# Real-Time MRI

## Ulm PhD Training

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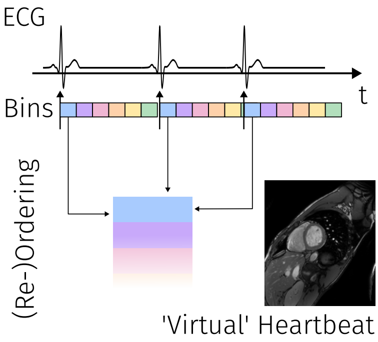
# Motion in MRI: Two different approaches

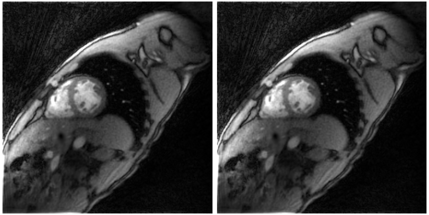
## Cine MRI

- Combine data from multiple heartbeats




## Real-Time (Cine) MRI

- One frame = one “timepoint”

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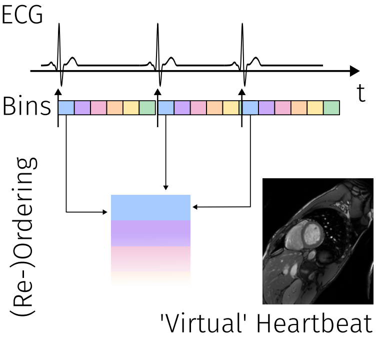


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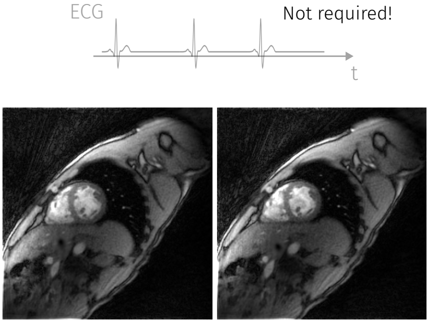

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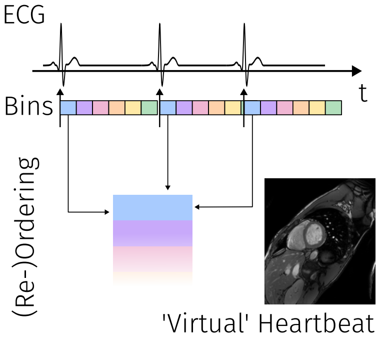


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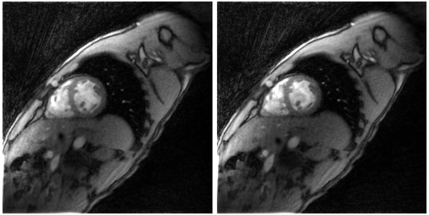

## Real-Time Reconstruction

“Live”, immediate reconstruction and display

# Advantages and Disadvantages with Cine MRI

## Advantages of Cine

- “More data”
- Comparatively easy reconstruction possible.
- 3D, special contrasts

## Problems with cine

- Assumes periodic motion.
- Breathhold not always possible.
- Impossible for people with arrhythmias.
- Not suitable for interventional MRI.

# Advantages and Disadvantages with Cine MRI

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- "More data"
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- 3D, special contrasts

## Advantages of RT-MRI

- No breathhold.
- No periodic motion assumption.
- Suitable for interventional MRI.

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# Ingredients for RT-MRI

Want: temporal resolution $\leq 40\,\text{ms}$ [1]
Typical TR is $\sim 2\,\text{ms}$.
→ ca. 20 spokes per frame → Insufficient data per frame.

## Sampling

- Pattern varies over time
  - Turn-based radial patterns
  - Golden angle patterns
  - ...

## Reconstruction

- Even using PI/CS, insufficient data.
- Incorporate data from future/past
- Directly, through regularization, ...

[1] Koktzoglou et al., *Radiology: Cardiothoracic Imaging*, 2024

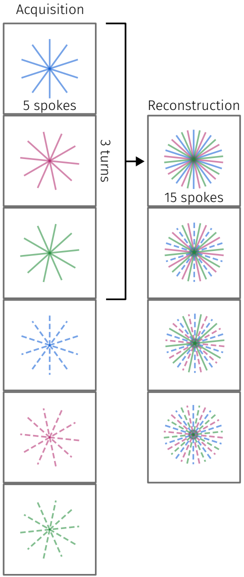
# A simple real-time MRI method: turn-based sliding window adjoint NuFFT

## Acquisition

- Acquisition with linear radial trajectory
- Turn by 1 / (turns · spokes) after every frame

## Reconstruction

- Adjoint Non-Uniform FFT (from k- to img space)
- Ram-Lak filter (compensate non-uniform sampling)
- Root-sum-of-squares coil combination.



