Compressive Sensing for Magnetic Resonance Imaging

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BIO5

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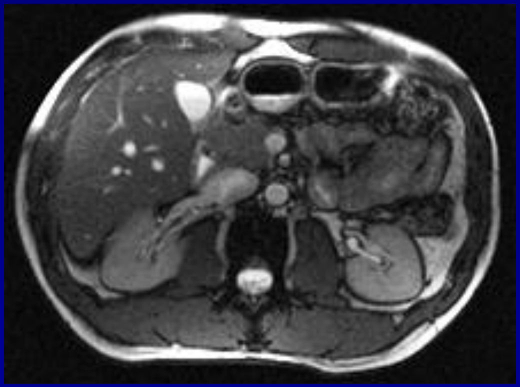
Overview

- Introduction to Magnetic Resonance Imaging (MRI)
- Introduction to Compressive Sensing
- Compressive MRI
  - T2 Mapping
  - Diffusion-Weighted MRI
  - Dynamic Contrast Enhanced MRI
- Future Directions and Conclusions

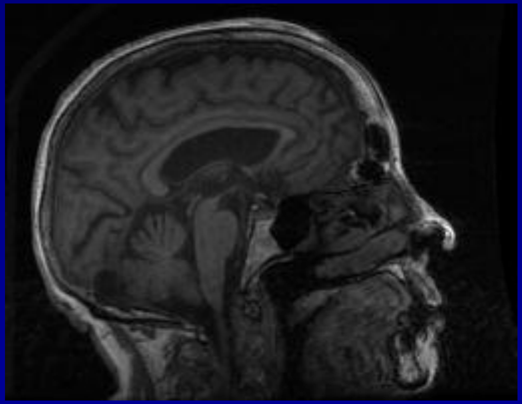
Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging

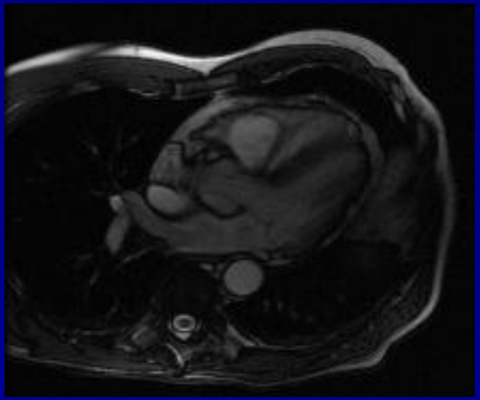
- MRI is a non-invasive imaging technique based on the principles of nuclear magnetic resonance.
- MRI is routinely used in the clinic to obtain highly detailed images of internal organs, blood vessels, muscle, joints, tumors, areas of infection, etc.



Abdomen

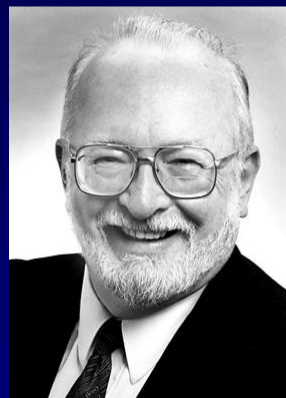


Brain



Heart

Magnetic Resonance Imaging



Paul C. Lauterbur

Sir Peter Mansfield

The Nobel Prize in Physiology or Medicine 2003 was awarded jointly to Paul C. Lauterbur and Sir Peter Mansfield "for their discoveries concerning magnetic resonance imaging"

Source: The Nobel Prize in Physiology or Medicine 2003". Nobelprize.org. 4 Apr 2012
http://www.nobelprize.org/nobel_prizes/medicine/laureates/2003/

Magnetic Resonance Imaging

Otto Stern

The Nobel Prize in Physics 1943 was awarded to Otto Stern "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton".

Source: "The Nobel Prize in Physics 1943". Nobelprize.org. 4 Apr 2012
http://www.nobelprize.org/nobel_prizes/physics/laureates/1943/

Magnetic Resonance Imaging

Isidor Isaac Rabi

The Nobel Prize in Physics 1944 was awarded to Isidor Isaac Rabi "for his resonance method for recording the magnetic properties of atomic nuclei".

Source: "The Nobel Prize in Physics 1944". Nobelprize.org. 4 Apr 2012
http://www.nobelprize.org/nobel_prizes/physics/laureates/1944/

Magnetic Resonance Imaging

Felix Bloch

Edward Mills Purcell

The Nobel Prize in Physics 1952 was awarded jointly to Felix Bloch and Edward Mills Purcell "for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith"

Source: "The Nobel Prize in Physics 1952". Nobelprize.org. 4 Apr 2012
http://www.nobelprize.org/nobel_prizes/physics/laureates/1952/

Magnetic Resonance Imaging

Richard R. Ernst

The Nobel Prize in Chemistry 1991 was awarded to Richard R. Ernst "for his contributions to the development of the methodology of high resolution nuclear magnetic resonance (NMR) spectroscopy".

Source: "The Nobel Prize in Chemistry 1991". Nobelprize.org. 4 Apr 2012
http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1991/

MRI: Advantages/Challenges

- Advantages
  - Non-invasive. No ionizing radiation
  - Arbitrary orientation
  - 2D, 3D, dynamic and functional imaging
  - Flexible contrast
- Challenges
  - High cost
  - Slow imaging, Long examinations

MRI Equipment is Expensive

MRI is the most expensive equipment in the hospital with high end models running into $3 million (Not including construction costs).

The cost of an MRI can range between $400 to $3,500 depending upon which procedure is performed.

In 2007, there were approximately 30 million MRI scans performed in the US, and MRI use continues to grow.

MRI Exams are Long

- A typical MRI examination consists of 5 to 20 sequences.
- Each of these sequences are chosen to provide a particular type of information about the subject tissues.
- Some MRI exams can require an hour to complete.

A Typical MRI Protocol

- Society for Cardiovascular Magnetic Resonance (SCMR) Recommended Cardiac MRI Protocol for Chronic Ischemic Disease:
  - Localizer Module
  - LV Function Module
  - Low Dose Dobutamine Cine
  - Stress/Rest Dynamic Module
  - Delayed Module

Localizer Module

- **Auto Detect Table Position**
- **Multi Plane Isocenter Localizer**
- **Axial Dark Blook Haste Localizer**
- **Two Chamber Localizer**
- **Four Chamber Localizer**
- **Short Axis Localizer**
- **Three Chamber Localizer**

LV Function Module

- **Two Chamber Cine**
- **Three Chamber Cine**
- **Four Chamber Cine**
- **Short Axis Cine**
- **Optional Short Axis Cine Radial**
- **Optional Short Axis Cine 3D Slab**
- **Optional Short Axis Cine Realtime**

Delayed Module

- **TI Scout**
- **Two Chamber Delayed**
- **Four Chamber Delayed**
- **Short Axis Delayed**
- **Optional TI Scout**
- **Optional Short Axis Delayed 3D**

Rapid MRI

- Faster imaging techniques are of great interest to MRI community.

Compressive Sensing

Compressive Sampling

- Compressive Sampling / Compressed Sensing (CS) is a recent mathematical framework for sampling.

- In contrast to traditional compression, CS aims to integrate compression into the data acquisition process.

- Nyquist /Shannon Theory describes sampling by exploiting the bandlimitedness of signals.

- CS Theory describes sampling by exploiting the sparsity or compressibility of signals.

- The main idea:

  If a signal has a sparse representation, it can be recovered from a small number of random linear measurements.

Compressive Sampling

- The number of measurements can be significantly smaller than suggested by the Nyquist sampling theorem.

- The reconstruction is formulated as a convex optimization problem.

- The theory is robust under noise.

- The theory can be extended to signals that are not strictly sparse, but compressible.

CS Theory

Suppose we would like to recover an N-dimensional signal $\mathbf{f} \in \mathbb{R}^N$ from a set of K linear measurements $\mathbf{g} \in \mathbb{R}^K$

Let $\mathbf{M}$ denote the linear measurement matrix

$$\mathbf{g} = \mathbf{M}\mathbf{f}$$

We are interested in the case when K << N

CS Theory

Let $\mathbf{f}$ be S-sparse in the basis Ψ. $\boldsymbol{\alpha} = \boldsymbol{\Psi}\mathbf{f}$

Exact recovery if $\mathbf{f}$ sufficiently sparse and **M** appropriately chosen (e.g. random) by solving:

$$\boxed{\hat{\mathbf{f}} = \arg\min_{\mathbf{f}} \| \boldsymbol{\Psi}\mathbf{f} \|_1 \text{ subject to } \mathbf{g} = \mathbf{M}\mathbf{f}}$$

CS Theory

For compressible signals and noisy measurements, the recovery problem can be stated as an unconstrained optimization problem

$$\boxed{\hat{\mathbf{f}} = \arg\min_{\mathbf{f}} \| \mathbf{\Psi f} \|_1 + \lambda \, \|\mathbf{Mf} - \mathbf{g}\|_2}$$

CS Theory

- A sufficient condition for accurate recovery in CS is that the sensing matrix obeys a condition known as the restricted isometry property (RIP).
- Initially, random sampling was proposed to satisfy RIP.
- However random sampling is not practical in many applications (e.g. MRI)
- Recent results indicate that accurate recovery is possible when the number of measurements exceeds

$$K > \text{Const.}\ \mu^2 S \log(N)$$

where μ denotes mutual coherence.

