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UCLA Health | Radiology

UCLA MAGNETIC RESONANCE Research Labs

Volumetric Imaging and Beyond

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Outline

- Background
- Volumetric Imaging by 2D Multi-Slice Imaging
- Break
- Volumetric Imaging by 3D Imaging
- One Step Further: Multi-Dimensional imaging

* Only a brief overview of volumetric imaging and associated acceleration techniques

* More fast imaging and acceleration technical details to be covered by Dr. Anthony Christodoulou

*** For lecture feedback**

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Volumetric Imaging
Why?

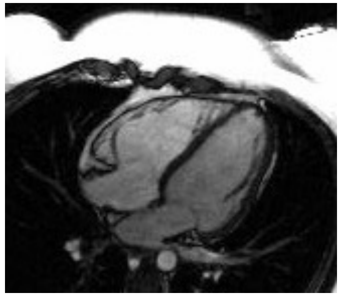
- Organs are three-dimensional (3D)

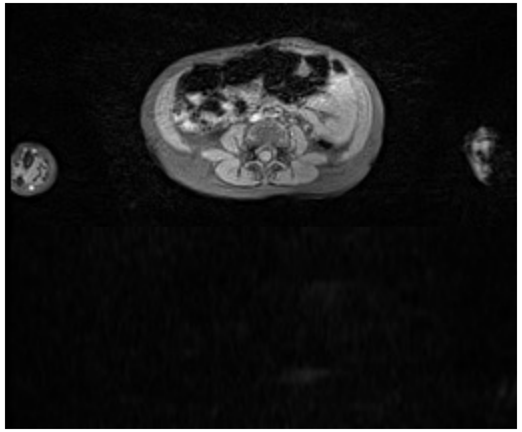
- Imaging modalities allow us to perform volumetric imaging
  - Ultrasound
  - Computer tomography (CT)
  - Magnetic resonance imaging (MRI)

- Typical reasons or situation why we might not prefer volumetric imaging
  - Not easy to acquire, i.e. requiring more knowledge and experience for the operators
  - Radiation dosage
  - Long acquisition time

Volumetric MR Imaging Common in MR Applications

- No concerns about radiation dosage in MRI
- Volumetric imaging is very common in clinical MRI applications for anatomy and function evaluation of organs
  - 2D multi-slice imaging
    - Cardiac: Short-axis and long-axis multi-slice evaluation (balanced SSFP, GRE), etc.
    - MSK: Multi-slice T1-, T2- and PD-weighted images (TSE), etc.
    - Neuro: Multi-slice diffusion (EPI), etc.
    - Body: Multi-slice diffusion (EPI), etc.
  - 3D imaging
    - Neuro: T1-weighted images (MPRAGE), etc.
    - Body: T1-weighted images (VIBE), etc.

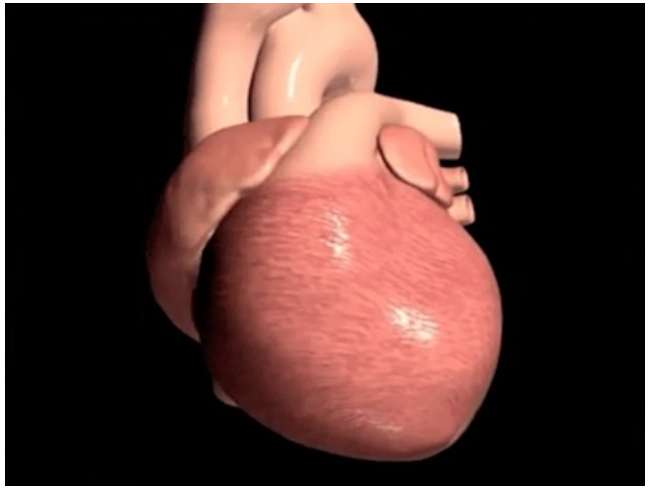




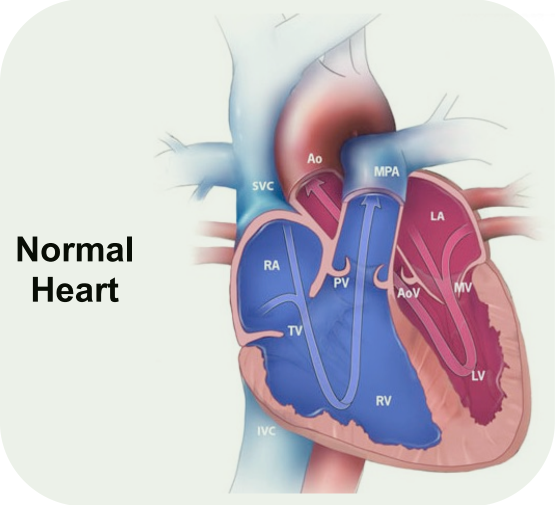
Volumetric MR Imaging
Easier than 2D to Acquire

- 2D cine imaging in clinical workflow
  - Multi-slice and multi-orientation prescription is challenging for inexperienced operators
  - Often needs expert and interactive supervision from physicians

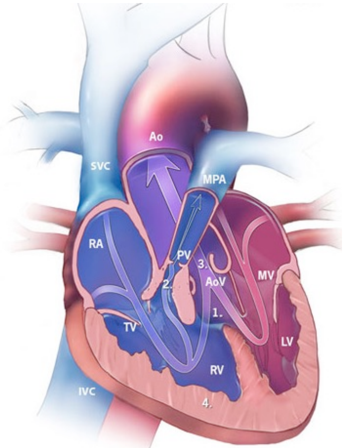
- Advantages of volumetric whole-heart imaging[1-6]
  - Easy imaging volume prescription
  - Isotropic voxel resolution
  - Flexibility for multiplanar reformatting
  - Higher SNR compared to 2D



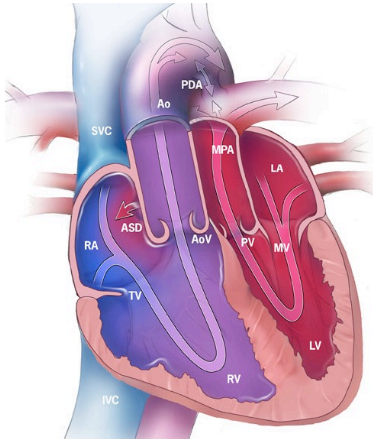
* Video courtesy of Jamil Aboulhosn, MD.



Tetralogy of Fallot



Dextro-Transposition of the Great Arteries (d-TGA)



1. Cruz et al. MRM 2017;77:1894-1908.
2. Holst et al. MRI 2017 Nov;43:48-55.
3. Küstner et al. NMR Biomed 2021;34:e4409.
4. Nguyen et al. Radiology 2021;300:162-173.
5. Bonanno et al. NMR Biomed 2021;34:e4589.
6. Braunstorfer et al. MRI 2022;94:64-72.

Heart illustrations courtesy of Centers for Disease Control and Prevention, National Center on Birth Defects and Developmental Disabilities.

Volumetric MR Imaging
What about Acquisition Time?

- A critical question

- Solution: Acceleration techniques
  - Parallel imaging => Also fundamental to 2D multi-slice imaging
    - GRAPPA
    - CAIPI
  - Compressed sensing
  - Deep learning

- We will talk more in detail later

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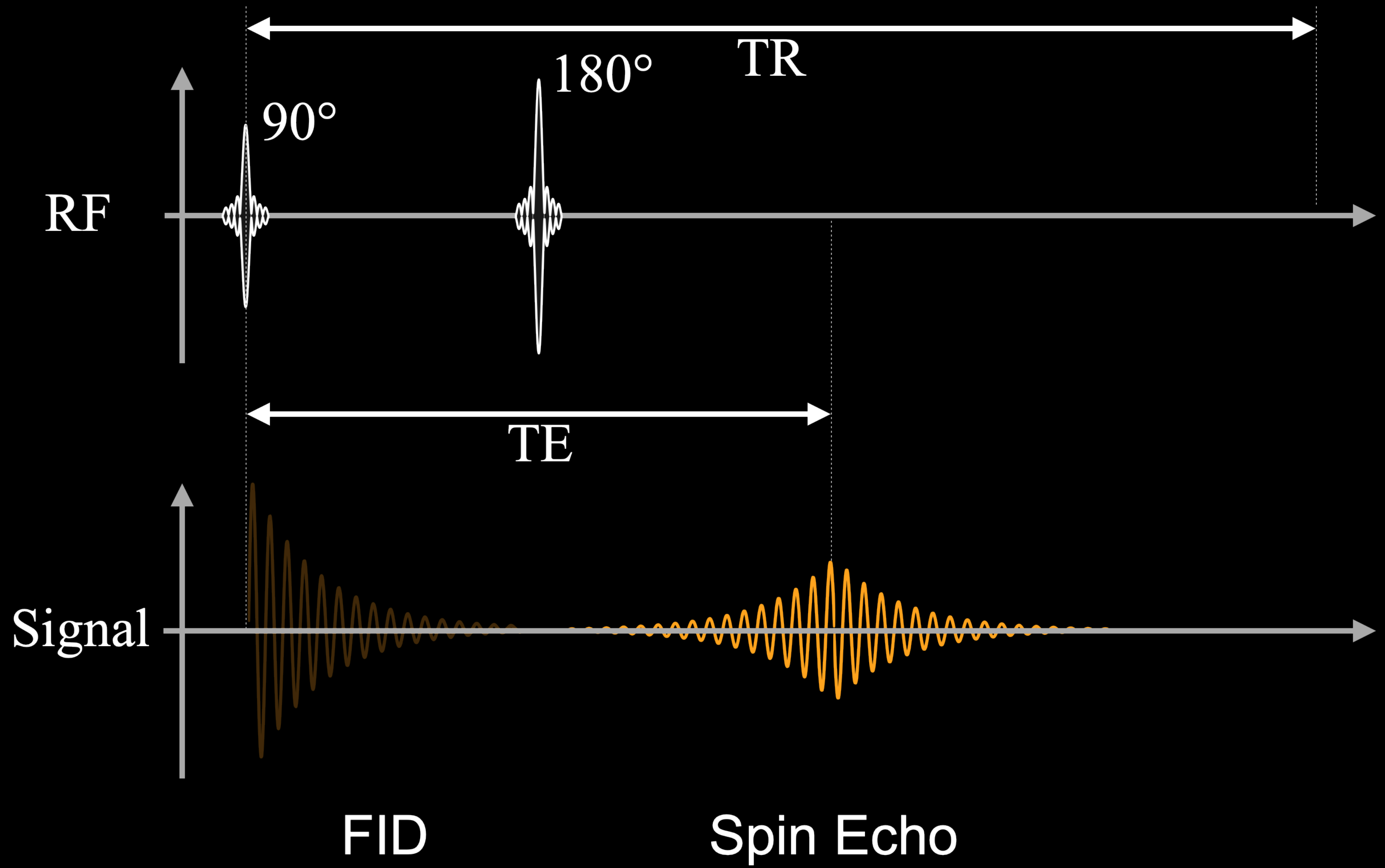
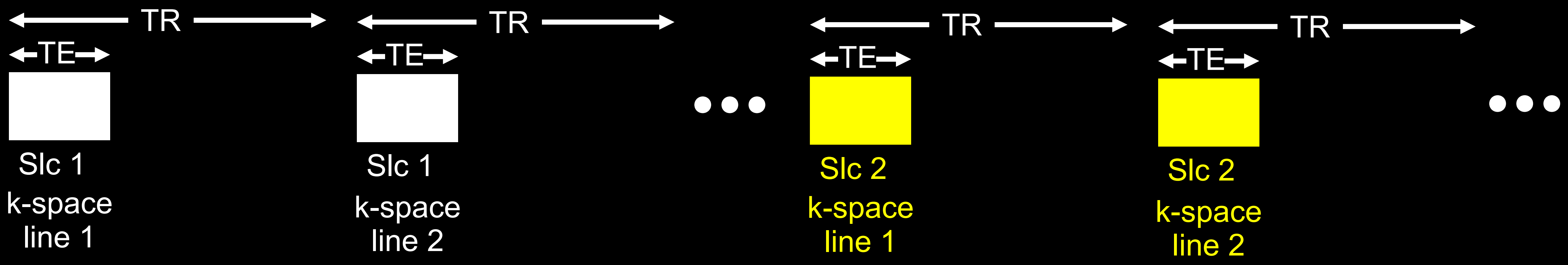
Single-Slice 2D Imaging
Illustrated using a Basic Spin Echo Sequence

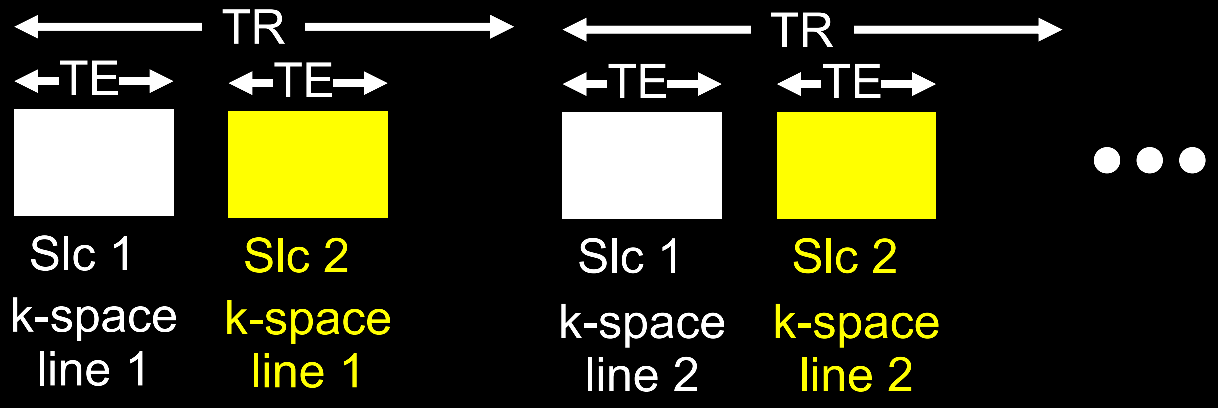


Multi-Slice 2D Imaging
Image Multiple Slices Sequentially



- Very straightforward and easy to implement
- Not efficient
  - Usually, TR (hundreds of ms or even seconds) much larger than TE (100 ms or shorter)

Multi-Slice 2D Imaging
Image Multiple Slices using Interleaved Acquisition

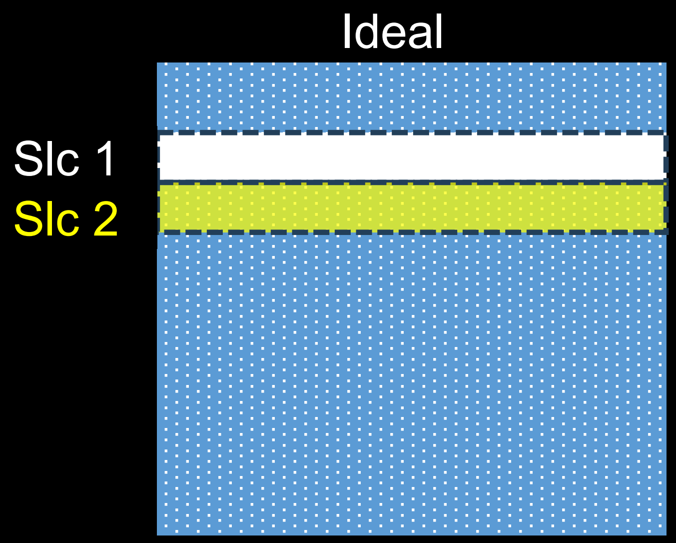


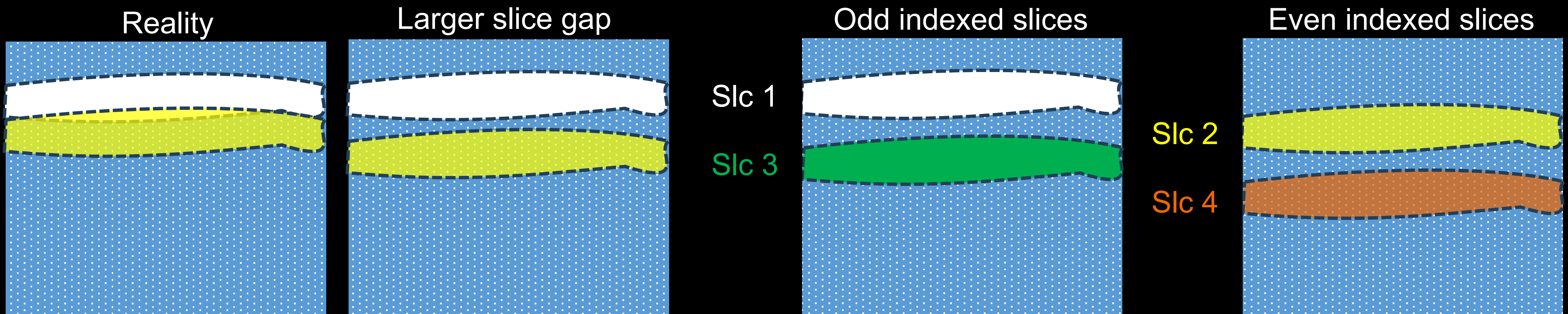
- The most commonly used multi-slice acquisition mode
- This can potentially accelerate the total acquisition by a factor of TR/TE

Multi-Slice 2D Imaging
Image Multiple Slices using Interleaved Acquisition

- Main disadvantage
  - Needs high-quality slice profile for the slice excitation
  - Otherwise slice crosstalk (overlapping) may exist

- Possible solutions to avoid slice crosstalk
  - Use larger slice gap (> 3mm)
  - Acquire odd- and even-indexed slices in two acquisitions



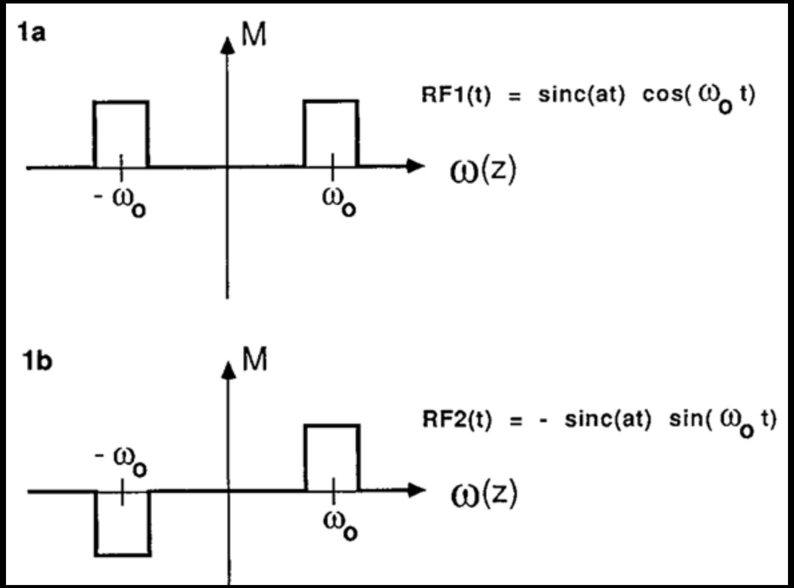


Multi-Slice 2D Imaging
Simultaneous Multi-Slice Imaging (SMS) Using Hadamard encoding

- Hadamard encoding
  - Avoid slice crosstalk via slice encoding and decoding

$\omega_0 = 2\pi\gamma G_{ss} z$ $RF(t) = \mathrm{sinc}(at)e^{i\omega_0 t}$

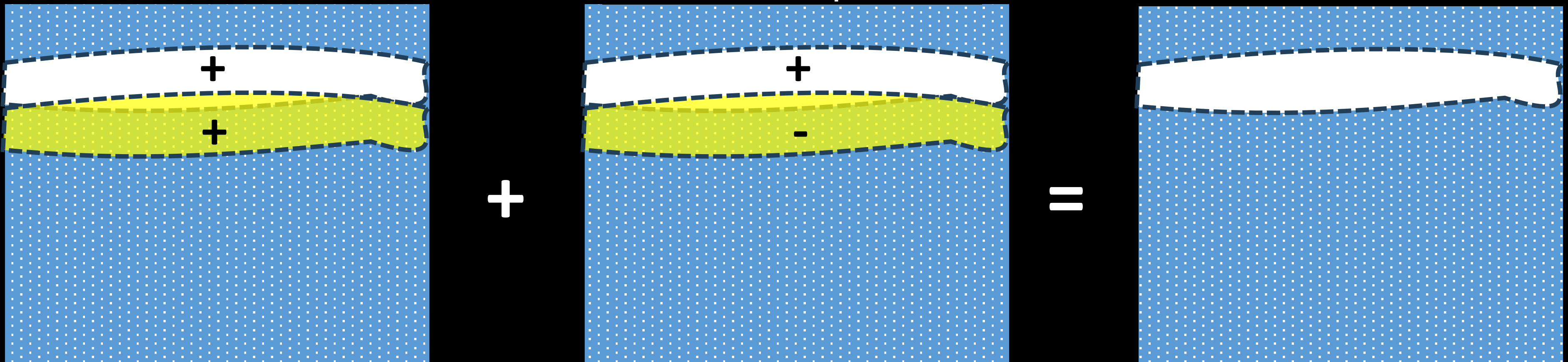
$$\begin{array}{cc} \omega_0 & -\omega_0 \end{array}$$
$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{array}{l} \text{cos modulation} \\ \text{sin modulation} \end{array}$$



Souza et al. J Comput Assist Tomogr 1988;12:1026-1030.

