Use of Magnetization Phase in Applications

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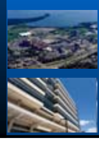
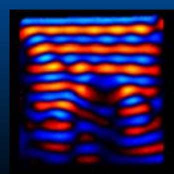




Objectives and Goals

- Appreciate the richness of phase information in MRI
- Understand the principles (and challenges) of encoding phase from physiological processes
- Review important examples of phase manipulation
  - Susceptibility weighted imaging
  - Chemical shift imaging
  - Velocity encoding
  - Magnetic resonance elastography

MR Data

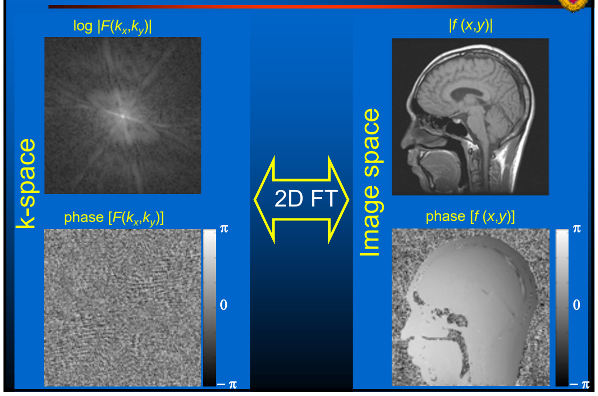
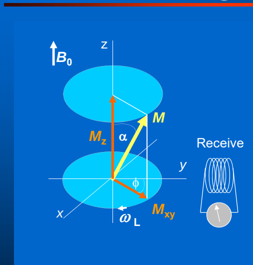
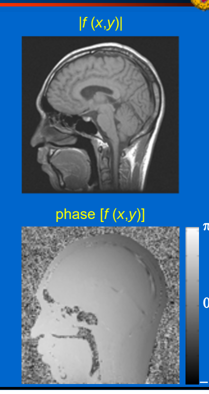


Image Space

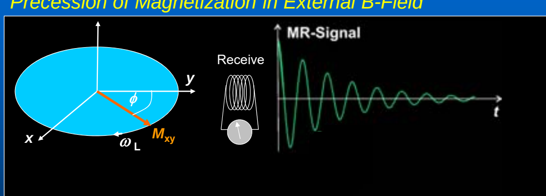




- Longitudinal Magnetization M_z
- Transverse Magnetization Mxy
- Phase ϕ

MR Signal

Precession of Magnetization in External B-Field



Phase

$$MR\text{-}Signal \sim \left|M_{xy}(\vec{r})\right| e^{i\omega_L(\vec{r})t}$$

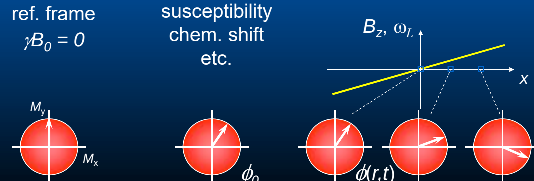
➔ Phase ~ Local Frequency $\quad \omega_L(\vec{r},t) = \gamma B(\vec{r},t)$

Phase Contributions

Phase determined by Larmor Frequency

$$\omega_L(\vec{r},t) = \gamma B_0 + \gamma \Delta B(\vec{r}) + \gamma \vec{r}\,\vec{G}(t) + other\ sources$$

Main field	***Local field***	***Local gradient***
Rotating ref. frame $\gamma B_0 = 0$	Static susceptibility chem. shift etc.	Frequency ~ location



Phase Contributions

$$\omega_L(\vec{r},t) = \gamma B_0 + \gamma \Delta B(\vec{r}) + \gamma \vec{r}\vec{G}(t) + other\ sources$$

Phase contributions

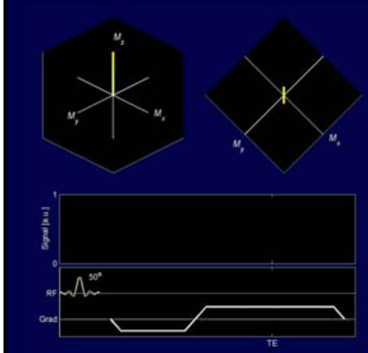
- Susceptibility
- Chemical Shift
- Motion (incl. Flow)
- T2 / T2* decay
- Acquisition Imperfection
  - B0 inhomogeneity
  - Eddy currents
  - DAQ timing
  - …
- …

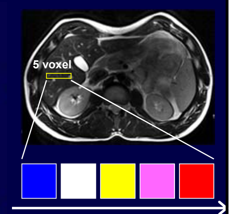
Applications with phase as contrast mechanism

- Susceptibility weighted imaging
- Chemical shift based imaging
- MR thermometry
- Current density measurements
- Positive contrast imaging
- Off-resonance angiography
- Phase Contrast MRI / velocity mapping
- MR elastography
- Diffusion
- .....

Accentuate desired contrast mechanism, suppress other phase contributions

Example for Phase Manipulation



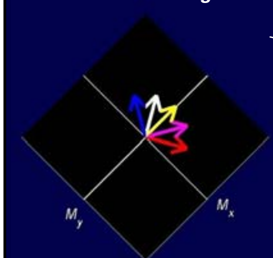


local field

Gradient Echo
Evolution of Magnetization

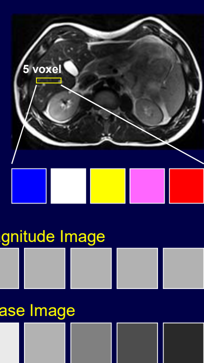
MR-Signal Phase | *Basics*

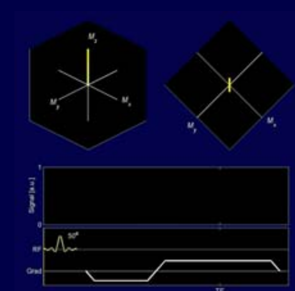
Gradient Echo at TE
- Transverse Magnetization

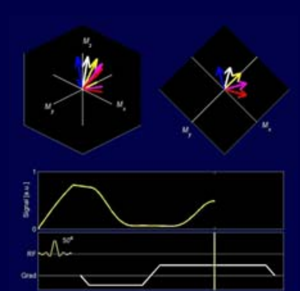


Phase: add. information on local field

FT →



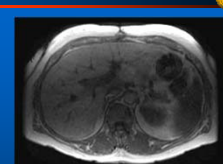




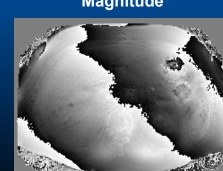
Background Phase

Background Phase
All images: unknown phase due to field changes, susceptibility, eddy currents, acquisition imperfections, etc.

