MPIBPC Campus Seminar

Dynamic Water/Fat Separation and Magnetic Field Inhomogeneity Mapping in the Regime of Real-Time MRI

Zhengguo Tan

Biomedizinische NMR
Max-Planck-Institut für biophysikalische Chemie Göttingen

Outline

- Brief introduction
  - Magnetic Resonance Imaging (MRI)
  - Real-Time MRI
- Theory
  - Water and fat resonance frequency difference and separation
- Dynamic water/fat separation and magnetic field inhomogeneity mapping
  - Triple-echo radial FLASH
  - Model-based reconstruction for joint estimation
- Summary & future work

Magnetic Resonance Imaging (MRI)

Siemens MAGNETOM Prisma 3 T

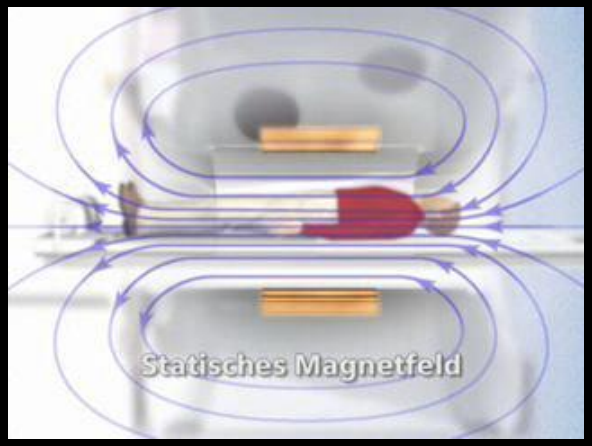
- Superconducting magnet
- Radiofrequency (RF) coil
- Gradient coils
- Receiver coil arrays

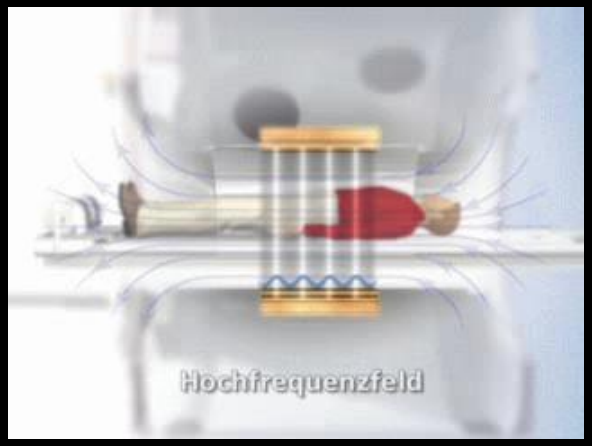
Thorax coil

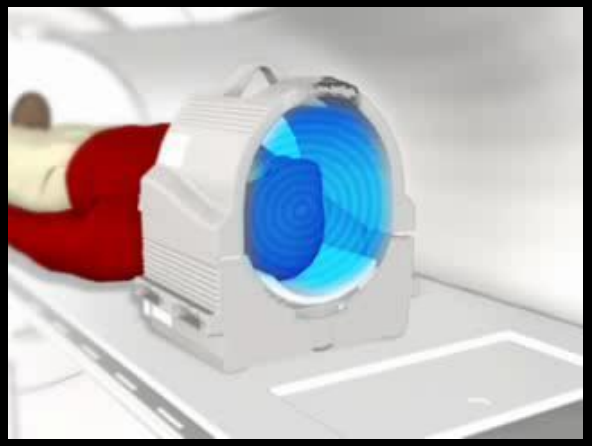
Head coil

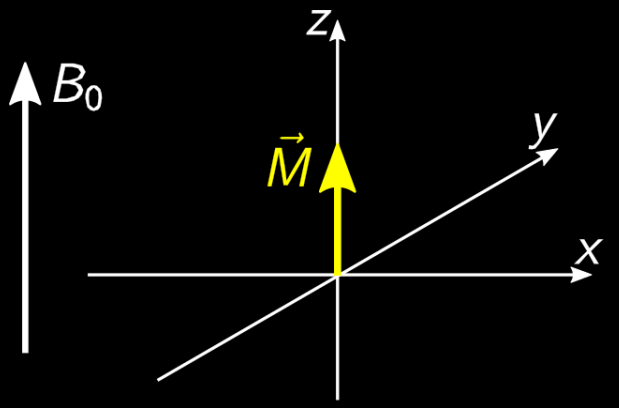
- ✓ No ionizing radiation
- ✓ Noninvasive imaging modality
- ✓ Excellent soft tissue contrast

Nuclear Magnetic Resonance

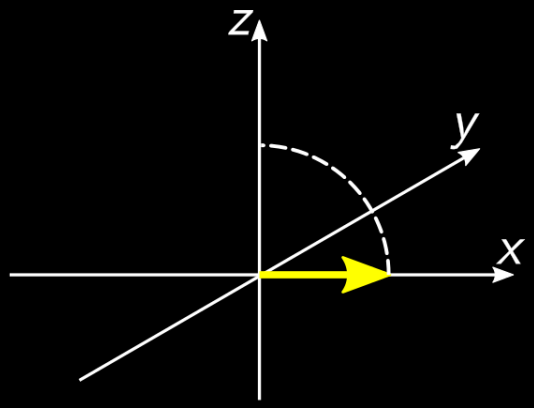




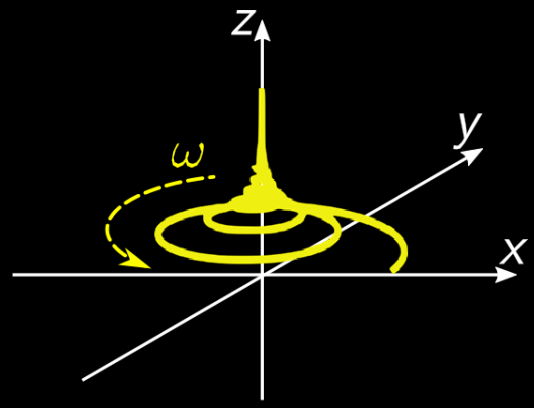




Equilibrium



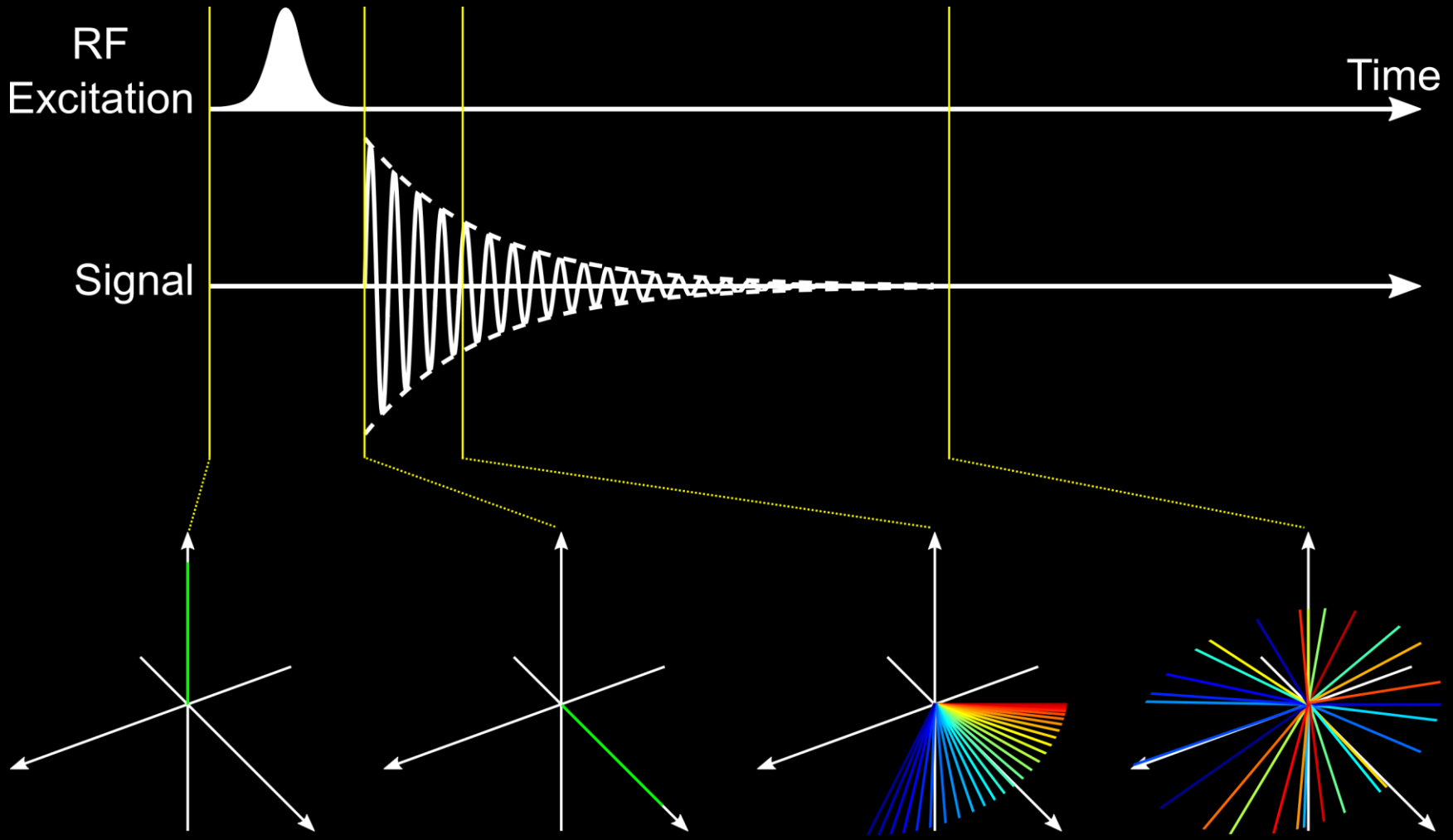
Excitation



Relaxation

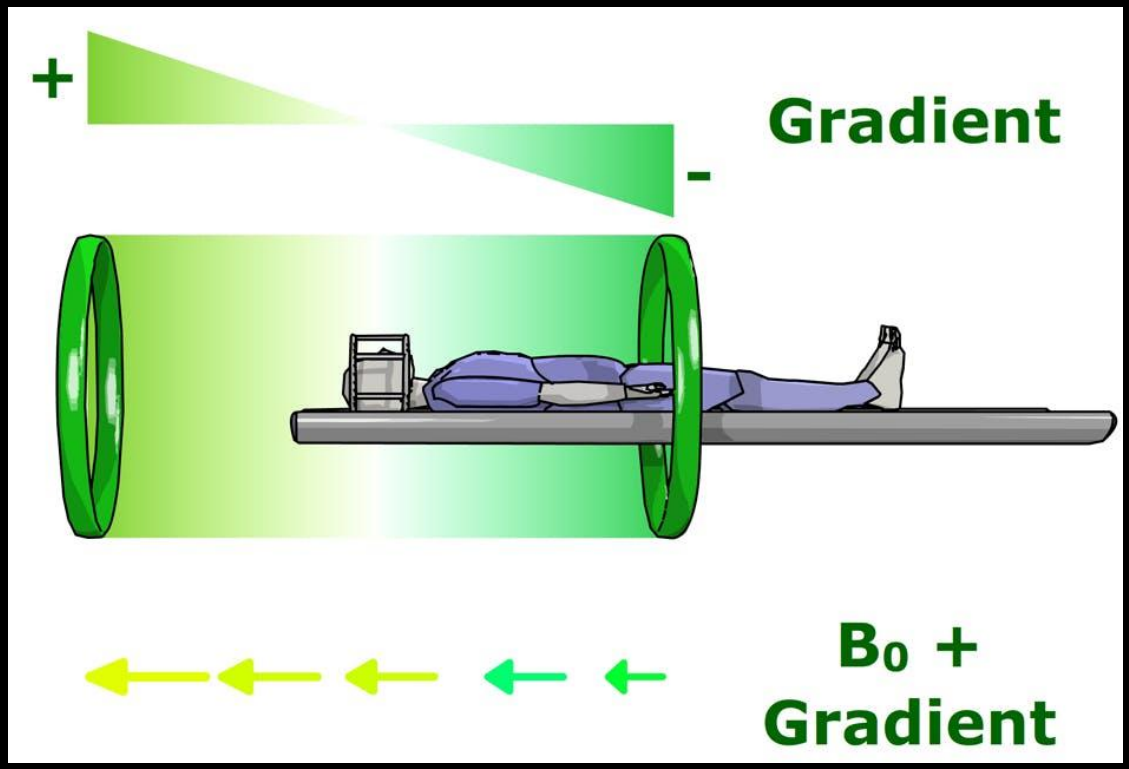
$$\omega = \gamma \cdot B_0$$

Nuclear Magnetic Resonance



Spatial Encoding in MRI

- e.g. Along the z direction (from foot to head)