The 1st acquisition

The 2nd acquisition



Multi-Slice 2D Imaging
Simultaneous Multi-Slice Imaging (SMS) Using Hadamard encoding

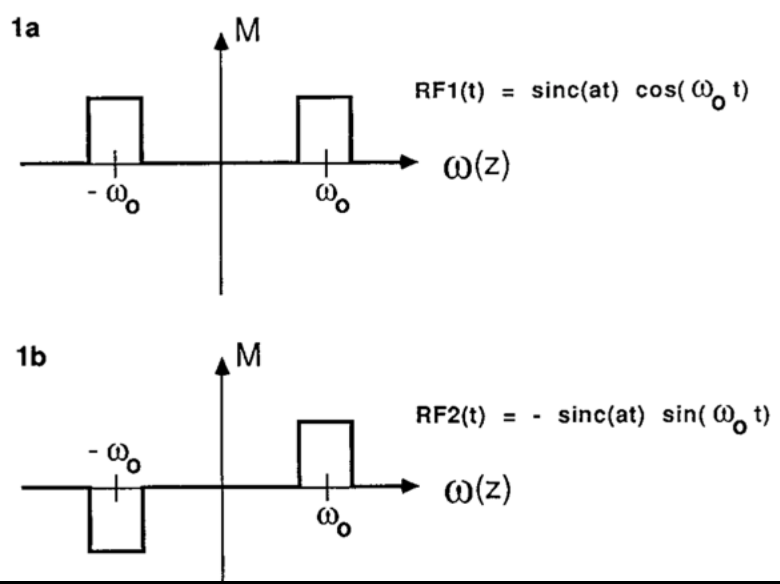
- Hadamard encoding
  - Avoid slice crosstalk via slice encoding and decoding

$\omega_0 = 2\pi\gamma G_{ss} z$

$\mathrm{RF}(t) = \mathrm{sinc}(at)e^{i\omega_0 t}$

$$\begin{matrix} \omega_0 & -\omega_0 \end{matrix}$$
$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{matrix} \text{cos modulation} \\ \text{sin modulation} \end{matrix}$$

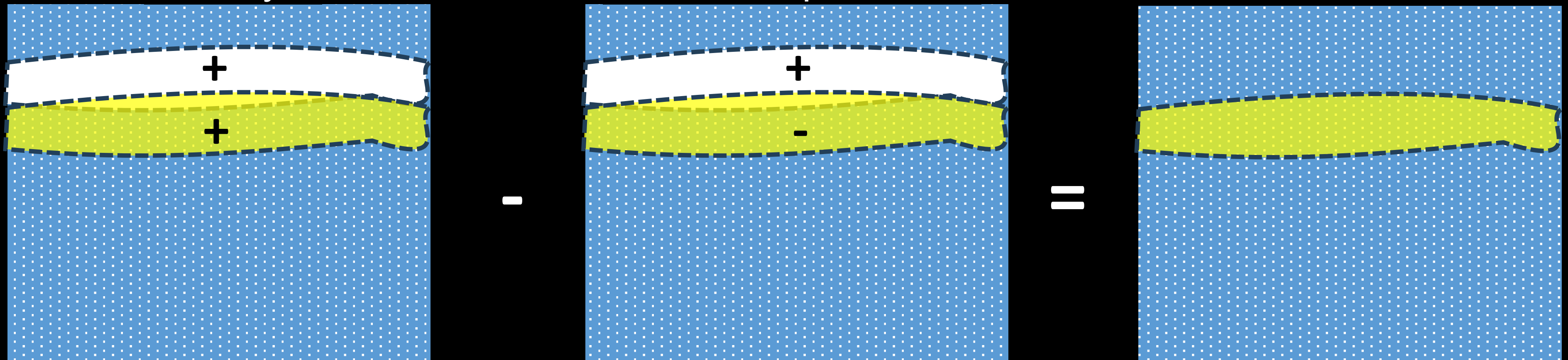
  - No time penalty only when averaging is used anyway



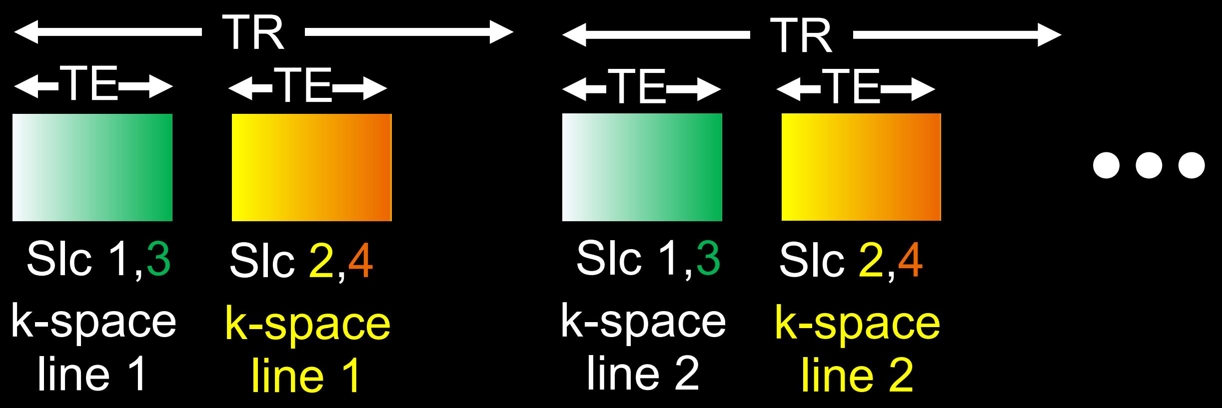
Souza et al. J Comput Assist Tomogr 1988;12:1026-1030.

Reality

A 2nd acquisition



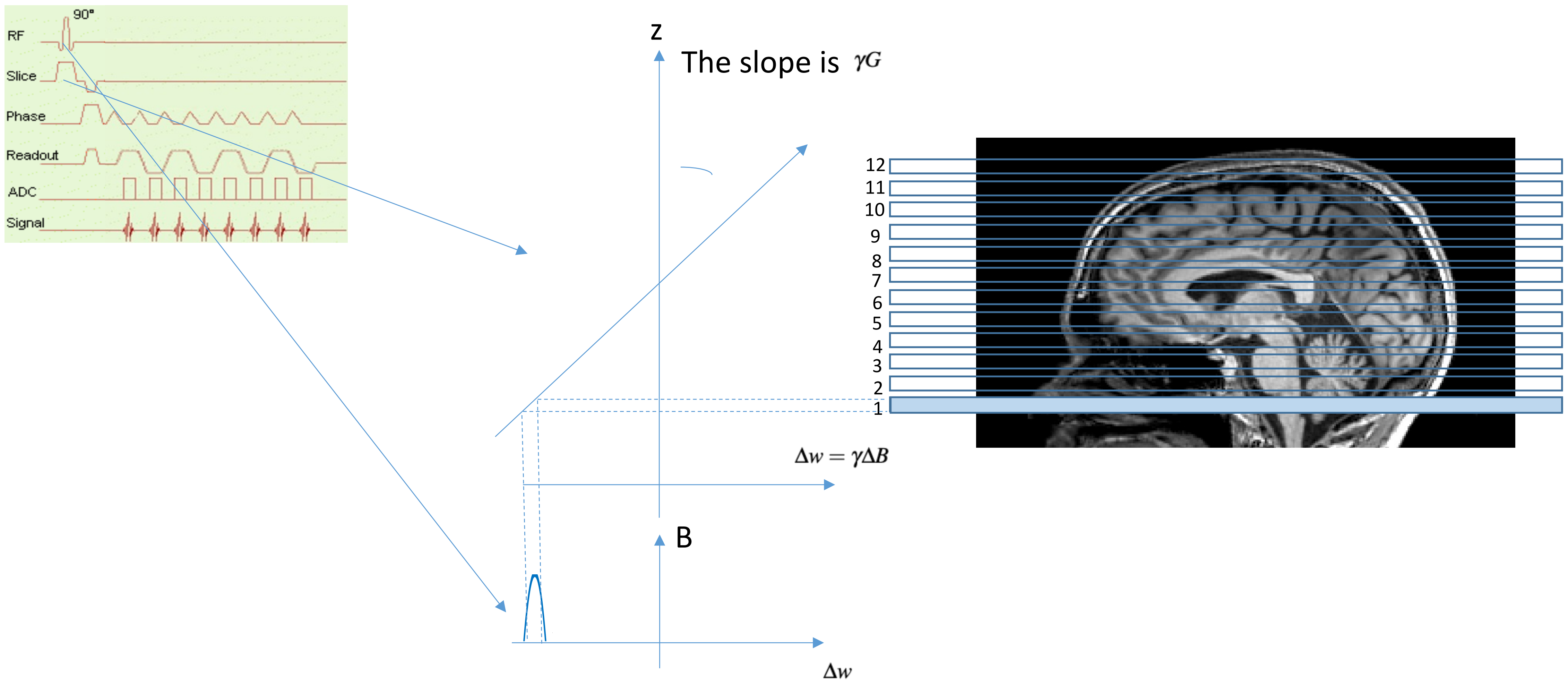
Multi-Slice 2D Imaging
State-of-the-Art Simultaneous Multi-Slice Imaging (SMS, MultiBand)



- Further accelerate the acquisition by the number of simultaneously acquired slices (when TR is sufficiently large)

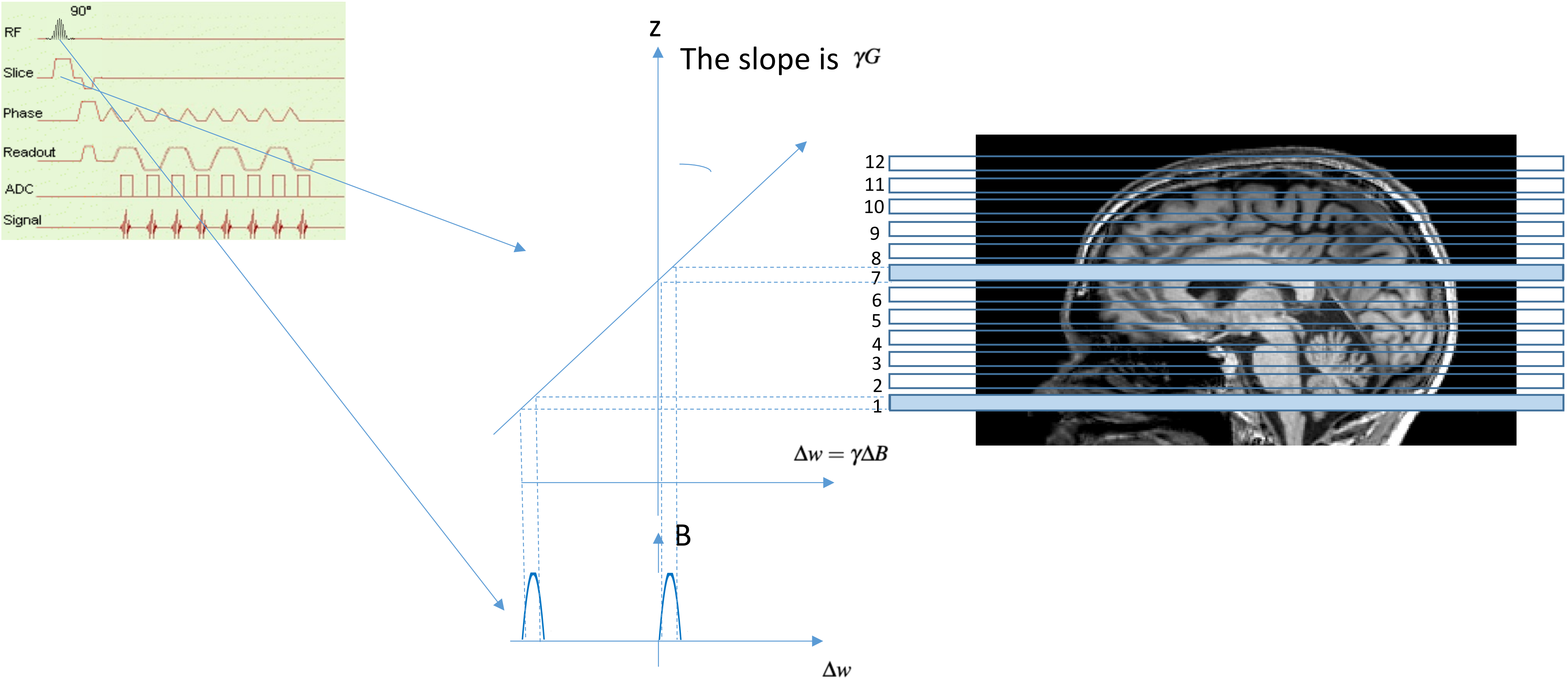
- Key innovations
  - Leveraging multi-coil sensitivity, especially in the slice direction, enabled this
  - Parallel imaging reconstruction to disentangle adjacent slices

Slice Excitation
Single Slice Selection



* Illustration courtesy of Deqiang Qiu, PhD.

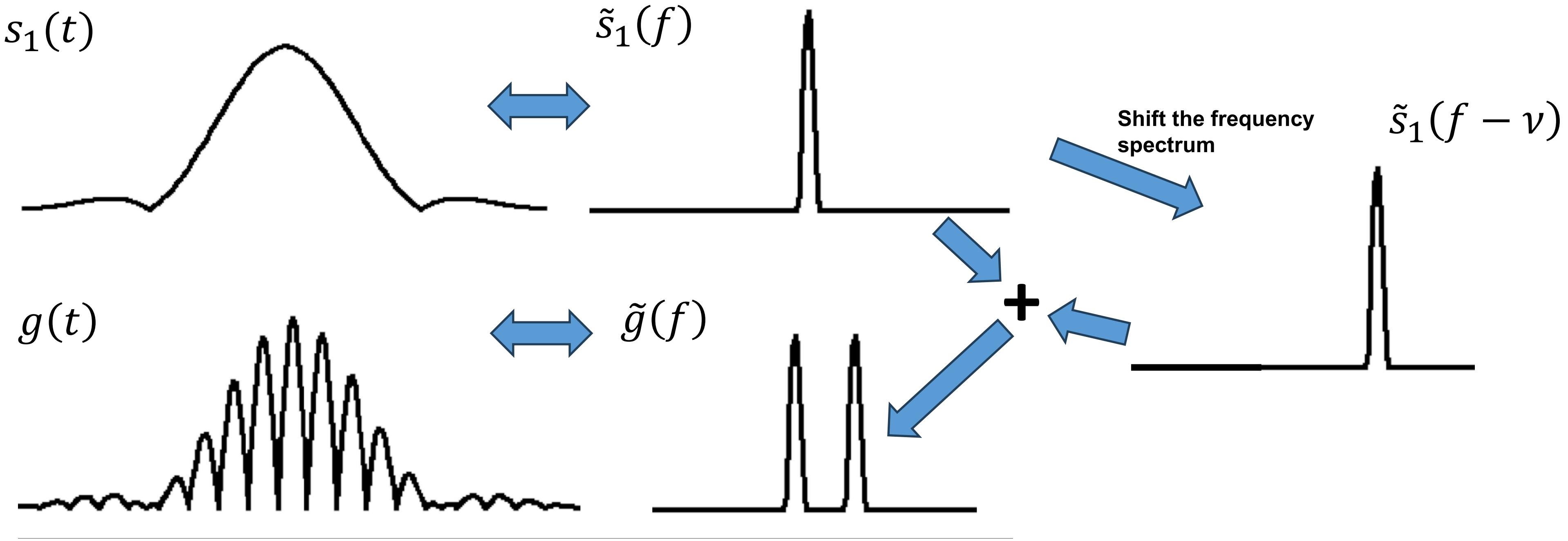
SMS RF Pulse
Multi-Slice Excitation



* Illustration courtesy of Deqiang Qiu, PhD.

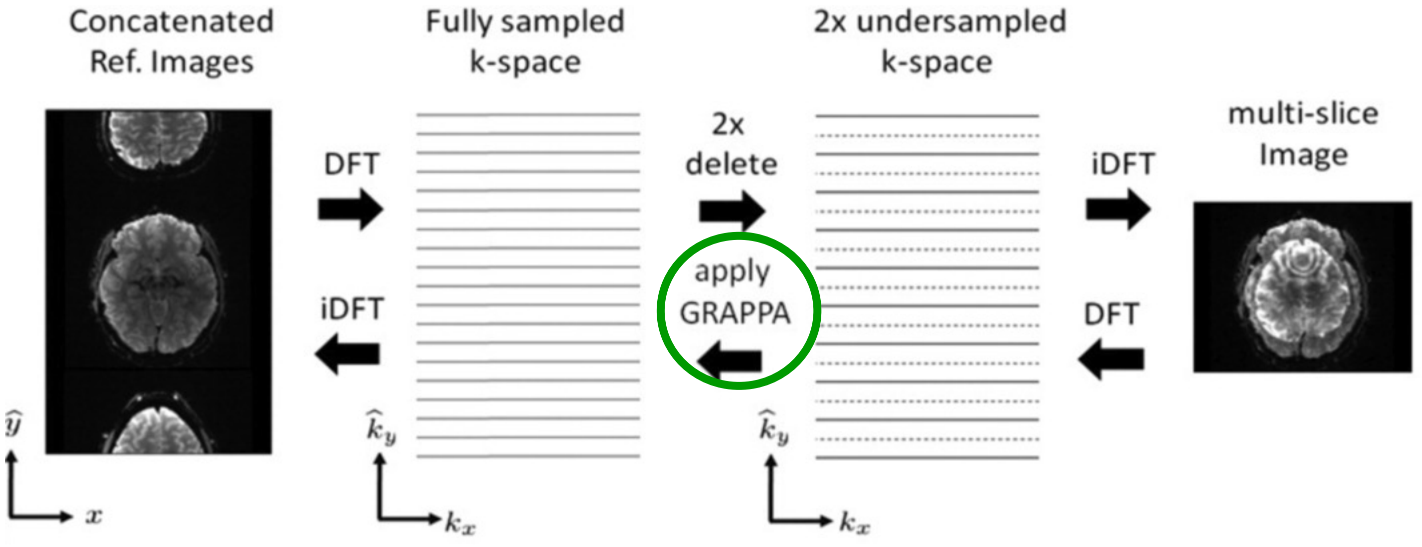
SMS RF Pulse
A Simple Method of Creating SMS RF Pulse for Excitation

