Managing fat in MRI: a technical perspective

Jingfei Ma, PhD, DABR
Department of Imaging Physics

THE UNIVERSITY OF TEXAS
MD Anderson Cancer Center
Making Cancer History®

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Outline

- *Background*
  - *why we are interested in managing fat in MRI*
- *Different fat suppression techniques*
  - *what they are and how they work*
  - *pros*
  - *limitations*
- *Summary and possible future development*

Fat in the body

- *Major body functions despite "bad press"*
  - *efficient energy storage*
  - *structural functions such as body insulation and organ protection*
  - *metabolic functions such as in transport and function of fat soluble vitamins (vitamin A, D, E and K)*
  - *and many other important functions*
- *Obesity is a culprit for some major diseases*
  - *Type 2 diabetes and coronary heart disease*
  - *Cancer (esophagus, breast, colon, prostate,…)*
  - *Nonalcoholic fatty liver disease (NAFLD) and nonalcoholic steatohepatitis (NASH)*

We need to watch our weight and manage the body fat!

Fat in MRI

- Fat is present in a lot of places in our body
- In MRI:
  - fat is one of the two primary sources of signal, besides water
  - Fat is bright in many sequences, particularly T1 and T2-weighted sequences
  - Fat signal is usually not of the primary interest, although it can aid diagnosis in certain situations
  - Fat obscures underlying or nearby pathology
  - Fat causes strong artefacts due to motion, chemical shift, etc.

Just like family doctors, radiologists usually do not like to see fat!

Fat suppression

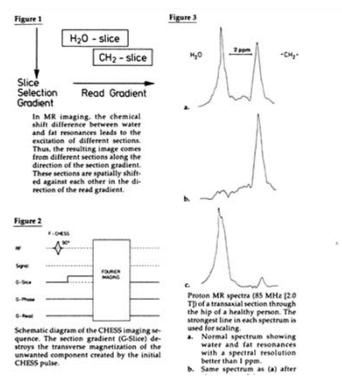
- Fat suppression is almost as old as MRI itself
- Fat suppression is desired and used in a large majority of clinical MRI studies
- Many different types of fat suppression techniques have been developed and continue to be developed
- Unfortunately, fat suppression is also one of the perennial image quality issues in MRI, besides motion.

Fat suppression techniques

Two major types:

- Magnetization preparatory techniques (control what goes in or "dietary type")
  - selective saturation such as CHESS
  - selective excitation
  - inversion recovery such as STIR
  - other variants
- Post-processing techniques (remove what's already in or "exercise type")
  - Dixon or Dixon type techniques
  - MT-based
  - balanced SSFP type

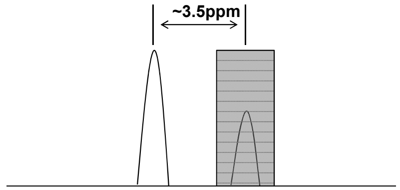
Chemical shift selective saturation



Frahm et al, Radiology 1985

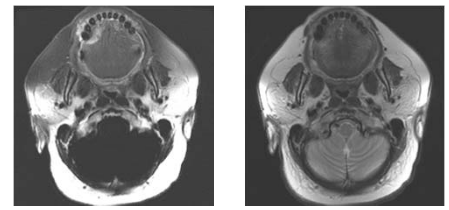
- a.k.a CHESS, ChemSat, FatSat...
- fat has a chemical shift that is separated from that of water by ca. 3.5 ppm
- selective excitation followed by gradient spoiling can be used to eliminate signal from one of the two species (fig. 3)
- any imaging sequence can in principle be preceded with the CHESS module (fig. 2)
- most widely used fat-suppression technique
  - flexibility
  - water signal is unperturbed

Chemical shift selective saturation



- ***Chemical shift separation needs to be larger than the bandwidth of the RF pulse → difficult for low-field systems***
- ***The*** 90^0 ***needs to be*** 90^0 ***pulse → B1 inhomogeneity.***
- ***The*** 90^0 ***pulse needs to cover fat and fat-only over the imaging FOV***
  - ***B0 inhomogeneity***
  - ***hard to meet in different imaging scenarios***