Compressive Sampling for MRI

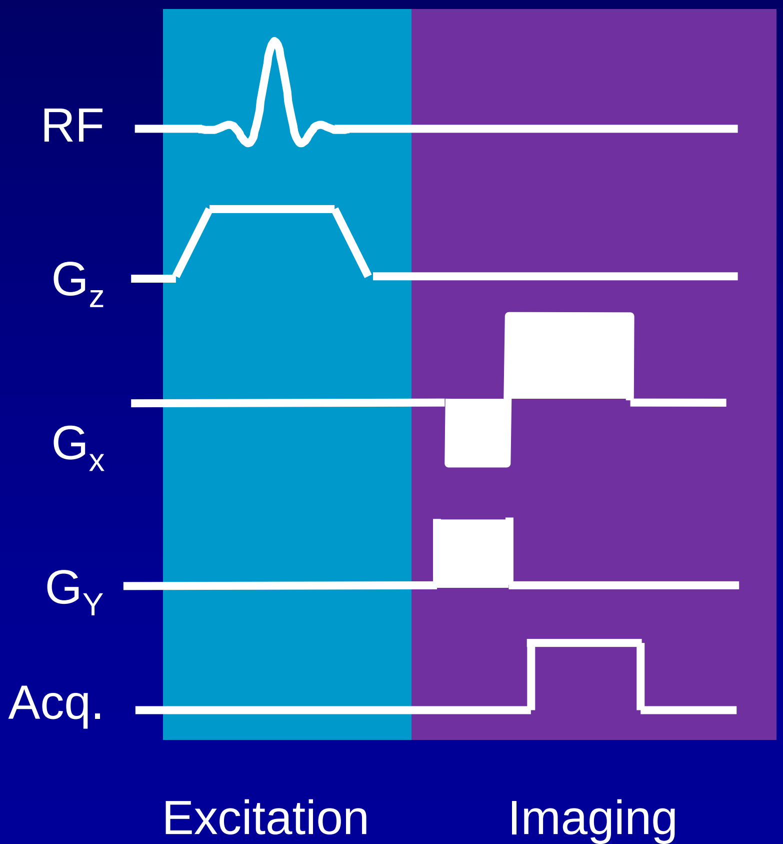
Compressive Sampling is of practical significance to MRI:

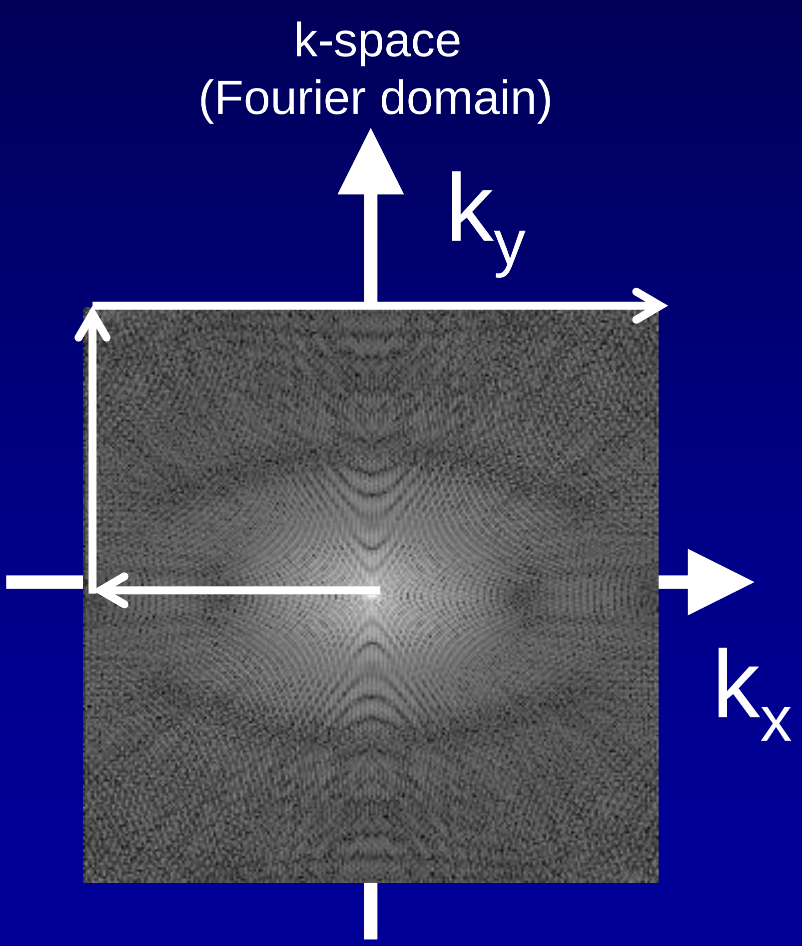
- MR imaging is performed using linear measurements of the object (in Fourier space).
- MR images often have compressible representations.
- Scan time is (approximately) proportional to the number of measurements (in many cases).

MR Data Acquisition

MRI: A k-space perspective

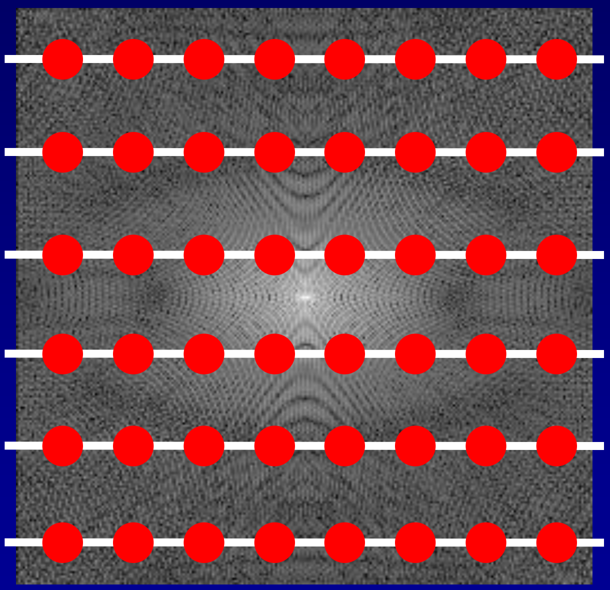
- MRI is performed by pulsing the field gradients and using RF excitation



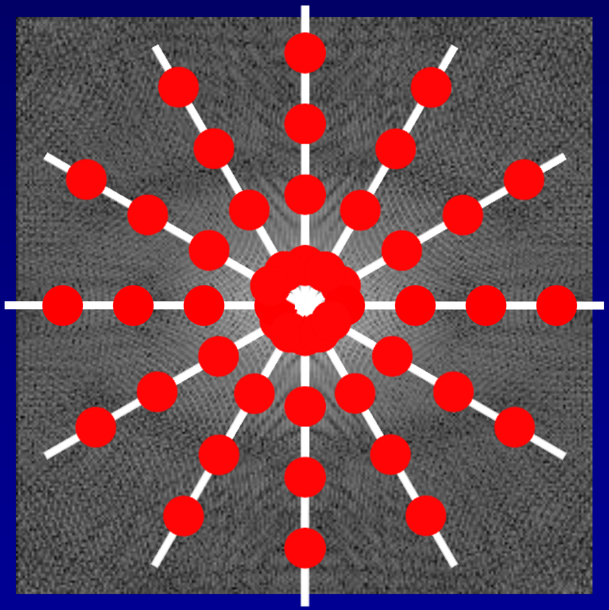


MRI:Sampling

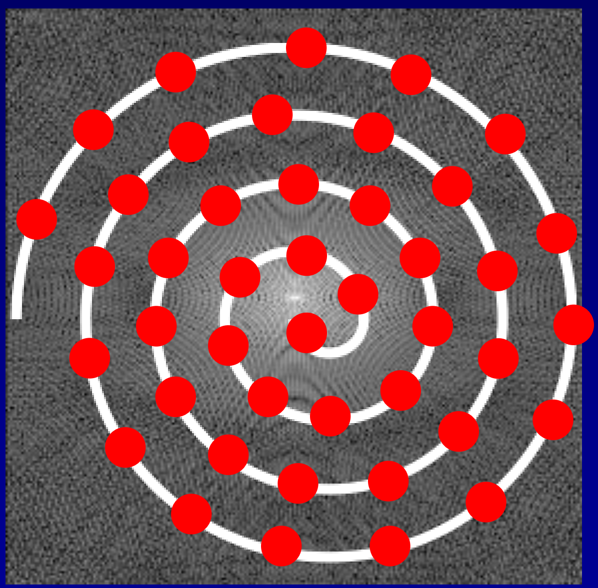
- In MRI, typical data acquisition trajectories include:



Cartesian



Radial

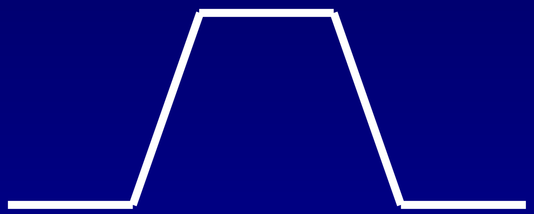


Spiral

Gradient Strength and Slew Rate

- Two important characteristics of gradients (amplifiers and coils) are slew rate and gradient strength:

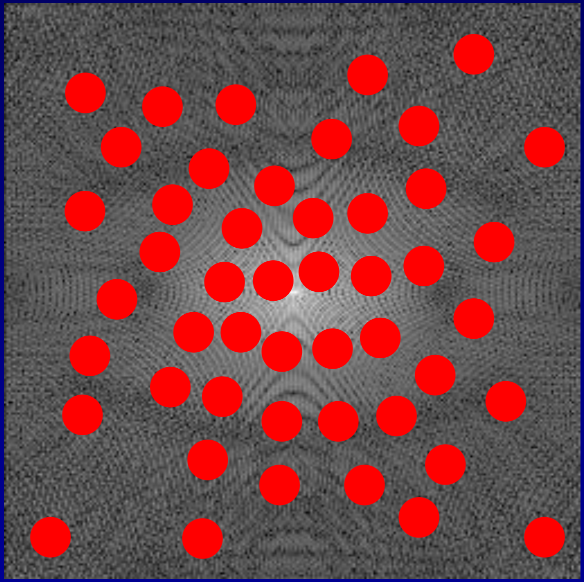
- Gradient strength determines how quickly we can move in k-space.



- Slew rate determines how quickly we can “turn” in k-space.

MRI:Sampling

- Given the gradient constraints, arbitrary partial Fourier measurements are impractical.



CS-MRI Applications:

T2 Mapping

Contrast in MRI

Contrast of an MR image is dependent on several parameters:

Magnetic Properties of the Tissue:

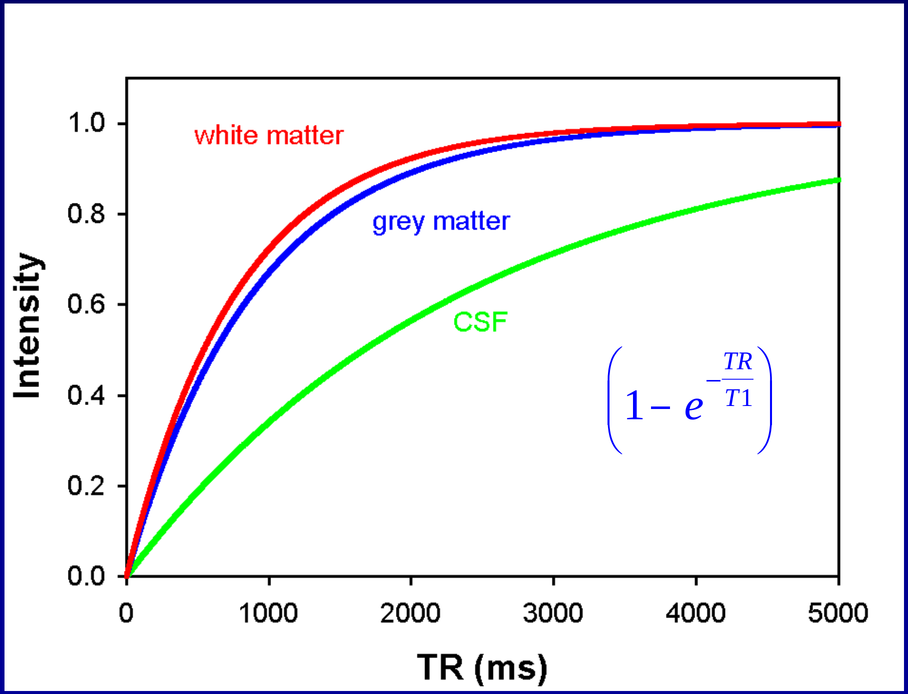
- Proton density ρ is the concentration of protons in the tissue.
- T1 and T2 relaxation times relate to specific tissue characteristics and define the way that the protons revert back to their resting states after RF excitation.