$$\vec{\omega} = \gamma \cdot (B_0 + \vec{G} \cdot \vec{r})$$

Courtesy: imaios.com

Spatial Encoding in MRI

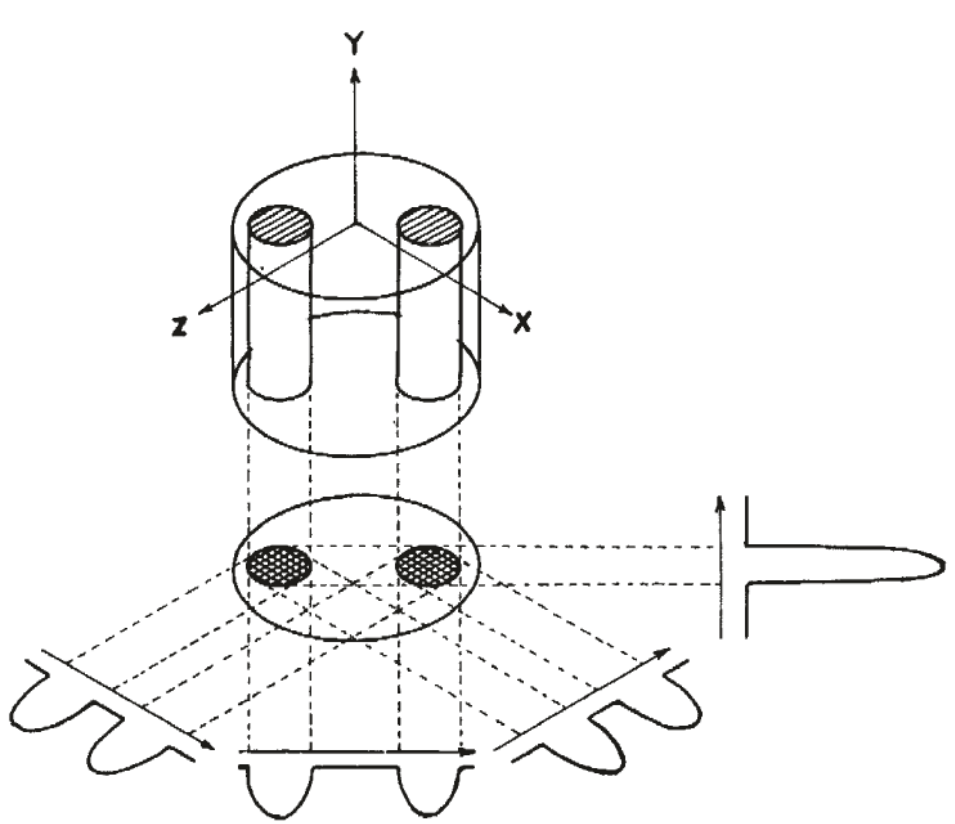
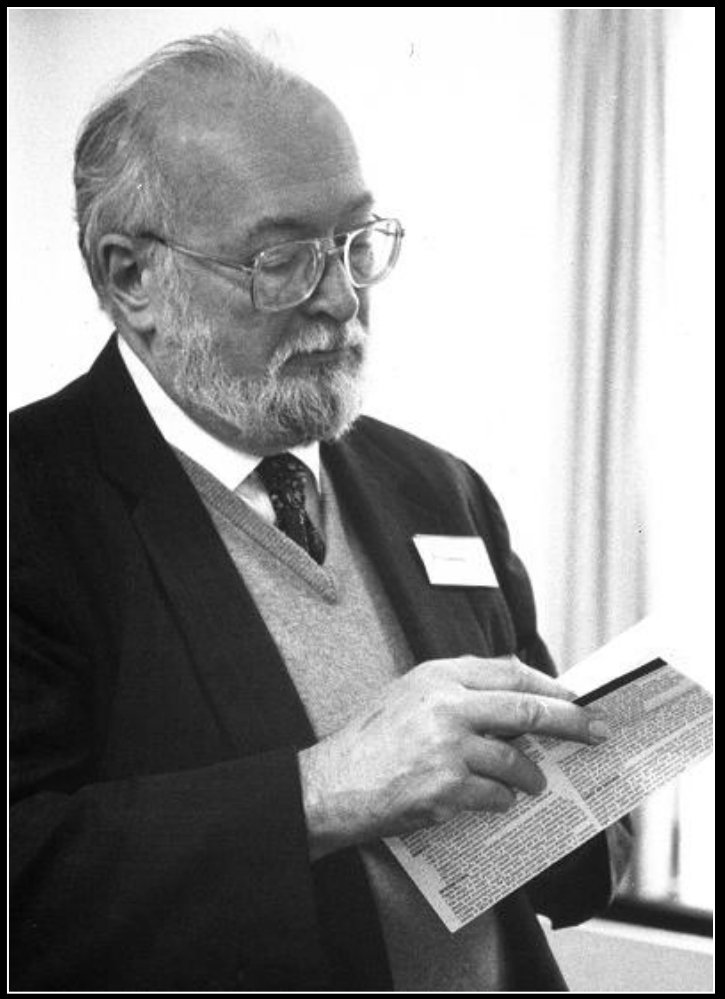


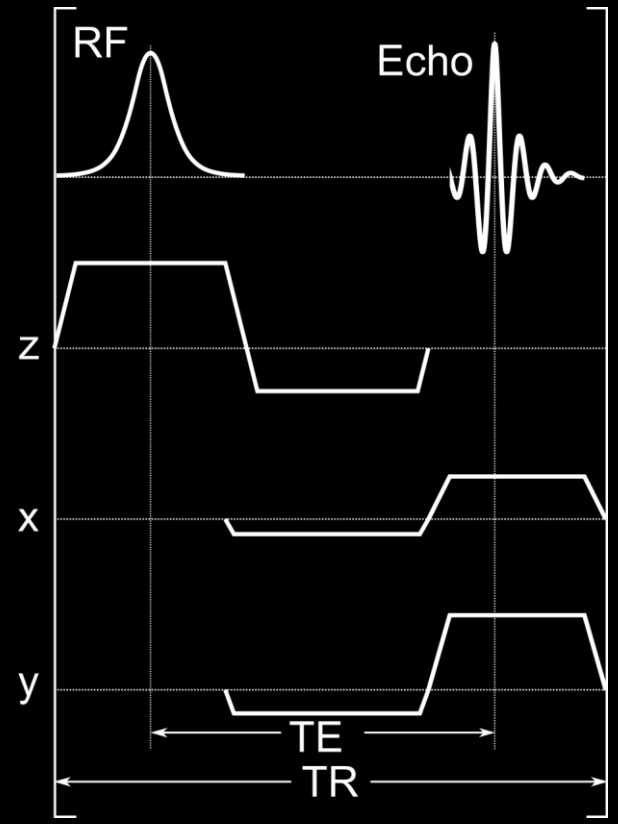
Fig. 1 Relationship between a three-dimensional object, its two-dimensional projection along the Y-axis, and four one-dimensional projections at 45° intervals in the XZ-plane. The arrows indicate the gradient directions.



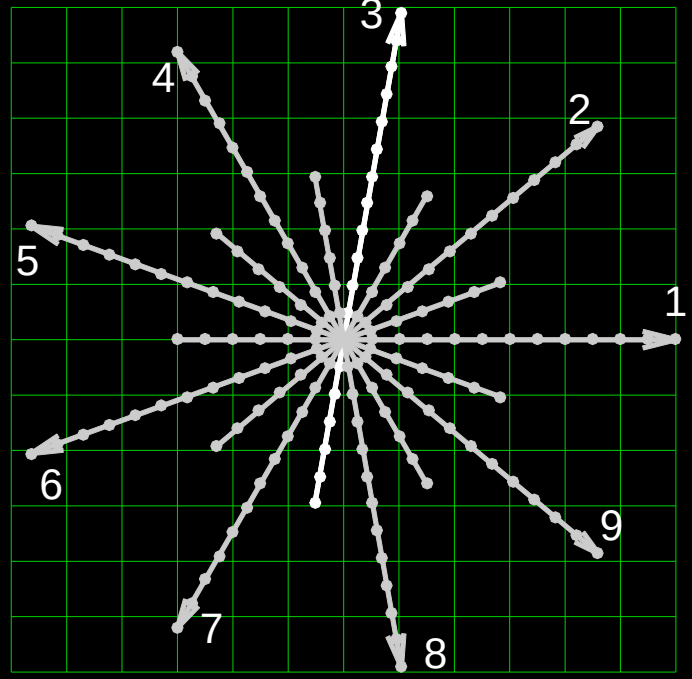
Paul C. Lauterbur: 2003 Nobel Prize Winner

Radial Sampling

Radial FLASH[1,2] sequence



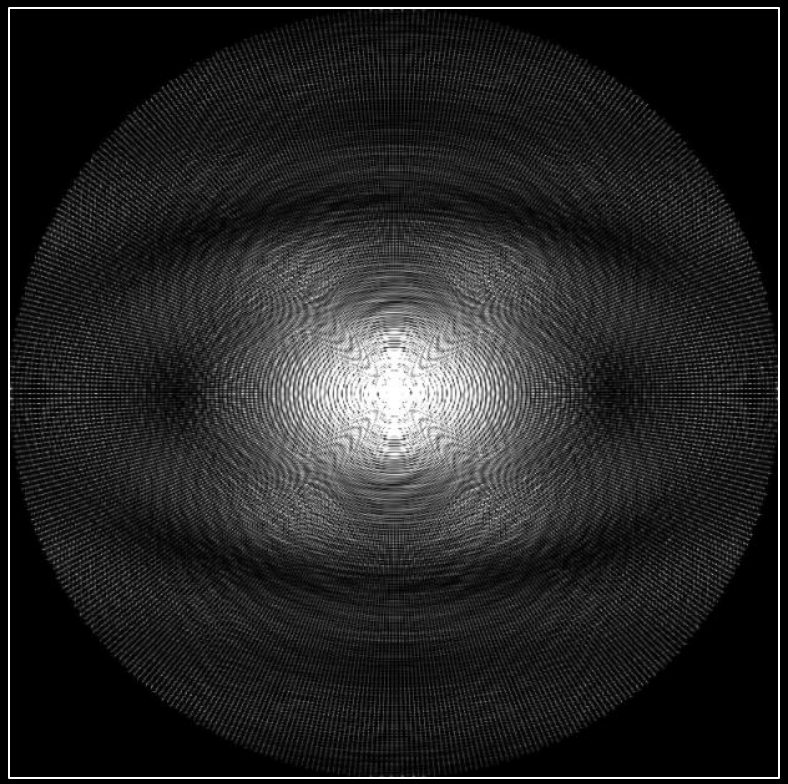
k-space trajectory



1. Frahm J, et al. German Patent (1985). 3. Frahm J, et al. US Patent (2010). FLASH: Fast Low Angle SHot.

Image Reconstruction

Fully-sampled k-space (401 spokes)