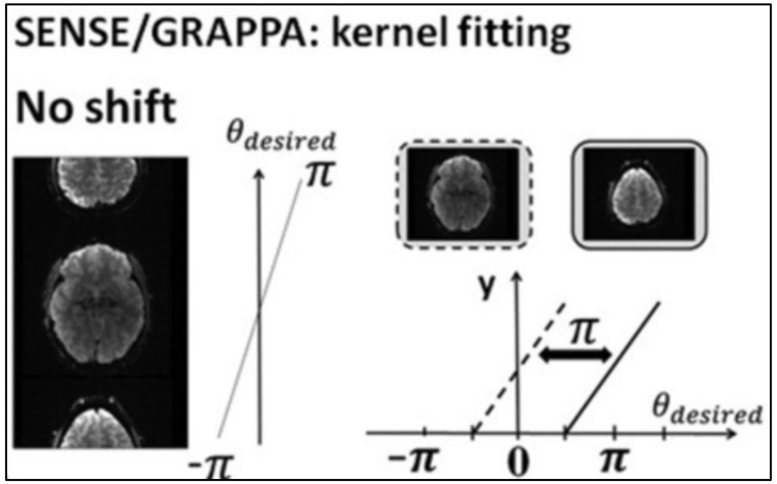
- Start with a single-band RF pulse $s_1(t)$ with the frequency spectrum of $\tilde{s}_1(f)$
- Shift the frequency spectrum to a different center frequency ν, then $s_2(t) = F^{-1}\tilde{s}_1(f-\nu) = s_1(t)e^{i2\pi\nu t}$
- Then sum them up: $g(t) = s_1(t) + s_2(t)$



SMS Data Reconstruction
GRAPPA

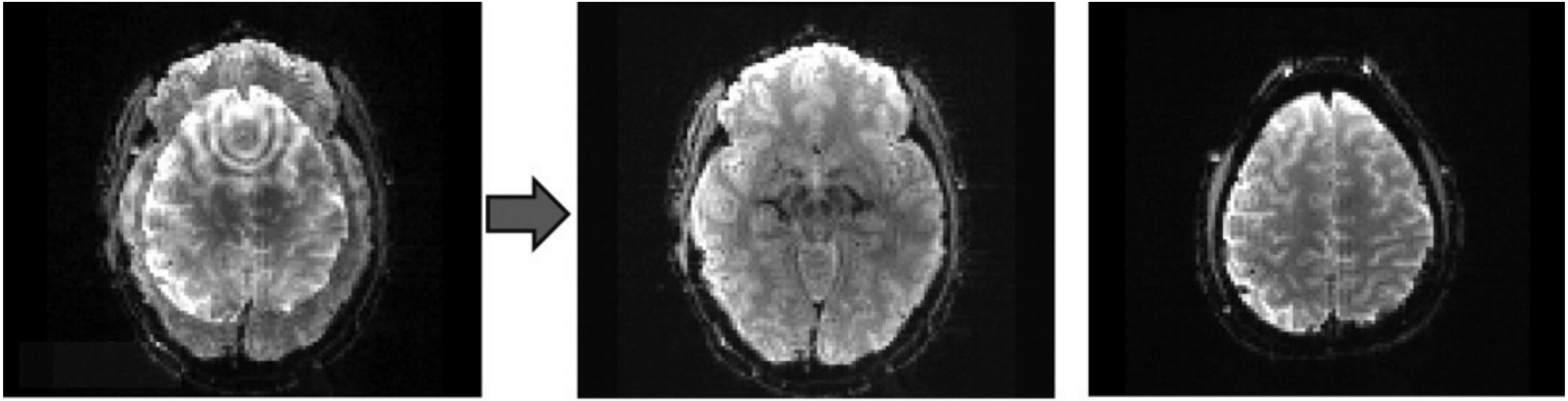
- Left -> right: k-space data of the concatenated slices are undersampled by 2× and reconstructed with the inverse DFTto produce the aliased multi-slice image
- Right -> left:
  - k-space data of the acquired aliased multi-slice image are viewed as a 2× undersampled dataset
  - A GRAPPA kernel is trained on concatenated reference images (acquired one slice at a time)
  - GRAPPA kernel is applied to undersampled k-space data to generate the full k-space which can be converted to an unaliased, but concatenated, image of the slices





Setsompop et al. Mag Reson Med 2012;67:1210-1224.

SMS Data Reconstruction
GRAPPA



Setsompop et al. Mag Reson Med 2012;67:1210-1224.

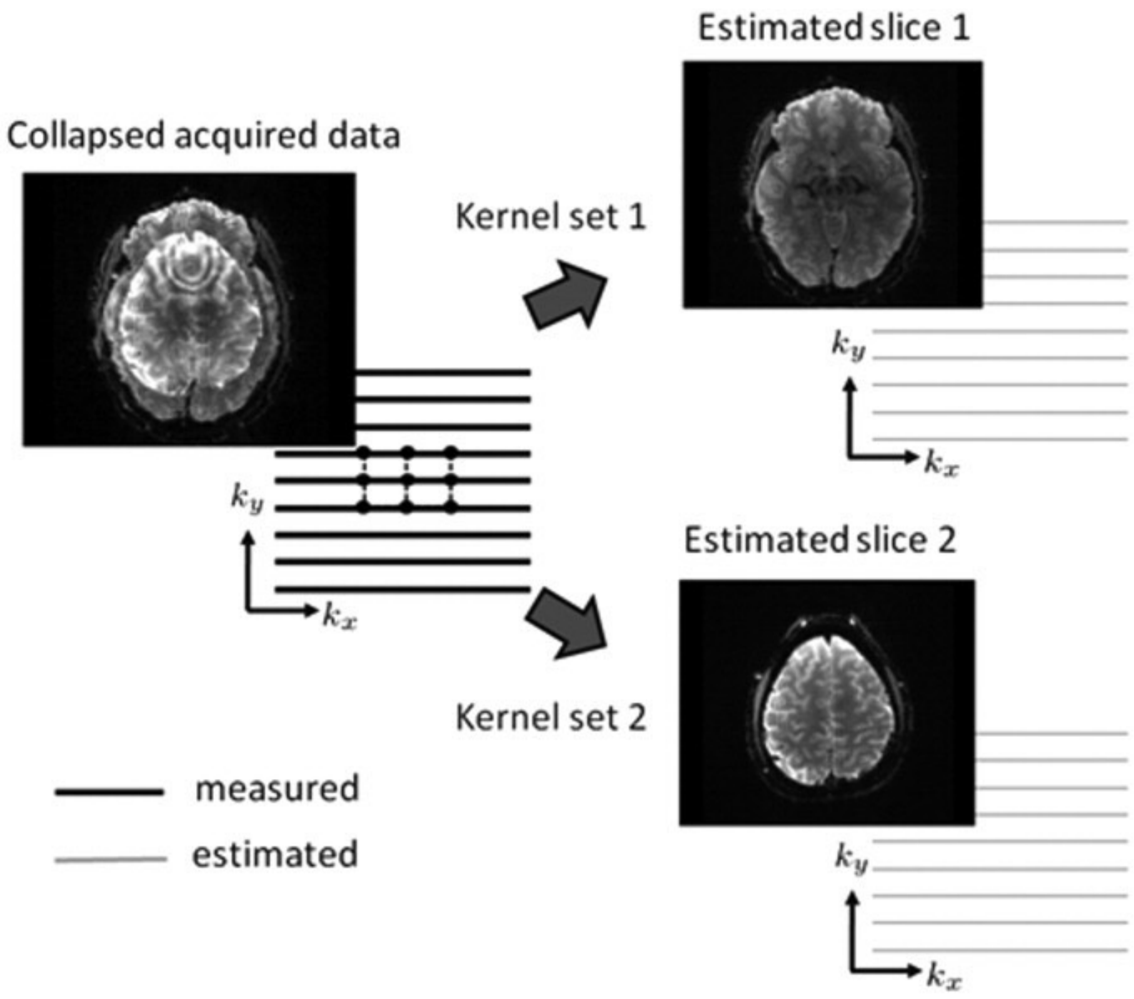
SMS Data Reconstruction
Slice-GRAPPA

- GRAPPA kernels are fit using data acquired from separately excited single-slice data (calibration)

$$S_{j,z}(k_x, k_y) = \sum_{\ell=1}^{L} \sum_{b_x=-B_x}^{B_x} \sum_{b_y=-B_y}^{B_y} n_{j,z,\ell}^{b_x,b_y} S_{\ell,\text{collapse}} \times (k_x - b_x \Delta k_x, k_y - b_y \Delta k_y).$$

- Two kernel sets are applied directly to the k-space data of the collapsed images to generate each of the two imaging slices

- Better than in-plane GRAPPA when using advanced techniques (FOV shift)



Setsompop et al. Mag Reson Med 2012;67:1210-1224.

Break time (10 minutes)

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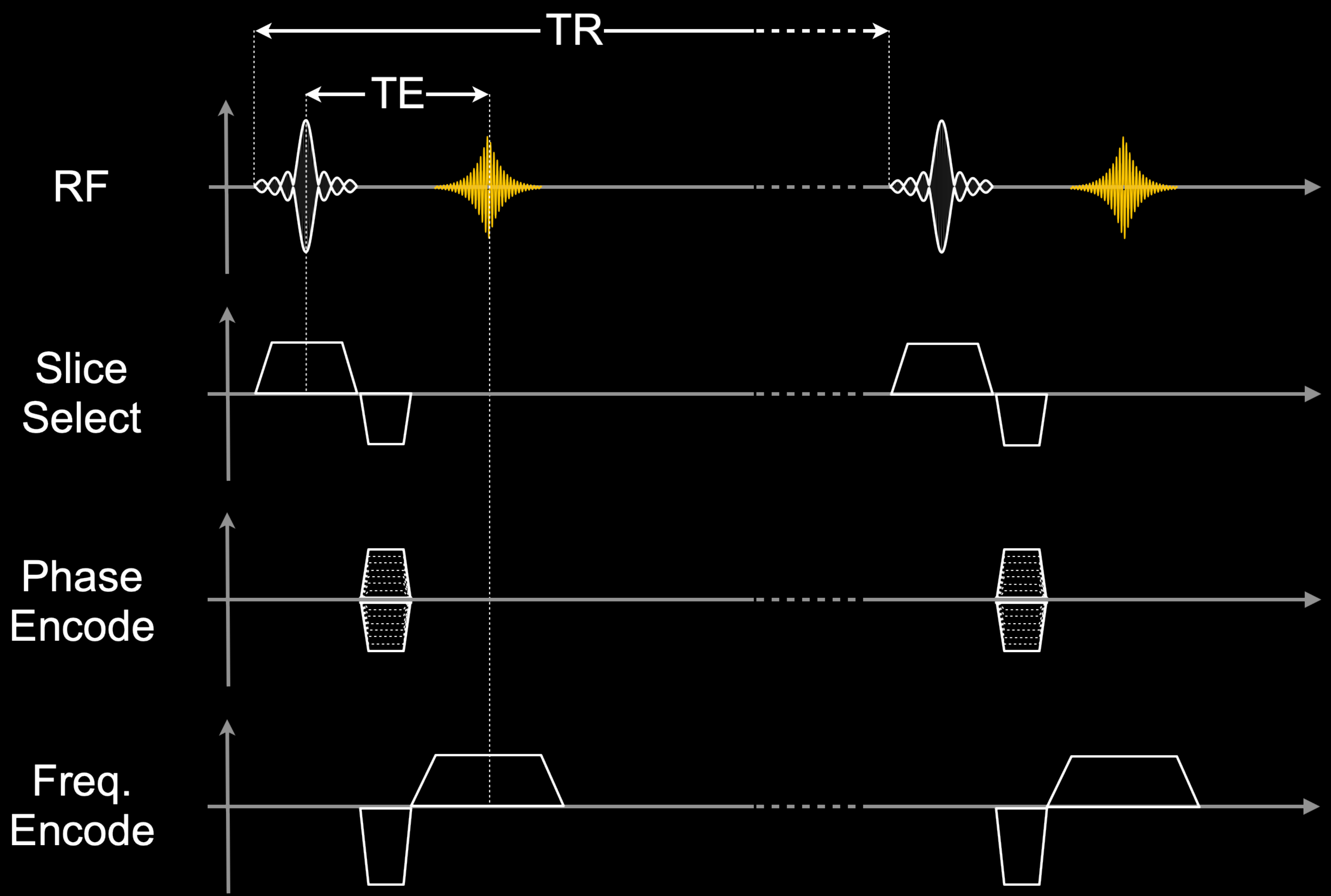
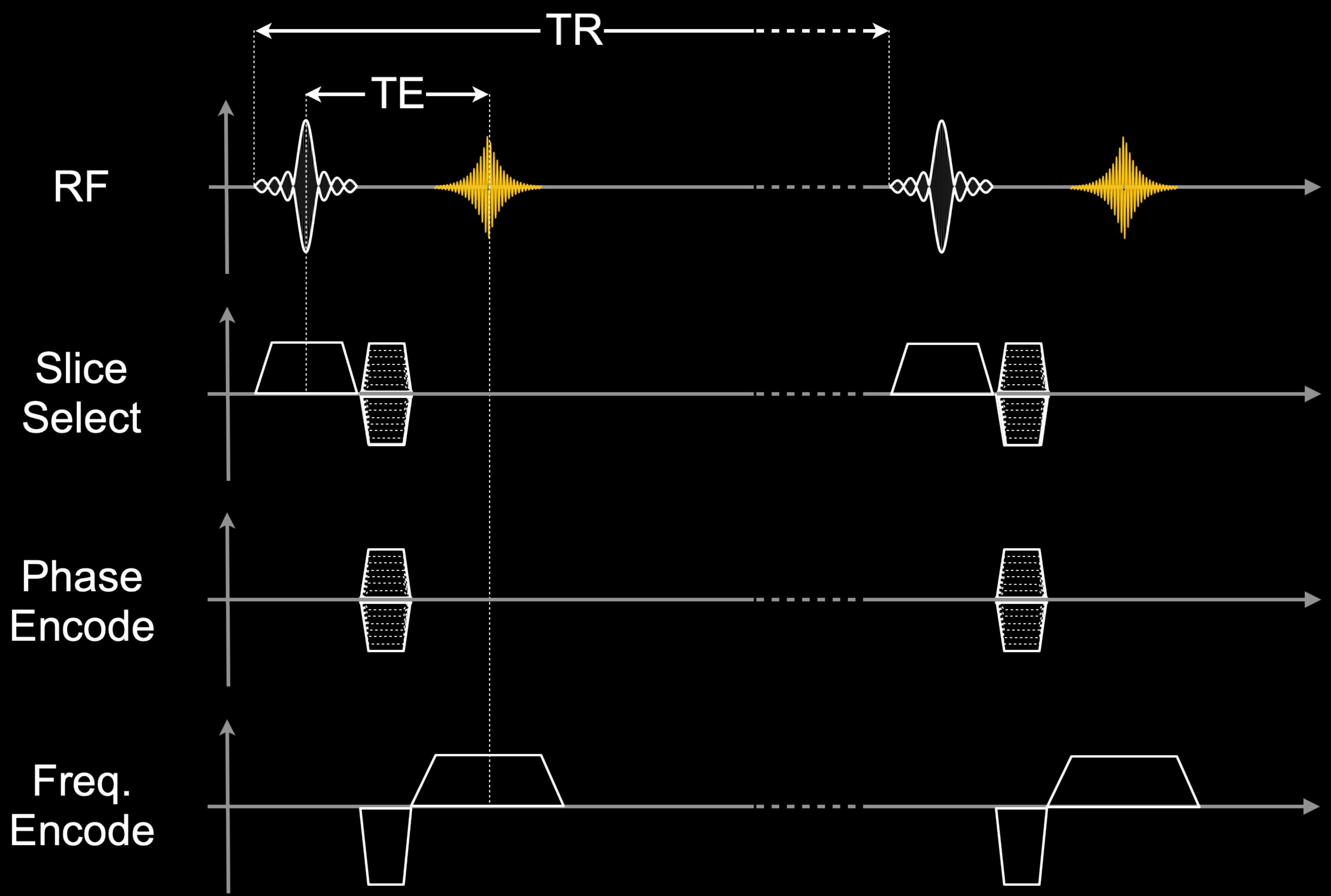
Single-Slice 2D Imaging
Example using a Basic Gradient Echo Illustration



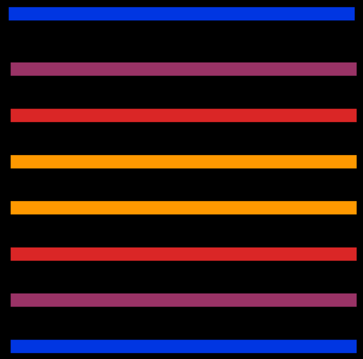
3D Volumetric Imaging
Example Using a Basic Gradient Echo Illustration



2D Imaging and 3D Volumetric Imaging
Typical Trajectories

2D

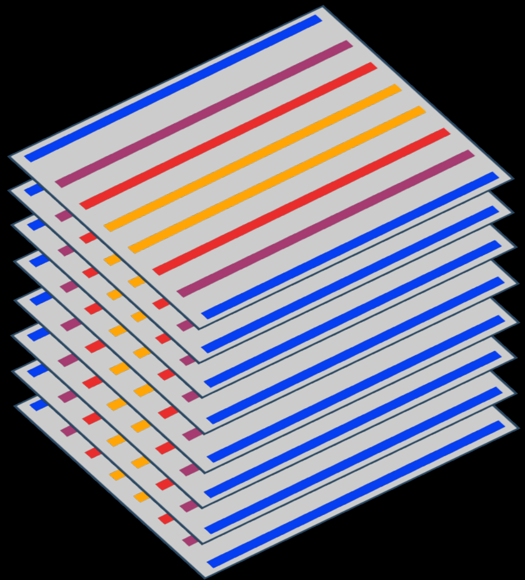
Cartesian



Radial

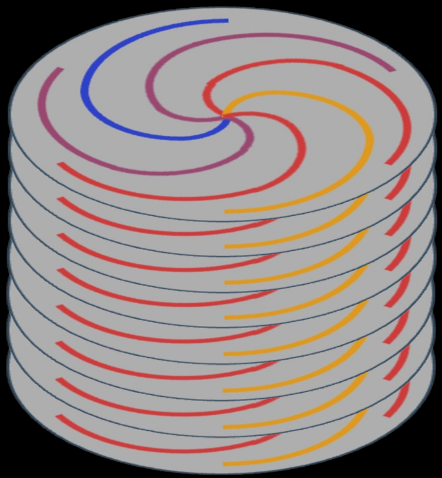
Spiral

3D



Stack-of-star
(or stack-of-radial)

Stack-of-spiral



3D Volumetric Imaging
Typical Reconstruction of Cartesian Data

- Perfectly described by the 3D DFT

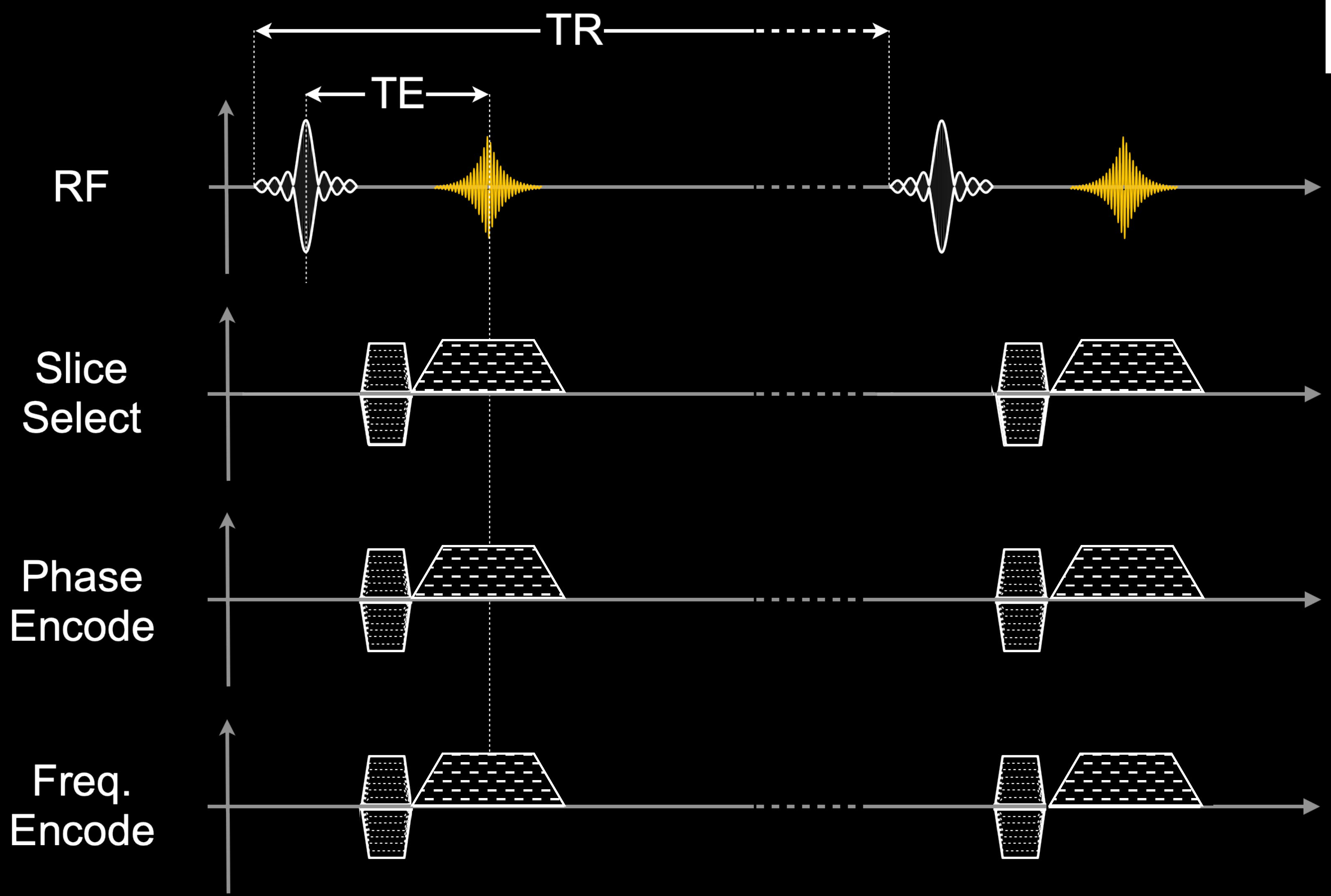
$$s(t) = \int_x \int_y \int_z m(x,y,z) e^{-i2\pi k_x(t)x} e^{-i2\pi k_y(t)y} e^{-i2\pi k_z(t)z} dxdydz$$
$$= M(k_x(t), k_y(t), k_z(t))$$

where

$$k_x(t) = \frac{\gamma}{2\pi} \int_0^t G_x(\tau) d\tau$$
$$k_y(t) = \frac{\gamma}{2\pi} \int_0^t G_y(\tau) d\tau$$
$$k_z(t) = \frac{\gamma}{2\pi} \int_0^t G_z(\tau) d\tau$$