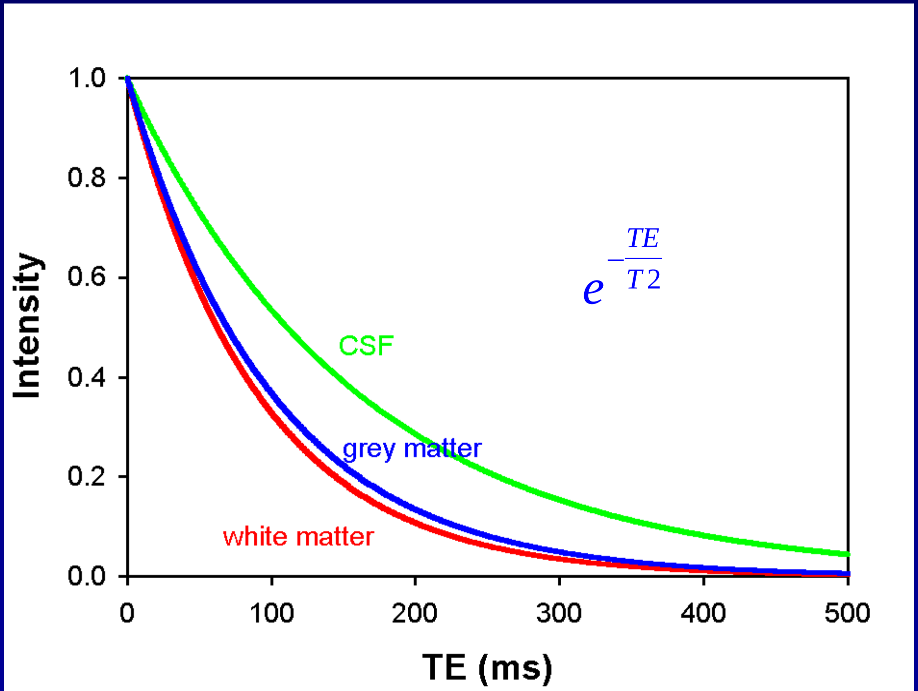
Imaging Parameters:

- TE=echo time
- TR= repetition time

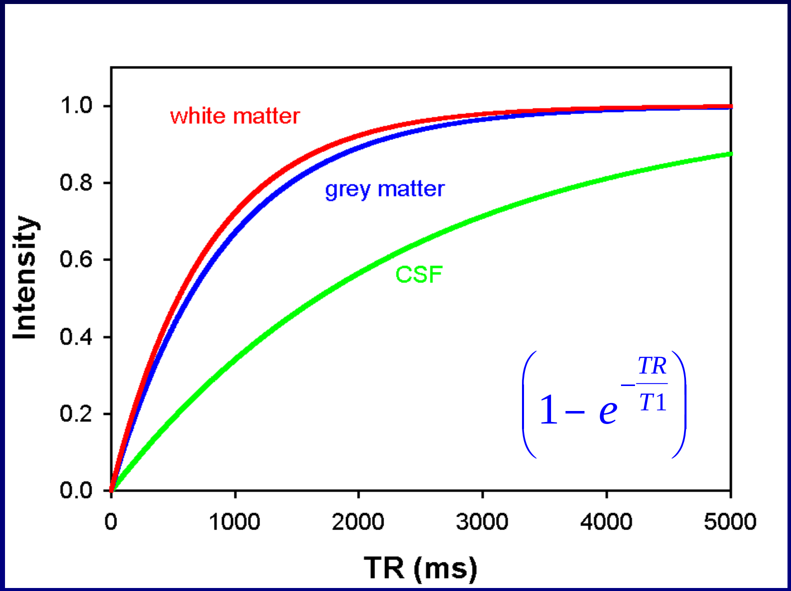
Contrast in MRI

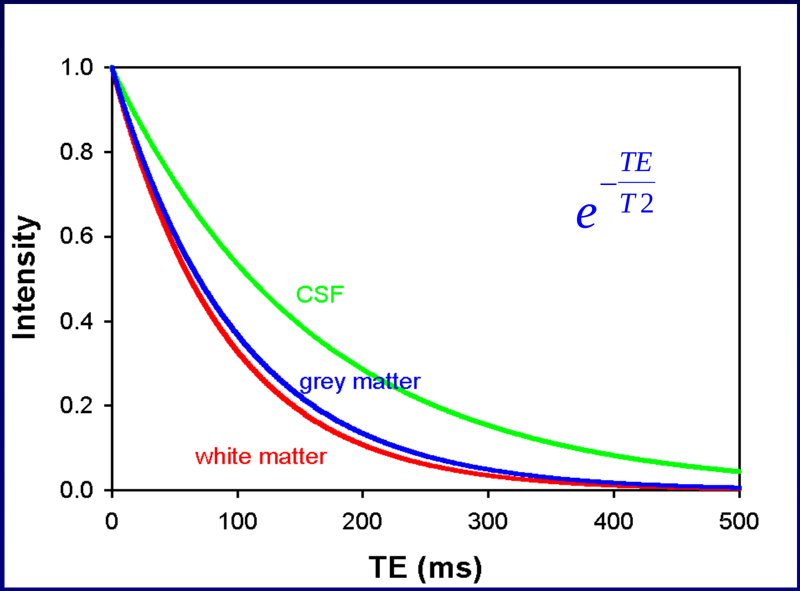
$$Intensity = \rho\left(1 - e^{-\frac{TR}{T1}}\right)e^{-\frac{TE}{T2}}$$