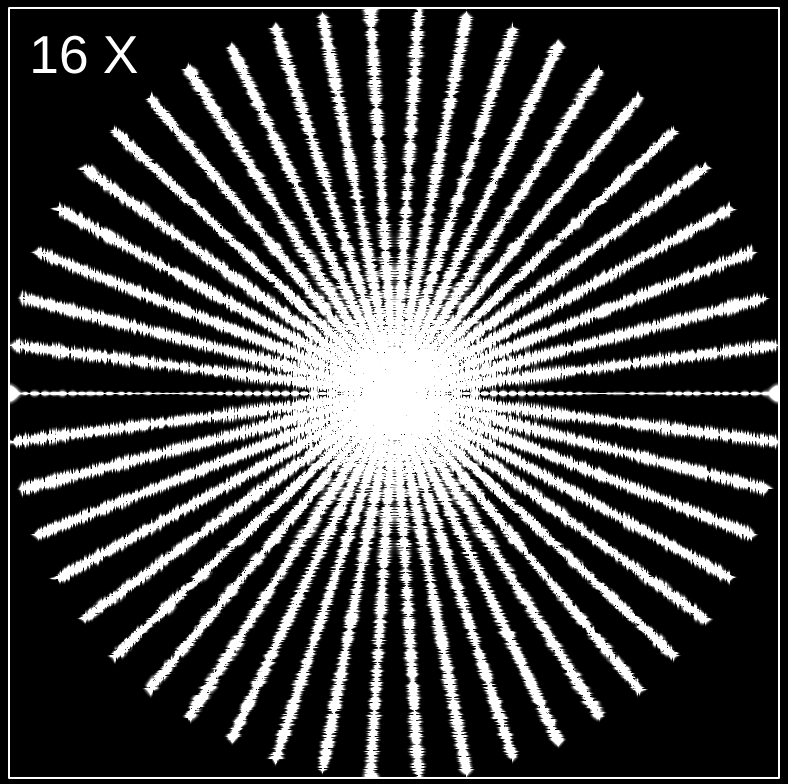
$\mathcal{F}$

Reconstructed image

- This acquisition takes about 1 sec, and requires the subject to be still

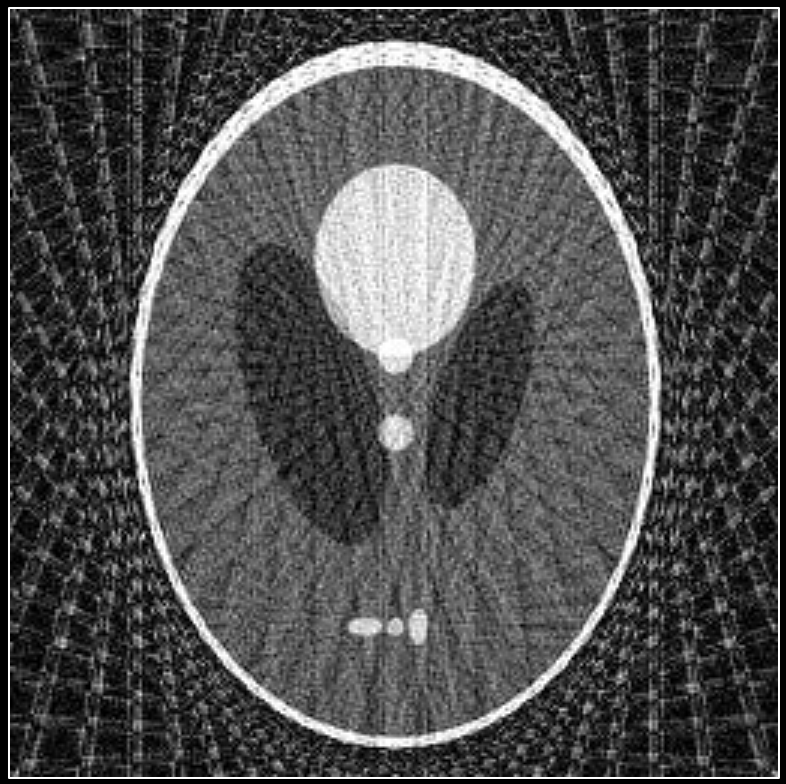
Radial Undersampling

Undersampled k-space (25 spokes)



$\mathcal{F}$

Reconstructed image

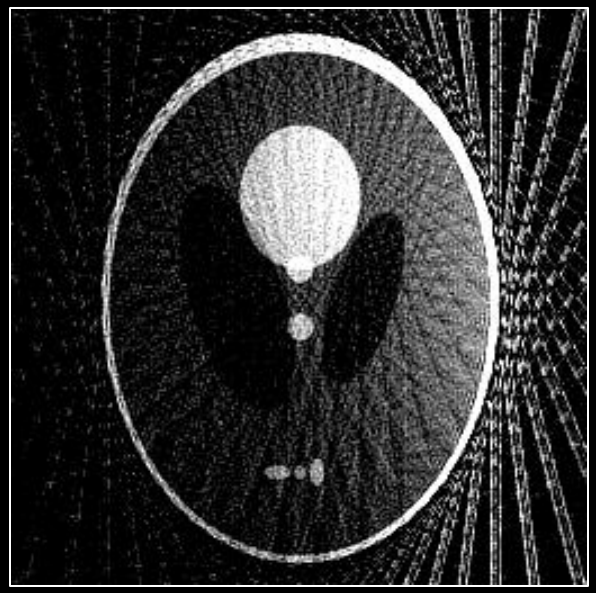
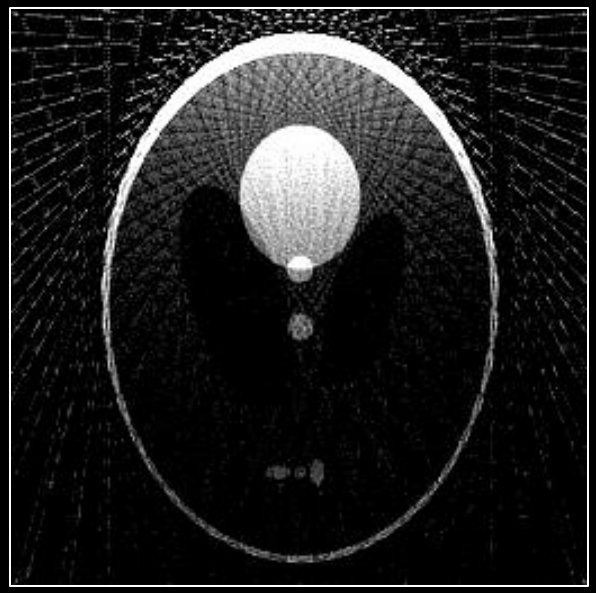
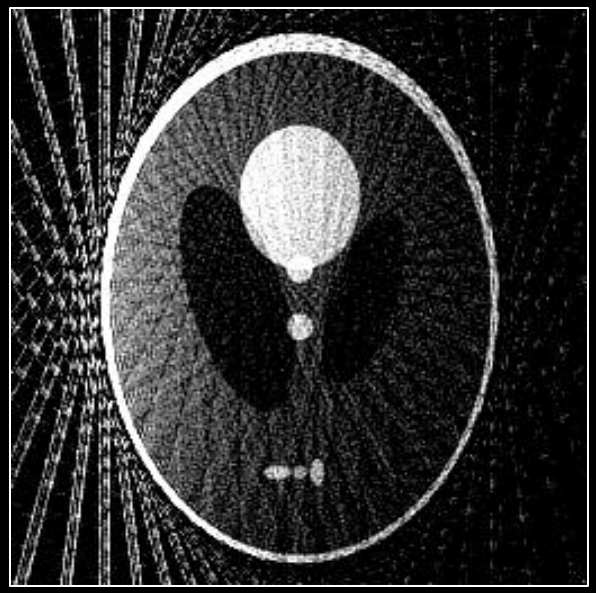


x Streaking artifacts and reduced SNR

✓ No spatial distortion, i.e. resistant to motion

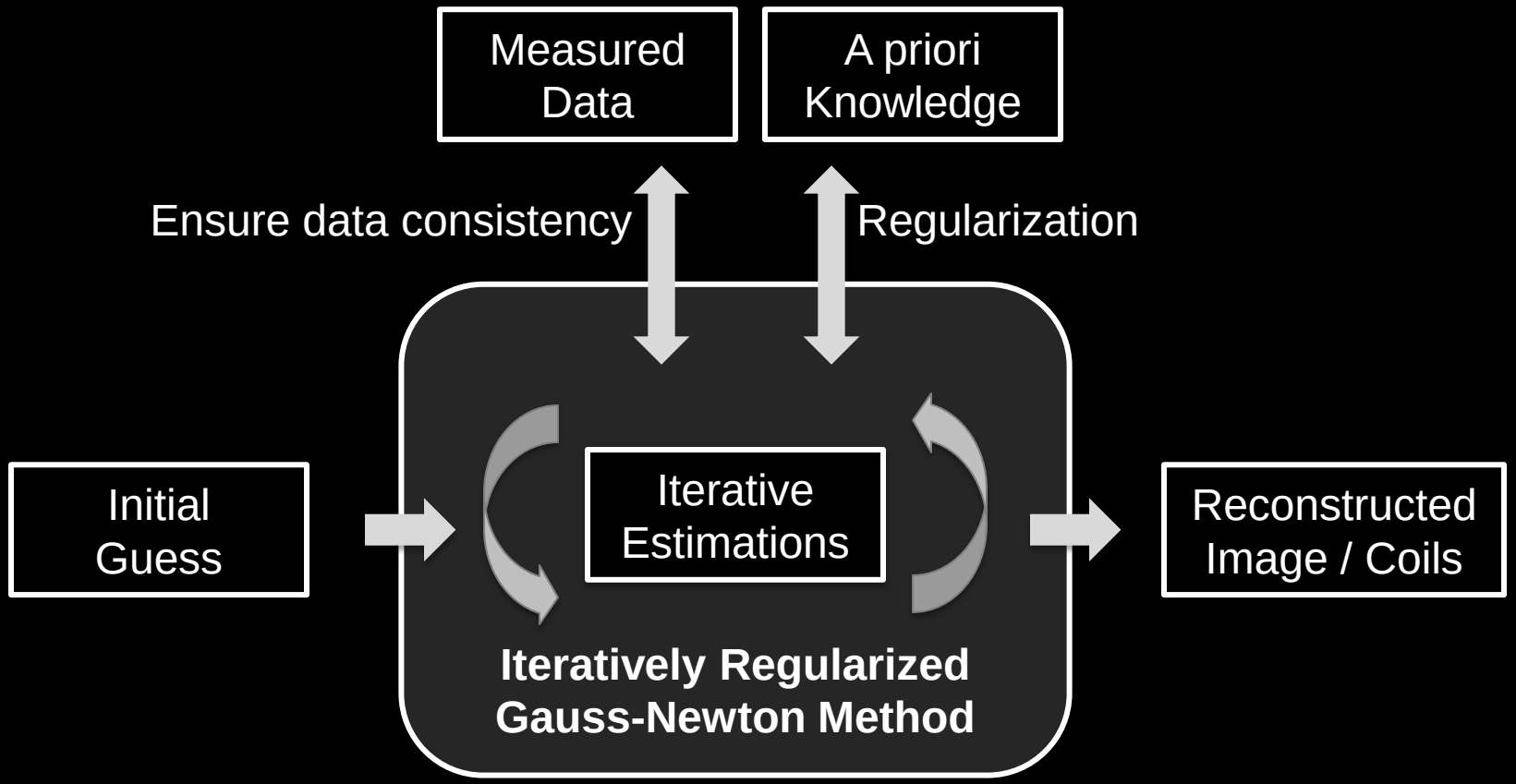
Zhang S, et al. MRI in real time: Advances using radial FLASH. *J Magn Reson Imaging* (2010).