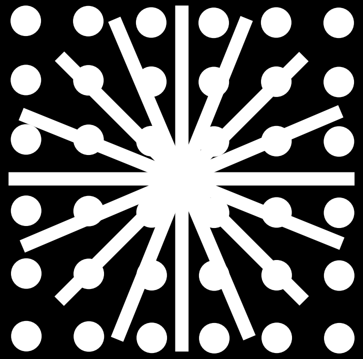
- Typically, 3D DFT is performed to reconstruct the images from k-space data
  - It can start from any dimension, x, y, or z. Gives practical convenience
  - Can leverage the Fourier Transform theory for algorithm development, etc

3D Volumetric Imaging
3D Radial Imaging ("Koosh-Ball")



3D Volumetric Imaging
Typical Reconstruction of Non-Cartesian Data

- **Reconstruction**
  - **Regridding**
    - **Stack-of-star k-space -> 3D Cartesian k-space**



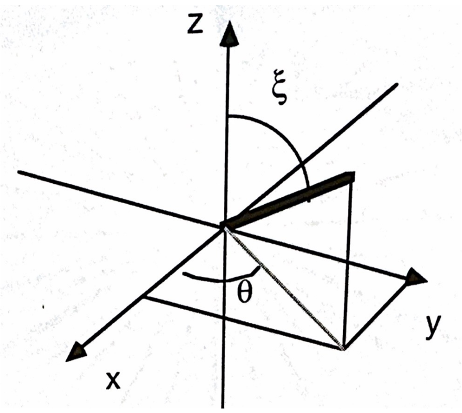
- **Other comprehensive steps need to be incorporated**
  - **Off-resonance correction**
  - **Density compensation**

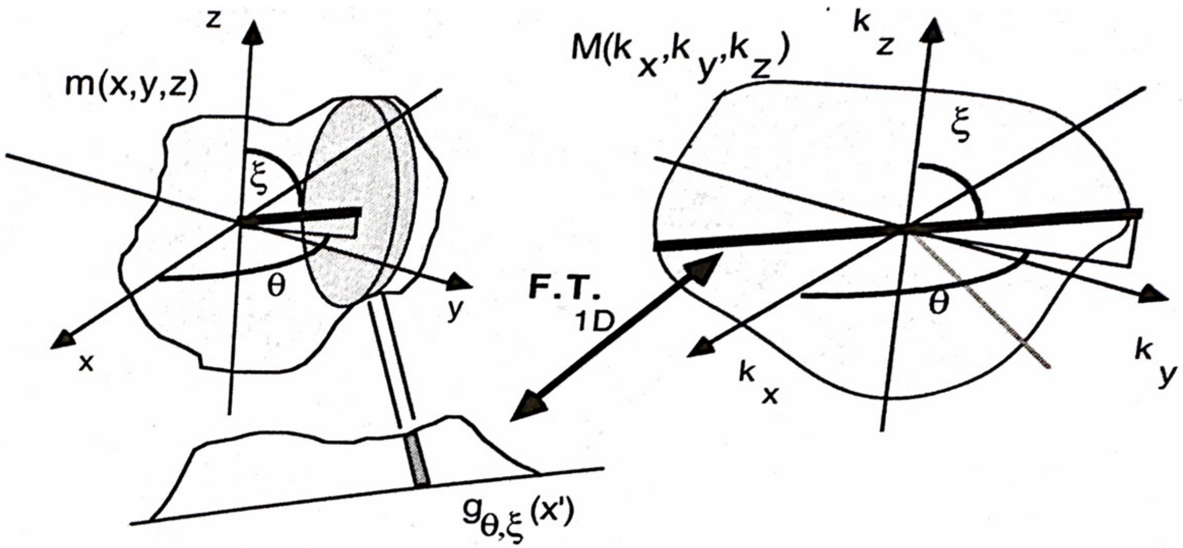
- **Finally, a DFT converts the 3D Cartesian k-space to 3D images**
- **Popular alternative: Nonuniform fast Fourier transform (NUFFT)**
  - **Open-source code at https://web.eecs.umich.edu/~fessler/code/**

1. Fessler et al. *IEEE transactions on signal processing* 2003;51:560-574.

A Useful Property for 3D Radial Imaging
3D Central Section Theorem

- The FT of 1D planar-integral projection at an orientation is equal to the 3D FT of the object along the radial line at that same orientation



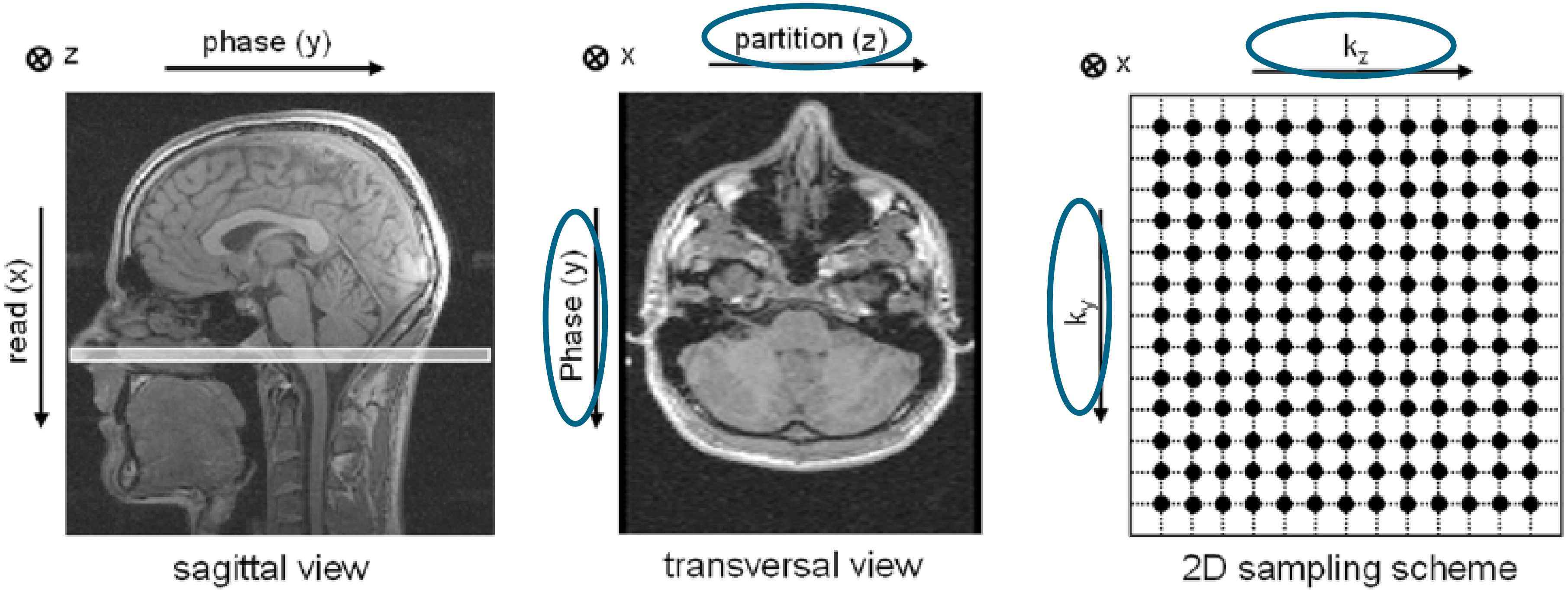


* Nishimura, Principles of Magnetic Resonance Imaging.

Volumetric MR Imaging
What about Acquisition Time?

- Solution: Acceleration techniques
  - Parallel imaging => Also fundamental to 2D multi-slice imaging
    - GRAPPA
    - CAIPI
  - Compressed sensing
  - AI -> Not in technical detail in this presentation

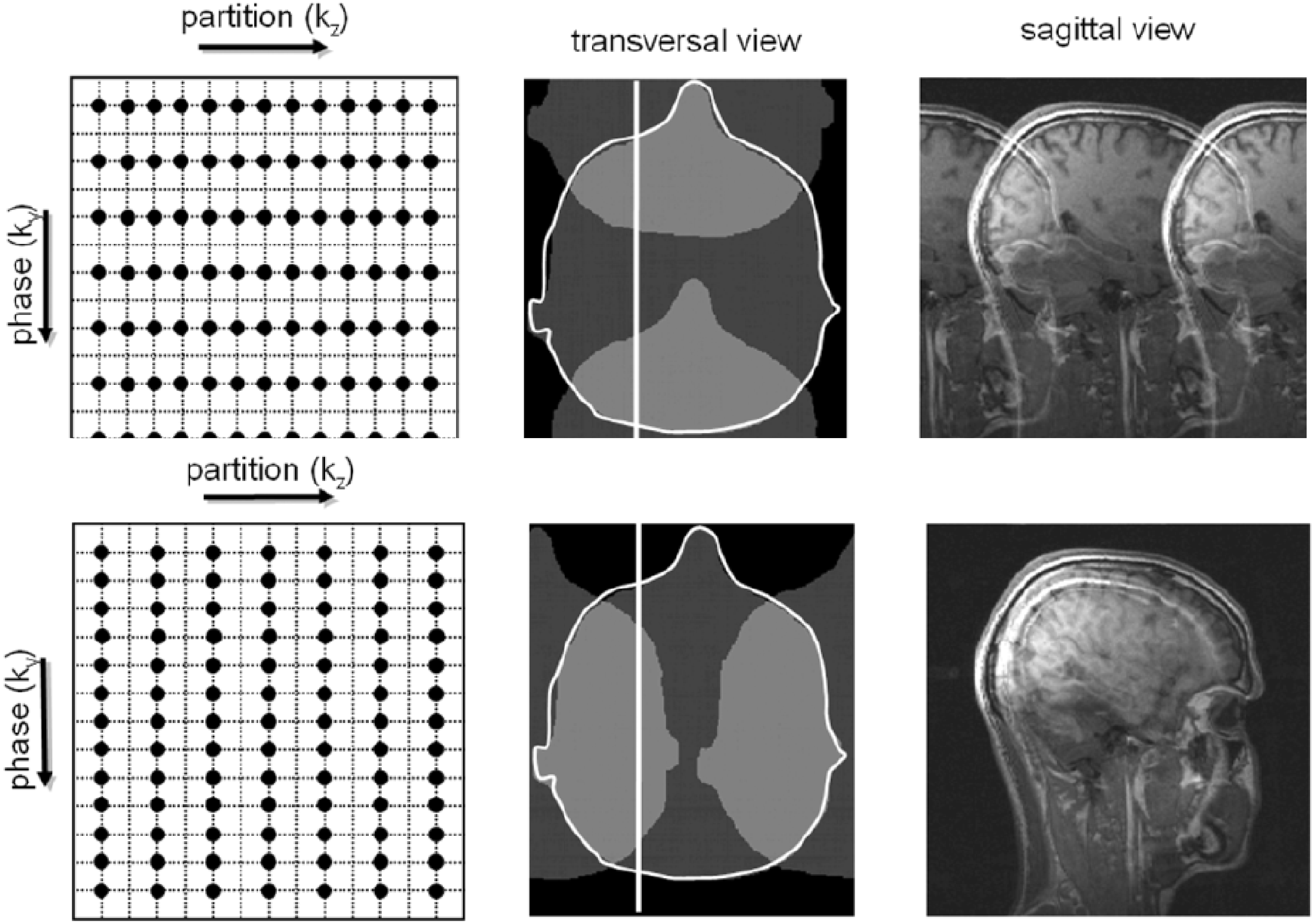
MR Data Sampling
Fully Sampled Acquisition



F. Breuer et al., Magn Reson Med **55** (2006)

Acquisition Acceleration by Parallel Imaging
Undersampling k-Space

Conventional, Ry = 2



Conventional, Rz = 2

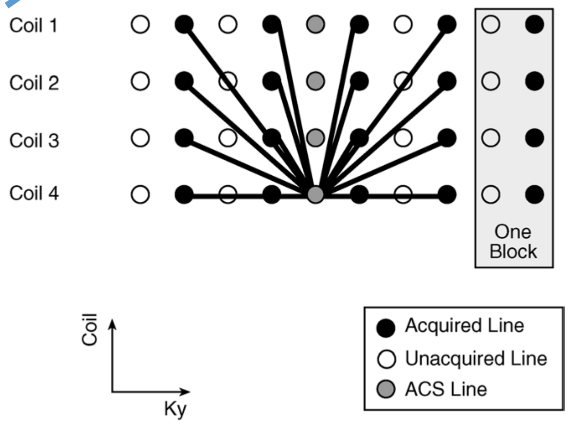
…and there'll be aliasing.

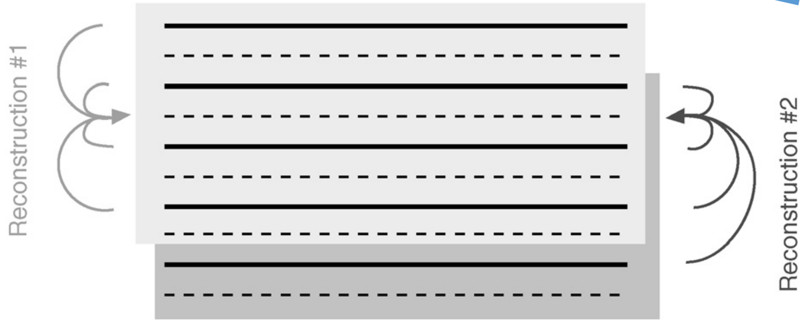
F. Breuer et al.,
Magn Reson Med **55** (2006)

Acquisition Acceleration by Parallel Imaging
From GRAPPA to CAIPIRINHA

GeneRalized Autocalibrating Partially Parallel Acquisitions

Controlled Aliasing In Parallel Imaging Results IN Higher Acceleration



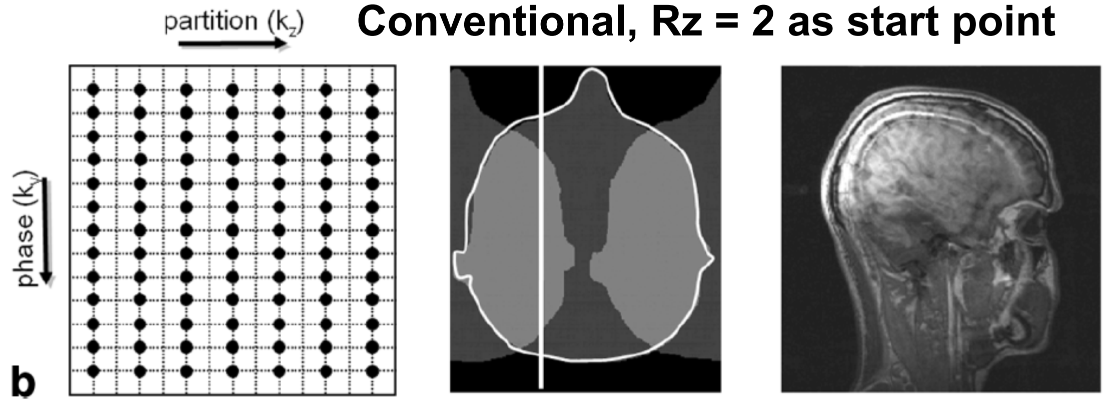


M. Griswold et al., Magn Reson Med **47** (2002)

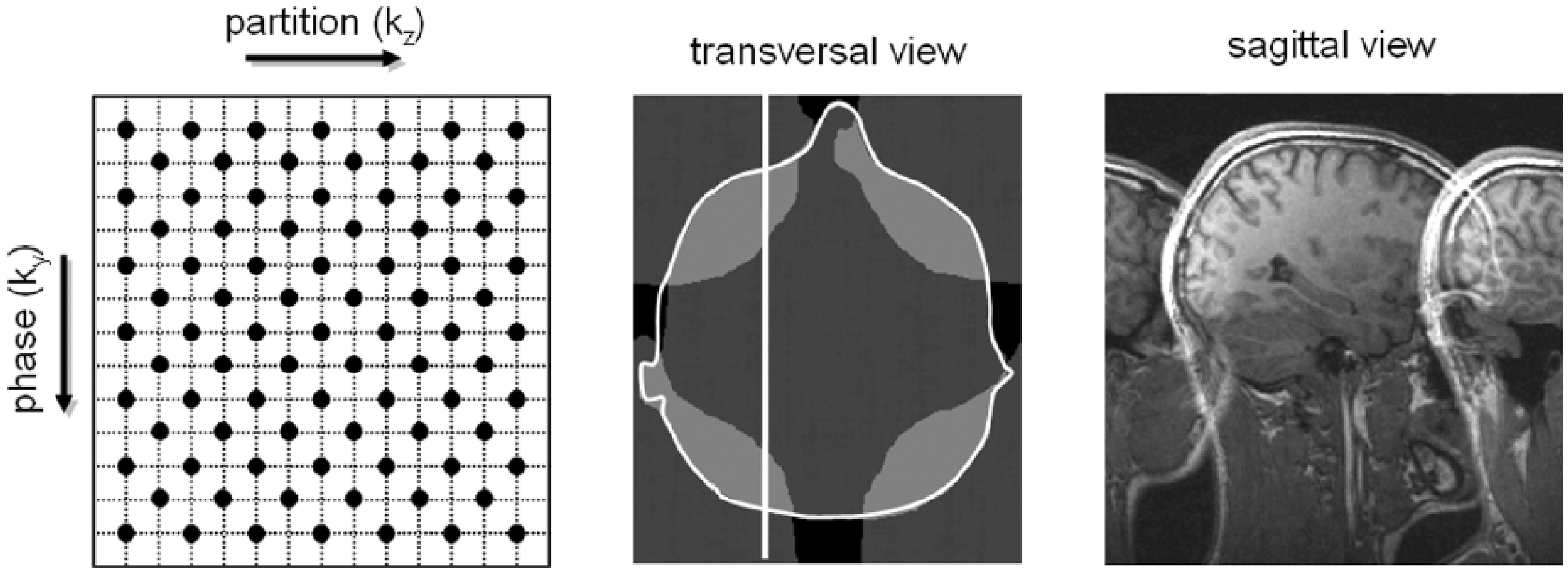
* ACS: Auto Calibration Signal

Acquisition Acceleration by Undersampling k-Space
CAIPIRINHA: Accelerate in Two Directions Simultaneously…