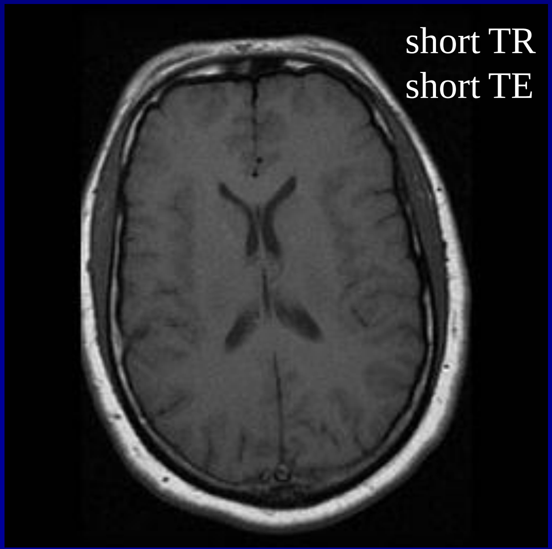


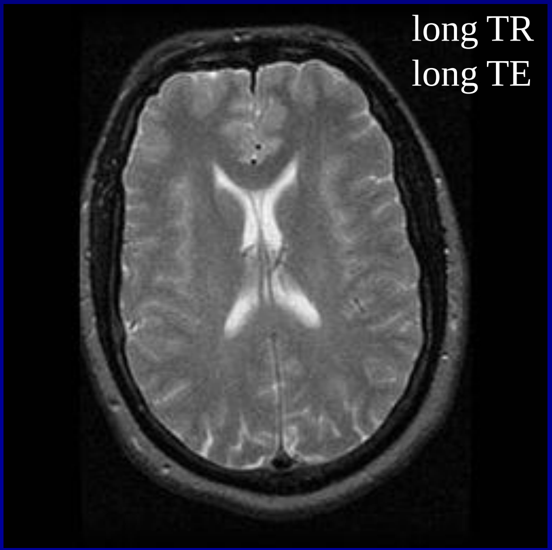


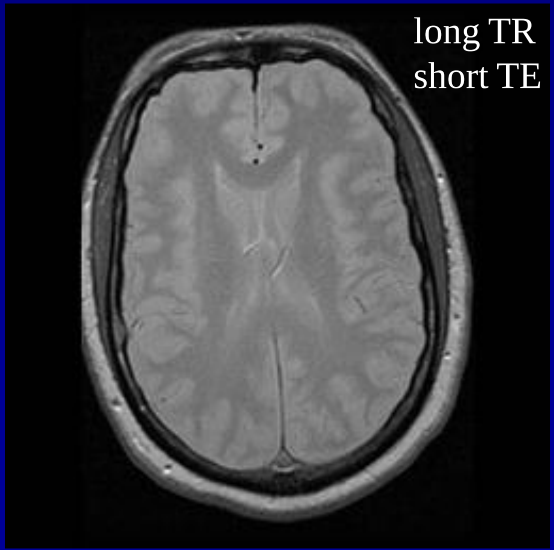
Contrast in MRI





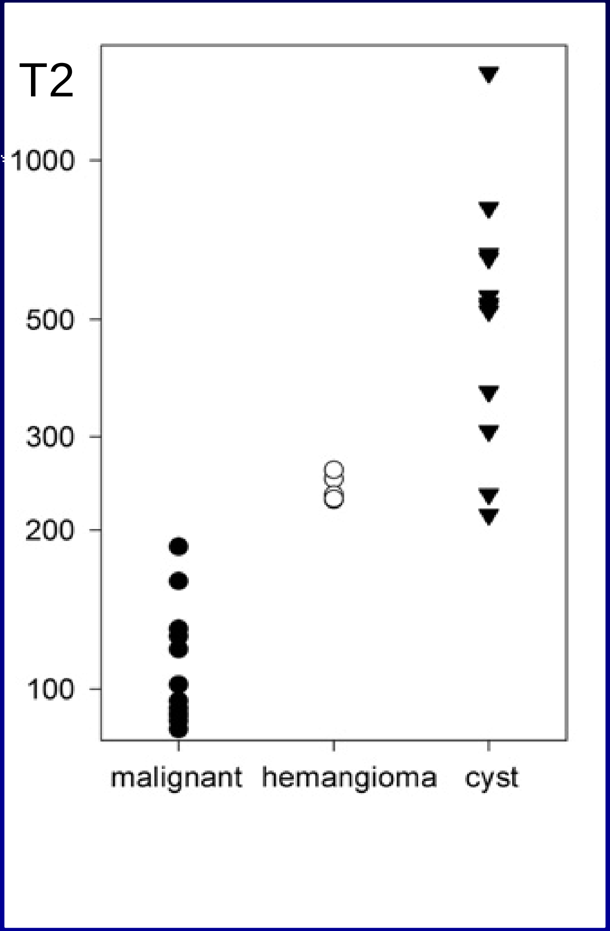


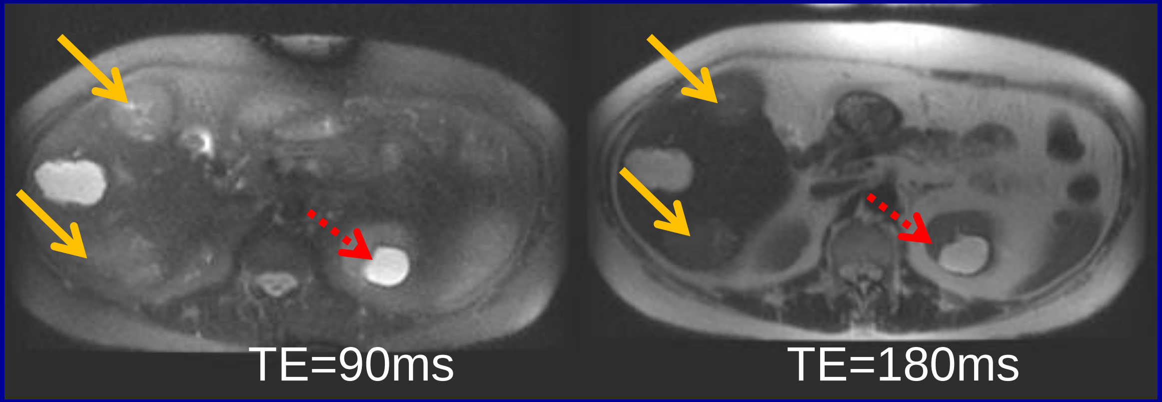




T2 Mapping

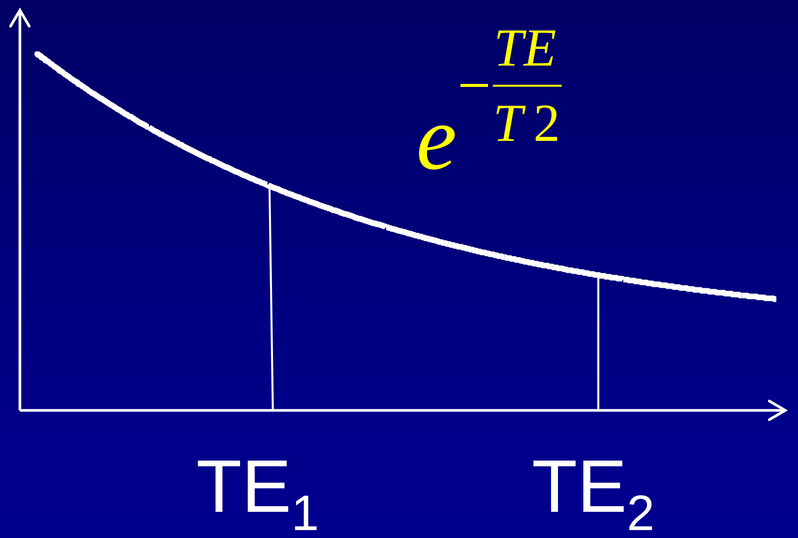
- One example of clinical use of T2 is liver lesion classification
- It has been shown that benign and malignant liver lesions can be well distinguished by their T2 values [Altbach MI, et al. JMRI, 2002]
- However, acquisition of data for T2 mapping can be very time consuming.





T2 Mapping

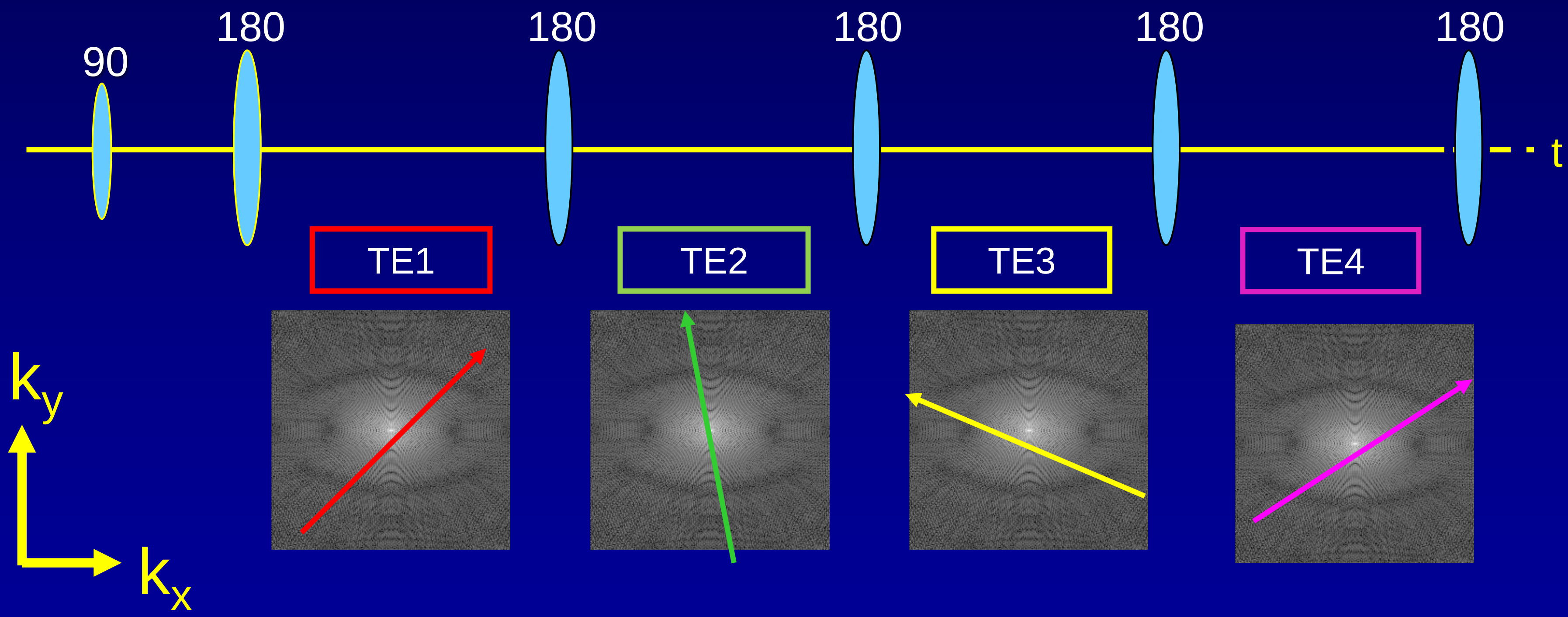
- In order to calculate a T2 value for each voxel, data must be acquired at different echo times:



- T2 mapping requires a spatio-temporal sampling.

Radial Fast Spin Echo

- During each excitation one k-space line per TE is acquired.



- If excitation is repeated sufficient times, fully sampled k-space data at each TE can be acquired.

Rapid T2 mapping

- Our goal is to reconstruct accurate T2 maps from highly undersampled spatio-temporal data.
- Several groups have recently proposed model-based algorithms to address this problem.

$$\hat{\mathbf{I}}_{\mathbf{0}}, \hat{\mathbf{T}}_{\mathbf{2}} = \arg\min_{\mathbf{I}_{\mathbf{0}}, \mathbf{T}_{\mathbf{2}}} \{ \sum_j \| FT_j (\mathbf{I}_{\mathbf{0}} \cdot e^{-TE_j / \mathbf{T}_{\mathbf{2}}}) - \vec{\mathbf{K}}_j \|^2 \}.$$

- To linearize the equation, we developed <u>Re</u>construction of <u>P</u>rincipal <u>Co</u>mponent Coefficient <u>M</u>aps (REPCOM) which is based on principal component decomposition.

Rapid T2 mapping

- We express the exponential decay as a weighted sum of basis vectors.

$$s_j = e^{-TE_j/T_2} \Rightarrow \vec{s} = c_1\vec{B}_1 + c_2\vec{B}_2 + \cdots + c_m\vec{B}_m$$

- The basis set is obtained as the principal components of a family of exponential decay curves for a given T2 range.

- A small number of principal components are shown to be sufficient to explain the temporal behaviour.