# Reconstruction with the Adjoint NuFFT

Usual centered DFT definition:

$$\mathcal{F}x(k) = \sum_{n=0}^{N-1} x_n e^{-2\pi i \frac{n-c}{N}(k-c)}$$

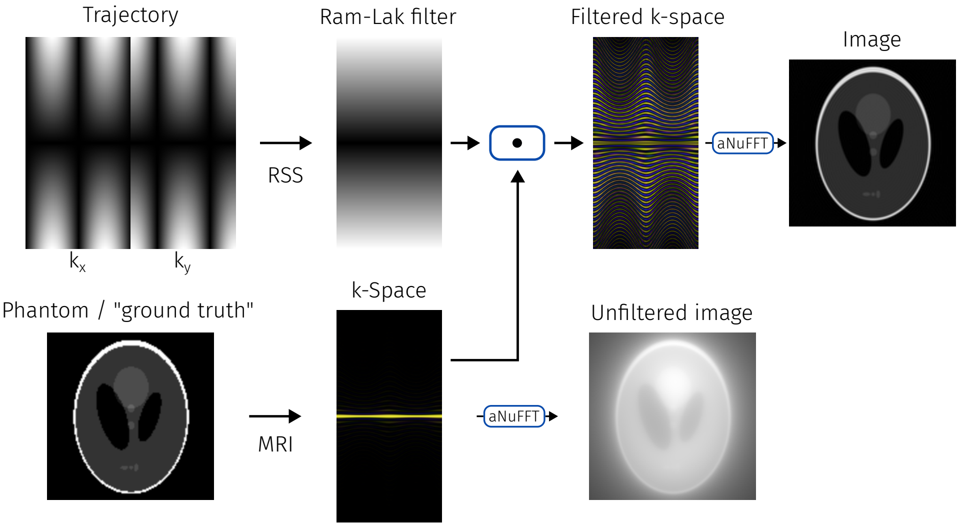
Non-uniform discrete Fourier Transform (Type I):

$$\mathcal{F}x(f_k) = \sum_{n=0}^{N-1} x_n e^{-2\pi i \frac{n-c}{N} f_k}$$

$x$=data,
$k$=k-space indices ($0 \ldots K-1$),
$N$=amount of samples in image space,
$c$=$\frac{N}{2}$ center,
$f_k$ k-space coordinates: **Trajectory**

- Problem: Inverse NuFFT is not straightforward.
- Adjoint can serve as a surrogate.
- But only if data is filtered, to revert effect of sampling density:

# Ram-Lak Filter[2] in Action




[2] Ramachandran et al., *Proceedings of the National Academy of Sciences*, 1971

# Sliding window applicability

## Problems

- Temporal resolution very limited
- Suboptimal image quality

## Uses

- Very simple reconstruction.
- Can help “debugging” reconstruction.
- Obtain fully-sampled calibration data.

# Recap: Iterative Reconstruction

The MRI forward operator:

$$A = \mathcal{P}\mathcal{F}\mathcal{C}$$

- $\mathcal{P}$ Pattern / Undersampling
- $\mathcal{F}$ Discrete Fourier Transform
- $\mathcal{C}$ Multiplication with coil sensitivies

Iterative MRI reconstruction solves

$$\text{argmin}_x ||Ax - y||_2^2 + \mathcal{R}(x)$$

Where

- $x$: image to be reconstructed
- $y$: raw data
- $\mathcal{R}$: Regularization term(s)

# Advancing the reconstruction

$$\text{argmin}_x ||Ax - y||_2^2 + \mathcal{R}(x) \tag{1}$$

## Iterative reconstruction

- BART provides an inverse NuFFT: `bart nufft -i`
- Effectively, solve Eq. 1 with $A = \mathcal{P}\mathcal{F}$, separately for every coil.

## Parallel imaging

- Using `bart pics -t trj ksp coils img`, solve with $A = \mathcal{P}\mathcal{F}\mathcal{C}$

## Regularization

- $\mathcal{R} \neq 0$: `bart pics -R`
- Penalize difference to previous frame.
- Remove sliding window.

# iterative Golden-angle RAdial Sparse Parallel MRI[3]

**Method:**

- Trajectory: (Tiny) Golden Angle trajectory
- Iterative reconstruction
- Regularization: Total variation along time: $\mathcal{R} = ||\nabla x||_1$

**In BART:**

```
bart pics -RT:1024:0:0.01 ksp coils img
```

- $1024 = 2^{10}$ bitmask for dimension 10 = TIME (by convention)
- `-RT` : TV Regularization

[3] Feng et al., *Magnetic Resonance in Medicine*, 2013

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Real-time reconstruction? TV-Norm needs whole dataset.

[3] Feng et al., *Magnetic Resonance in Medicine*, 2013

# Regularized Nonlinear Inversion[4]

## Nonlinear forward operator

- Optimization variable now includes coil sensitivities: $x = (\rho, c)$
- New forward operator: $F(x) = \mathcal{P}\mathcal{F}(\rho \cdot c)$

## Optimization problem

- Problem formulation: $\text{argmin}_x ||F(x) - y||_2^2 + \alpha(||\rho||_2^2 + ||Wc||_2^2)$
- Non-linear optimization: Need to solve for coil sensitivies AND image.
- Image/Coil ambiguity: Regularization forces smooth coils (Sobolev Norm $||Wc||_2$)

## Real-Time NLINV

- Equation solved framewise
- l2-regularization on difference to previous frame

[4] Uecker et al., *Magnetic Resonance in Medicine*, 2008

# Final touches

## Data import/preprocessing

- No data? `bart phantom`
- Coil compression: `bart cc`

## Postprocessing

- Filtering: `bart filter`
- Export: `bart toimg`

## Some of the things which were omitted:

- Non-Iterative RT MRI methods: k-t-SENSE etc.
- See also [5]

[5] Wang et al., *Investigative Magnetic Resonance Imaging*, 2021

# Hands-On!