Conventional, Rz = 2 as start point



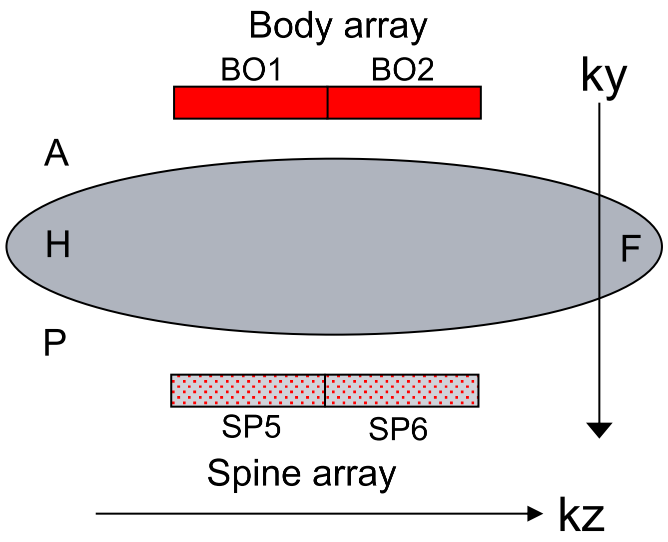
CAIPIRINHA, Rz = 2, ΔKz = 1



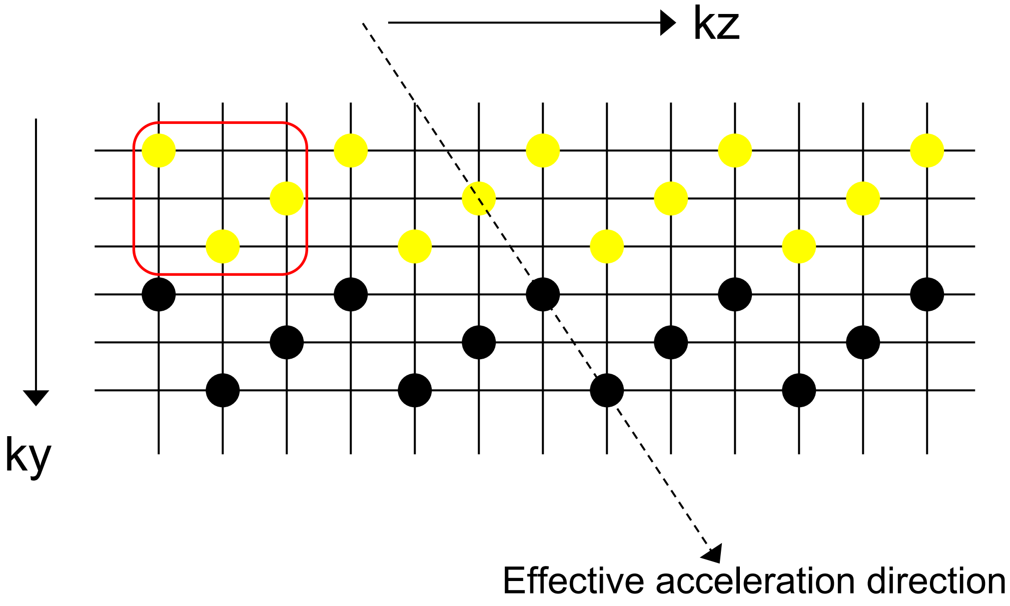
F. Breuer et al., Magn Reson Med **55** (2006)

Acquisition Acceleration by Undersampling k-Space
CAIPIRINHA: Accelerate in Two Directions Simultaneously…

1st number: PE accel, 2nd number: SS accel, 3rd number: delta kz shift

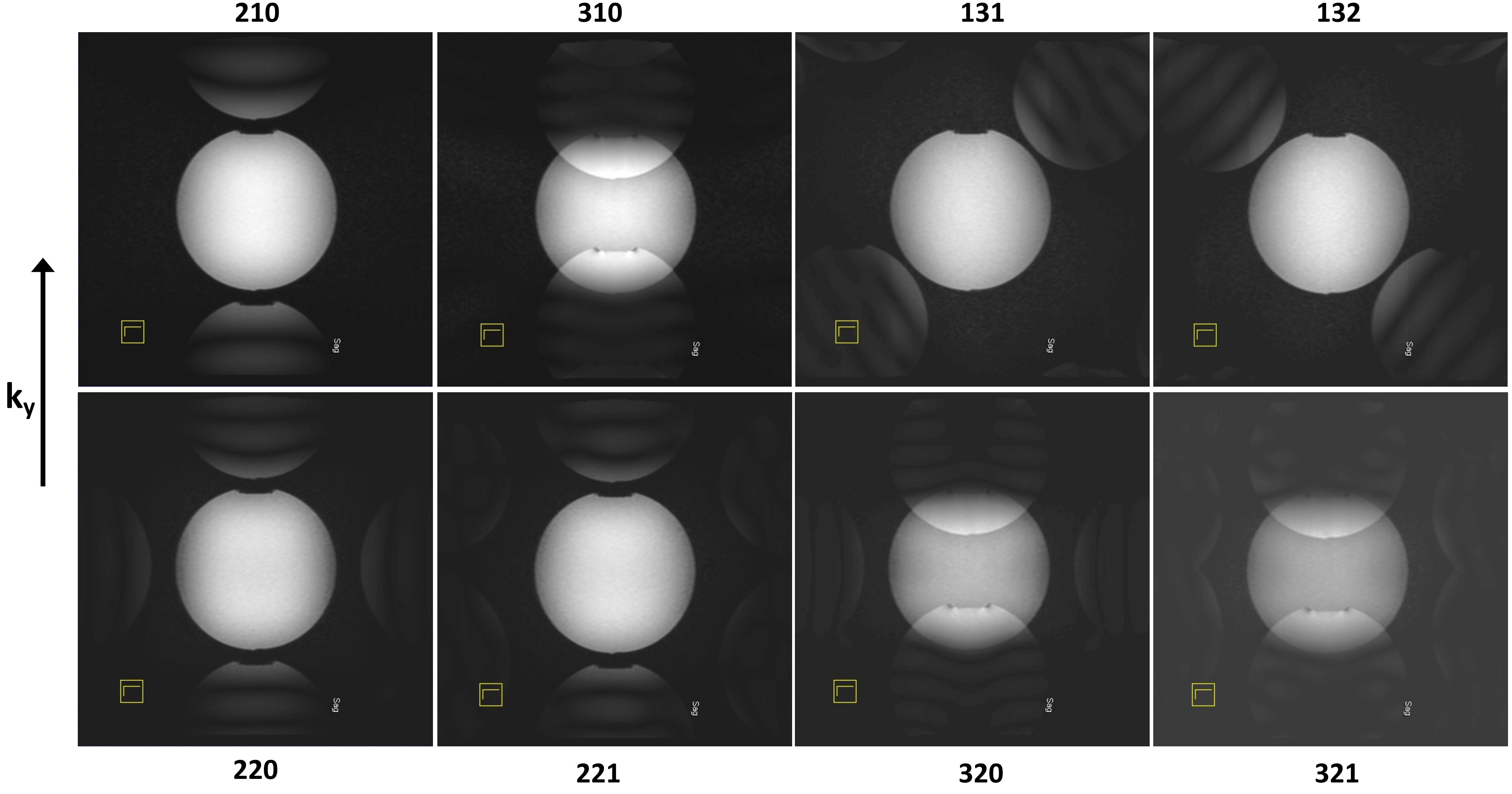


Overall acceleration factor = 3
CAIPIRINHA sampling pattern 132



Deshpande et al, ISMRM (2012)

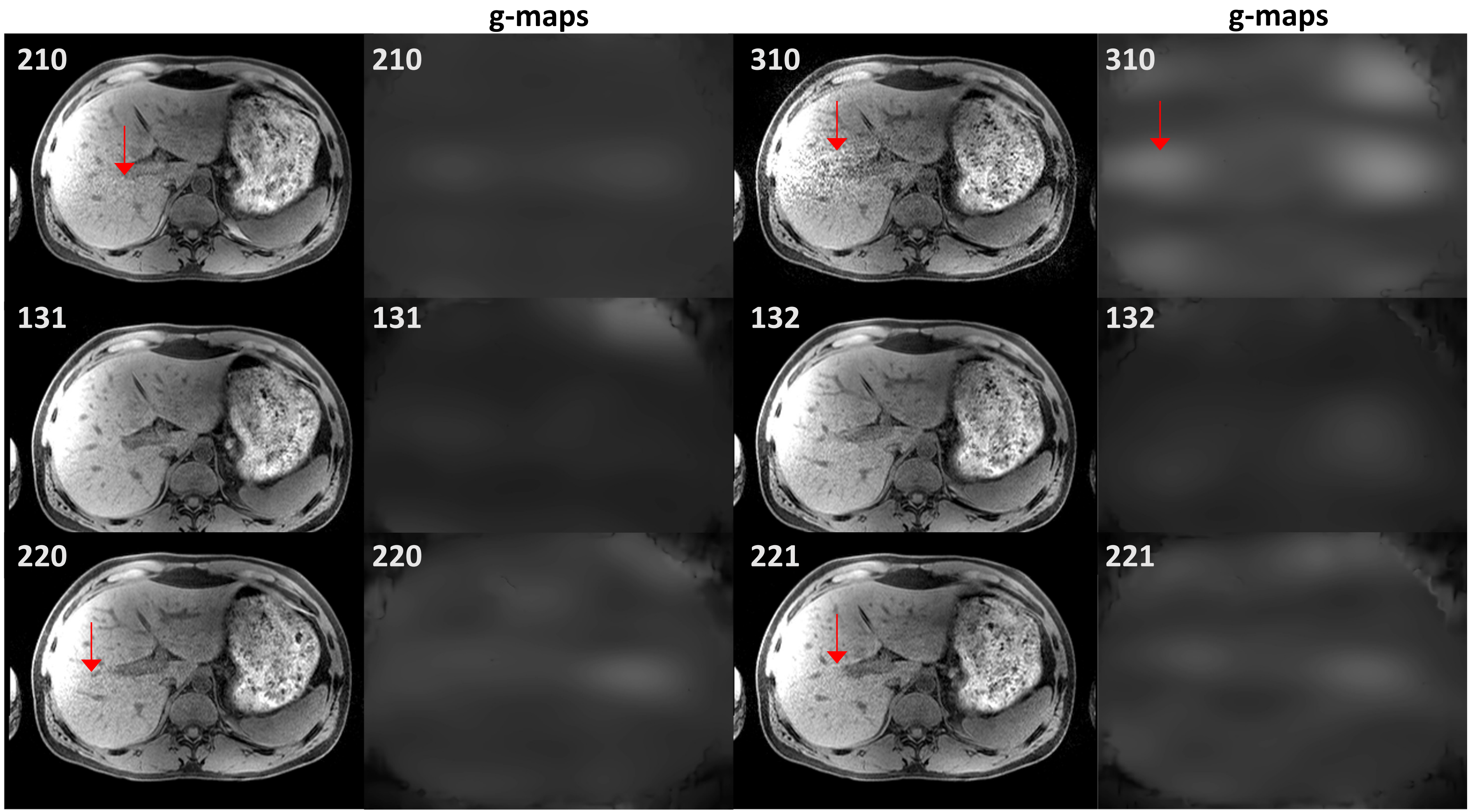
Acquisition Acceleration by Undersampling k-Space
Aliasing Corresponding to Various Patterns - Phantoms



*** Only body coil was used**

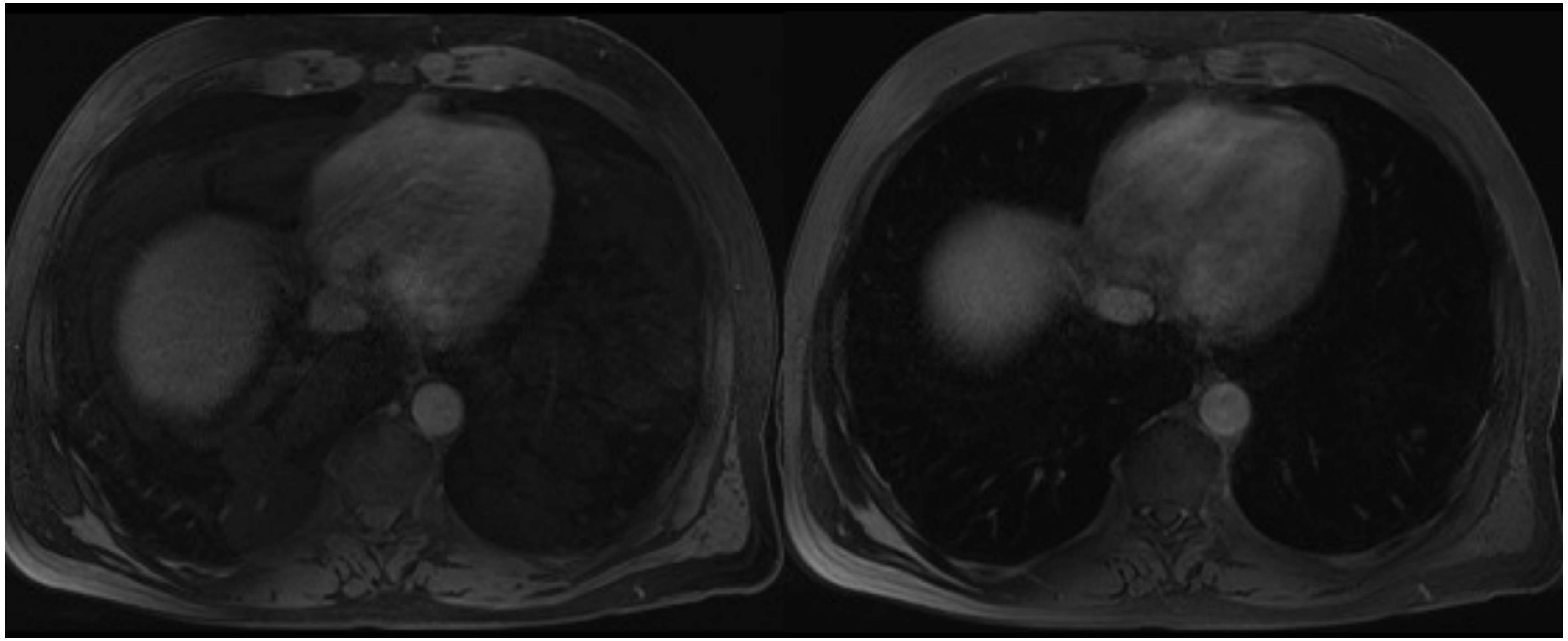
Deshpande et al, ISMRM (2012)

Acquisition Acceleration by Undersampling k-Space
Influence of Sampling Patterns



Deshpande et al, ISMRM (2012)

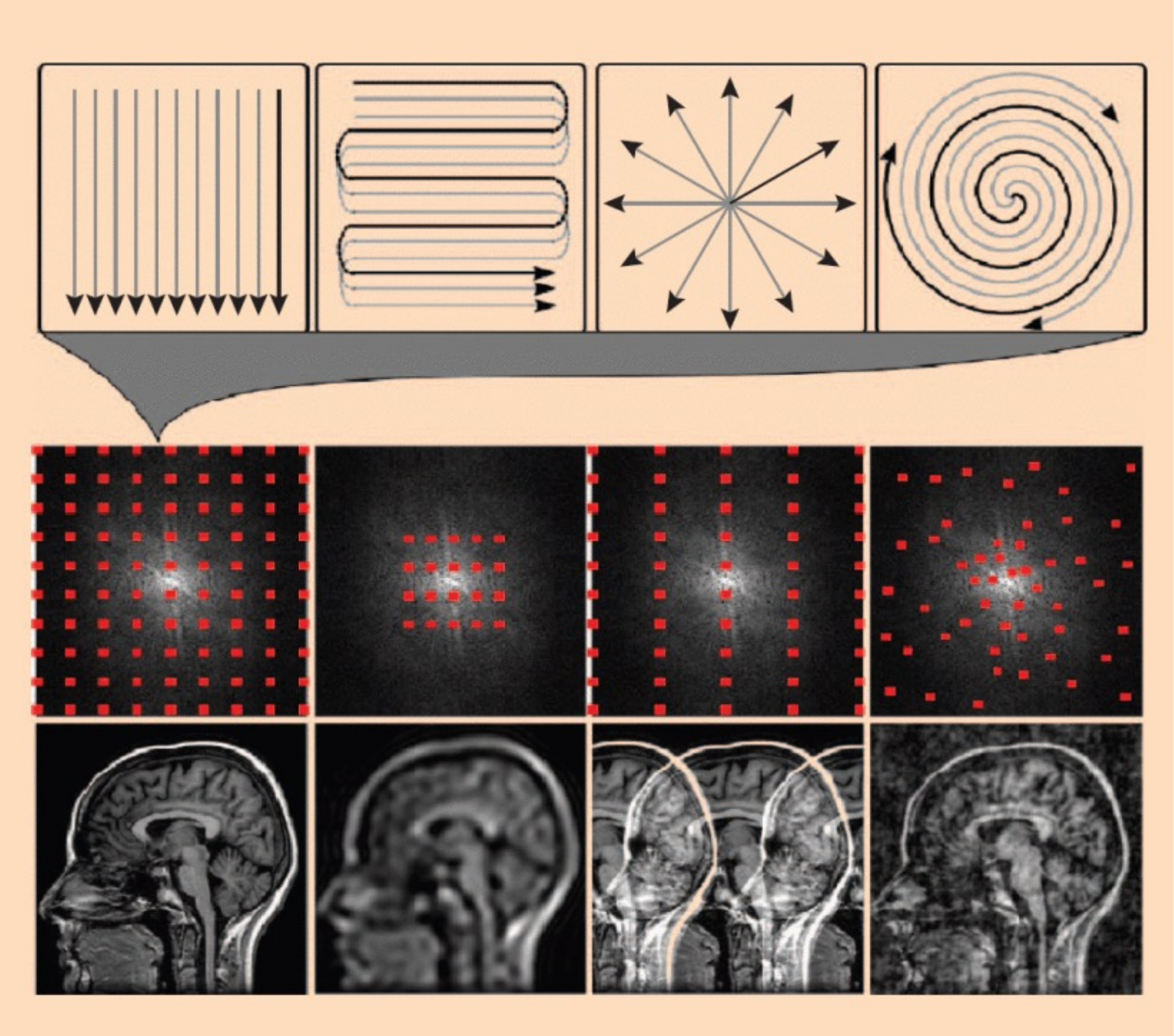
Acquisition Acceleration with CAIPIRINHA
Keep Spatial Resolution, Reduce Breath-Hold Time



Conventional VIBE, acc factor 2
21-24s TA
320 Matrix, 3mm

CAIPIRINHA VIBE, acc factor 4
12s TA
320 Matrix, 3mm

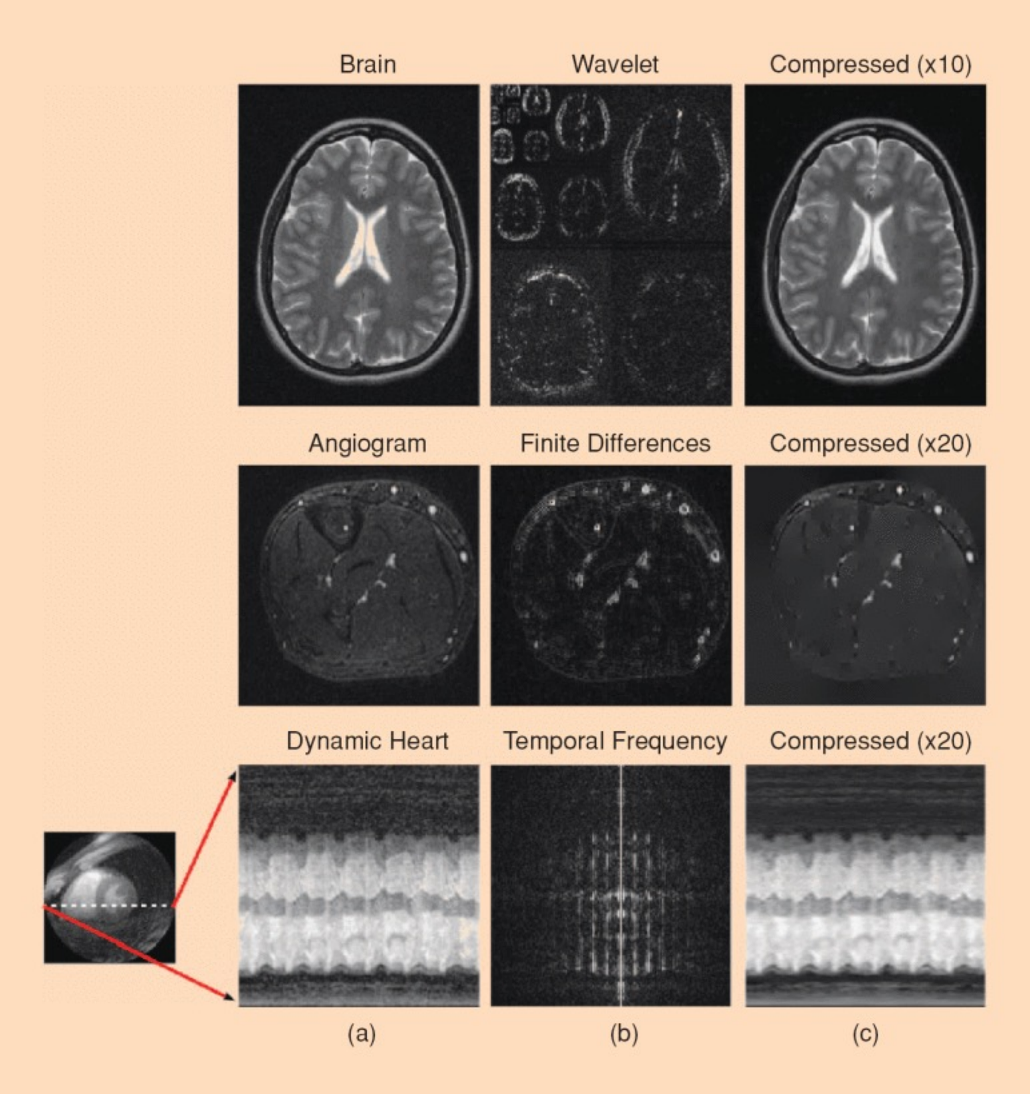
Acquisition Acceleration by Parallel Imaging
From Parallel Imaging to Compressed Sensing (CS)



Lustig, et al. *IEEE signal processing magazine* 2008;25:72-82.