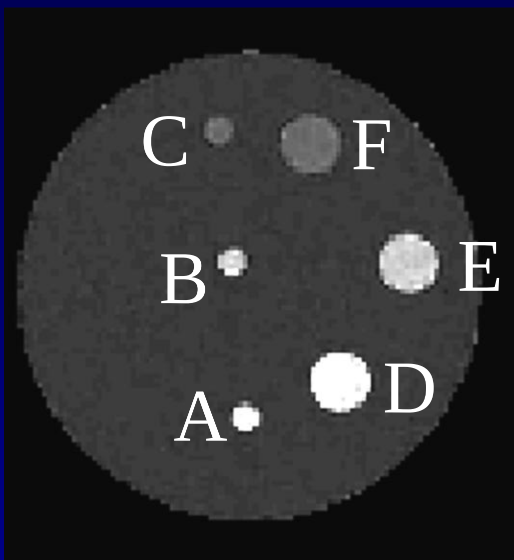
Rapid T2 mapping

- Denote the matrices of coefficient maps to be C_i , the Principal Component basis matrix to be $\widehat{B} = [B_1, \cdots, B_n]$

$$\arg\min_{c_1, c_2, \ldots, c_n} \sum_{j=1}^{ETL} \| FT\{\sum_i C_i \widehat{B}_{i,j}\} - K_j \|^2 + Spatial\ \ Sparsity\ \ Penalty$$

- Spatial sparsity penalty terms are total variation and the l_1 norm of the wavelet coefficients of the PC maps

T2 estimation for small objects



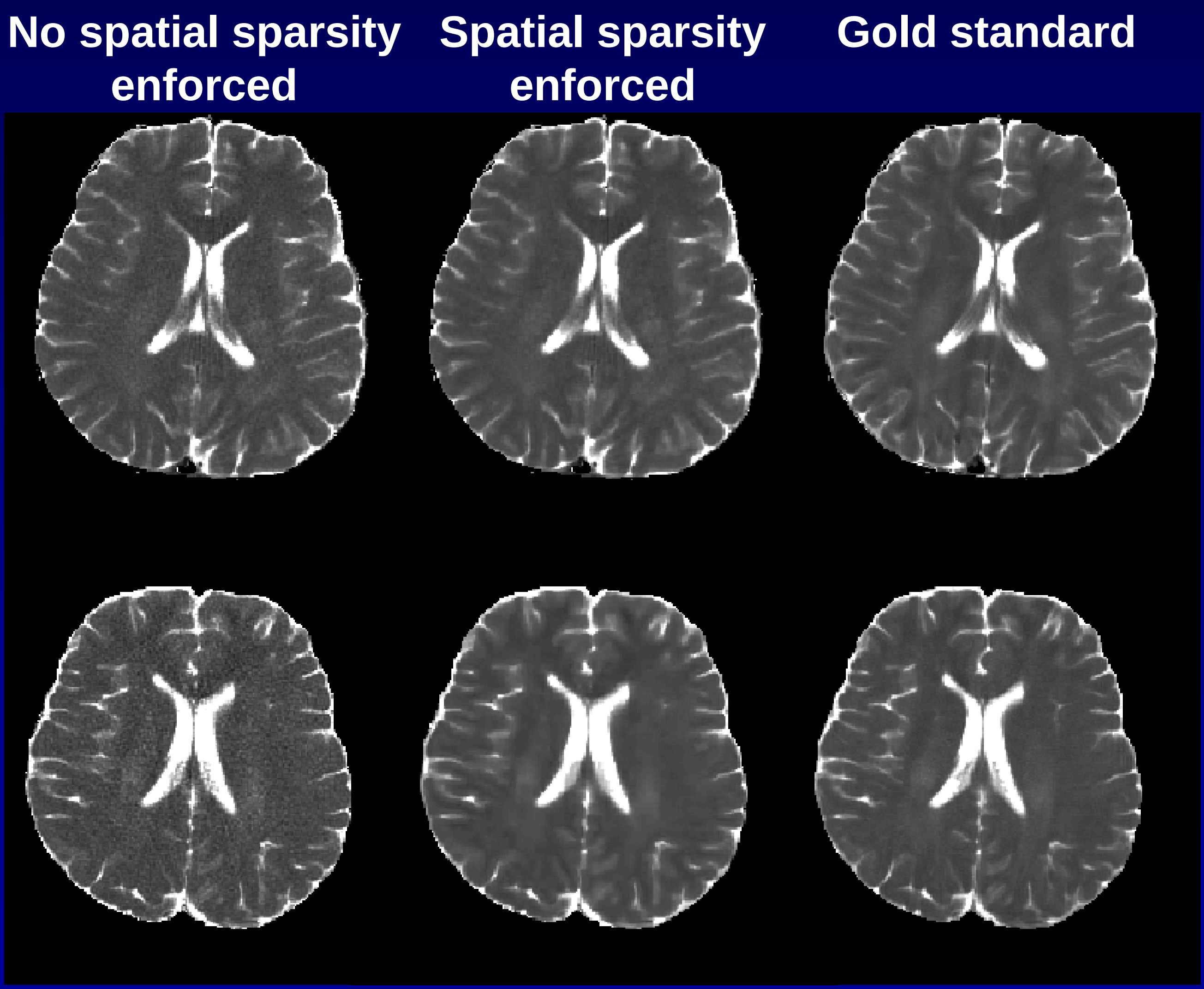
T_{2b} = 45 ms

Multi-echo spin-echo, radial
Echo spacing = 8.29ms ETL = 16
TR = 1 s, 8 mm slice, Single channel transmit/receive coil

vial	Gold standard	REPCOM	Non-linear model-based algorithm	ES
A	233.2 ms	**0.21%**	-5.23%	-19.34%
B	167.3 ms	**-0.24%**	-13.03%	-4.36%
C	83.2 ms	**0.72%**	-6.73%	8.05%
D	231.9 ms	**1.60%**	13.45%	-8.41%
E	168.2 ms	**0.24%**	-1.43%	-5.47%
F	83.8 ms	**-0.48%**	-3.94%	2.03%

Huang C, et al. MRM, 67:1355–1366 (2012); Huang C, et al. ISMRM 2011; Block KT, et al. IEEE-MI, 2009; Altbach MI, et al. JMRI, 2002

Benefit of enforcing sparsity

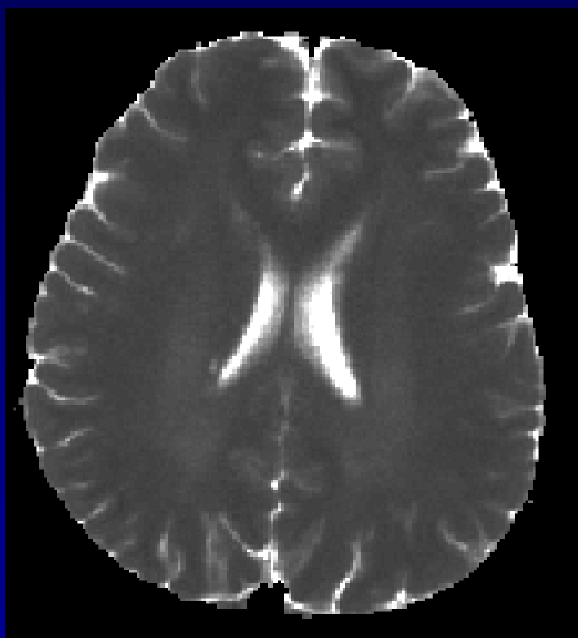


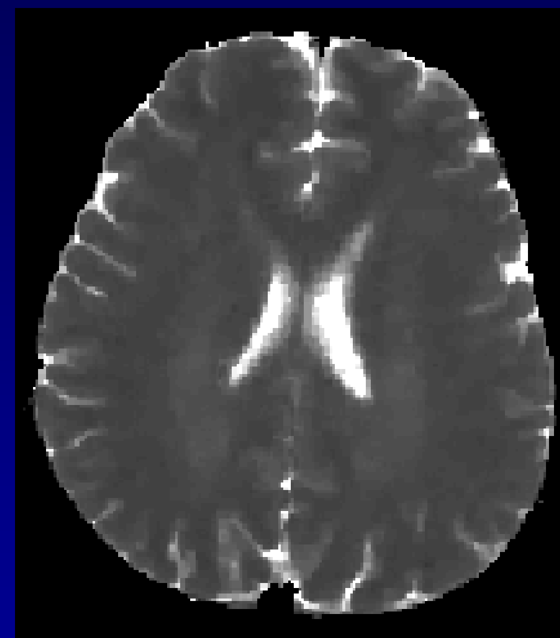
Huang C, et al. MRM, 67:1355–1366 (2012)

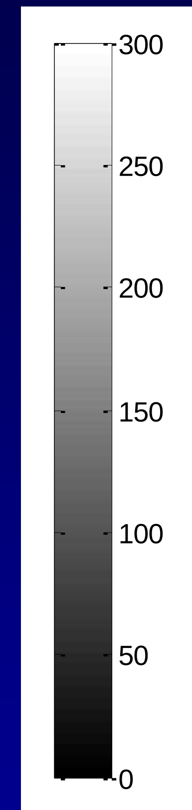
Application - Brain

17 mins

1 min 20 sec







Gold standard T2 map

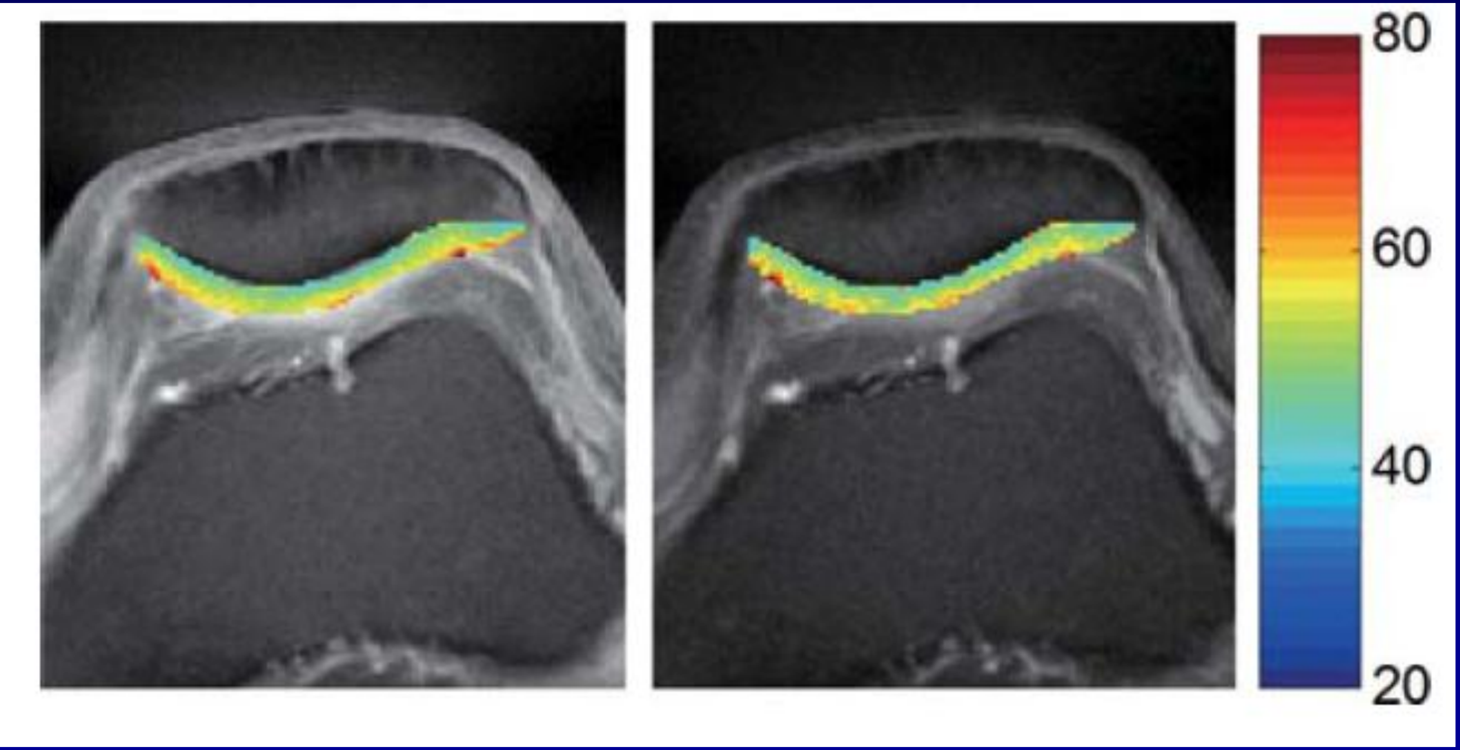
T2 map by REPCOM

Multi-echo spin-echo, radial
Echo spacing = 9.07 ms, ETL = 16 TR = 4 s
5 mm slice 8-channel receive coil
256 k-space lines per TE for gold standard
16 k-space lines per TE for REPCOM

