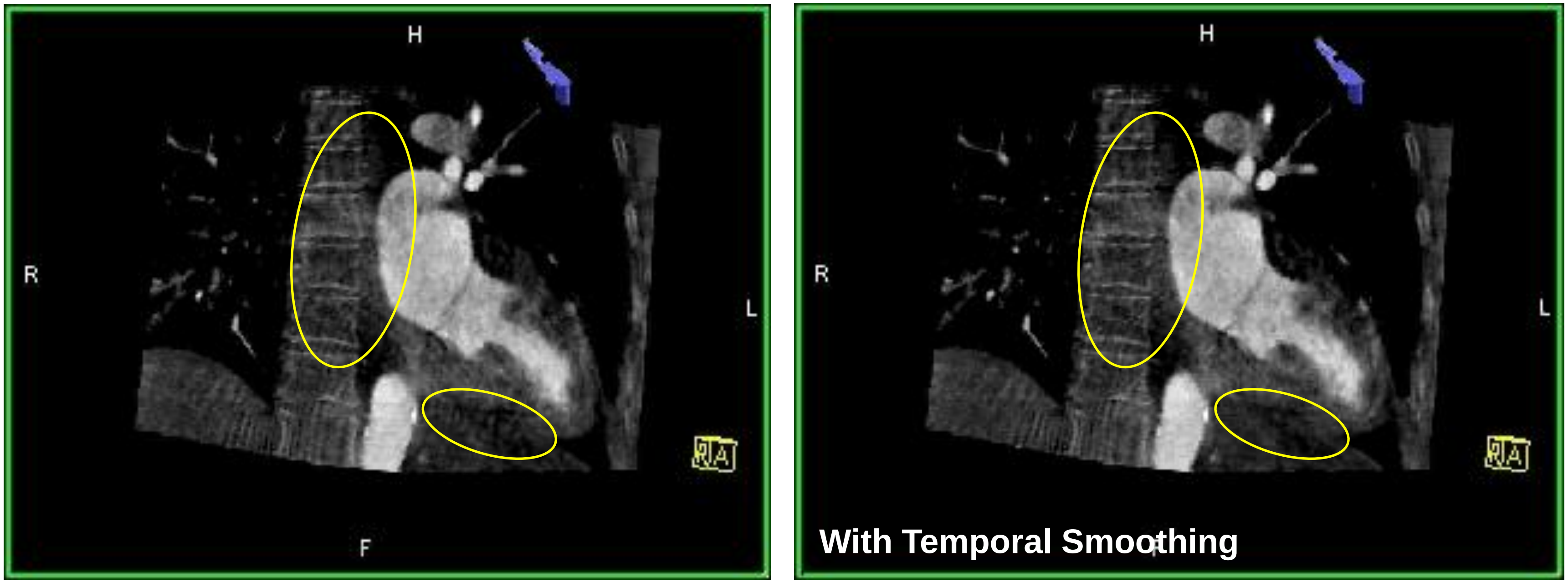


Fig.: Reconstructions for patient 1, animation of 10 phases in the cardiac cycle.

In Motion (Short Axis)