➔ Need ***phase subtraction*** to isolate phase change from physiological process



Magnitude

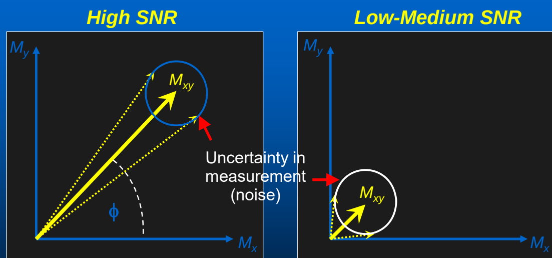


Phase

Note: Phase subtraction increases error of phase difference $\sigma_{\Delta\phi}$ by $\sqrt{2}$

➔ High *SNR* for accurate phase measurements

SNR & Phase Error

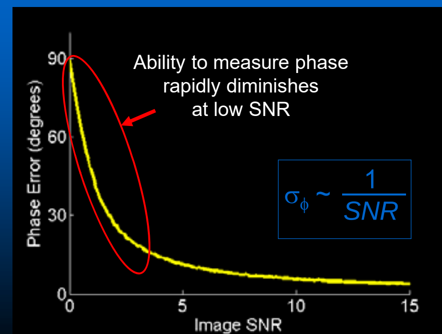


Confident phase measurement

?? phase ??

$\sigma_\phi \sim \frac{1}{SNR}$ ➔ High SNR Performance Critical for Robust Phase Imaging

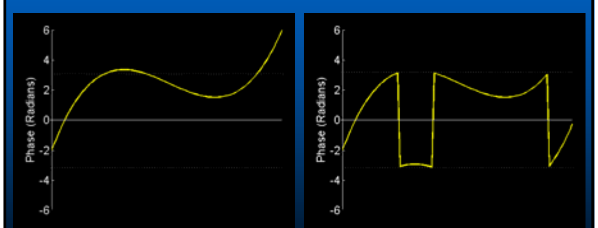
SNR & Phase Error



Phase Wrap

Phase Wrap

$$e^{i\varphi} = e^{i(\varphi+n2\pi)}$$



➔ Phase has limited dynamic range between $-\pi$ and $+\pi$

Susceptibility Weighted Imaging

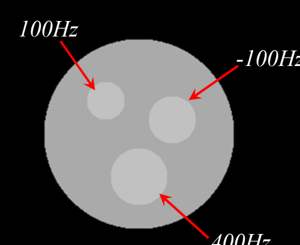
- *Concept:* species with high susceptibility create local increases/decreases in the local magnetic field
  - Iron (ferritin) deposits
  - Hemosiderin (iron-storage complex)
  - Deoxygentated vs oxygenated hemoglobin
  - Fat
- Phase rapidly develops at longer echo times

SWI: *Overview of Method*

- Acquire two or more images at different echo times
- Calculate phase difference between the images
  - Unwrap the phase map if needed
- Create a *phase mask* based on unwrapped phase map
- Multiply the original image with the phase mask to *weight the magnitude image* based on local susceptibility
- SWI image incorporates signal losses from T2* behavior (magntitude) as well as the enhanced changes from the phase mask

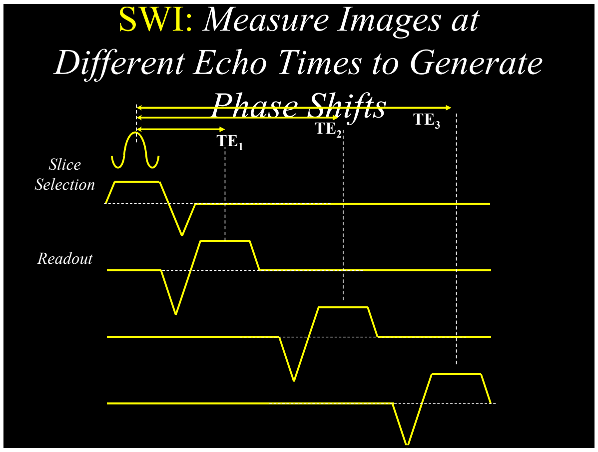
Reichenbach et al, Radiology 1997
Haacke et al, MRM, 2004
Sehgal et al, JMRI, 2005