Parallel Imaging Using Multiple Receiver Coils

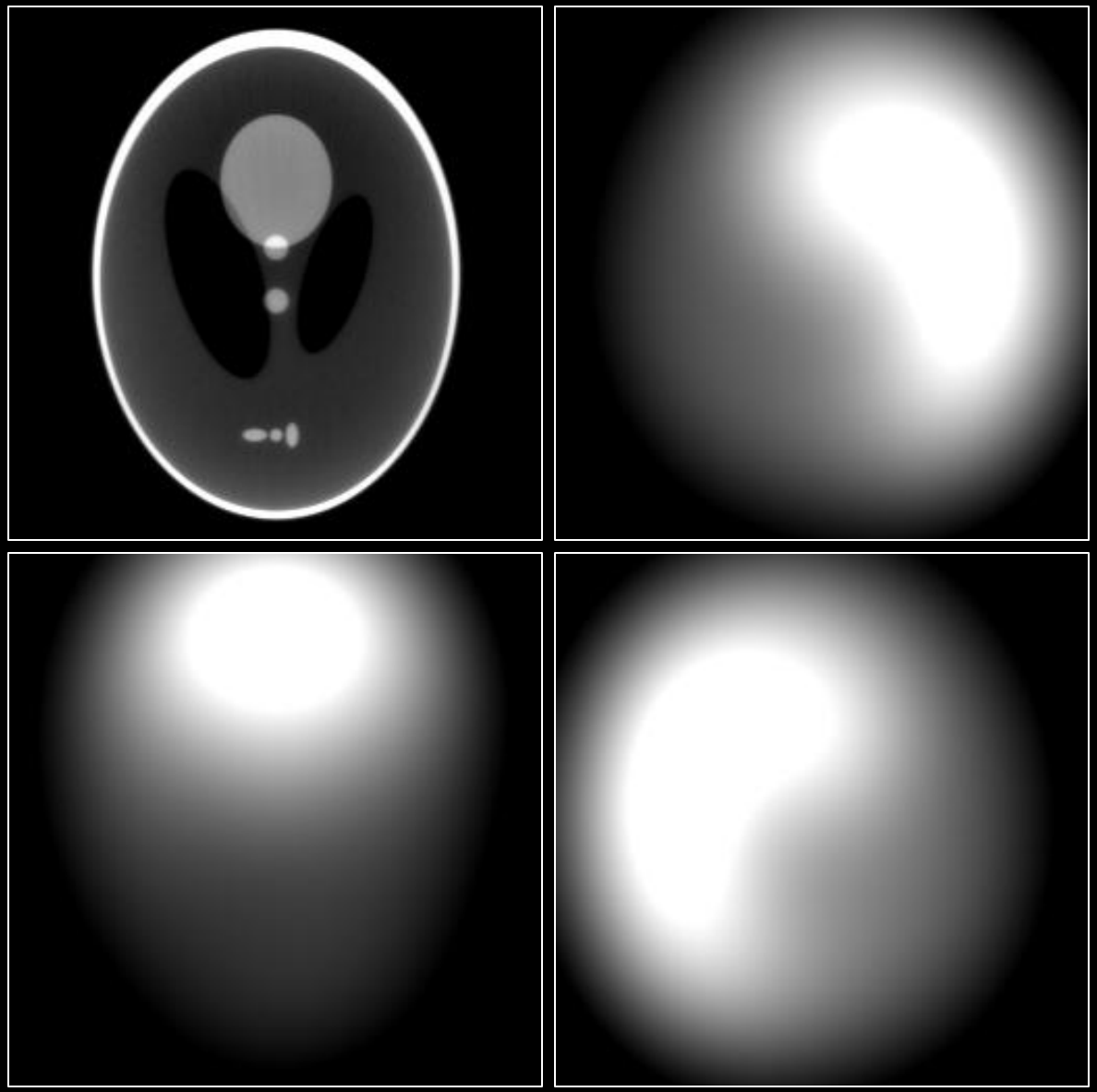
- Simultaneous multi-coil acquisition without the cost of extra time
- How to better estimate the image given the redundant measurements?

Parallel Imaging as Nonlinear Inversion



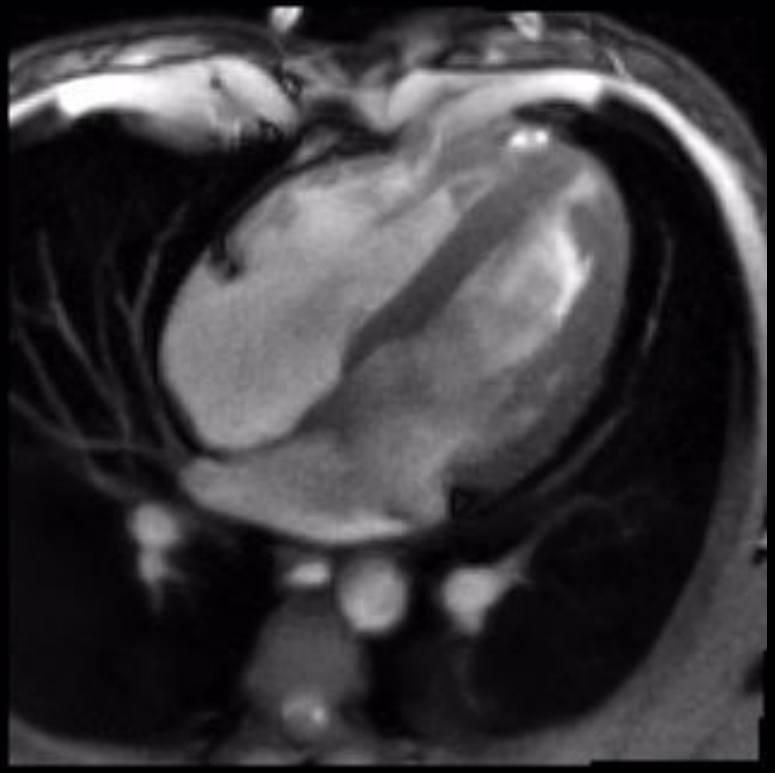
Uecker M, et al. *Magn Reson Med* (2008)

Parallel Imaging as Nonlinear Inversion

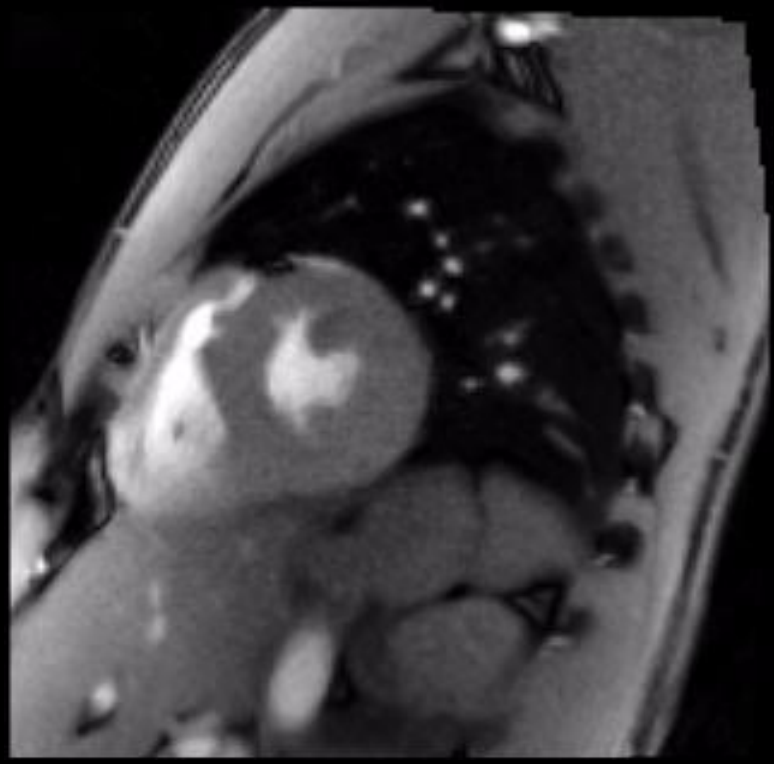


Real-Time MRI

Four-chamber view



Short-axis view



RF-Spoiled Radial FLASH, 1.6 × 1.6 × 6 mm^3,

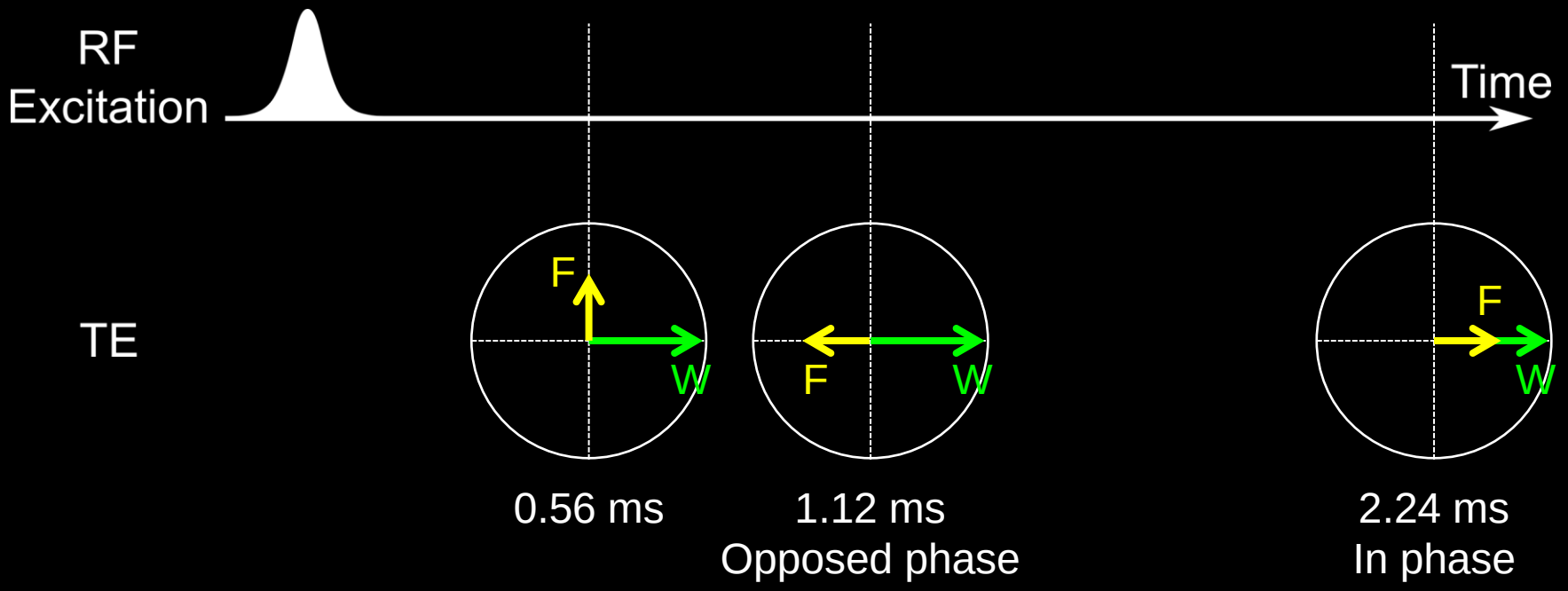
17 Spokes, 30 Frames per Second

Outline

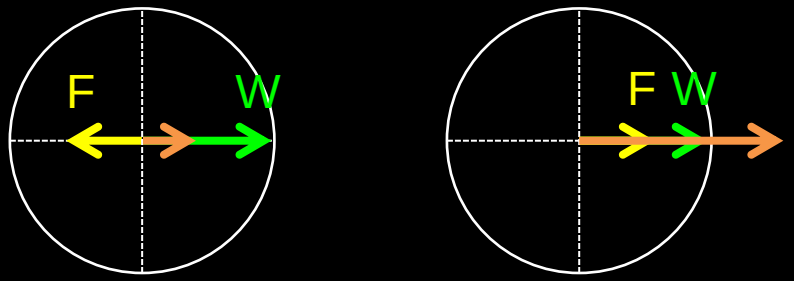
- Brief introduction
  - Magnetic Resonance Imaging (MRI)
  - Real-Time MRI
- Theory
  - Water and fat resonance frequency difference and separation
- Dynamic water/fat separation and magnetic field inhomogeneity mapping
  - Triple-echo radial FLASH
  - Model-based reconstruction for joint estimation
- Summary & future work

Water and Fat Frequency Difference

- Protons in water (H2O) precess differently from protons in fat (CH2)



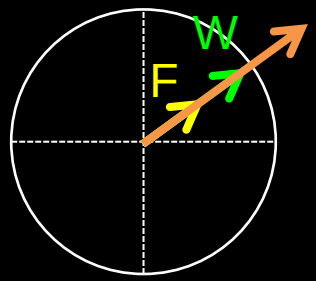
Simple Water/Fat Separation



$$\Rightarrow \begin{cases} W = (I_{ip} + I_{op})/2 \\ F = (I_{ip} - I_{op})/2 \end{cases}$$

Acquired echo

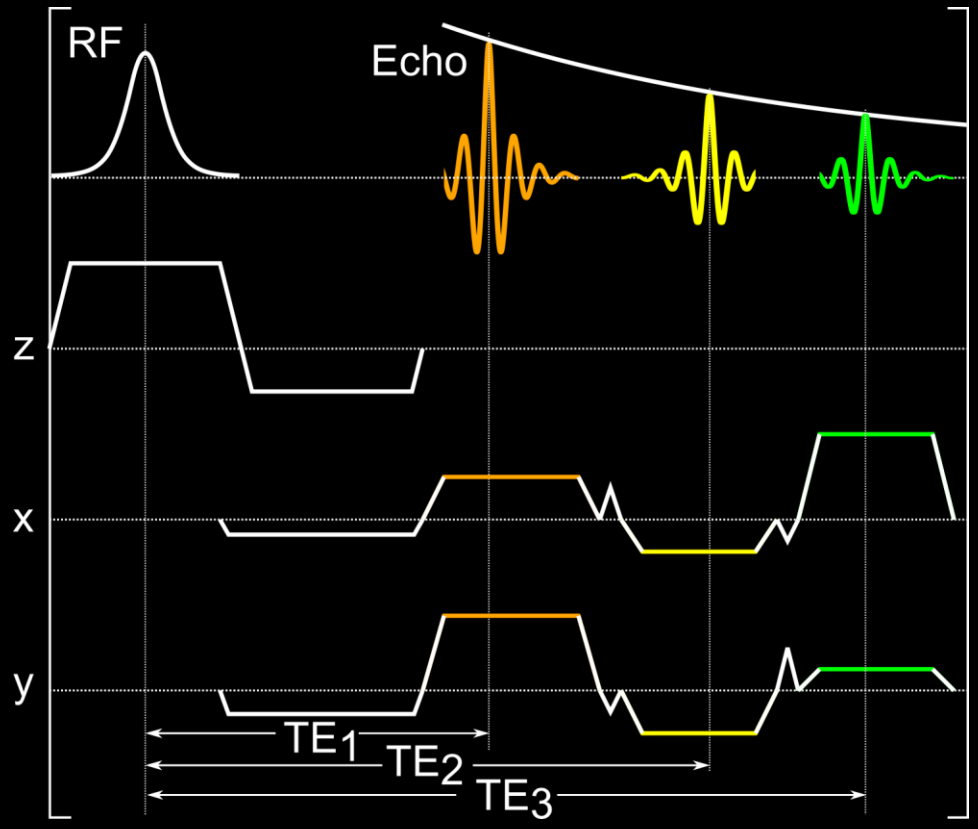
- Magnetic field inhomogeneities cause “crosstalk”, i.e. water/fat swaps
  - System imperfection
  - Tissue susceptibility
  - Air-tissue interface