Huang C, et al. MRM, 67:1355–1366 (2012)

Application - Cartilage

17 mins **2 min 12 sec**

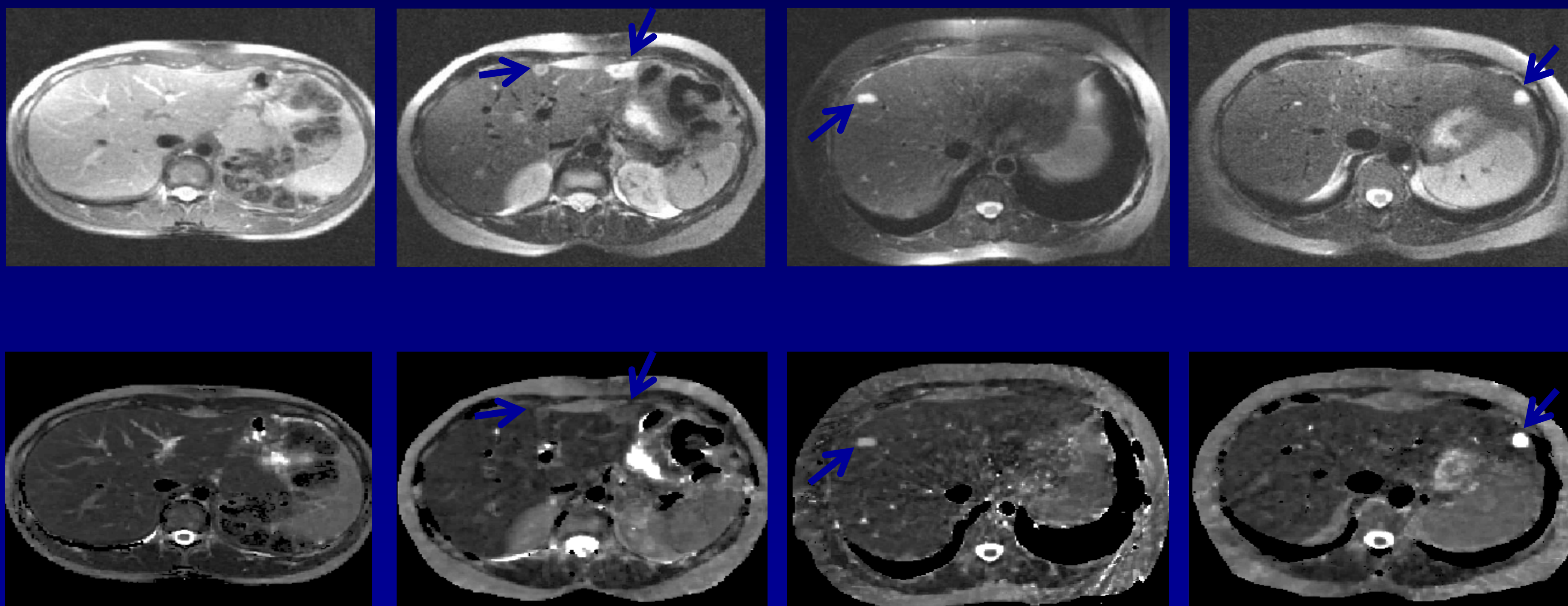


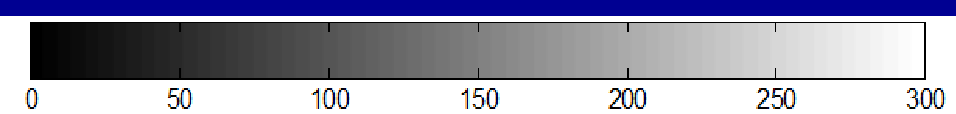
Multi-echo spin-echo, radial, 2 average
Echo spacing = 8.38 ms ETL = 8 TR = 2 s
5 mm slice 8-channel receive coil
256 k-space lines per TE for gold standard
32 k-space lines per TE for REPCOM

Huang C, et al. MRM, 67:1355–1366 (2012)

Application – Abdominal Imaging

~20 sec





Multi-echo spin-echo, radial, Echo spacing ~ 8.8 ms
35.4 ms preparatory time was added in front of the 1st TE
ETL = 16 TR = 1.5 s ~ 1.8 s
8 mm slice 8-channel torso receive coil
12 or 16 k-space lines per TE

Huang C, et al. MRM, 67:1355–1366 (2012)

CS-MRI Applications:

Dynamic Contrast Enhanced Magnetic Resonance Imaging (DCE-MRI)

DCE-MRI

DCE-MRI is a method of imaging the physiology of the microcirculation.

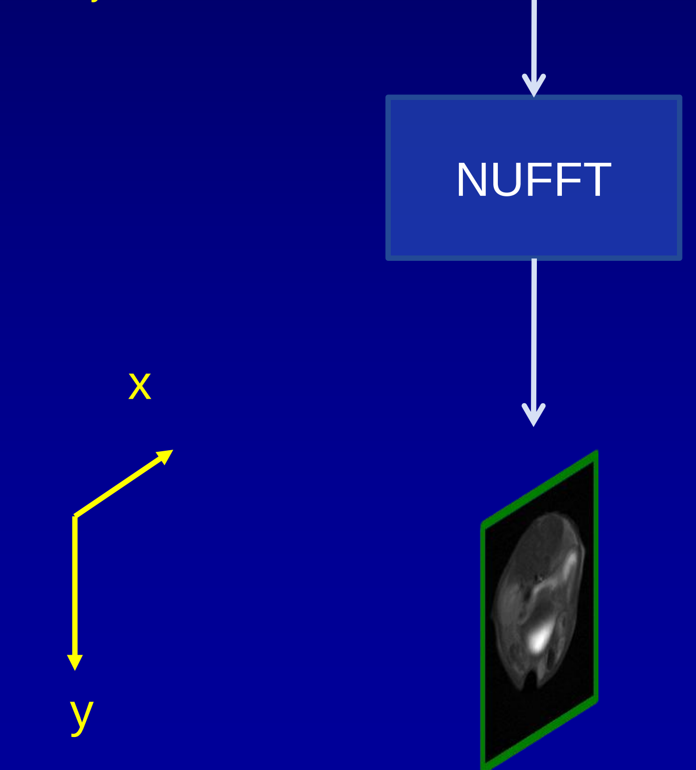
The DCE-MRI technique is based on the continuous acquisition of 2D or 3D MR images during the distribution of an intravenously administered paramagnetic contrast agent.

The contrast agent is gadolinium-(Gd) based and is able to enter the extravascular extracellular space via the capillary bed.

The pharmacokinetics of Gd distribution is modeled by a multi-compartment model.

However, imaging of time-varying objects is a challenging task when both high spatial resolution and high temporal resolution is desired.

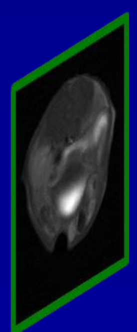
DCE-MRI



- Low Temporal Resolution

\+ High Spatial Resolution

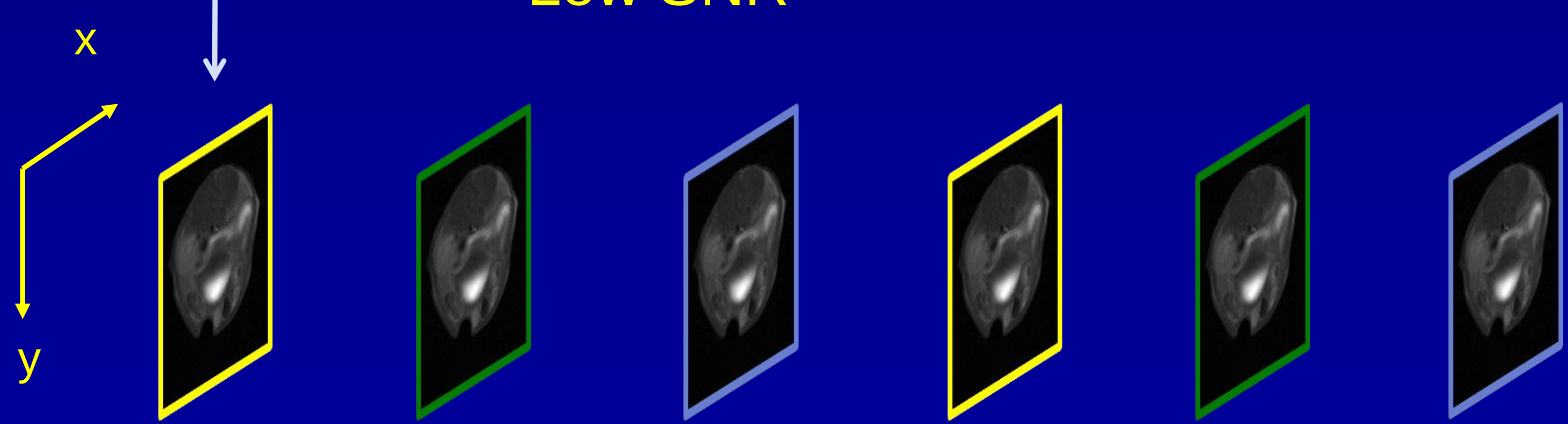
\+ High SNR



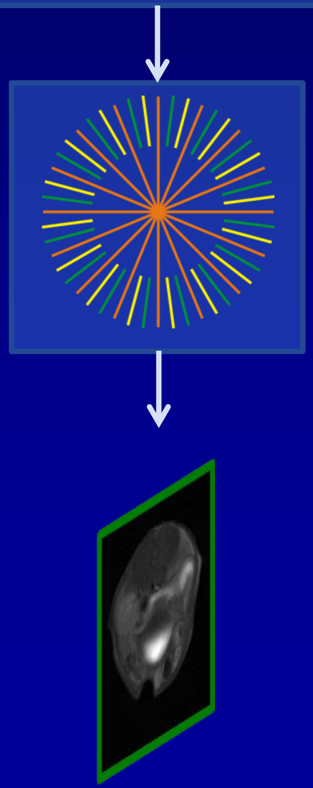
DCE-MRI

NUFFT

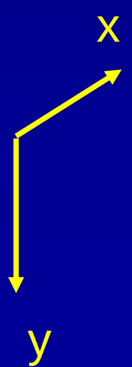
+ High Temporal Resolution
- Spatial Undersampling Artifacts
- Low SNR