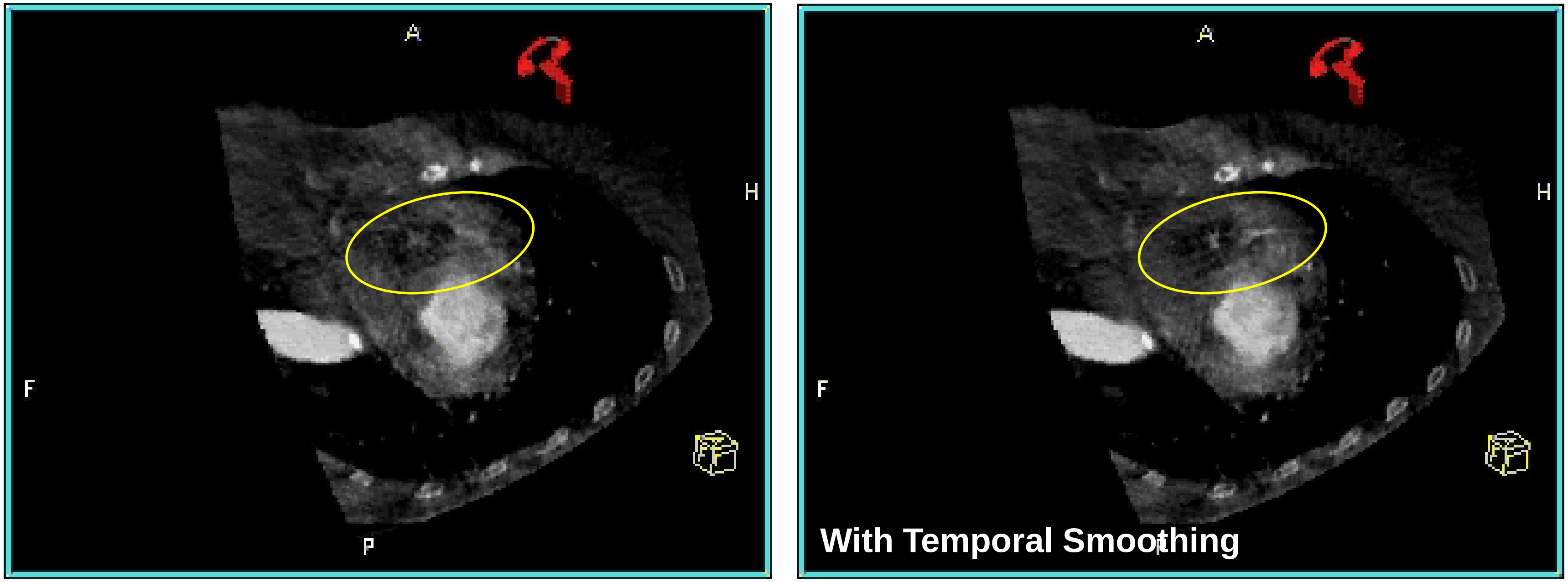


Fig.: Reconstructions for patient 1, animation of 10 phases in the cardiac cycle.

Summary

- Improving initial images for motion compensated reconstruction:

Heart Rate Informed 3-D Motion Detection

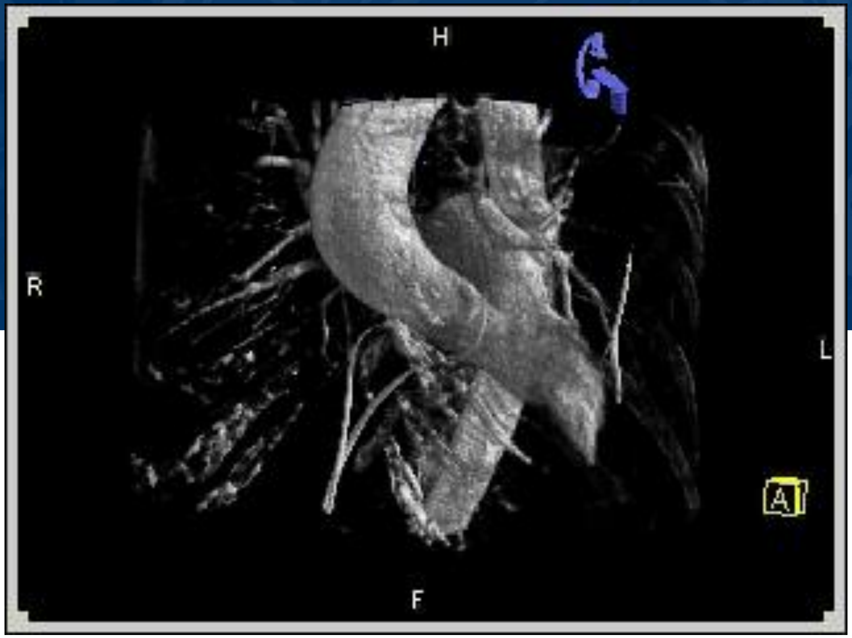
- Frequency analysis of acquired projection images over time
- Efficient parallel computation for a single frequency

↓

Adaptive Temporal Smoothing

- Based on spatial distribution of detected cardiac motion magnitudes
- Reduces temporal inconsistency while keeping the heart pace :-)

- For other protocols: potential extension of motion detection to, e.g., irregular heartbeat (arrhythmia)



Thanks for your attention!

Any questions?