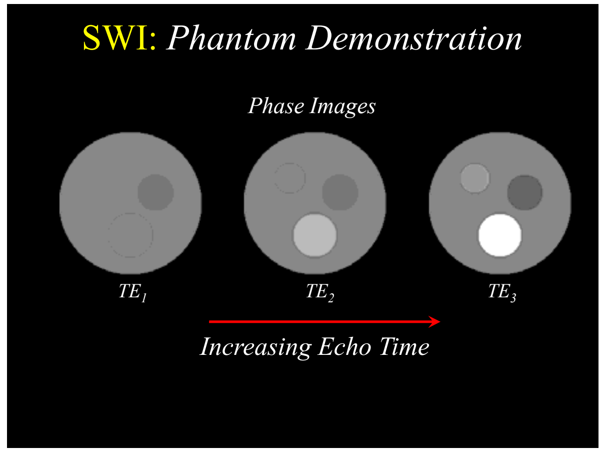
SWI: *Phantom Demonstration*

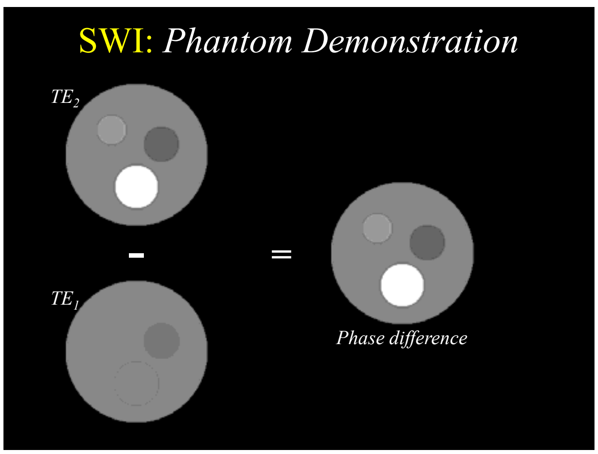


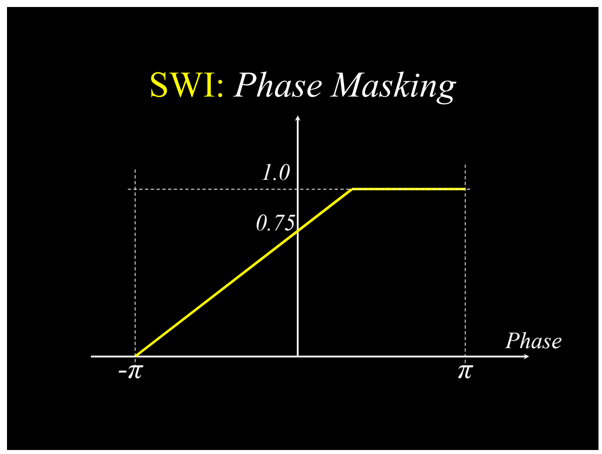
Magnitude

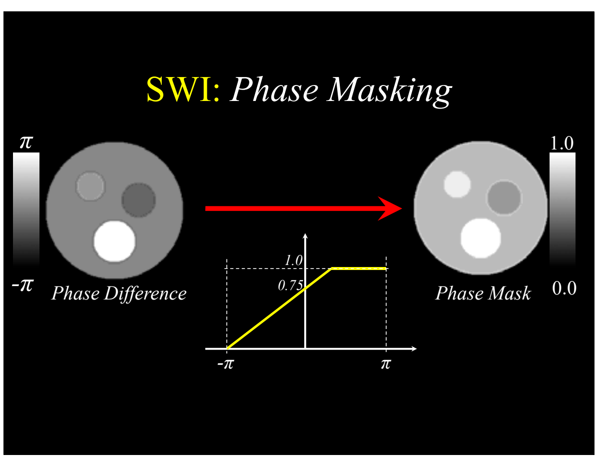
"Lesions" with different susceptibility may show poor contrast on Magnitude Image

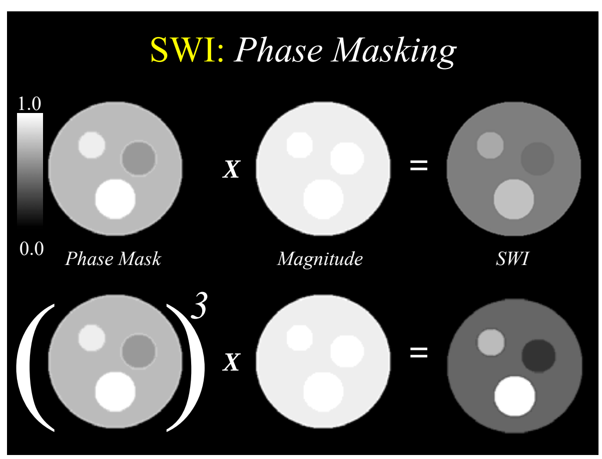

SWI: Measure Images at Different Echo Times to Generate Phase Shifts
TE1
TE2
TE3
Slice Selection
Readout


SWI: Phantom Demonstration
Phase Images
TE1
TE2
TE3
Increasing Echo Time


SWI: Phantom Demonstration
TE2
-
=
TE1
Phase difference


SWI: Phase Masking
1.0
0.75
Phase
-π
π

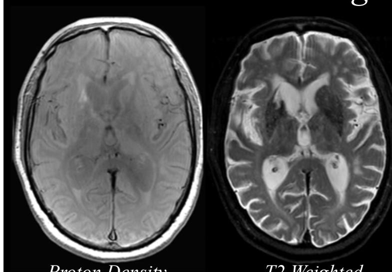

SWI: Phase Masking
π
-π
Phase Difference
1.0
0.75
-π
π
Phase Mask
1.0
0.0


SWI: Phase Masking
1.0
0.0
Phase Mask
X
Magnitude
=
SWI
3
X
=

SWI: *Applications*

Mostly Neuro Applications
- Visualization of venous vasculature and blood products
  - Micro-hemorrhage
  - Tumor vascularity
  - Trauma
  - Vascular Dementia
  - Compromised tissue in brain after stroke
- Iron detection and quantification in the brain
- Calcium deposits

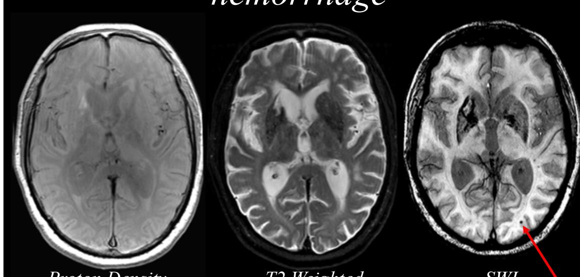
Example: *Tiny intraparenchymal hemorrhage*



Proton Density *T2 Weighted*

Images courtesy Mayo Clinic and Shen Hao, GE China

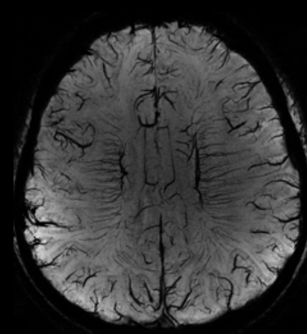
Example: *Tiny intraparenchymal hemorrhage*



Proton Density *T2 Weighted* *SWI*

Images courtesy Mayo Clinic and Shen Hao, GE China

SWI @ 7T

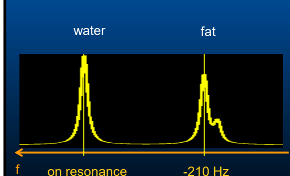


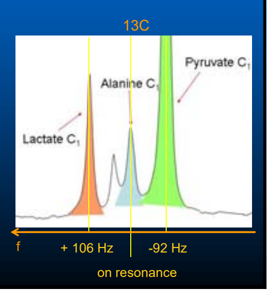
215µm x 215µm x 1000µm
TE = 16 ms
TR = 45 ms
FA = 25°
8 section MIP