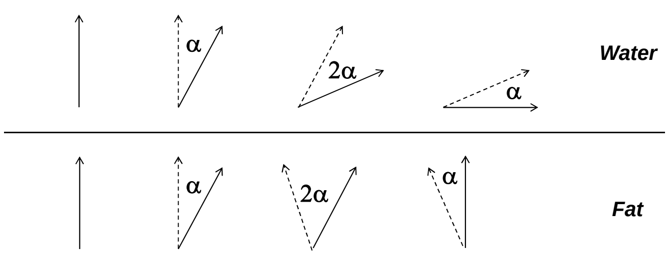
Chemical shift selective saturation



Fatsat on **No fatsat**

Selective excitation

Binomial RF pulses:



Selective excitation

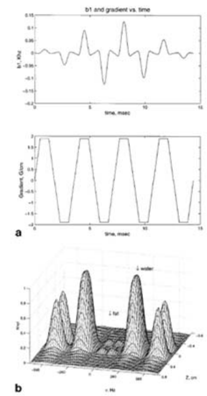


FIG. 5. a: RF and gradient waveforms for a type II spsp water-selective excitation pulse. Pulse parameters and tip angles are the same as in Fig. 3. The synthesizer frequency is set on the fat resonance and a phase of π radians is applied between subpulses by inverting the amplitudes of even subpulses. b: $|M_{xy}(z, \nu)|$ for this pulse. The fat is not excited and the water at ν = 260 Hz is selectively excited by M_y.

Spectral-spatial RF pulses (1st described by Meyers, Pauly, et al in 1990)

- ***Typically a set of RF sub-pulses modulated under a broad RF envelop and played under an oscillating gradient waveform***
- ***Each subpulse selects a spatial slice***
- ***Phase accumulation or adjustment of RF phases between subpulses is used for spectral selectivity***
- ***RF envelop controls the spectral content***

Zur, Magnetic Resonance in Medicine 2000

Selective excitation

- *Typically much longer than conventional RF pulses*
- *Much more demanding on system hardware and gradient and RF fidelity*
- *The maximum width of the subpulse is determined by water-fat frequency separation*
- *Most successfully used in echo planar imaging-based pulse sequences*

Short-tau inversion recovery (STIR)

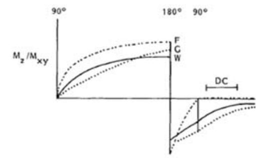
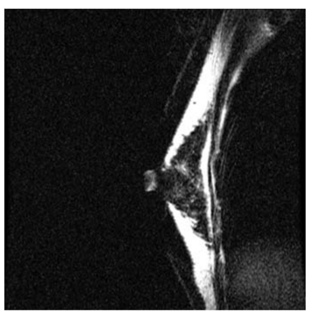


FIG. 6. Changes in M_z/M_{xy} with time for fat (F), white matter (W), and grey matter (G) using a fat suppressed short inversion time inversion recovery sequence. The signal from G is greater than that for W and F gives no signal using field echo data collection (DC).

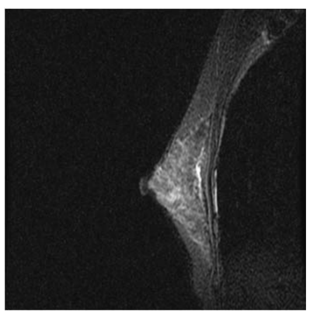
Bydder and Young, J. Comput Assist Tomogr 1985

- ***non-selective 180 inversion pulse followed by a wait time until fat magnetization crosses the null point (thus T1-selective)***
- ***the IR pulse is usually adiabatic, removing B1 sensitivity***
- ***independent of B0-inhomogeneity***
- ***Probably the most robust fat suppression technique***
- ***Drawbacks include reduced SNR, increased scan time, and altered contrast/inadvertent suppression of water-signals with short T1.***

Short-tau inversion recovery (STIR)

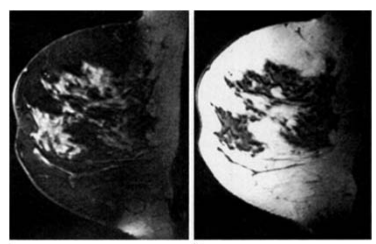


FatSat



STIR

Other variants: spectral inversion



a. b.