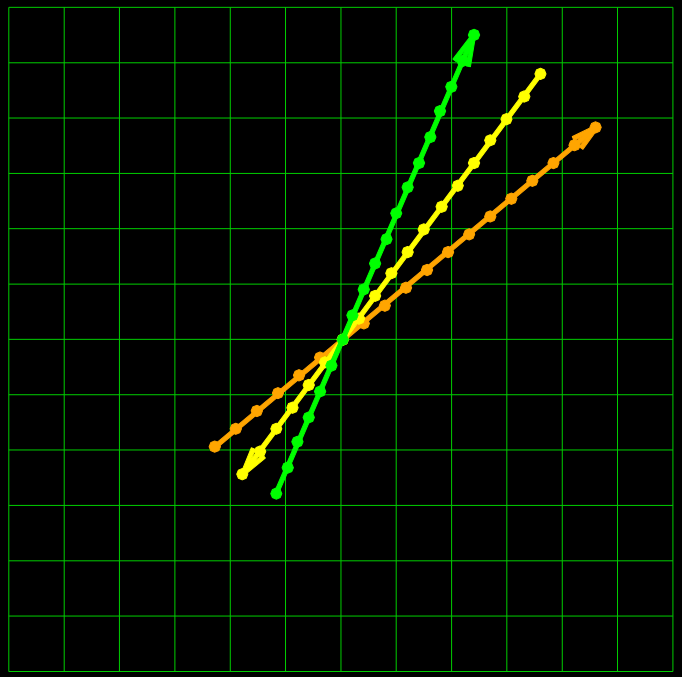
Outline

- Brief introduction
  - Magnetic Resonance Imaging (MRI)
  - Real-Time MRI
- Theory
  - Water and fat resonance frequency difference and separation
- Dynamic water/fat separation and magnetic field inhomogeneity mapping
  - Triple-echo radial FLASH
  - Model-based reconstruction for joint estimation
- Summary & future work

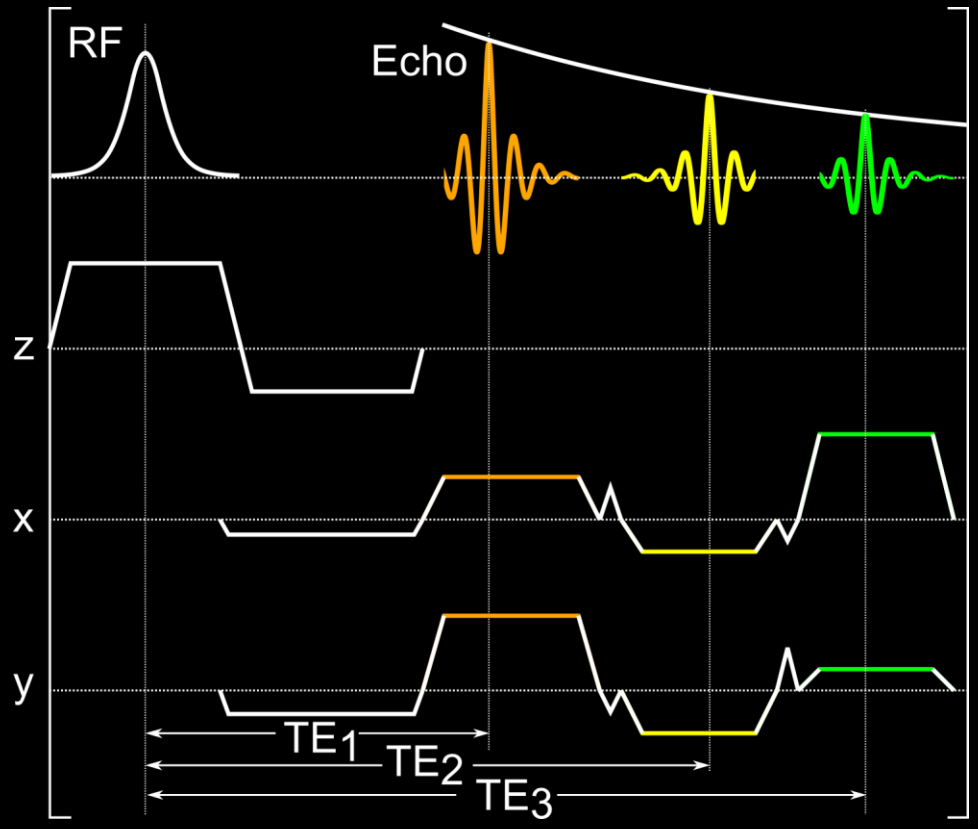
Triple-Echo Radial FLASH Acquisition



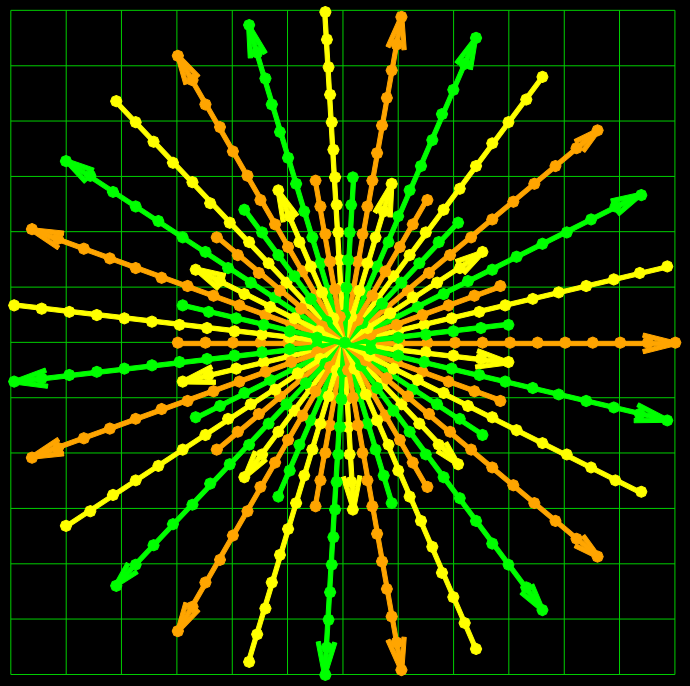
Radially-sampled k-space



Triple-Echo Radial FLASH Acquisition



Radially-sampled k-space



Triple-Echo Radial FLASH Acquisition

	Liver	Heart
Field of view (mm^2)	320 x 320	320 x 320
Voxel size (mm^3)	1 x 1 x 6	1.6 x 1.6 x 6
Flip angle (^{o})	8	8
Echo time (ms)	1.33 / 2.87 / 3.93	1.26 / 2.66 / 3.69
Repetition time (ms)	4.80	4.43
Shots per frame	33	9
Time per frame (ms)	158	40
Temporal resolution (fps)	6	25

Outline

- Brief introduction
  - Magnetic Resonance Imaging (MRI)
  - Real-Time MRI
- Theory
  - Water and fat resonance frequency difference and separation
- Dynamic water/fat separation and magnetic field inhomogeneity mapping
  - Triple-echo radial FLASH
  - Model-based reconstruction for joint estimation
- Summary & future work

Image Reconstruction

- Nonlinear nonconvex inversion

$$\Phi(x) = \underset{x}{\operatorname{argmin}} \underbrace{\|y - F(x)\|_2^2}_{\text{Data consistency term}} + \alpha \underbrace{\|Rx\|_2^2}_{\text{Regularization}}$$