From M. Haacke et al, AJNR 2009

Chemical Shift Imaging

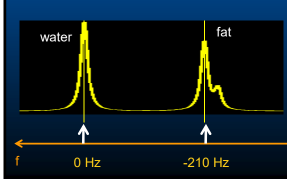
Separate metabolites with different chemical shifts, e.g.
- Fat / Water Seperation for Fat Suppression or Fat Quantification
- Metabolite maps for hyperpolarized gas imaging (13C) for Lactate, Alanin, and Pyruvate

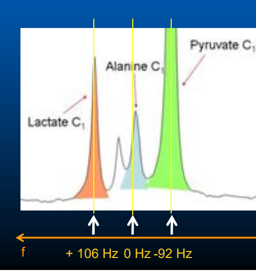




Chemical Shift Imaging

MR Spectroscopy
- High spectral information, low spatial information, long scan times
- No a priori information exploited





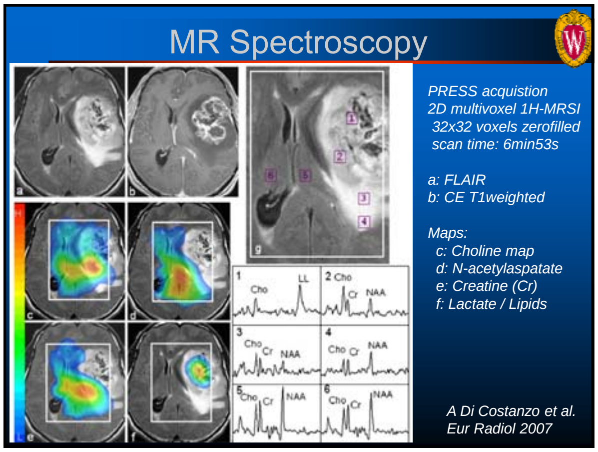
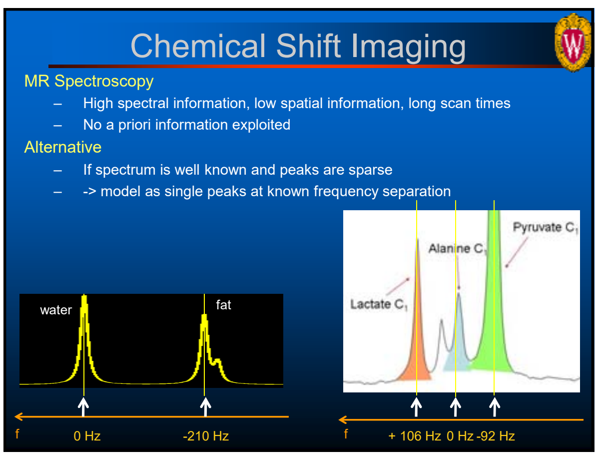
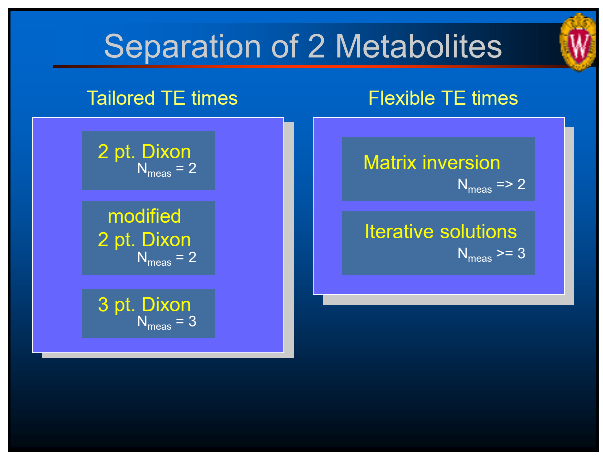
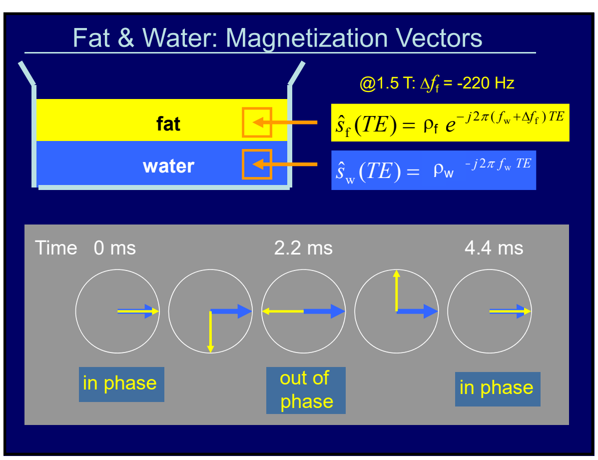
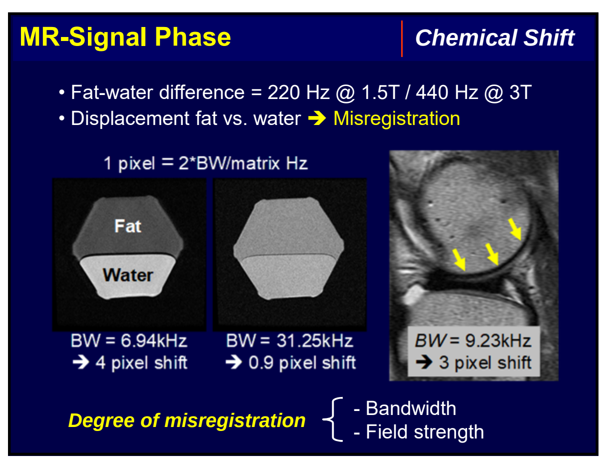

MR Spectroscopy
PRESS acquistion
2D multivoxel 1H-MRSI
32x32 voxels zerofilled
scan time: 6min53s
a: FLAIR
b: CE T1weighted
Maps:
c: Choline map
d: N-acetylaspatate
e: Creatine (Cr)
f: Lactate / Lipids
A Di Costanzo et al.
Eur Radiol 2007