Acquisition Acceleration by Compressed Sensing (CS) Principle - Sparsity

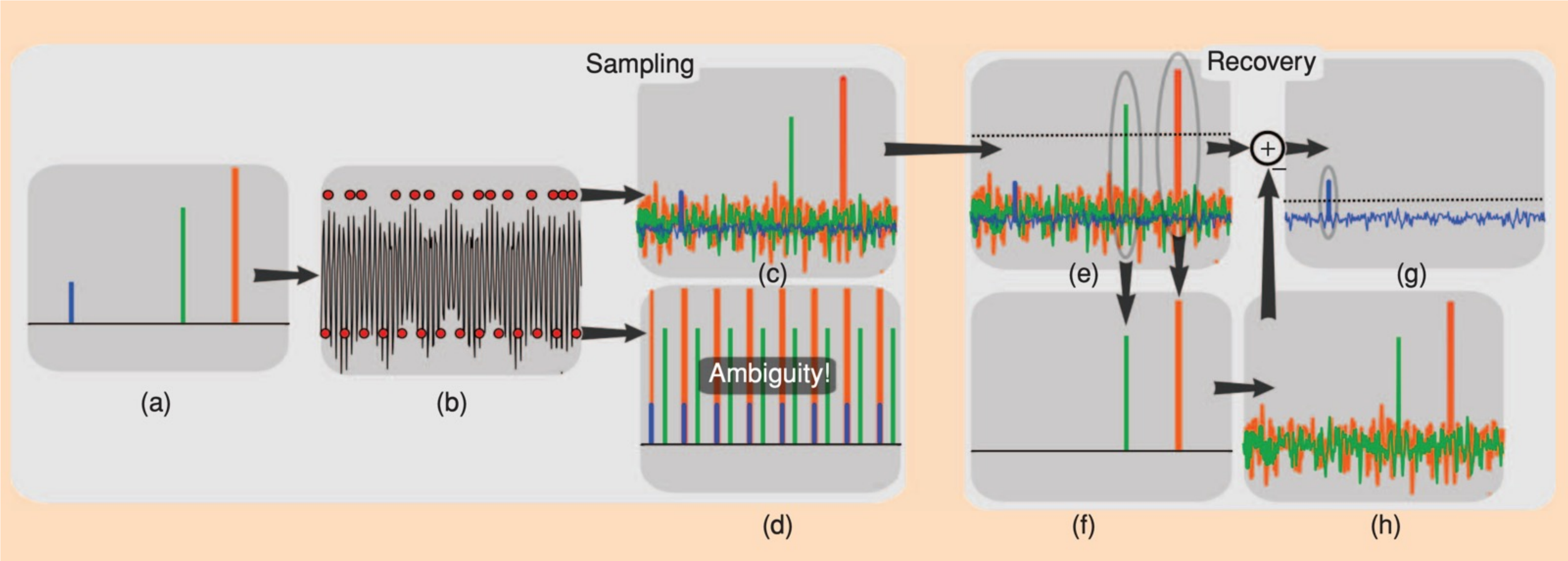
- Transform sparsity of MR images
  - Different sparsifying transforms can be used
  - Several largest coefficients are preserved while all others are set to zero



Lustig, et al. *IEEE signal processing magazine* 2008;25:72-82.

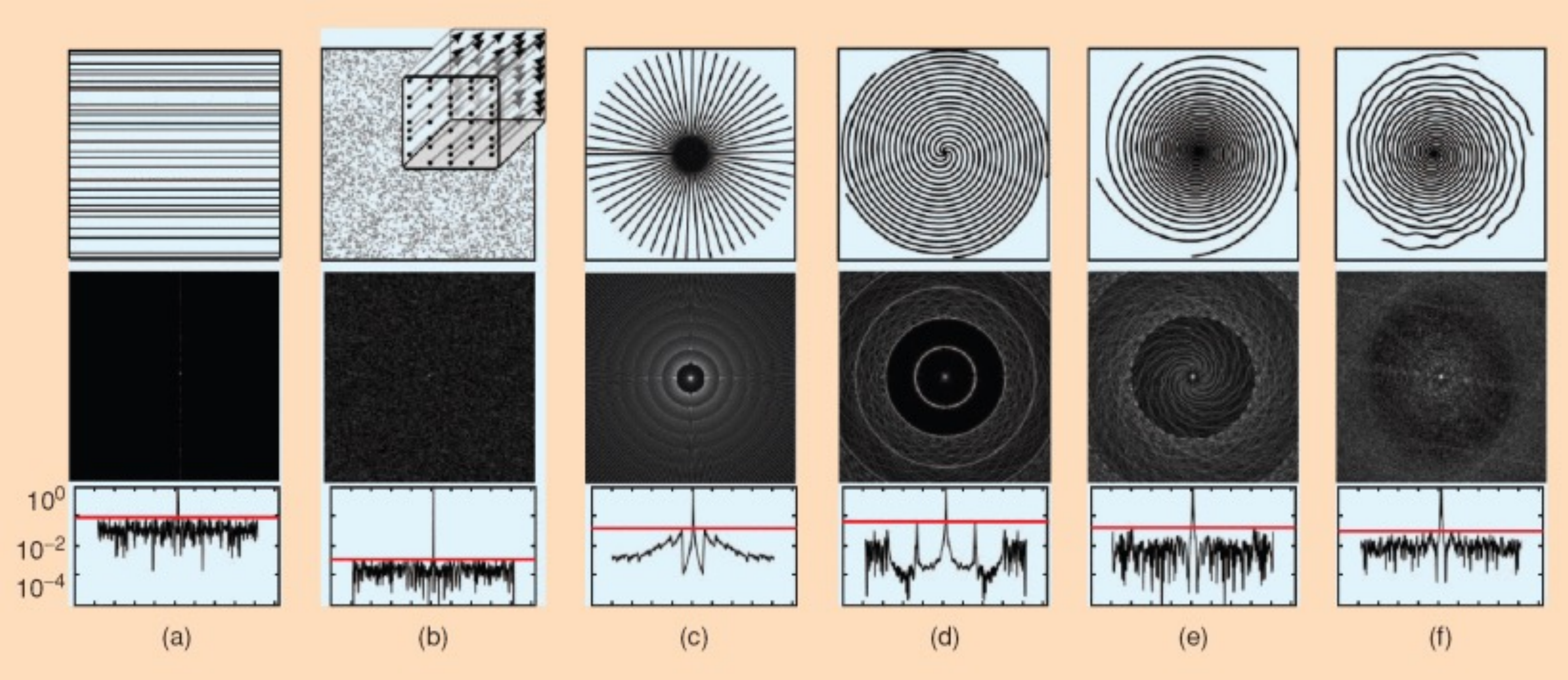
Acquisition Acceleration by Compressed Sensing (CS) Principle - Interference Cancellation

- Random undersampling can help recover highly accelerated data acquisition
  - Nonlinear iterative techniques are usually performed
  - With the knowledge of the k -space sampling scheme and underlying original signal



Lustig, et al. *IEEE signal processing magazine* 2008;25:72-82.

Acquisition Acceleration by Compressed Sensing (CS) Principle – Incoherence of MRI k-Space Sampling Trajectories



Lustig, et al. *IEEE signal processing magazine* 2008;25:72-82.

Acquisition Acceleration by Compressed Sensing (CS) Principle – Reconstruction

- Reconstruction of the CS data is essentially an optimization problem

$$\begin{aligned} \text{minimize} \quad & \|\Psi m\|_1 \\ \text{s.t.} \quad & \|\mathcal{F}_S m - y\|_2 < \epsilon \end{aligned}$$

m is the reconstructed complex image

Ψ is the linear operator of the sparsifying transform

$\mathcal{F}_S$ is the undersampled Fourier transform (e.g. NUFFT)

y is the acquired k-space data

ϵ is the fidelity weighting parameter (roughly the expected noise level)

$\|x\|_1 = \sum_i |x_i|$ is the ℓ_1 norm

- A package called BART for CS MRI recon is available at https://mrirecon.github.io/bart/

Lustig, et al. *IEEE signal processing magazine* 2008;25:72-82.

Outline

- Background
- Volumetric Imaging by 2D Multi-Slice Imaging
- Break
- Volumetric Imaging by 3D Imaging
- One Step Further: Multi-Dimensional imaging

Multi-Dimensional Imaging

3D (volumetric)

4D

- 3D + cardiac motion
- 3D + respiratory motion
- 2D + cardiac motion + respiratory motion

5D

- 3D + cardiac motion + respiratory motion

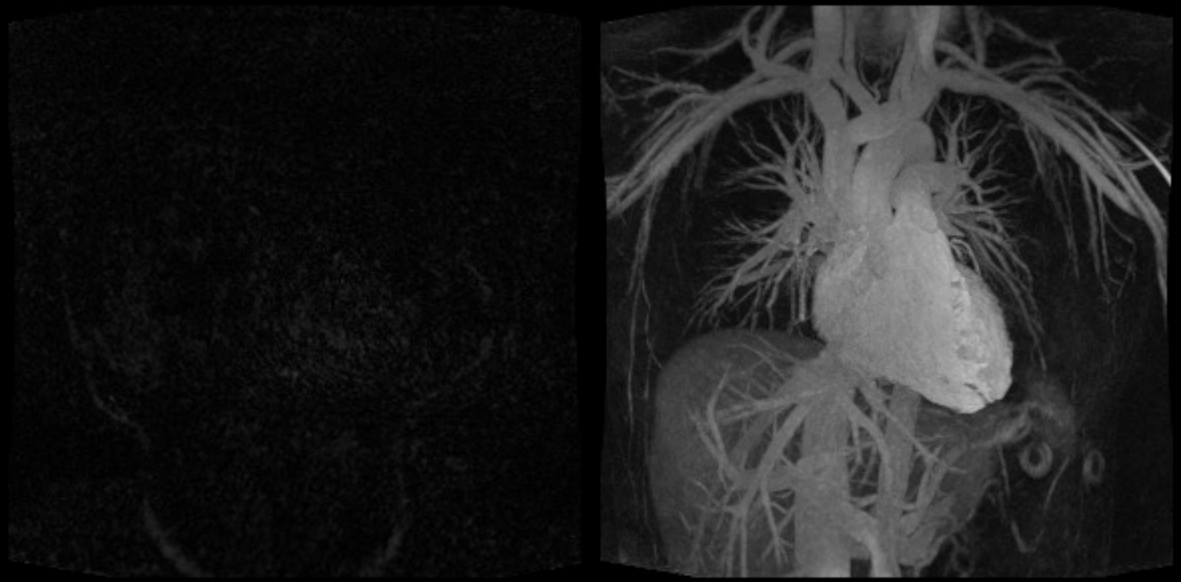
ND

- 2D/3D spatial dimensions + cardiac/ respiratory motion dimensions + physiological measurement dimensions

Other combinations possible

Whole Heart Imaging (3D)
Ferumoxytol-Enhanced Free-Breathing Coronary MR Angiography

- Low resolution image navigation (iNAV)[1]
- Incoherent Cartesian sampling pattern[2]
- Non-rigid motion-compensated iterative reconstruction[3]



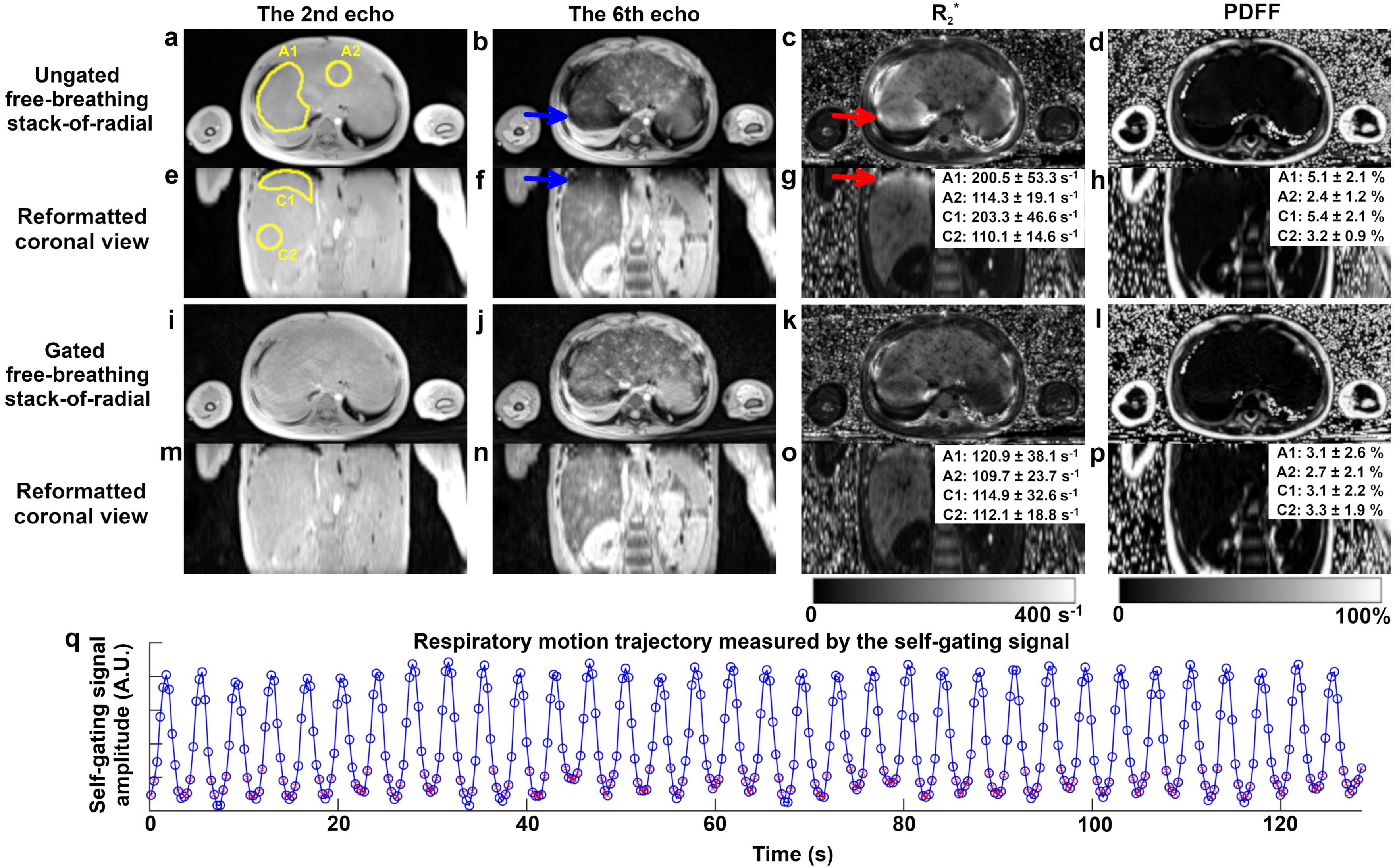
1. Henningsson et al. MRM 2012;67:437-445.
2. Prieto et al. JMRI 2015;41:738-746.
3. Cruz et al. MRM 2017;77:1894-1908

* Courtesy of Kim-Lien Nguyen, MD, University of California, Los Angeles.

Whole Liver Imaging (3D)
Motion-Compensated Radial GRE Dixon for Fat/$R2^*$ Quantification

A 2-Year-Old Patient

- A free-breathing multi-echo stack-of-radial sequence[1]
- Soft-gated self gating[2,3]



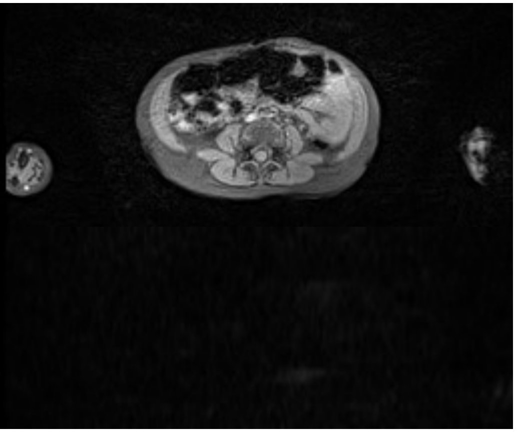
1. Zhong et al. JMRI 2021;53:118-129.
2. Grimm et al. ISMRM 2012. p598.
3. Grimm et al. ISMRM 2013. p3749.