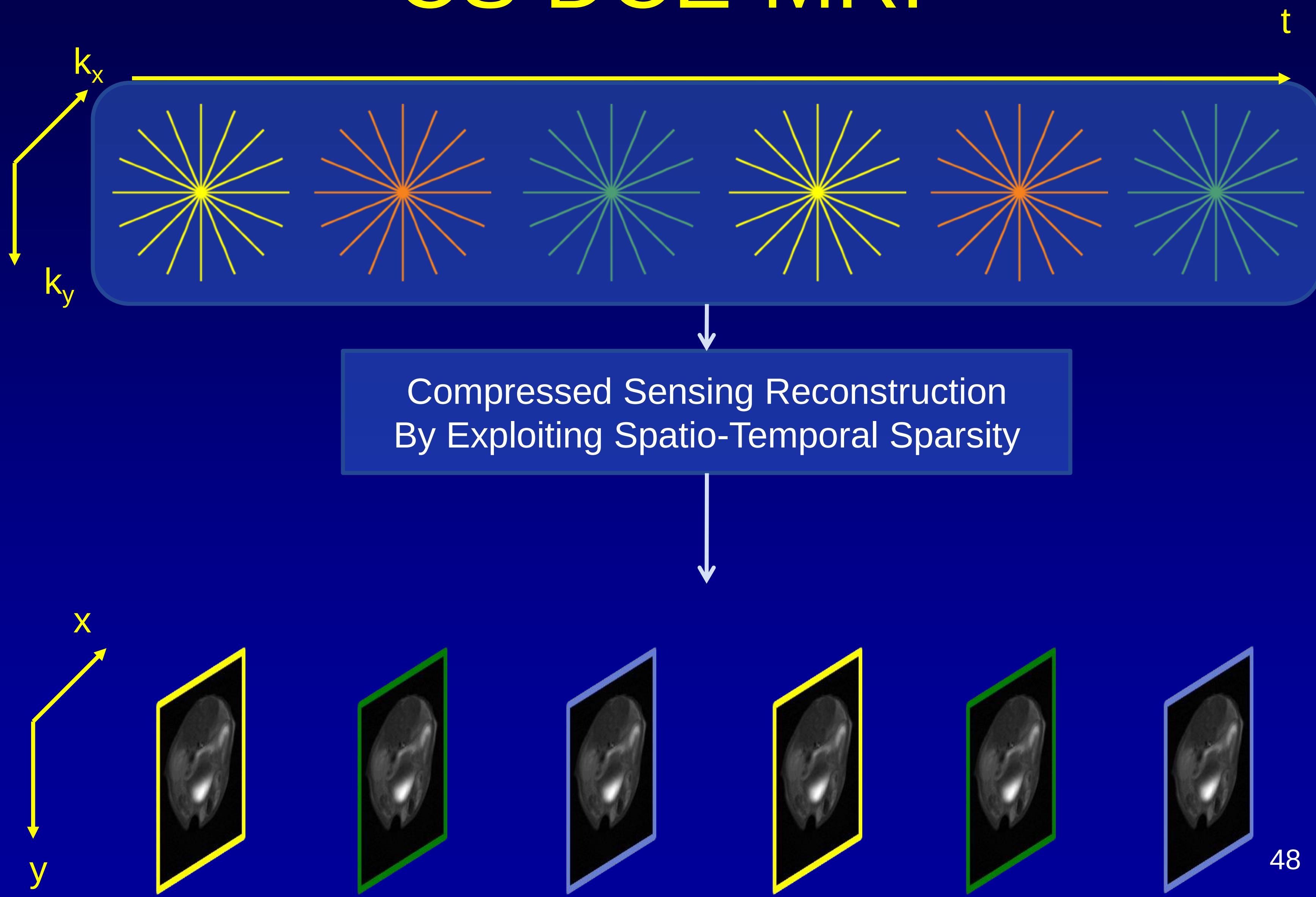
“Radial Keyhole”



- Reduced Temporal Resolution
+ Reduced Undersampling Artifacts
+ High SNR



CS DCE-MRI



t
k_x
k_y
Compressed Sensing Reconstruction
By Exploiting Spatio-Temporal Sparsity
x
y

CS Problem

$$\min_{\mathbf{f}}(\|\mathbf{M}\mathbf{f}-\mathbf{g}\|_2+\lambda_1\|\boldsymbol{\Psi}\mathbf{f}\|_1+\lambda_2 \mathrm{TV}_2(\mathbf{f}))$$

$\mathbf{f}$: Dynamic object being imaged

$\mathbf{g}$: Dynamic k-space data

$\mathbf{M}$: Undersampled radial Fourier Matrix

$\boldsymbol{\Psi}$: 3D (2D+t) Wavelet Transform Matrix

TV_2 : 2D Total Variation

λ_1, λ_2 : Regularization parameters

Experimental Setup

Goal: Quantitatively assess renal function in mice

- RAD-FSE data sets, TR=100ms, TE=9ms
  - 64 time points, 256 radial views, 256 points along each radial view.
  - Gd-DOTP injected IV at time point 20.

- Datasets retrospectively subsampled to simulate accelerated acquisition.

- Temporal dimension: Haar wavelet Spatial dimensions: Symlets

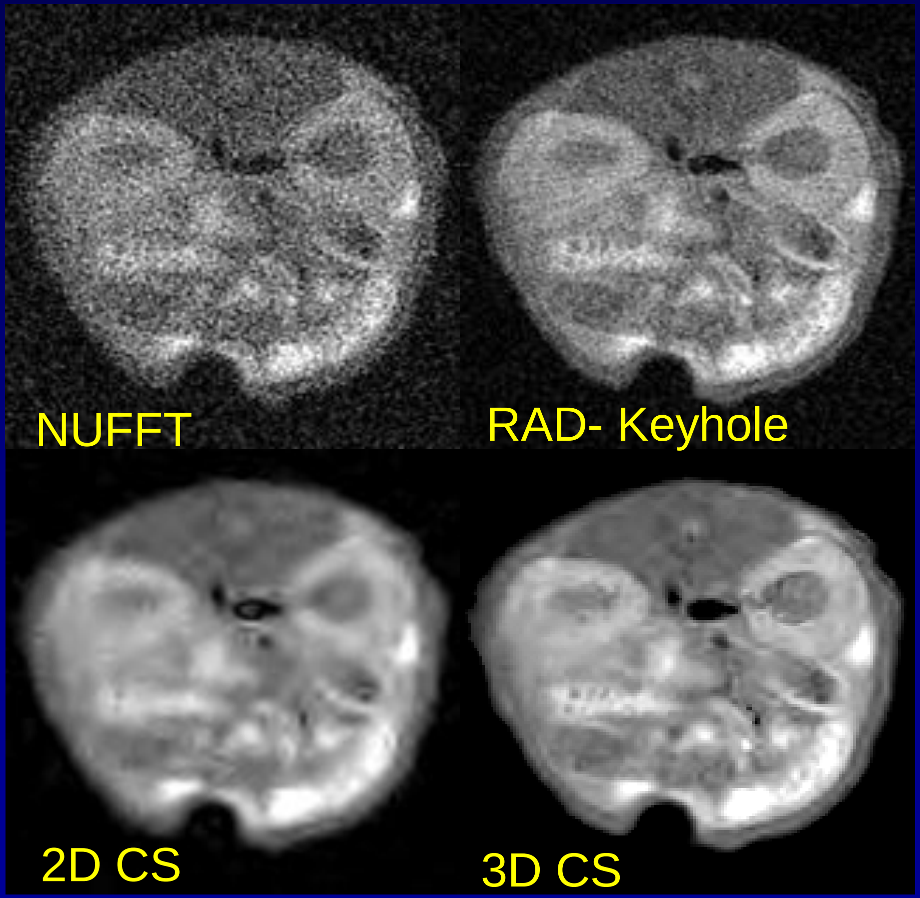
- Reconstructed dynamic images and pre-contrast T1 map fitted to a 2-compartment pharmacokinetic model.

Results

64 radial views

~ 6.3X acceleration

Time point 20

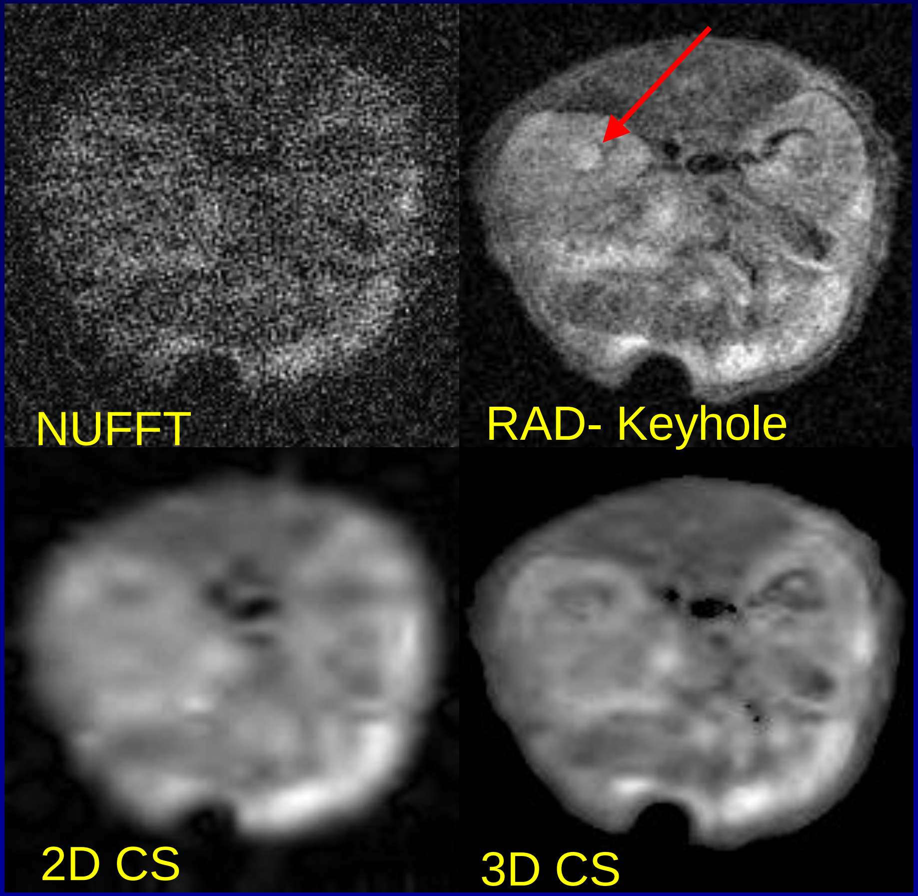


Results

16 radial views

~ 25.2X acceleration

Time point 19



Two-Compartment Pharmacokinetic Model

$$\boxed{\begin{array}{c}\textbf{Plasma Compartment}\\ C_P\,,\,v_P\end{array}} \underset{\longleftarrow}{\overset{\longrightarrow}{K^{GF}}} \boxed{\begin{array}{c}\textbf{Filtrate Compartment}\\ C_e\,,\,v_e\end{array}}$$