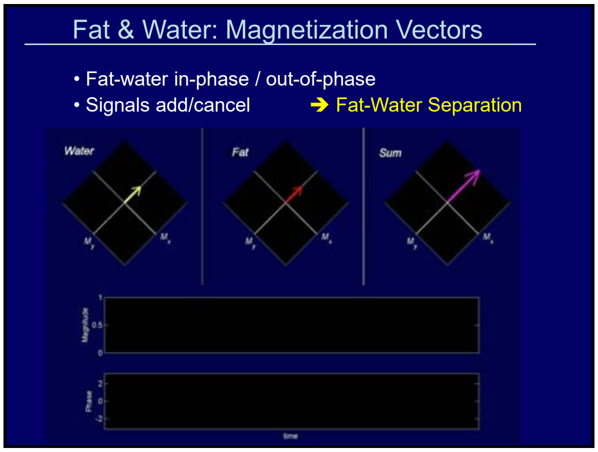

Fig. 1 Example of 2D-multivoxel proton spectroscopic imaging (1H-MRSI) performed using a 3.0-T MR scanner (Signa Horizon LX) with a standard head coil, and the protocol (PROBE/SI) and the software (Functool Performance) provided by the manufacturer (General Electric Medical Systems, Milwaukee, WI). In brief, a point-resolved spectroscopy (PRESS) pulse sequence, with repetition time (TR) 1,500 ms, echo time (TE) 144 ms, field of view (FOV) 24 cm, phase 16, section thickness 10 mm and acquisition time 6 min 53 s, provided a spectroscopic data set, which was spatially zerofilled to 32×32 images with a final voxel resolution of 7.5×7.5×10 mm (0.56 cm3). Fluid-attenuated inversion recovery (FLAIR) (a) and contrast-enhanced T1-weighted (b) images from a 45-year-old man with a left fronto-temporo-parietal glioblastoma. Choline (Cho) (c), N-acetylaspartate (NAA) (d), creatine (Cr) (e) and lactate/lipids (LL) (f) maps. Localizing FLAIR image (g) and spectra (1–6) from the corresponding boxes in g. Color scale: red strongest signal intensity; blue weakest signal intensity. Higher spatial resolution improves the ability to recognize the spatial heterogeneity of high-grade gliomas. The spectrum 1, showing a low level of Cho, undetectability of Cr and NAA, and high LL peak, suggests the presence of necrosis. The spectrum 2, in the margins of glioma, presents the typical tumor pattern, characterized by an abnormal Cho/NAA ratio (<1). The spectra 3 and 4, in an apparently edematous region surrounding the enhanced margins of glioma, show low metabolite levels, as compared to the normal spectra 5 and 6, but different pattern: the spectrum 3 has a tumor pattern and suggests the presence of infiltrating tumor cells; the spectrum 4 has a normal Cho/NAA ratio and suggests noninfiltrated vasogenic edema
A Di Costanzo et al.
Eur Radiol 2007

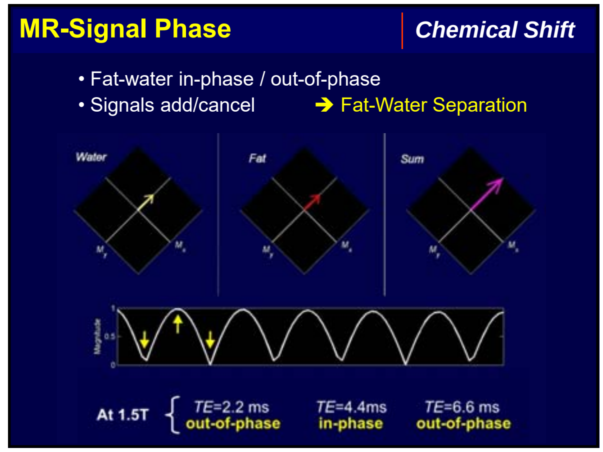

Chemical Shift Imaging
MR Spectroscopy
– High spectral information, low spatial information, long scan times
– No a priori information exploited
Alternative
– If spectrum is well known and peaks are sparse
– -> model as single peaks at known frequency separation
water
fat
f
0 Hz
-210 Hz
Pyruvate C1
Alanine C1
Lactate C1
+ 106 Hz 0 Hz -92 Hz

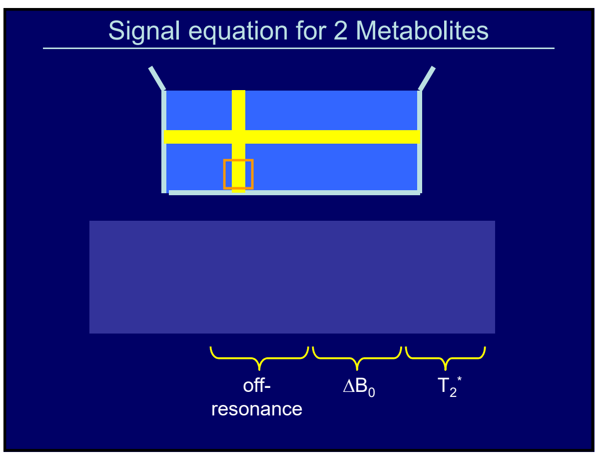

Separation of 2 Metabolites
Tailored TE times
Flexible TE times
2 pt. Dixon
Nmeas = 2
modified
2 pt. Dixon
Nmeas = 2
3 pt. Dixon
Nmeas = 3
Matrix inversion
Nmeas => 2
Iterative solutions
Nmeas >= 3

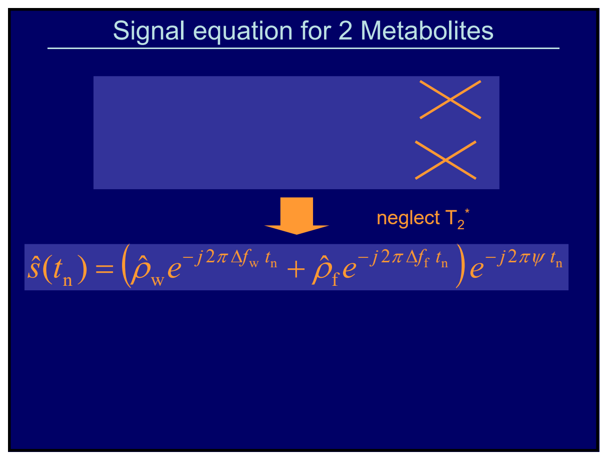

Fat & Water: Magnetization Vectors
@1.5 T: Δff = -220 Hz
fat
water
ŝf(TE) = ρf e−j2π(fw+Δff)TE
ŝw(TE) = ρw e−j2π fw TE
Time 0 ms
2.2 ms
4.4 ms
in phase
out of phase
in phase