Whole Liver Imaging (3D + Respiratory Motion) Acceleration Using a XD-GRASP Variant Algorithm

Current method

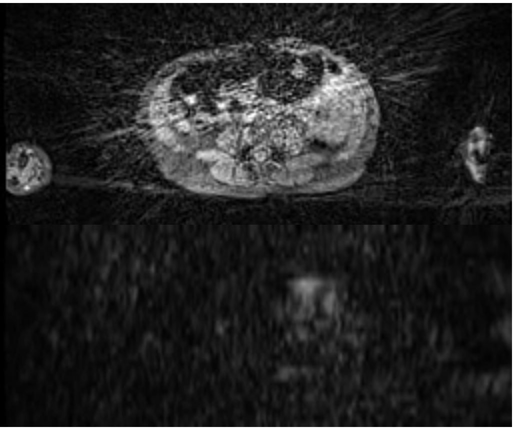
Soft-gating 40%

404 views, acq time: 2:34



Soft-gating 40%

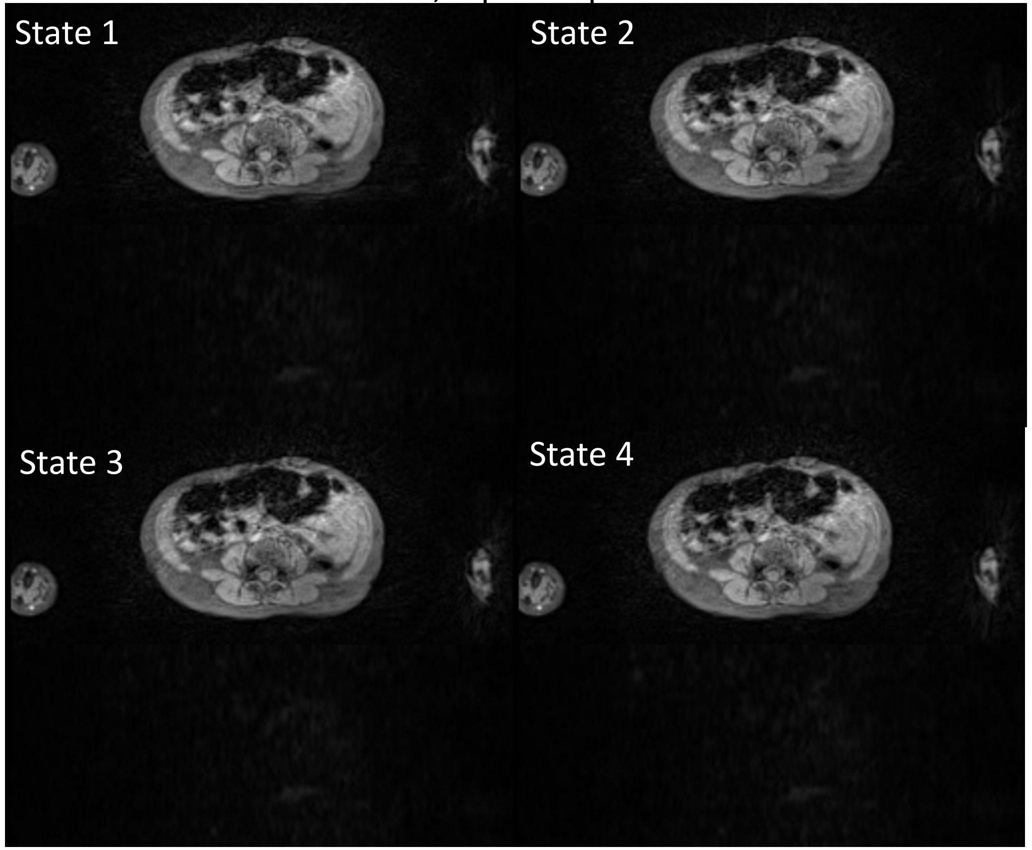
101 views, equiv acq time ~40s



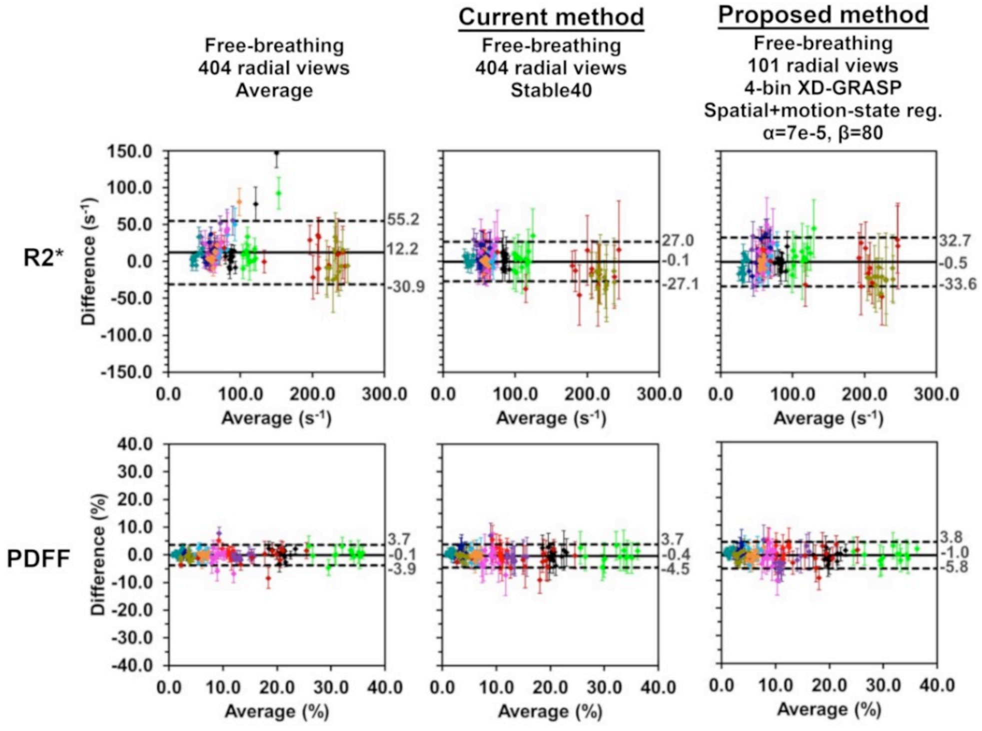
Proposed method

Multi-dimensional regularization (XD-GRASP variant)

101 views, equiv acq time ~40s



* Compatible with quantitative imaging



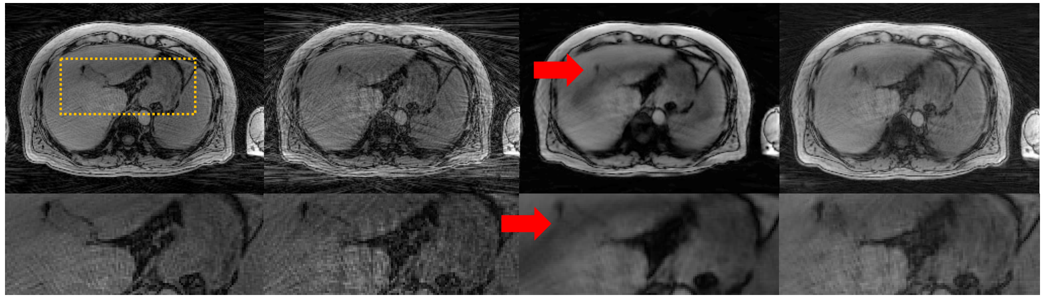
* Data from 6 clinical subjects and 5 healthy subjects.

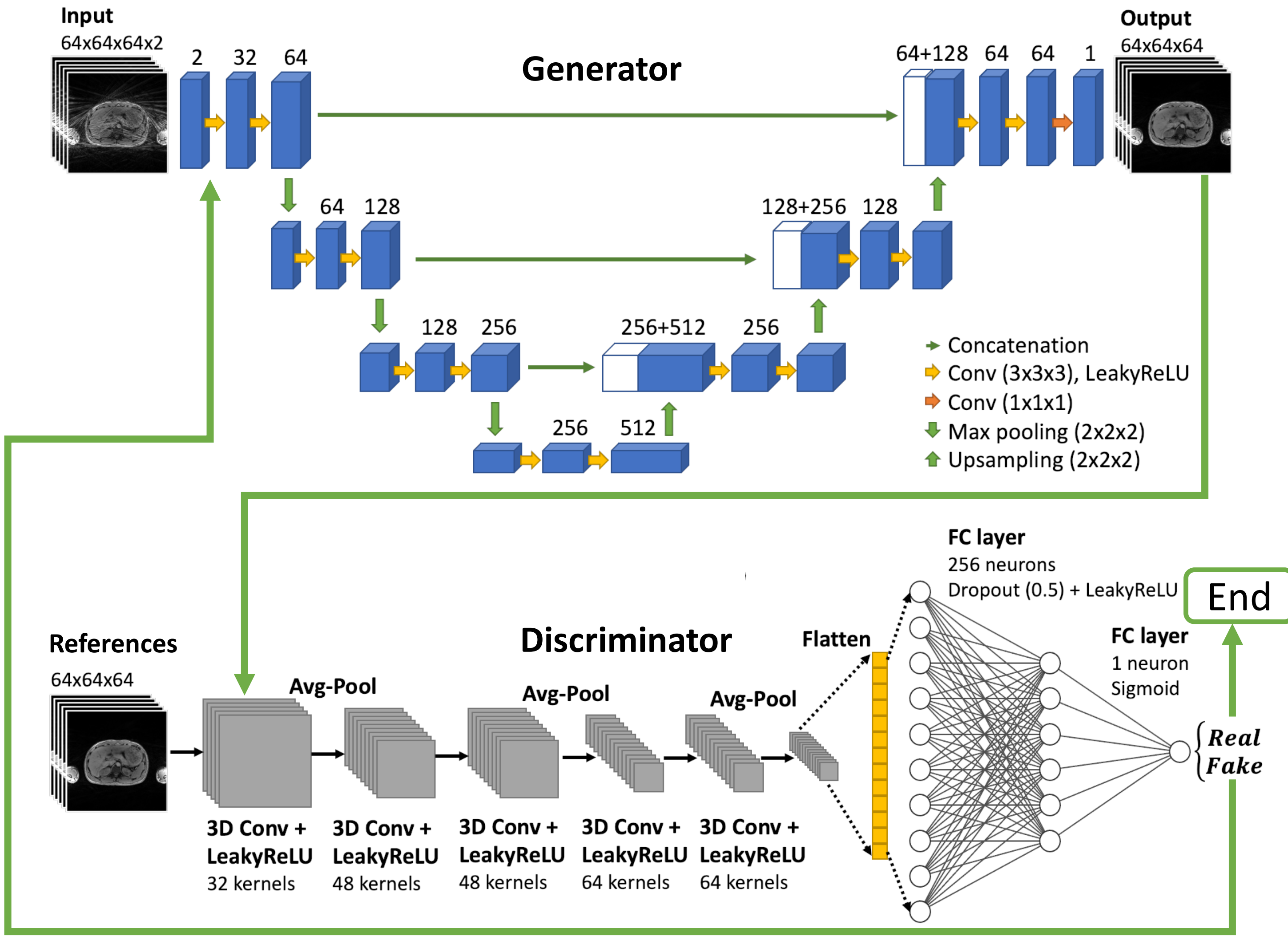
1. Zhong et al. Mag Reson Med 2024;92:1149-1161.

Whole Liver Imaging (3D) Acceleration Using GAN Networks

A generative adversarial network (GAN) to accelerate radial whole liver imaging[1,2]

- Image to image network: Easy to implement and train
- Focused on magnitude images



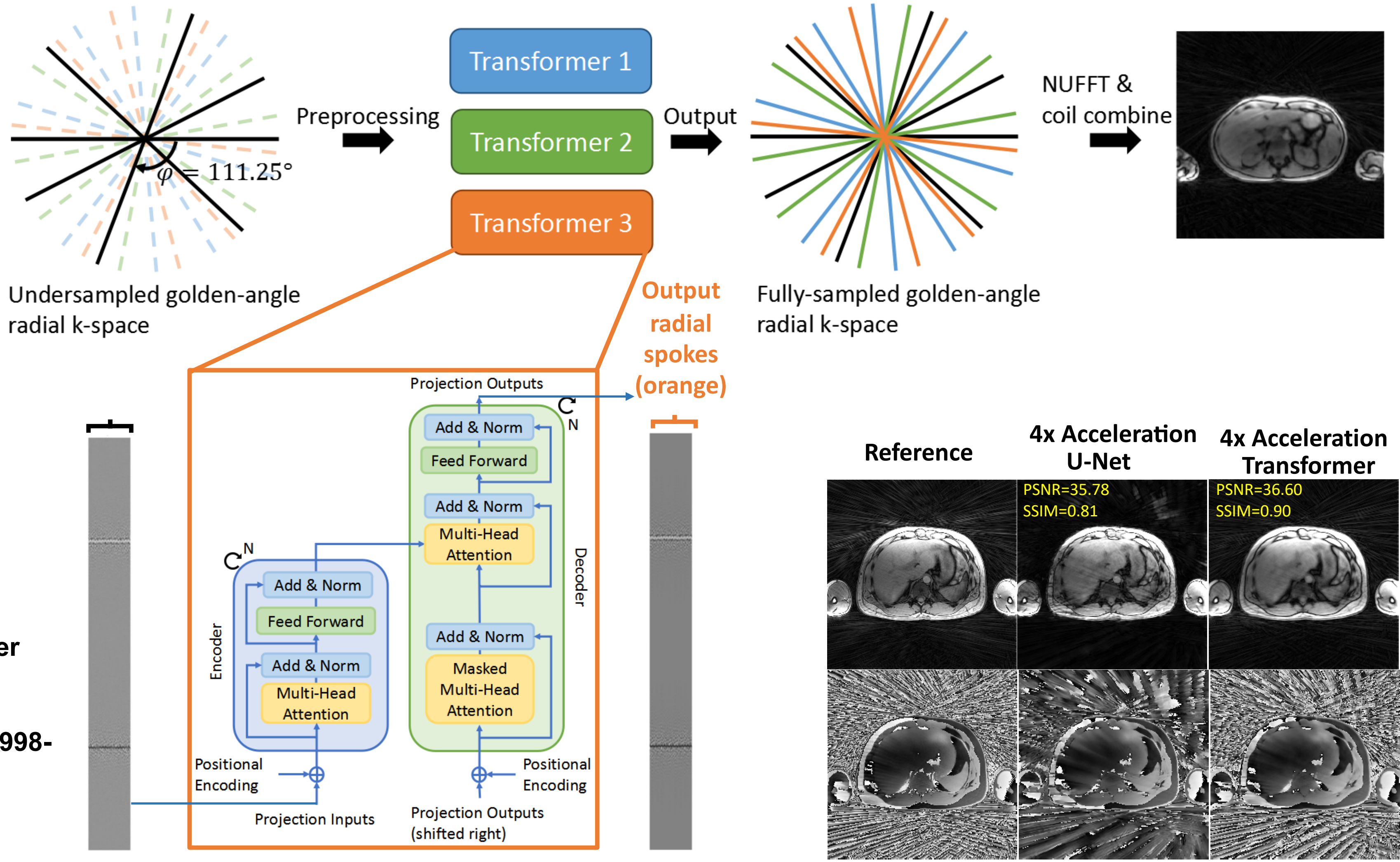


1. Gao et al. MRI 2023;95:70-79.
2. Hu et al. Full patent US20220381861A1, 2022.

Whole Liver Imaging (3D) Acceleration Using Transformer Networks

A k-space to k-space transformer network[1-3]

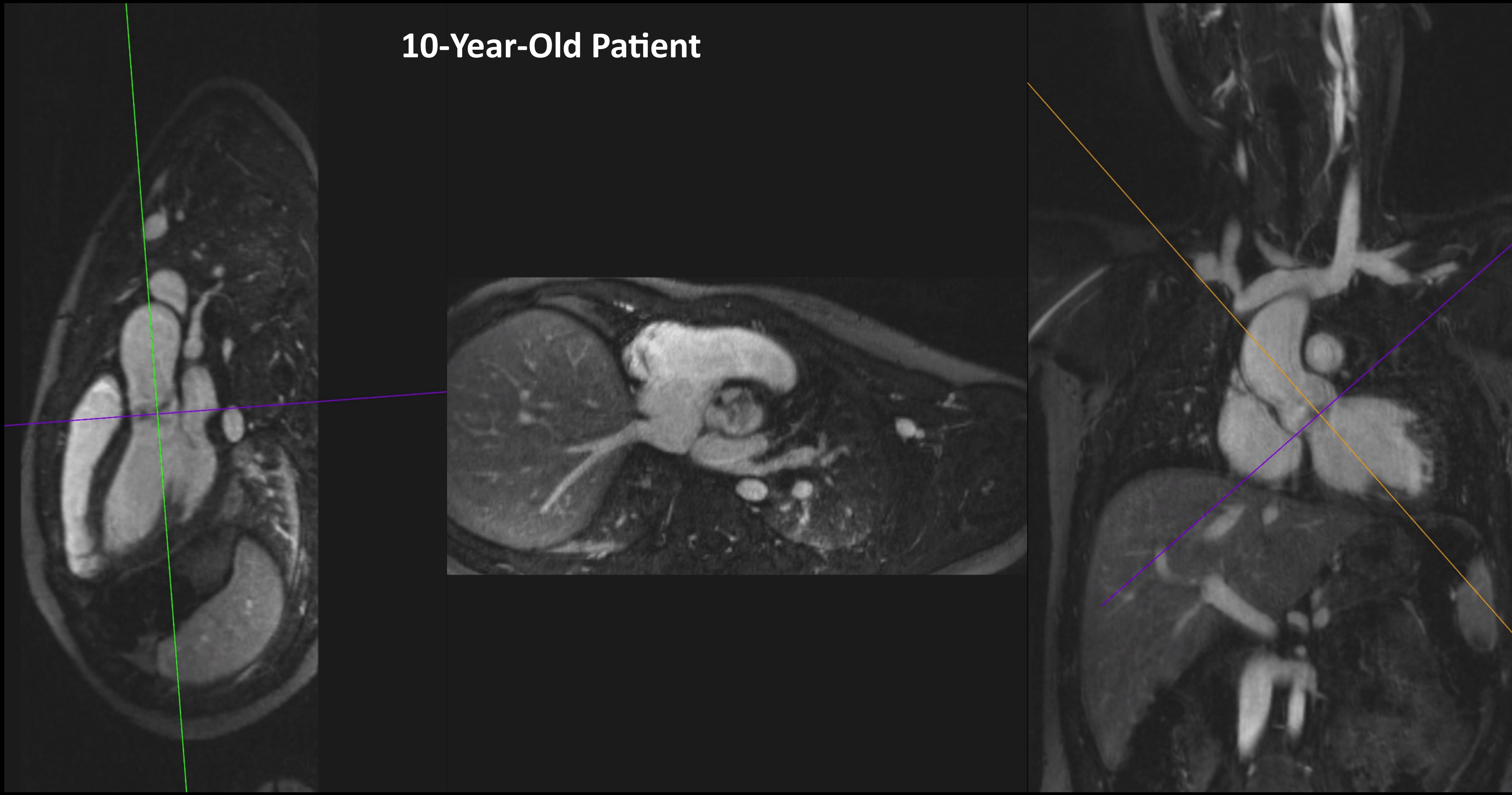
- Requires relatively less data for training compared to image to image networks[1]
- Enforces k-space data consistency[4,5]



1. Gao et al. MICCAI 2022. Lecture Notes in Computer Science, vol 13436.
2. Gao et al. Full patent US20230342993A1, 2023.
3. Vaswani et al. Adv Neural Inf Process Syst 2017;5998-6008.
4. Hyun et al. Physics in Medicine & Biology 2018;63:135007.
5. Yang et al. IEEE transactions on medical imaging 2017;37:1310-1321.

Whole Heart Imaging (3D + Cine)
4D MUSIC

- High resolution steady-state imaging with contrast enhancement[1]
- Double gating: ECG + respiratory



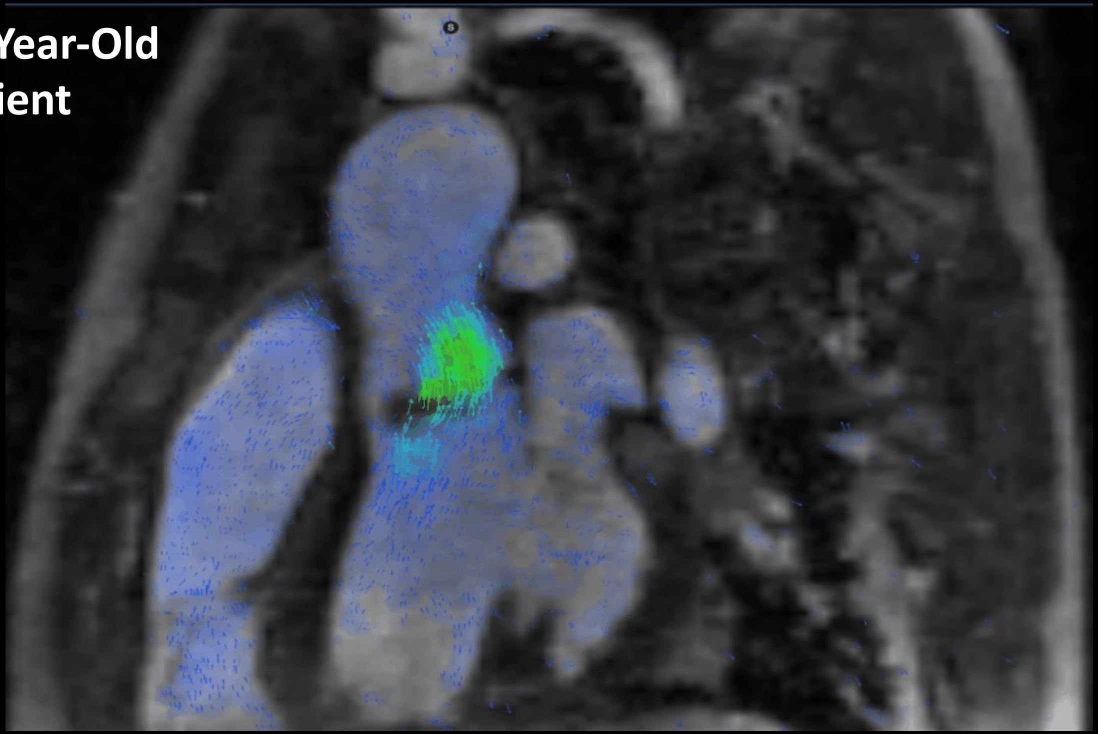
1. Han et al. MRM 2015;74:1042-1049.