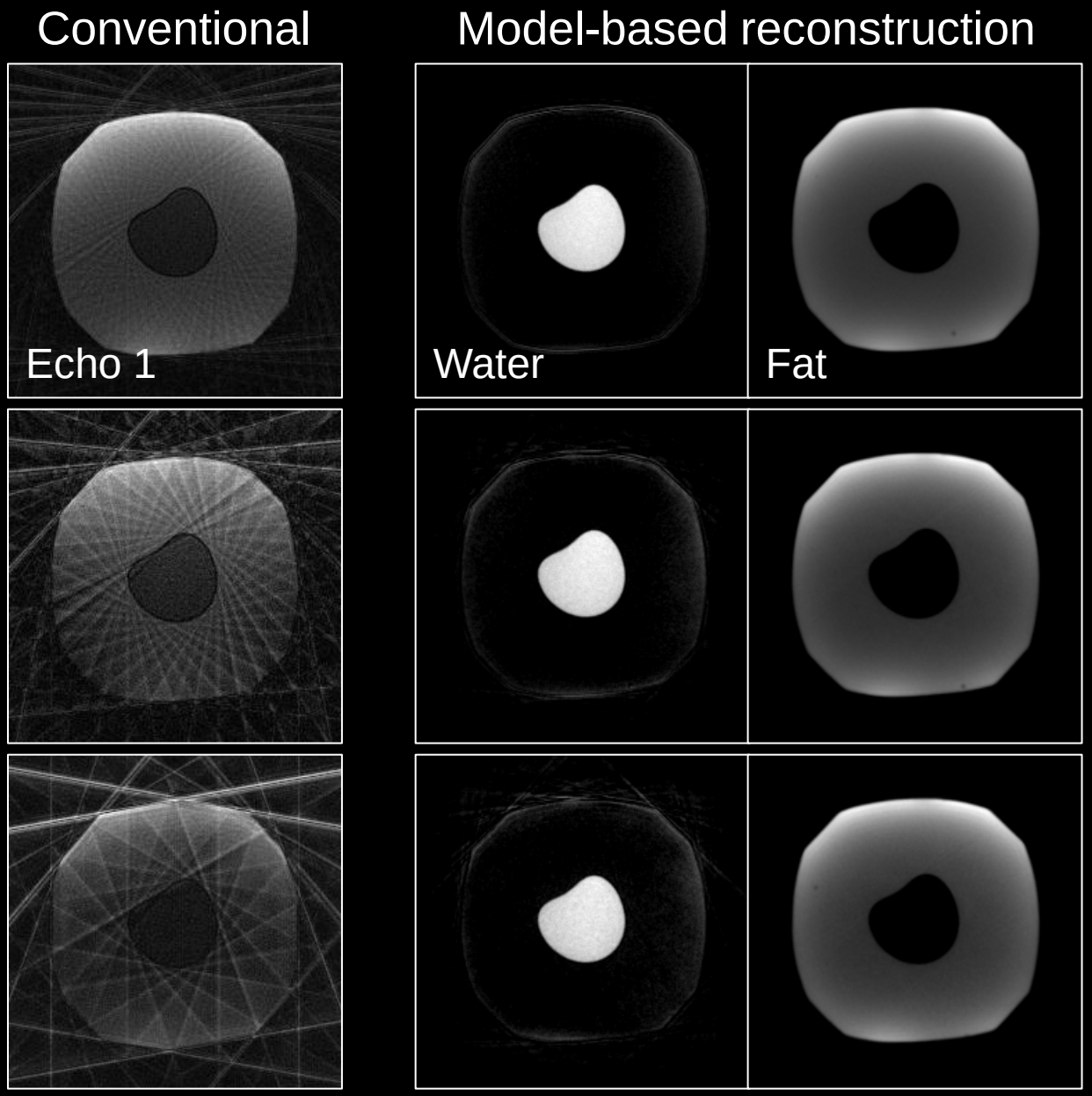
- Forward model

$$F_{j,m}(x) = P_m \mathcal{F}\{\rho_m \cdot c_j\}$$

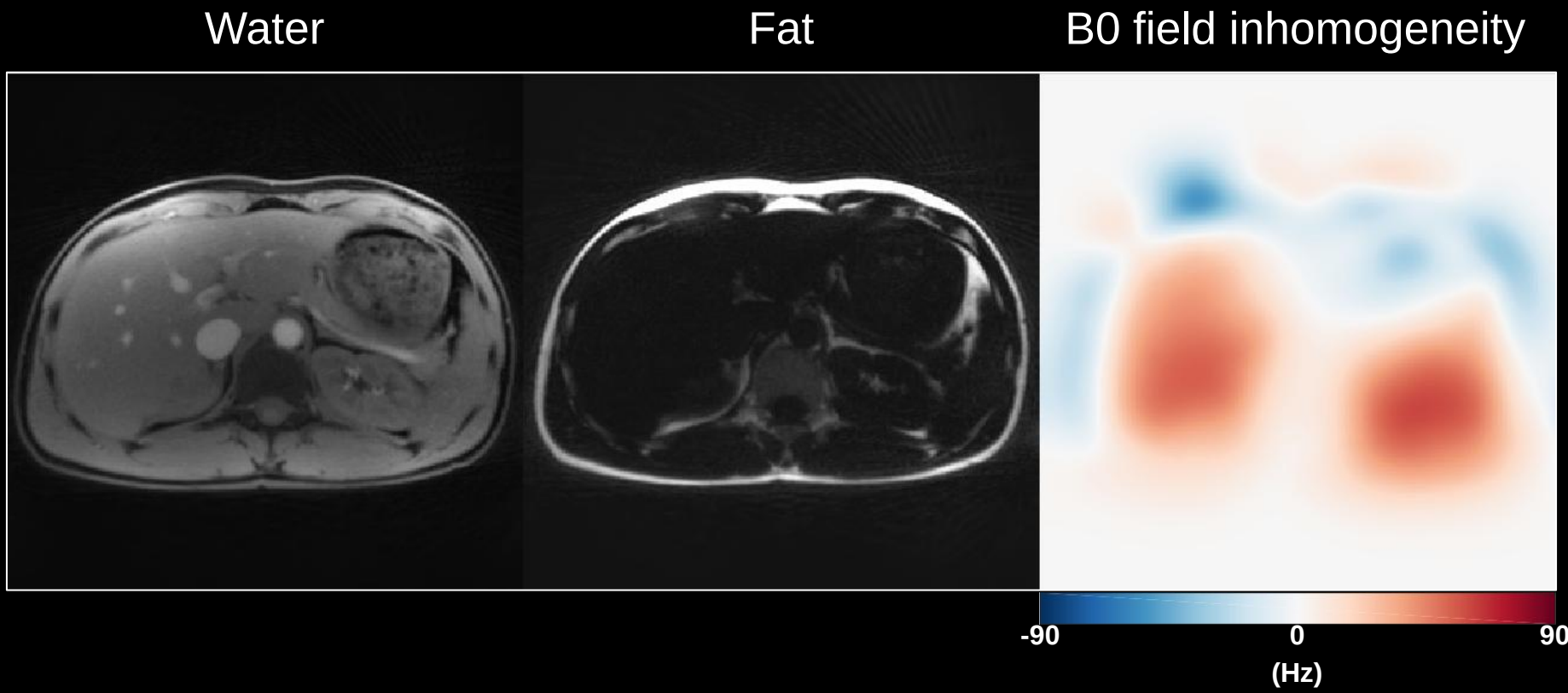
Coil sensitivities

$$(\mathbf{W} + \mathbf{F} \cdot z_m) \cdot \exp(i 2\pi f_{B_0} \mathrm{TE}_m)$$

Results: Static Water/Fat Phantom



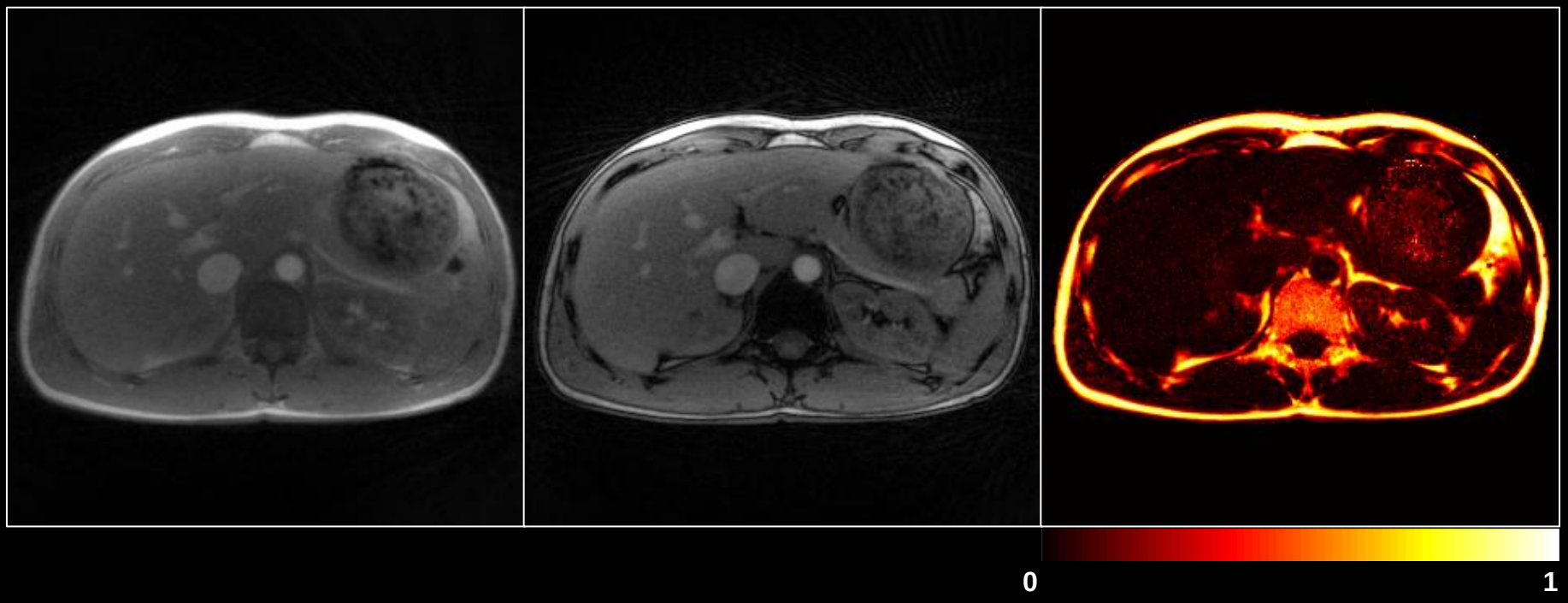
Results: Liver



RF-Spoiled Triple-Echo Radial FLASH, 1 × 1 × 6 mm^3,

33 Shots, 6 Frames per Second

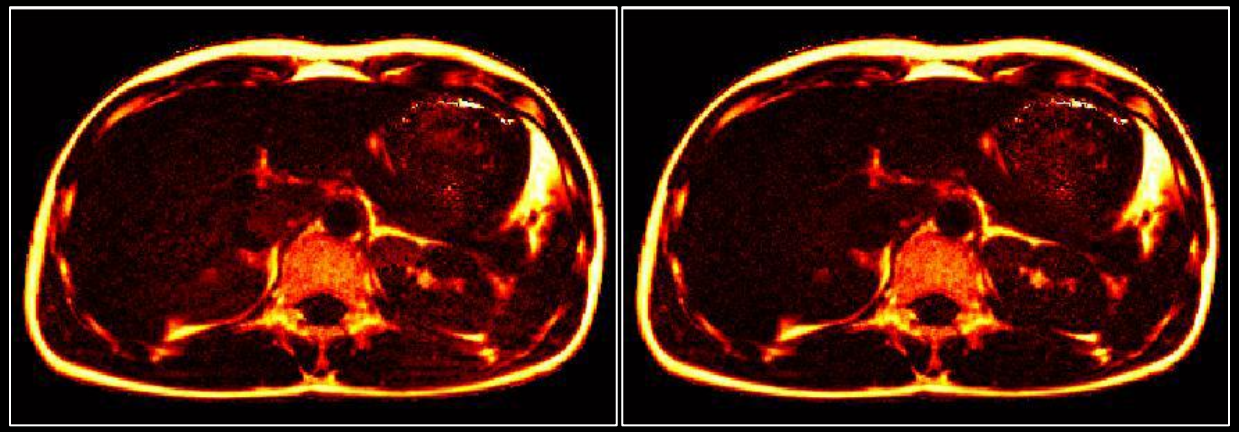
Results: Synthetic In- and Opposed-Phase Images



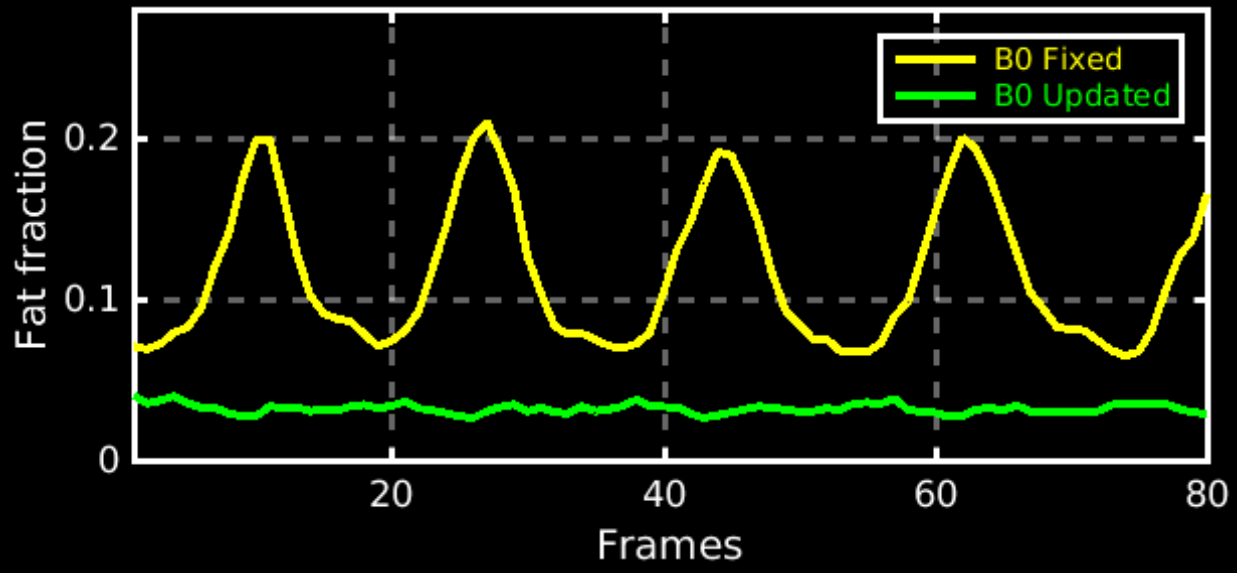
Results: Breathing Perturbs Field Homogeneity