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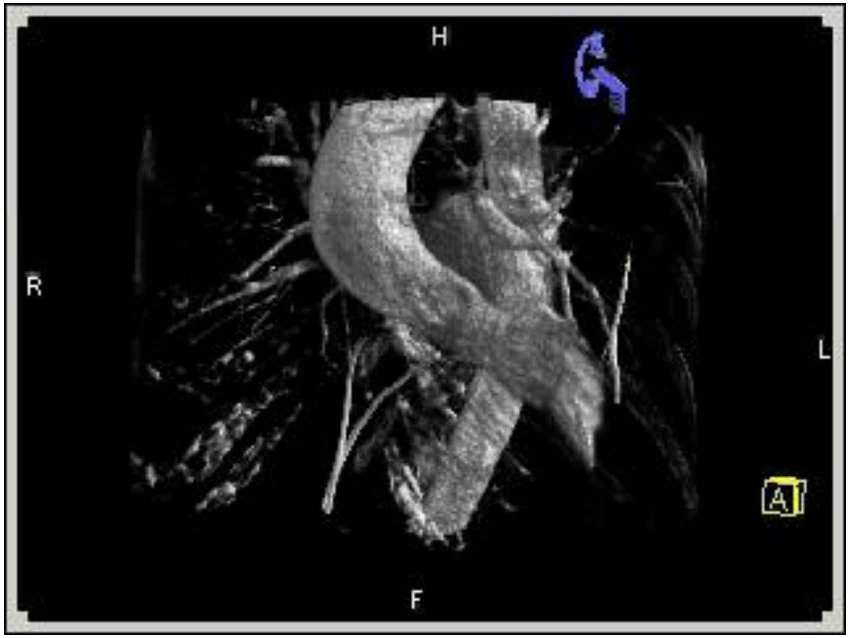
In Motion (Long Axis)

Fig.: Reconstructions for patient 1, animation of 10 phases in the cardiac cycle.

In Motion (VRT)



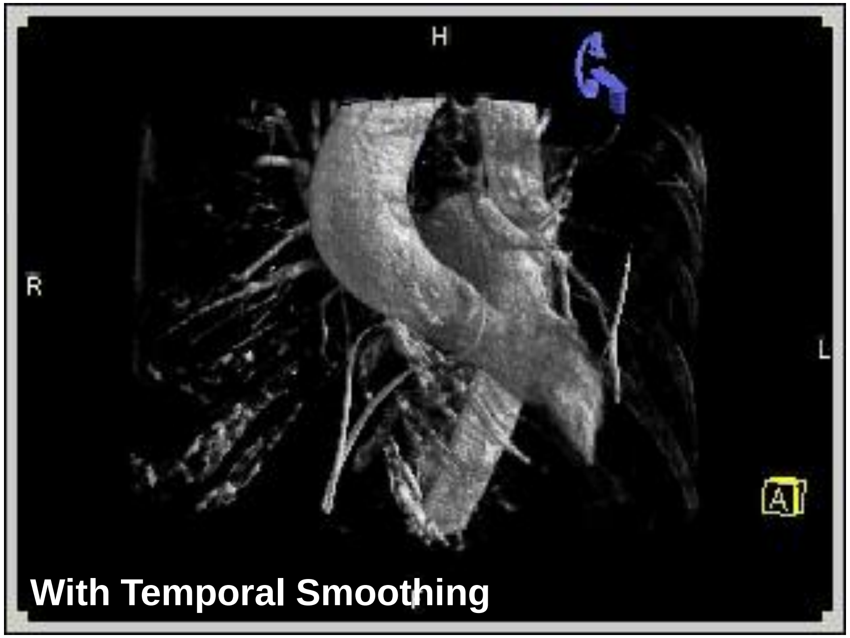


Fig.: Reconstructions for patient 1, animation of 10 phases in the cardiac cycle.

Frequency Analysis

- Computing $\boldsymbol{M}(\mathbf{x})$ in parallel (with FFT): memory in $\mathcal{O}(N_{\text{voxels}} \cdot N_{\text{proj}}) \Rightarrow$ prohibitive, unless done blockwise!

- Better approach: Görtzel filter [1]
  - Computes DFT for a single frequency efficiently
  - Two-stage recursive filter (i.e., constant memory footprint)

- Advantages over FFT (in our use case):
  - Memory complexity of $\mathcal{O}(N_{\text{voxels}})$ vs. $\mathcal{O}(N_{\text{voxels}} \cdot N_{\text{proj}})$
  - Runtime complexity of $\mathcal{O}(N_{\text{proj}})$ vs. $\mathcal{O}(N_{\text{proj}} \cdot \log N_{\text{proj}})$

[1] Goertzel et al.: **An algorithm for the evaluation of finite trigonometric series**, *American Mathematical Monthly*, 1958.