$$C_k(\tau) = K^{GF}\left(1+\frac{v_p}{v_e}\right)\int_0^{\tau} C_p(t)\,dt - \frac{K^{GF}}{v_e}\int_0^{\tau} C_k(t)\,dt + v_p C_p(\tau)$$

K^{GF} – Volumetric Filtration Rate, mL^{-1}

v_e – Extracellular Volume Fraction

v_p – Plasma Volume Fraction

Fitted

C_p – Arterial Input Function

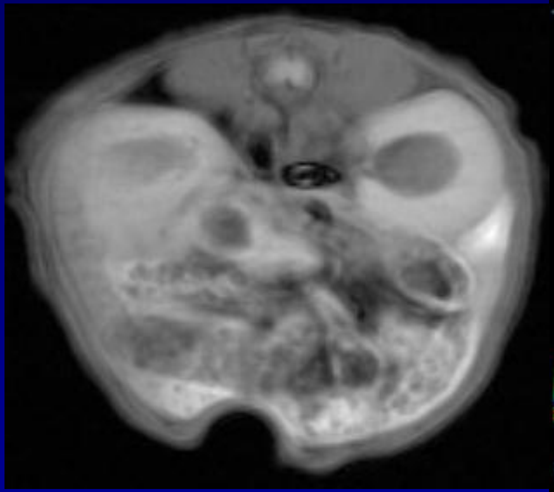
C_k – Concentration of Gd

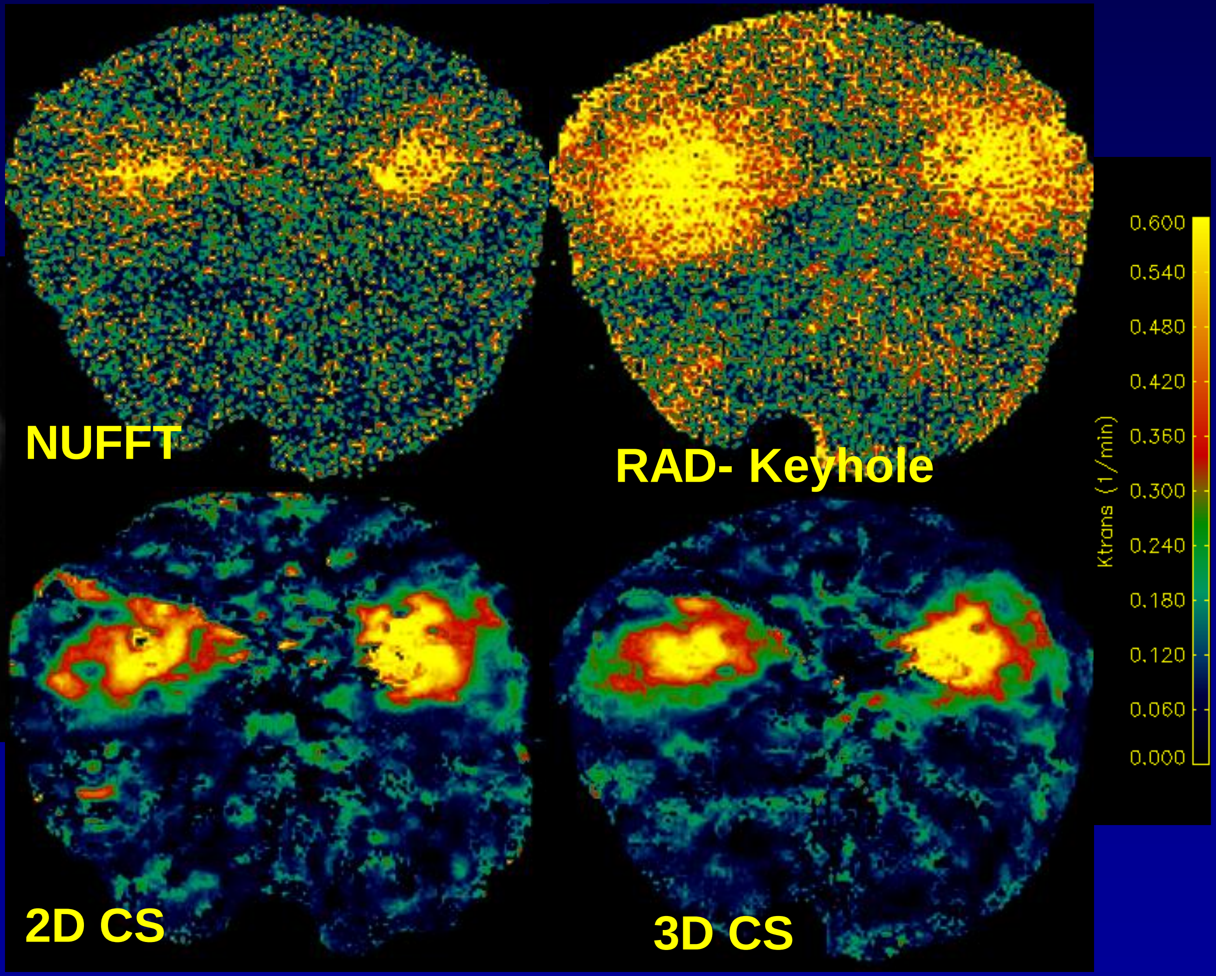
Measured

Raghunand et al., MRM 55:1272-1280, 2006.

Volumetric Filtration Function

Anatomical Reference





16 radial lines: ~25.2 x acceleration

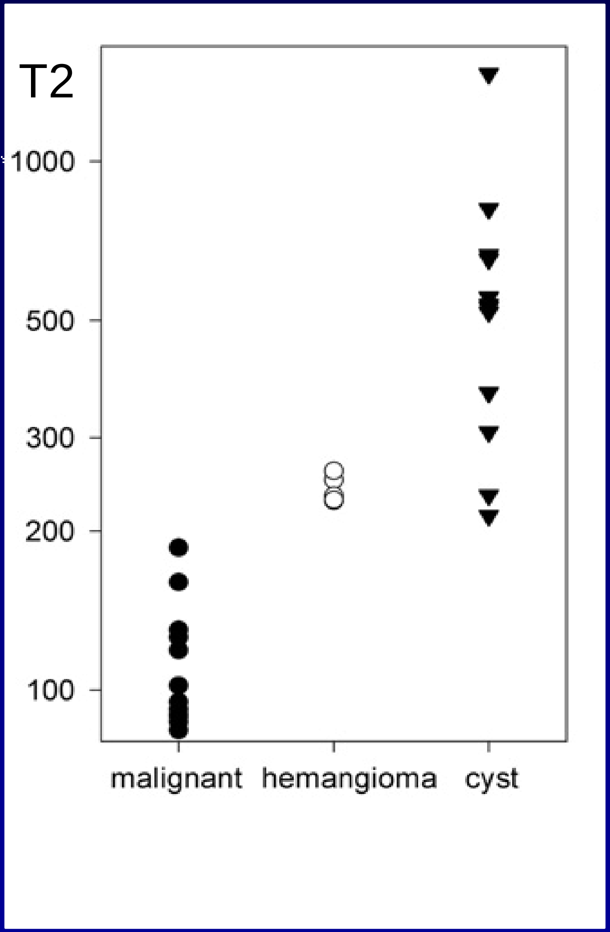
CS-MRI:
Future Directions

Task-Specific MRI

- Many CS MRI problems have been formulated as estimation tasks.

- However, in many cases detection or classification is the real task.

- Design compressive MRI techniques to achieve maximum task-specific performance.



Random vs. Adaptive

- Most CS MRI applications use “random” Fourier measurements
  - Radial Fourier
  - Randomly Undersampled Cartesian Fourier

- Is there any value to updating what you want to measure next based on what you have already measured?

- Recent *Adaptive Task-Specific Compressive Imaging* techniques demonstrate advantages of adaptation in certain applications.

M. A. Neifeld, “Adaptation for Task-Specific Compressive Imaging”

Non-Fourier Encoding in MRI

Implementation of Three-Dimensional Wavelet Encoding Spectroscopic Imaging: In Vivo Application and Method Comparison

Richard Young and Hacene Serrai*

Dynamically Adaptive MRI with Encoding by Singular Value Decomposition

Gary P. Zientara, Lawrence P. Panych, Ferenc A. Jolesz

A Dynamically Adaptive Imaging Algorithm for Wavelet-Encoded MRI

Lawrence P. Panych, Ferenc A. Jolesz

Multislice Imaging with Adiabatic Pulses Using Transverse Hadamard Encoding

ROBIN A. DE GRAAF AND KLAAS NICOLAY

IEEE TRANSACTIONS ON MEDICAL IMAGING, VOL. 30, NO. 4, APRIL 2011 893

Compressed-Sensing MRI With Random Encoding

Justin P. Haldar*, *Student Member, IEEE*, Diego Hernando, *Student Member, IEEE*, and Zhi-Pei Liang, *Fellow, IEEE*

Conclusions

•MRI is a non-invasive imaging technique that is widely used in the clinic.

• One of the major challenges in MRI is the lengthy examinations.

• There are numerous open problems in CS MRI and solutions can have significant impact on healthcare.

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