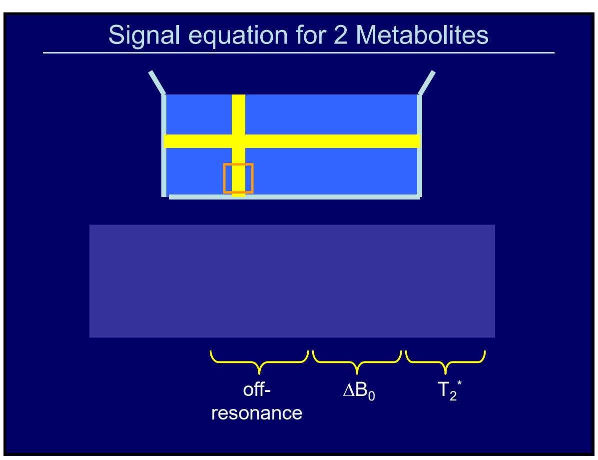

MR-Signal Phase
Chemical Shift
• Fat-water difference = 220 Hz @ 1.5T / 440 Hz @ 3T
• Displacement fat vs. water → Misregistration
1 pixel = 2*BW/matrix Hz
Fat
Water
BW = 6.94kHz
→ 4 pixel shift
BW = 31.25kHz
→ 0.9 pixel shift
BW = 9.23kHz
→ 3 pixel shift
Degree of misregistration
- Bandwidth
- Field strength

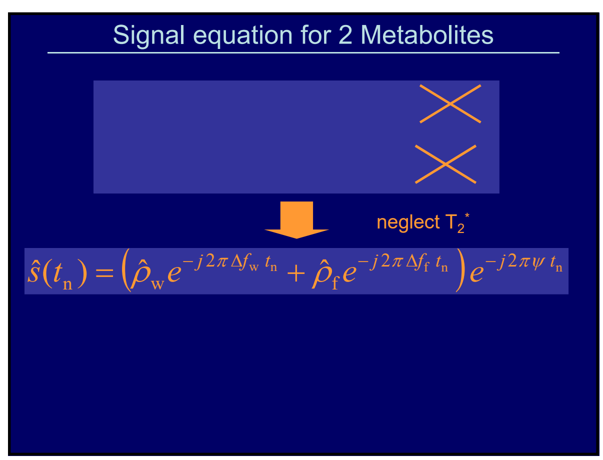

Fat & Water: Magnetization Vectors
• Fat-water in-phase / out-of-phase
• Signals add/cancel
➔ Fat-Water Separation
Water
Fat
Sum


MR-Signal Phase
Chemical Shift
• Fat-water in-phase / out-of-phase
• Signals add/cancel
➔ Fat-Water Separation
Water
Fat
Sum
At 1.5T
TE=2.2 ms
out-of-phase
TE=4.4ms
in-phase
TE=6.6 ms
out-of-phase


Signal equation for 2 Metabolites
off-
resonance
ΔB_0
T_2^*


Signal equation for 2 Metabolites
neglect T_2^*
$\hat{s}(t_n) = \left(\hat{\rho}_w e^{-j2\pi\Delta f_w t_n} + \hat{\rho}_f e^{-j2\pi\Delta f_f t_n}\right) e^{-j2\pi\psi t_n}$


Signal equation for 2 Metabolites
off-
resonance
ΔB_0
T_2^*


Signal equation for 2 Metabolites
neglect T_2^*
$\hat{s}(t_n) = \left(\hat{\rho}_w e^{-j2\pi\Delta f_w t_n} + \hat{\rho}_f e^{-j2\pi\Delta f_f t_n}\right) e^{-j2\pi\psi t_n}$

2-point Dixon

WT Dixon, Radiology, 1984

0

protons: on resonance
neglect ψ (ΔB_0)

$$\hat{s}(t_n) = |\hat{\rho}_w| + |\hat{\rho}_f| e^{-j2\pi\Delta f_f t_n}$$

choose echo times: $2\pi\Delta f_f t_{in} = 0 \bmod 2\pi$ $\quad 2\pi\Delta f_f t_{out} = \pi \bmod 2\pi$

$$\hat{s}(t_{in}) = \hat{\rho}_w + \hat{\rho}_f$$
$$\hat{s}(t_{out}) = \hat{\rho}_w - \hat{\rho}_f$$

2-point Dixon

WT Dixon, Radiology, 1984

Simple 2-Point Dixon Method

Acquire in-phase & out-of-phase images

Subtract / add complex images to separate water & fat

At 1.5T { *TE* = 2.2ms out-of-phase | *TE* = 4.4ms in-phase | *TE* = 6.6ms out-of-phase .....

3-point Dixon

G Glover et al., JMRI, 1991

0

choose echo times $2\pi\Delta f_f t_1 = 0$ $\quad 2\pi\Delta f_f t_2 = \pi$ $\quad 2\pi\Delta f_f t_3 = 2\pi$

estimate fieldmap: $\phi = 2\pi\psi\,(t_2 - t_1) \approx \frac{1}{2}\angle \hat{s}(t_1)^* \hat{s}(t_3)$

$$\hat{s}(t_1) = \rho_w + \rho_f$$
$$\hat{s}(t_2) = (\rho_w - \rho_f)e^{-j\phi}$$
$$\hat{s}(t_3) = (\rho_w + \rho_f)e^{-j2\phi}$$

3-point Dixon: Phantom

G Glover et al., JMRI, 1991

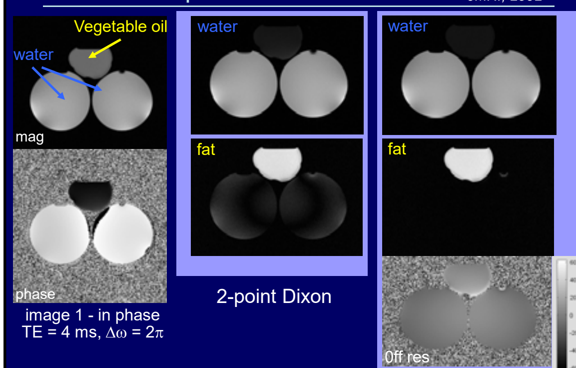


image 1 - in phase
TE = 4 ms, $\Delta\omega = 2\pi$

2-point Dixon

3-point Dixon

Solving for ‚arbitrary‘ TE‘s

$$\hat{s}(t_n) = \left(\underline{\hat{\rho}_w} e^{-j2\pi\Delta f_w t_n} + \underline{\hat{\rho}_f} e^{-j2\pi\Delta f_f t_n}\right) e^{-j2\pi\underline{\psi} t_n}$$