B0 fixed as 0

B0 updated

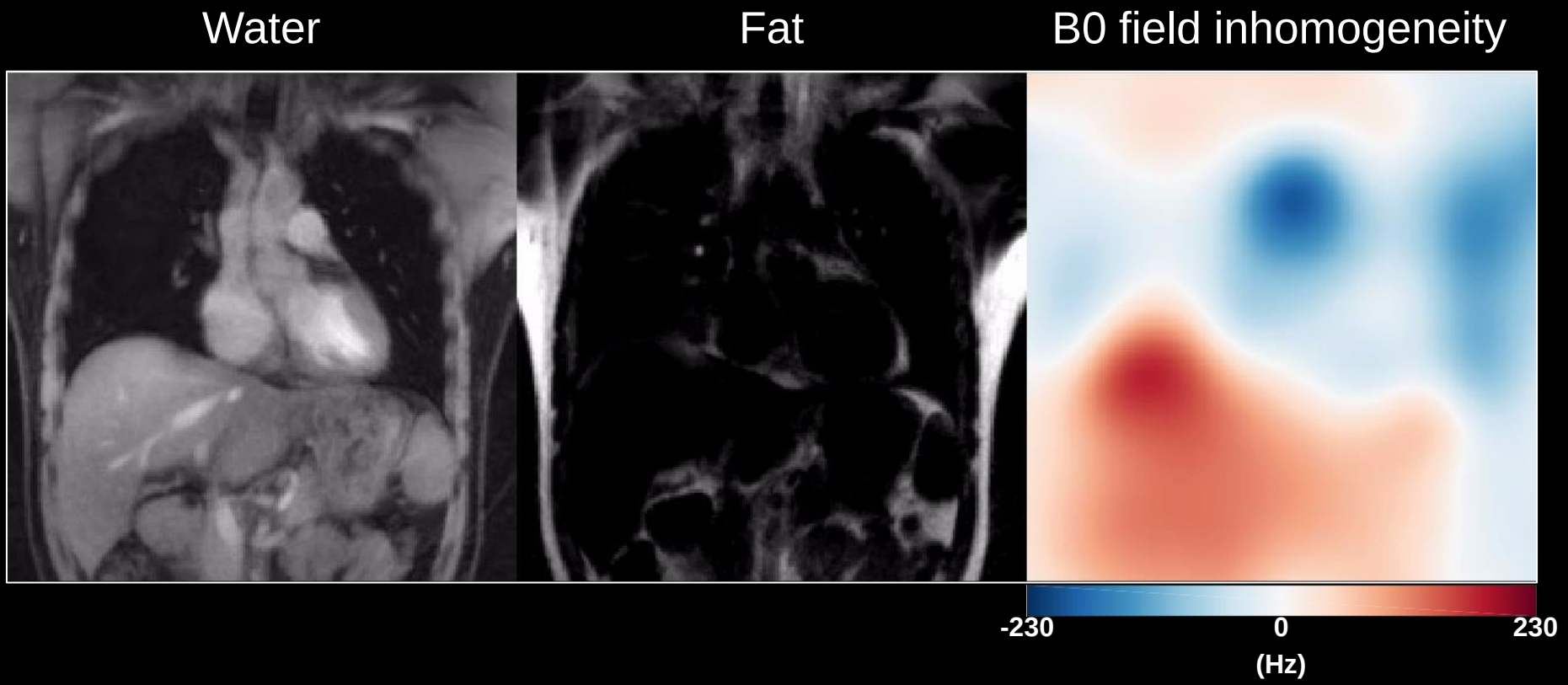


Large B0 inhomogeneities during inspiration in the spleen and the right lobe of the liver



- FF overestimation
- Water and fat swap
- "Crosstalk" between the true water and fat signals

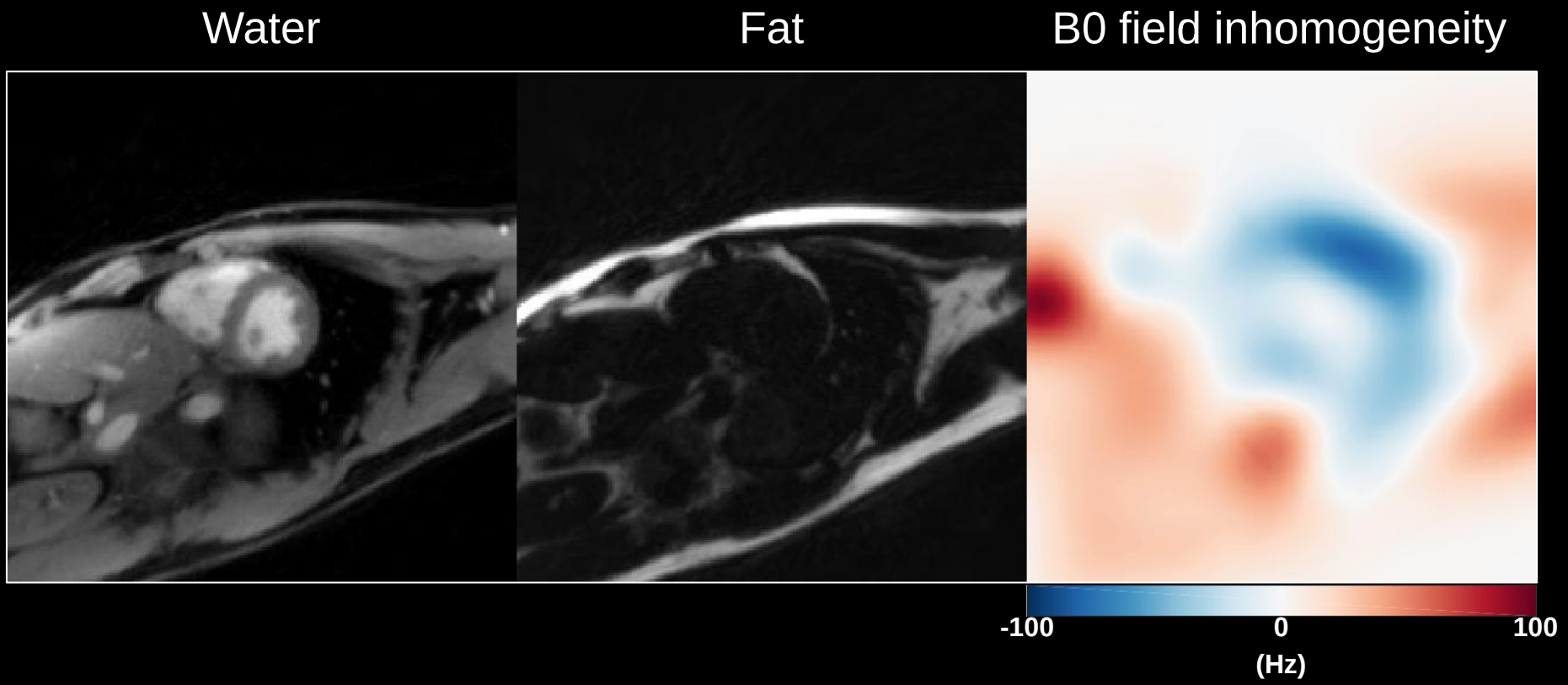
Results: Heart in the Bulbus View



RF-Spoiled Triple-Echo Radial FLASH, 1.6 × 1.6 × 6 mm^3,

9 Shots, 25 Frames per Second

Results: Heart in the Short-Axis View



RF-Spoiled Triple-Echo Radial FLASH, 1.6 × 1.6 × 6 mm^3,

9 Shots, 25 Frames per Second

Outline

- Brief introduction
  - Magnetic Resonance Imaging (MRI)
  - Real-Time MRI
- Theory
  - Water and fat resonance frequency difference and separation
- Dynamic water/fat separation and magnetic field inhomogeneity mapping
  - Triple-echo radial FLASH
  - Model-based reconstruction for joint estimation
- Summary & future work

Summary

- Development of a triple-echo multi-spoke radial FLASH sequence
- Development of a model-based reconstruction
  - Joint water/fat separation and B0 field inhomogeneity mapping
  - Applicable to dynamic imaging at high spatiotemporal resolution
- Physiological motions (e.g. breathing) perturb magnetic field
- Provide fat fraction as a potential biomarker for fatty diseases

Future Work

- Extension to quantitative T2* mapping – tissue oxygenation !

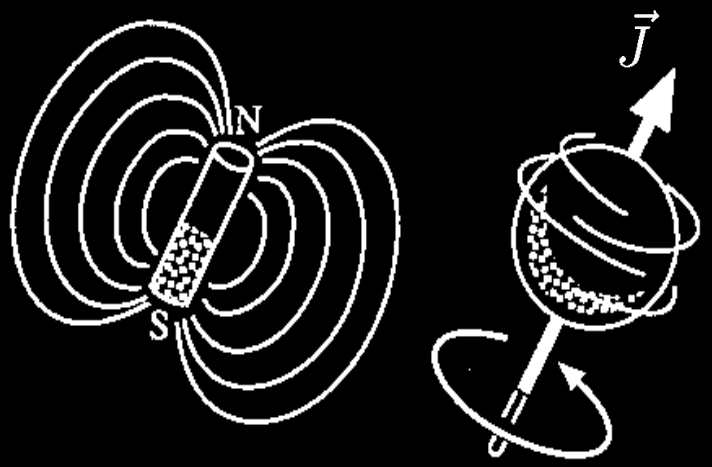
Acknowledgements

- BiomedNMR
  - Prof. Dr. Jens Frahm
  - Dr. Dirk Voit
  - Dr. Arun Joseph
  - Dr. Volkert Roeloffs
  - Dr. Oleksandr Kalentev
  - Dr. Klaus-Dietmar Merboldt
  - Dr. Thomas Michaelis
  - Dr. Maaike van Zalk
  - Jakob Klosowski
  - Jost Kollmeier
  - Kurt Böhm
- Universitätsmedizin Göttingen
  - Prof. Dr. Martin Uecker
- CAI^{2}R at NYU / Siemens
  - Dr. Thomas Benkert
  - Prof. Dr. Kai Tobias Block
- ISMRM Fat-Water Toolbox
- You !!!

The Hydrogen Atom

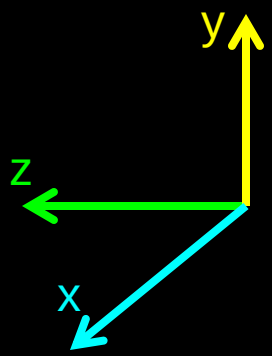
- Hydrogen Atom
  - Atomic number of 1, i.e. 1 proton
  - Has a spin of 1/2
  - Natural abundance of 99.985 %

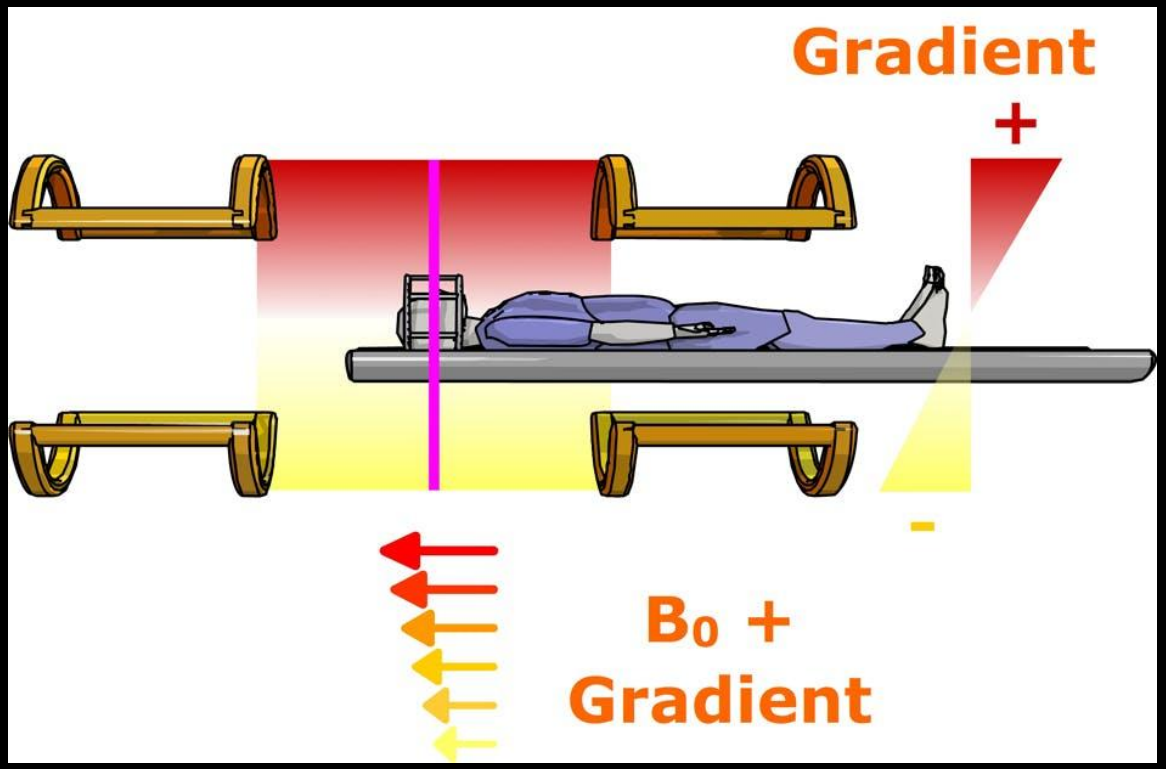
- Protons
  - Possess a positive charge
  - Have an angular moment (spin)
  - Produce a magnetic field



Spatial Encoding in MRI

- Along the y direction (from posterior to anterior)