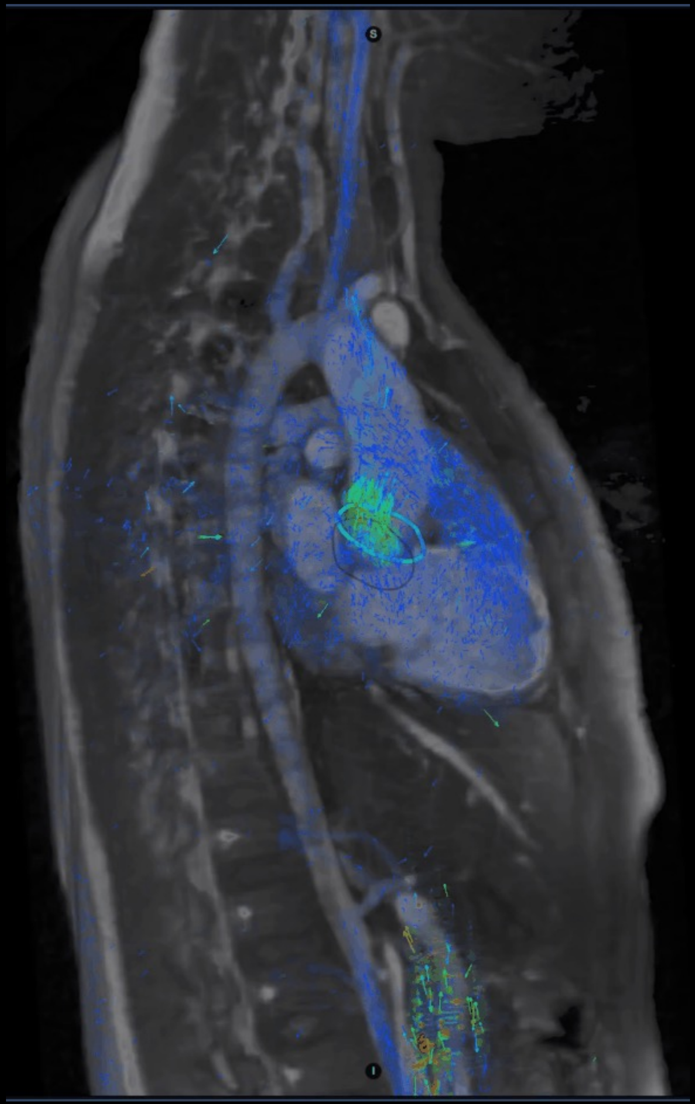
* Courtesy of Paul Finn, MD, University of California, Los Angeles.

Whole Heart Imaging (3D + Cine)
4D Flow

- 4D + 3D velocity encoding
- Double gating: ECG + respiratory navigator

10-Year-Old Patient

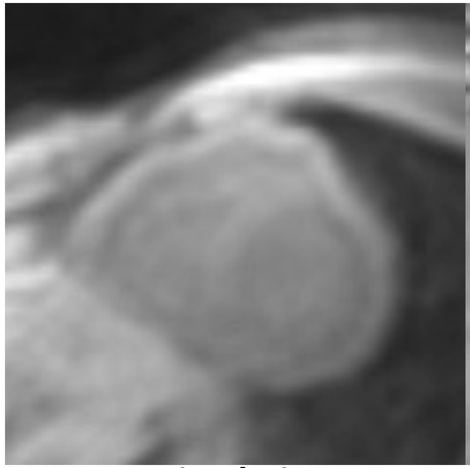


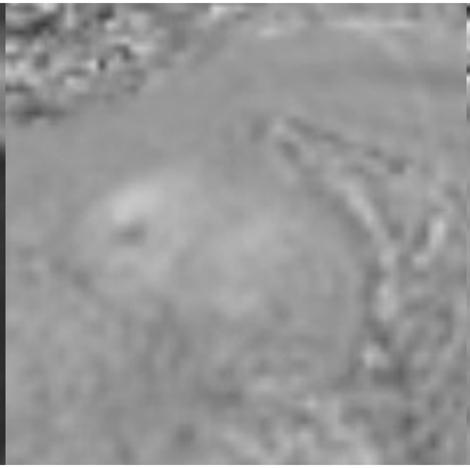


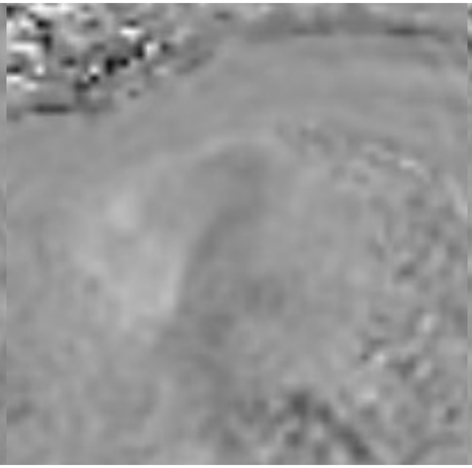
* Courtesy of Paul Finn, MD, University of California, Los Angeles.

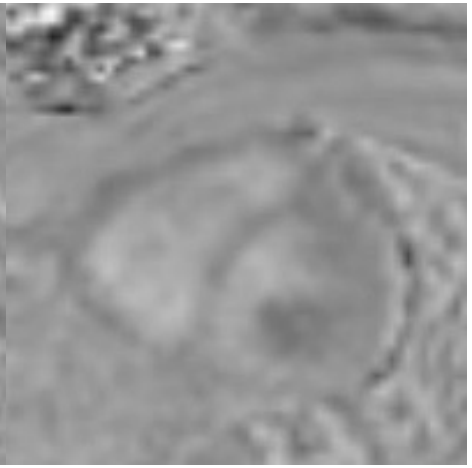
Multi-Dimensional Strain Imaging
4D (3D Spatial + Time) Displacement-Encoding (DENSE) Data

- Short-axis view reconstructed online directly


Magnitude image


Phase image encoded in horizontal direction


Phase image encoded in vertical direction

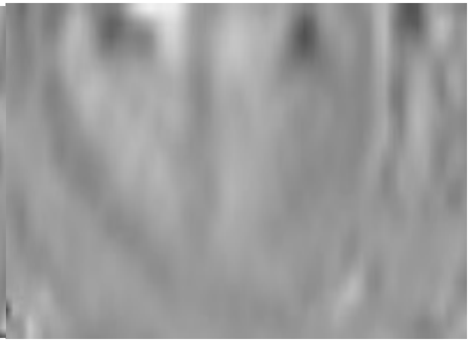

Phase image encoded in through-plane direction

- Long-axis view reformatted offline from short-axis data


Magnitude image

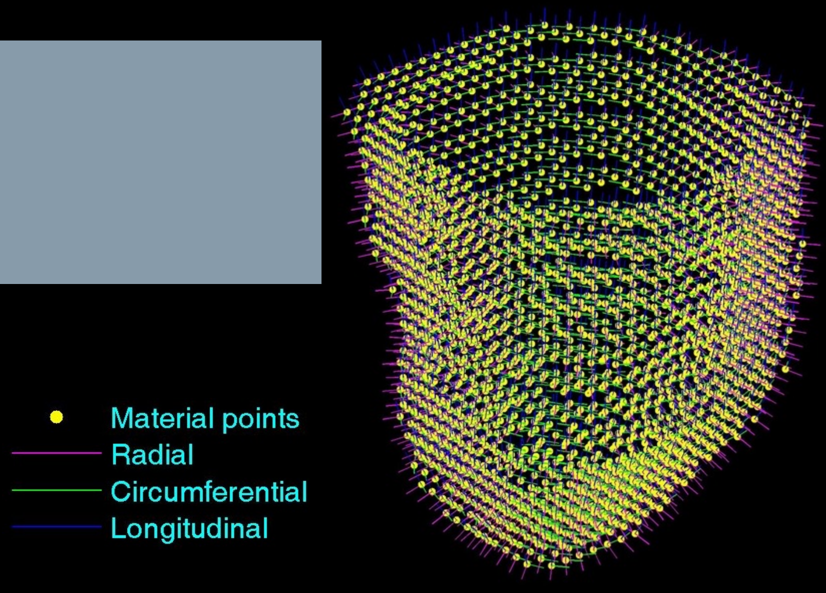

Phase image encoded in horizontal direction


Phase image encoded in through-plane direction

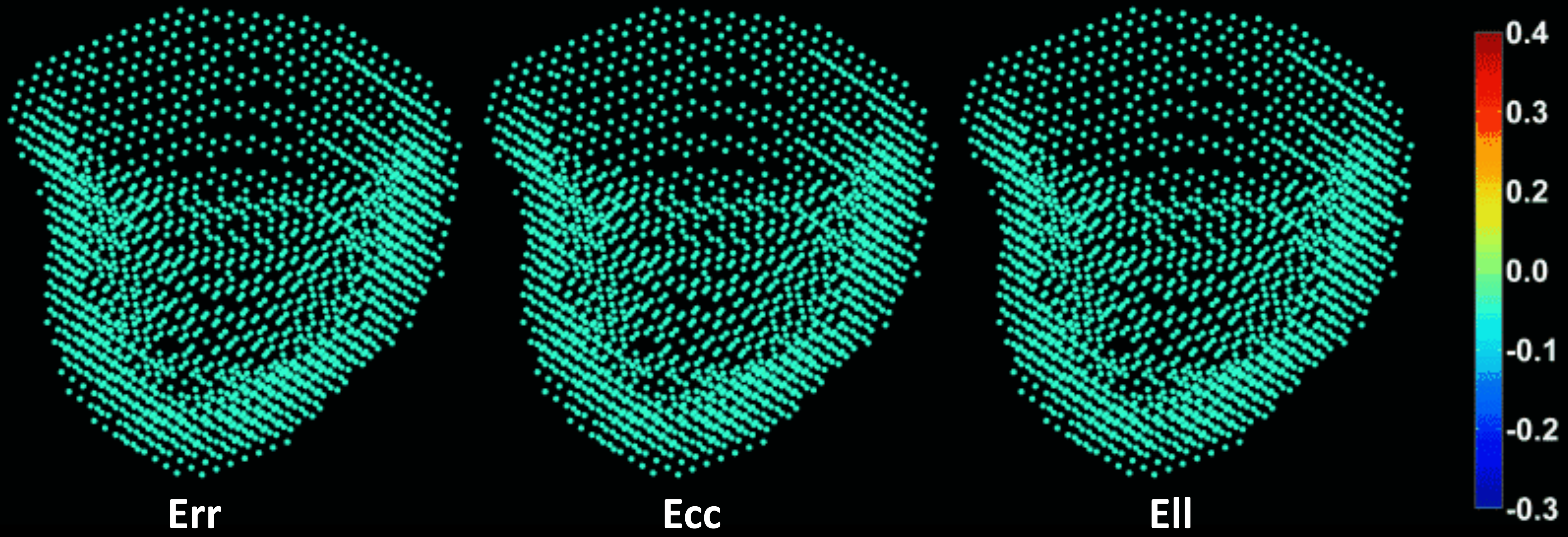

Phase image encoded in vertical direction

1. Zhong et al. MRM 2010; 64:1089-109.

Whole Heart Imaging (3D + Cine)
4D DENSE for LV Strain Imaging

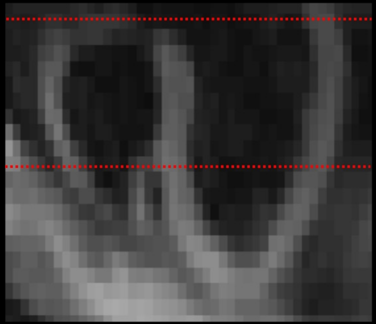


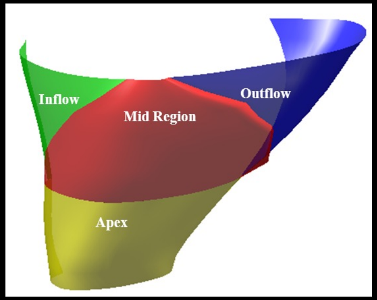
Ellipsoid visualization of short- and long-axis views

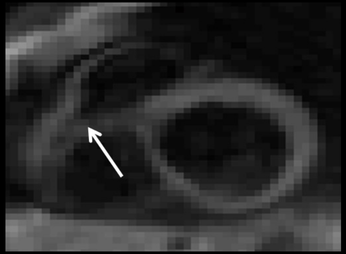


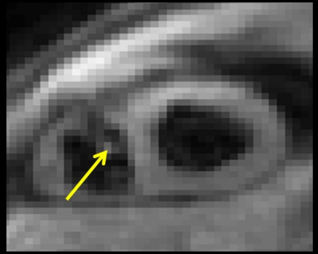
1. Zhong et al. MRM 2010; 64:1089-1097.

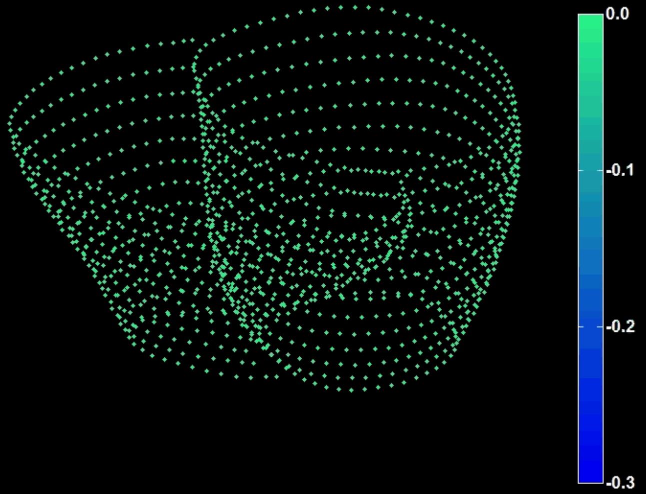
Whole Heart Imaging (3D + Cine)
4D DENSE for LV + RV

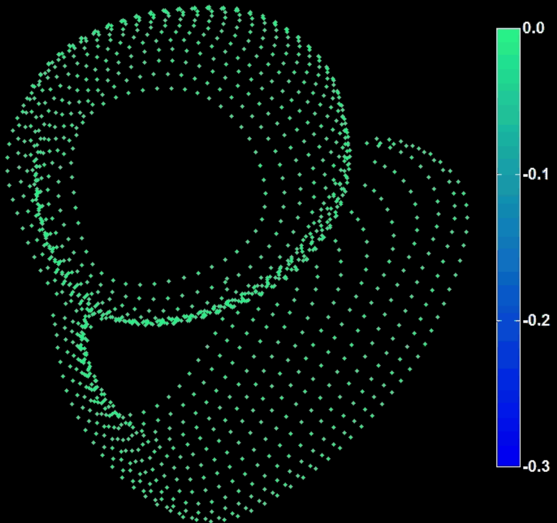


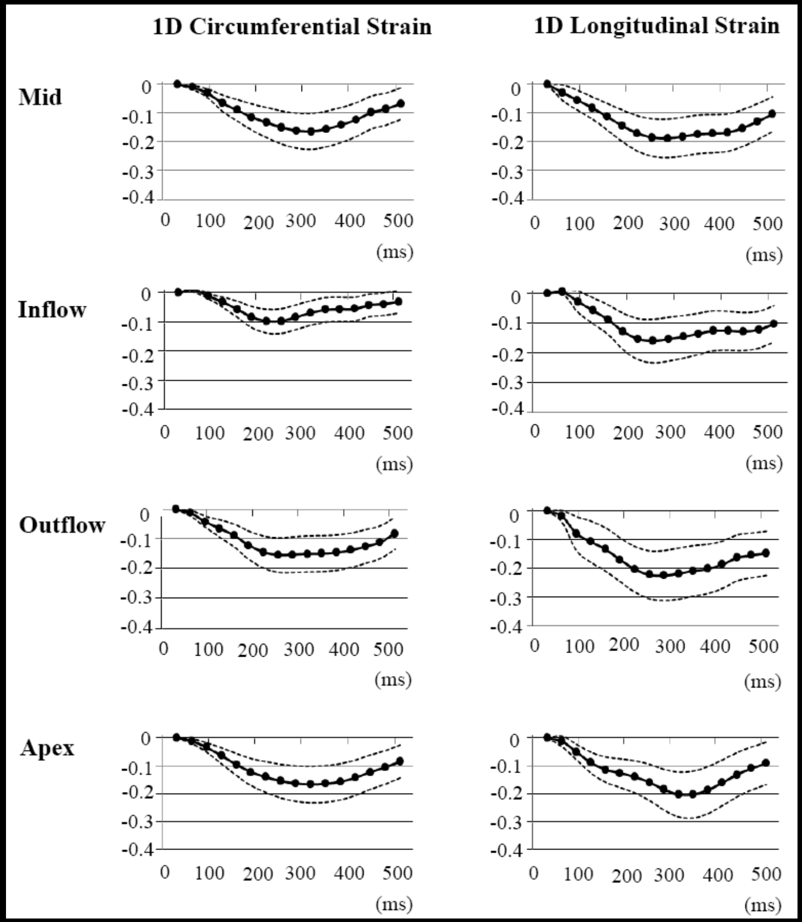












1. Auger et al. JCMR 2012;14:4.

Summary

Volumetric imaging is important for various MRI applications in different organs

Volumetric imaging can be accomplished by
- (Simultaneous) multi-slice 2D imaging
- Volumetric 3D imaging

Acceleration techniques are crucial for both the data acquisition and reconstruction
- Parallel imaging
- Compressed sensing
- AI

Many potential applications
- CV
- Neuro
- Body

*** For lecture feedback**

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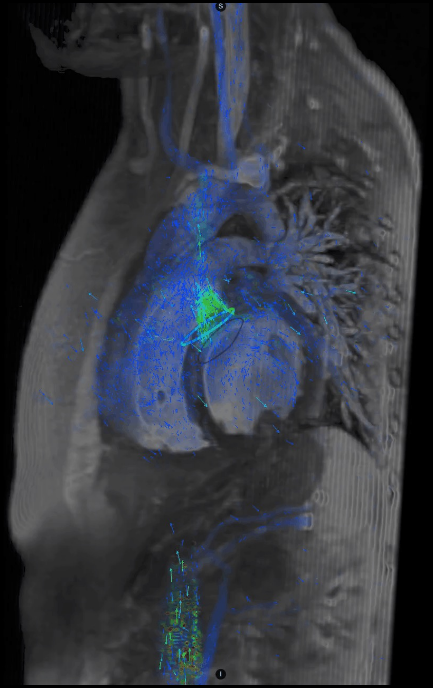
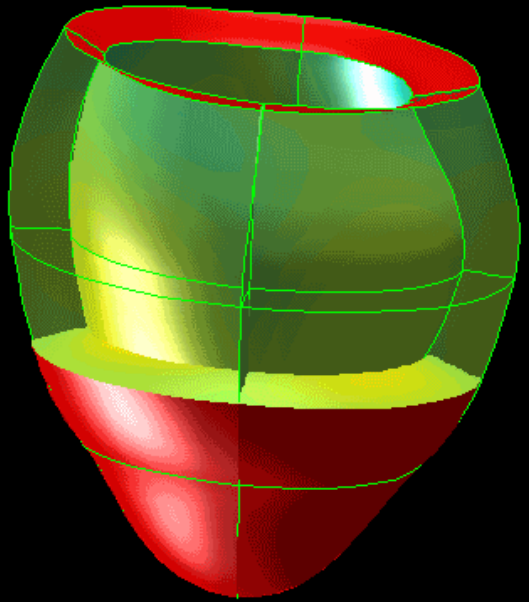
- Patrick Helm, PhD

Siemens

- Vibhas Deshpande, PhD
- John Kirsch, PhD

Thank You for Your Attention





* Conceptual images courtesy of Paul Finn, MD and Patrick Helm, PhD.