5 unknowns: 2×complex
1×scalar

Simple solution: Fieldmap=0 -> Matrix Inversion

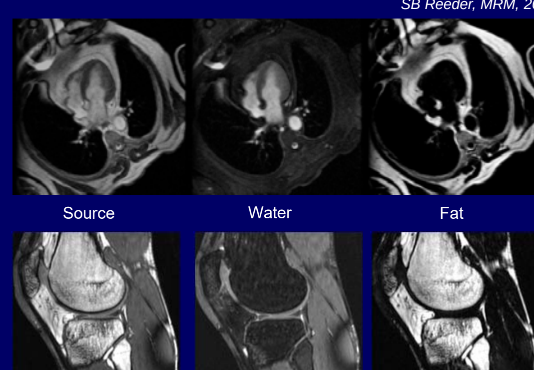
Matrix Notation: $\hat{\mathbf{S}} = \mathbf{A}\,\hat{\boldsymbol{\rho}}$

Better solution: iterative approach

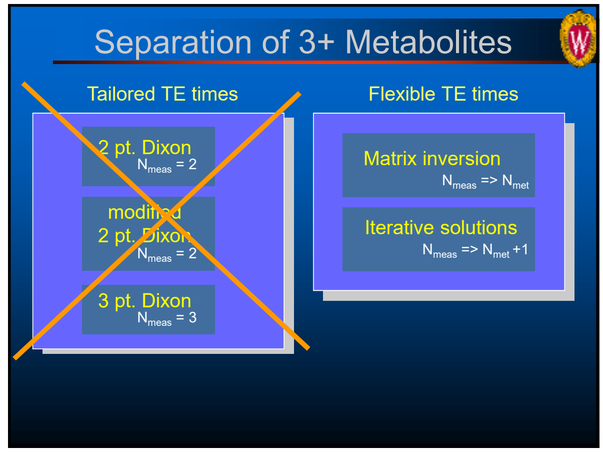
- estimate field map ΔB_0
- no phase unwrapping required
- ‘free choice‘ of TR und ΔTE

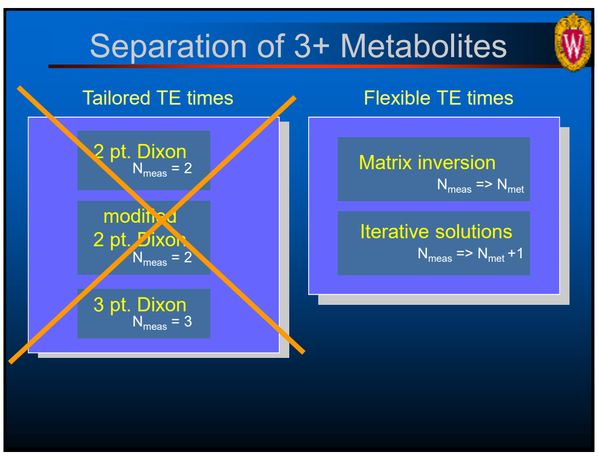
Fat Water Separation with IDEAL

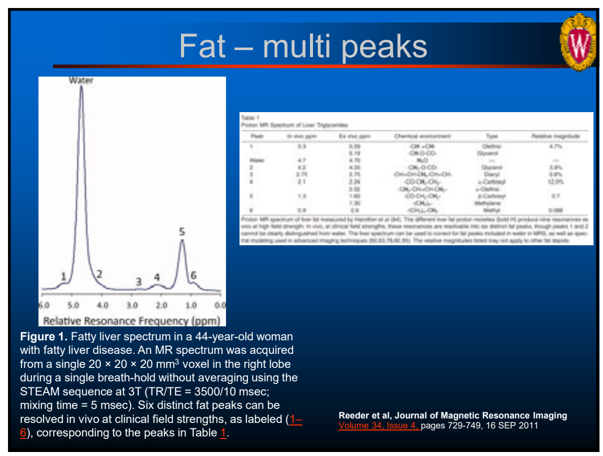
SB Reeder, MRM, 2004

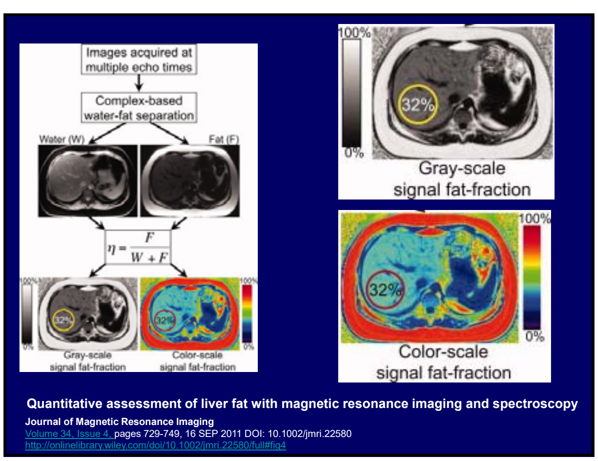


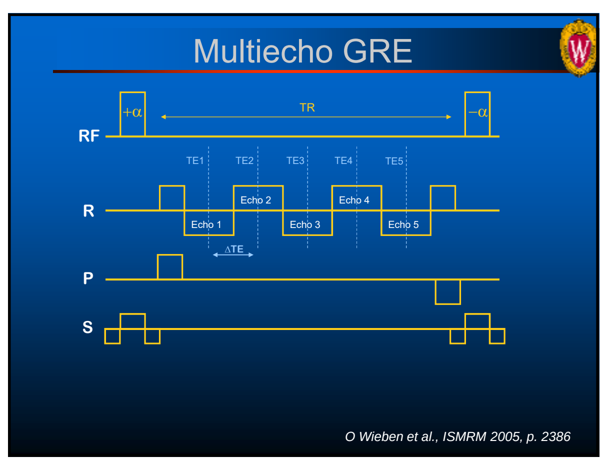

GE Scanner Console ca. 1997


Separation of 3+ Metabolites
Tailored TE times
2 pt. Dixon
$N_{meas} = 2$
modified
2 pt. Dixon
$N_{meas} = 2$
3 pt. Dixon
$N_{meas} = 3$
Flexible TE times
Matrix inversion
$N_{meas} \Rightarrow N_{met}$
Iterative solutions
$N_{meas} \Rightarrow N_{met} + 1$