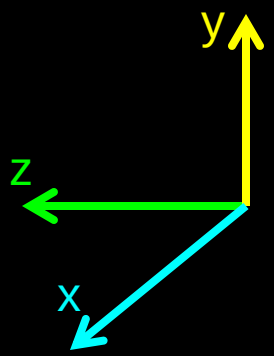


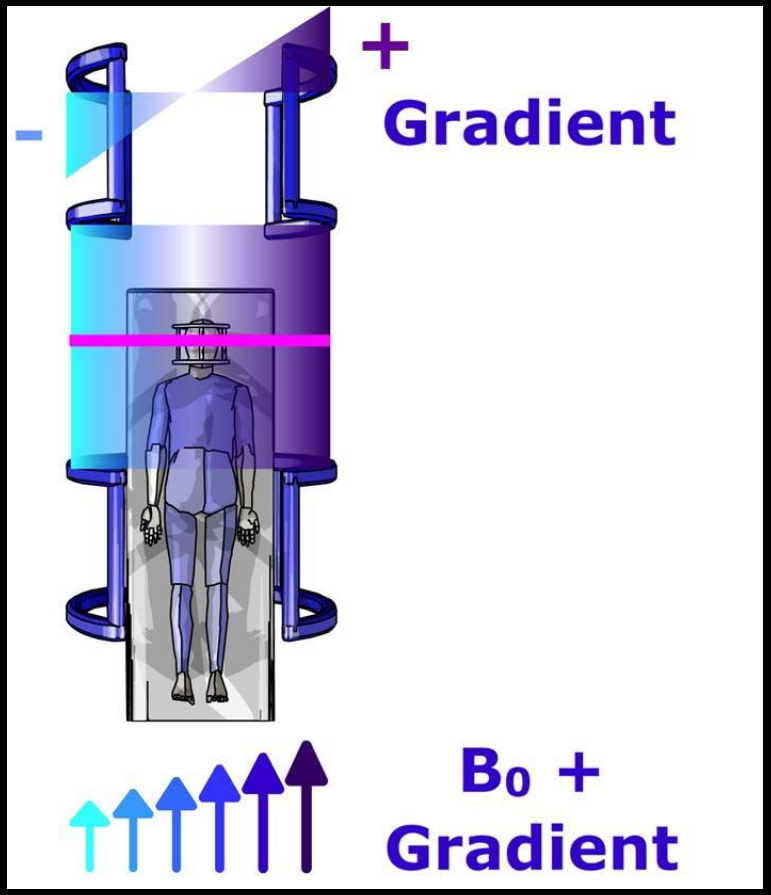


Courtesy: imaios.com

Spatial Encoding in MRI

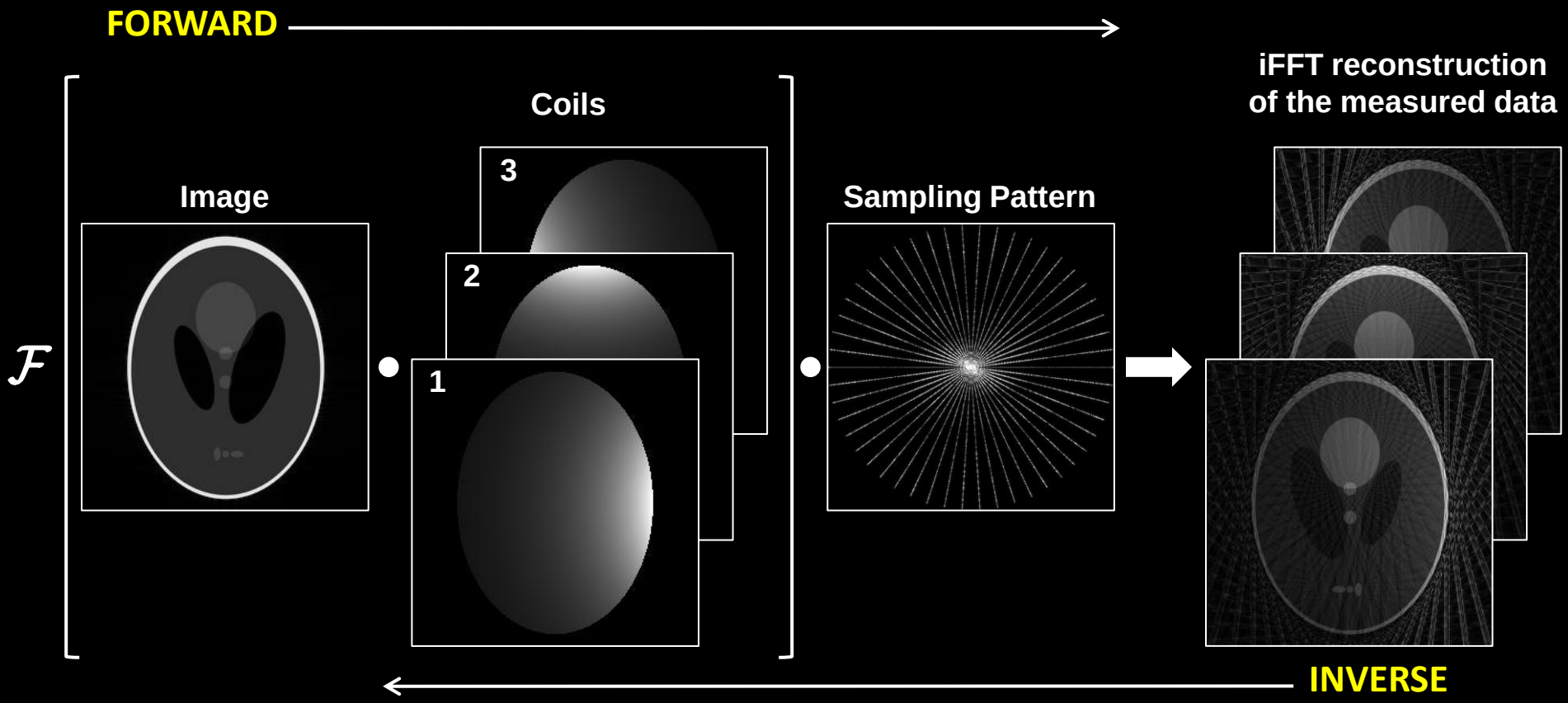
- Along the x direction (from right to left)





Courtesy: imaios.com

Parallel Imaging



- Can we do better than direct iFFT reconstruction?

Bloch Equation

$$\frac{d\vec{M}}{dt} = \vec{M} \times \gamma\vec{B} - \frac{M_x\vec{x} + M_y\vec{y}}{T_2} - \frac{(M_z - M_0)\vec{z}}{T_1}$$

where

$\gamma =$ gyromagnetic ratio

$T_1 =$ spin-lattice (longitudinal) relaxation time constant

$T_2 =$ spin-spin (transverse) relaxation time constant

$M_0 =$ equilibrium sample magnetization due to B0 field

$\vec{x}, \vec{y}, \vec{z} =$ unit vectors in x, y, z – directions respectively

Simple Proton Spectroscopic Imaging (Dixon Method)

- 2-Point chemical shift encoding (known as Dixon method)[1] $(0, \pi)$

$$\begin{cases} I_{ip} = W + F \\ I_{op} = W - F \end{cases} \Rightarrow \begin{cases} W = (I_{ip} + I_{op})/2 \\ F = (I_{ip} - I_{op})/2 \end{cases}$$

  - Echo times must be selected to meet in- and oppo-phase condition
  - Magnetic field inhomogeneities cause "crosstalk", i.e. water/fat swaps

$$\text{with} \begin{cases} I_{ip} = (W + F) \cdot \Psi_{ip} \\ I_{op} = (W - F) \cdot \Psi_{op} \end{cases} \Rightarrow \begin{cases} \tilde{W} = [W(\Psi_{ip} + \Psi_{op}) + F(\Psi_{ip} - \Psi_{op})]/2 \\ \tilde{F} = [W(\Psi_{ip} - \Psi_{op}) + F(\Psi_{ip} + \Psi_{op})]/2 \end{cases}$$

$$\Psi_m = \exp(i 2\pi f_{B_0} \cdot TE_m)$$

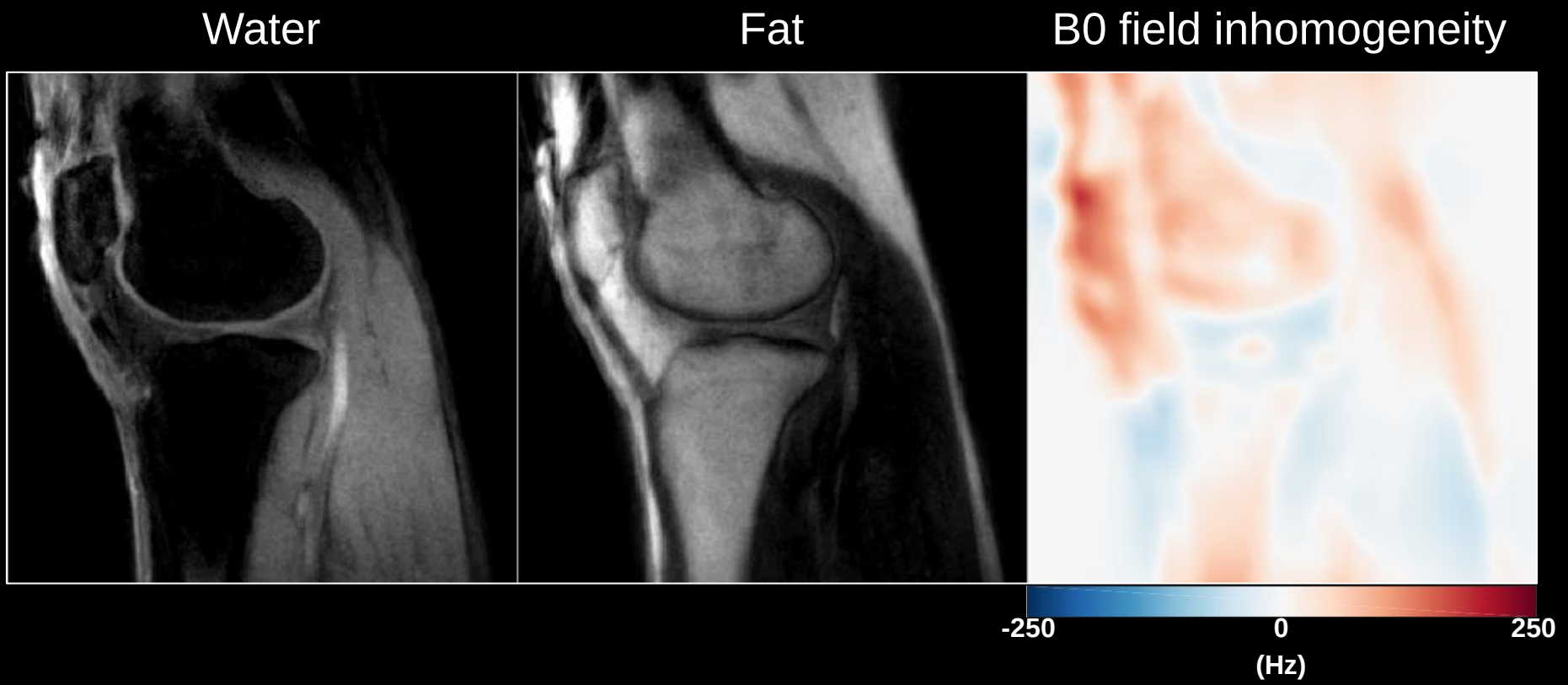
- x-Point Dixon method[2] $(0, \pi, 2\pi)$ or $(0, \pi, 2\pi, 3\pi)$
  - Much longer acquisition

1. Dixon T. Simple proton spectroscopic imaging. *Radiology* (1984).
2. Glover G. Multipoint Dixon technique for water and fat proton and susceptibility imaging. *J Magn Reson Imaging* (1991).

Triple-Echo Radial FLASH Acquisition

	Knee	Liver	Heart
Field of view (mm^2)	160 x 160	320 x 320	320 x 320
Voxel size (mm^3)	0.5 x 0.5 x 3	1 x 1 x 6	1.6 x 1.6 x 6
Flip angle (^{o})	16	8	8
Echo time (ms)	1.97 / 4.64 / 6.34	1.33 / 2.87 / 3.93	1.26 / 2.66 / 3.69
Repetition time (ms)	7.79	4.80	4.43
Shots per frame	9	33	9
Time per frame (ms)	70	158	40
Temporal resolution (fps)	14	6	25

Results: Knee



RF-Spoiled Triple-Echo Radial FLASH, 0.5 × 0.5 × 3 mm^3,

9 Shots, 14 Frames per Second