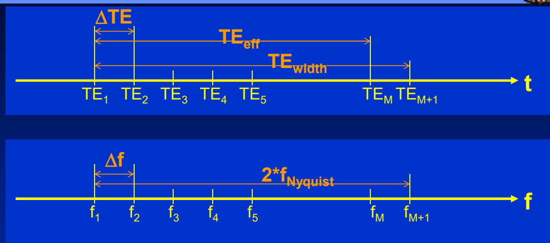

Separation of 3+ Metabolites
Tailored TE times
2 pt. Dixon
$N_{meas} = 2$
modified
2 pt. Dixon
$N_{meas} = 2$
3 pt. Dixon
$N_{meas} = 3$
Flexible TE times
Matrix inversion
$N_{meas} \Rightarrow N_{met}$
Iterative solutions
$N_{meas} \Rightarrow N_{met} + 1$


Fat – multi peaks
Water
1
2
3
4
5
6
6.0 5.0 4.0 3.0 2.0 1.0 0.0
Relative Resonance Frequency (ppm)
Figure 1. Fatty liver spectrum in a 44-year-old woman with fatty liver disease. An MR spectrum was acquired from a single 20 × 20 × 20 mm³ voxel in the right lobe during a single breath-hold without averaging using the STEAM sequence at 3T (TR/TE = 3500/10 msec; mixing time = 5 msec). Six distinct fat peaks can be resolved in vivo at clinical field strengths, as labeled (1–6), corresponding to the peaks in Table 1.
Reeder et al, Journal of Magnetic Resonance Imaging
Volume 34, Issue 4, pages 729-749, 16 SEP 2011


Images acquired at multiple echo times
Complex-based water-fat separation
Water (W)
Fat (F)
$\eta = \frac{F}{W+F}$
100%
0%
32%
Gray-scale signal fat-fraction
Color-scale signal fat-fraction
Quantitative assessment of liver fat with magnetic resonance imaging and spectroscopy
Journal of Magnetic Resonance Imaging
Volume 34, Issue 4, pages 729-749, 16 SEP 2011 DOI: 10.1002/jmri.22580
http://onlinelibrary.wiley.com/doi/10.1002/jmri.22580/full#fig4


Multiecho GRE
RF
+α
TR
−α
TE1
TE2
TE3
TE4
TE5
R
Echo 1
Echo 2
Echo 3
Echo 4
Echo 5
ΔTE
P
S
O Wieben et al., ISMRM 2005, p. 2386

EPSI – Timing Properties



$f_{Nyquist} = 1 / (2*\Delta TE)$

$\Delta f = 2*f_{Nyquist} / M = 1 / (\Delta TE*M) = 1 / TE_{width}$

$TE_{eff} = \Delta TE*(M-1)$

EPSI – Proof of principle

Proof of principle

FLASH images (no need for ultrashort TR)

Single echo measurements (no 'EPI problems')

3 components

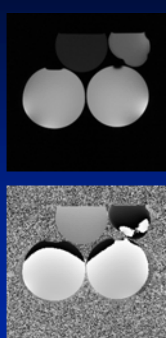
- Water – Acetone - Fat

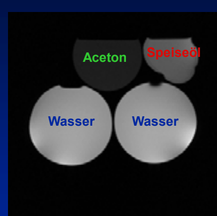
Imaging Sequence

- TR = 40 ms
- 20 Echos: 5 ms <= Te <= 4 ms
- ΔT = 1 ms -> $f_{Nyquist}$ = 500 Hz
- T_{width} = 20 ms -> Δf = 50 Hz

Data from 28 Jan 04 - SPGR

SPGR – Mag and Phase



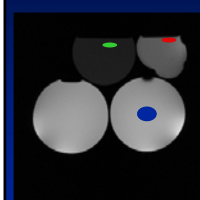


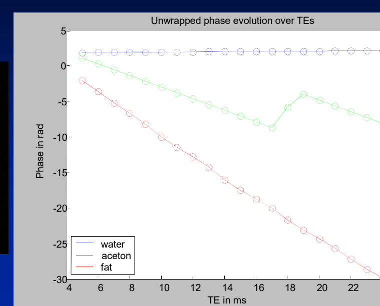
T_{width} = 20ms, ΔTE = 1 ms

-> Δf = 50 Hz, $f_{Nyquist}$ = 500

Data from 28 Jan 04 - SPGR

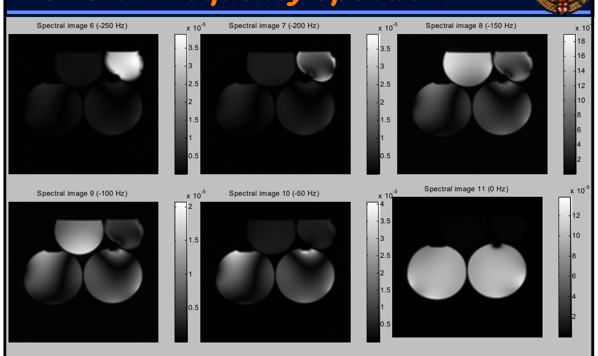
SPGR – Phase vs. TE





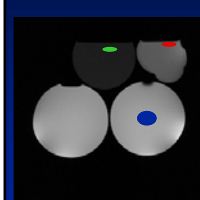
Data vom 28 Jan 04 - SPGR

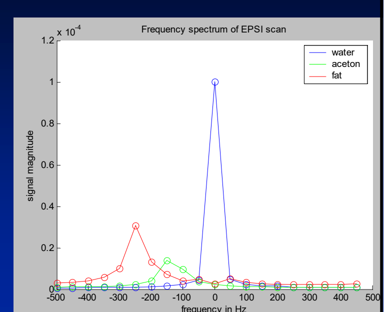
SPGR – Frequency Spectrum



Data vom 28 Jan 04 - SPGR

SPGR – Frequency Spectrum





Data vom 28 Jan 04 - SPGR