Figure 9. Images of a healthy volunteer, obtained with fat **(a)** and water **(b)** suppression with the same 100-msec TP but with the frequency of the inversion pulse set to the fat and water resonances, respectively. Note the good suppression of fat and water in the respective images. Imaging parameters were as follows: 16-cm FOV, 1.5-mm section thickness, 64 × 256 × 192 matrix, 30° flip angle, and TE/TR = 3.2/11.6. The total imaging time was 2.7 minutes. A prototype phased-array coil was used for this acquisition. Either fat or water suppression was attained in 2.7 minutes for this volume image. In these images, B_0 inhomogeneity resulted in nonuniform suppression, especially in the chest wall.

Foo et al, Radiology 1994

Challenges of the magnetization preparatory approaches

- ChemSat and selective excitation are based on the chemical shift difference of fat, and are all intrinsically sensitive to B0 inhomogeneity
- STIR is only T1-specific, reduces SNR, and may cause contrast change
- Preparatory pulses take up time and may be difficult to implement with fast sequences
- ChemSat → spin echo, fast spin echo
- STIR → fast spin echo
- Spectral spatial pulse → echo planar imaging
- Application of the preparatory pulses to only a selected region of k-space for gradient echo and fast gradient echo sequences

The Dixon technique

W. Thomas Dixon, Ph.D.

Simple Proton Spectroscopic Imaging[1]

Simple modification of a spin echo imaging pulse sequence generates useful spectroscopic information at 0.35 T. New images are produced that show water only, fat only, and the difference between water and fat intensity. Imaging speed, spatial resolution, and signal-to-noise ratio are comparable with ordinary imaging. The method provides new parameters for tissue characterization and improved contrast between some organs.

Index terms: Magnetic resonance, spectroscopy • Magnetic resonance, technology

Radiology 1984; 153: 189–194

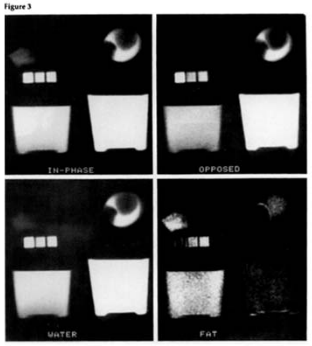
MAGNETIC resonanc... one of the most widely used spectroscopic techn... a rapidly growing imaging technique a... chniques that combine spectroscopy ... e been demonstrated on the nuclei of hy... m (3), carbon (5), and P-31 (2, 4, 6).

There is a g... these techniques. For example, in an ... ectrum, which has about 6 lines, can ... ons of ATP, phosphocreatine, and inorganic ... e simultaneously. Complicated results like this are usually ... ed as spectra from specified regions in an organism rather than images at specified chemical shifts.

Since most of the total nuclear magnetization in a body comes from protons in water, and most of what is left, from protons in fat, an unsophisticated approach may skim off a good fraction of the possible benefits of spectroscopy at low cost. The technique demonstrated here simply separates an image at the water chemical shift from one at the CH_2 chemical shift.

Almost 1000 citations !

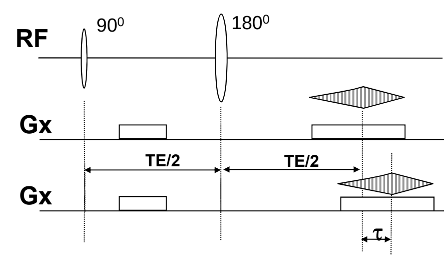
Figure 3

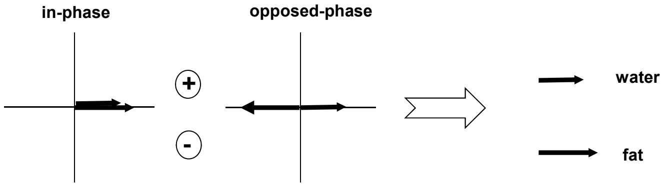


Spectroscopic images. The material above the three squares is Bluebonnet Margarine (Nabisco). Below is Dawn detergent (Proctor and Gamble). The hen's egg is above a container of 0.1% $CuSO_4$ in water. The doped water container has no fat in it so it is bright on the water image but nearly invisible on the fat image. The detergent appears on all images; its relative brightness on the water and fat images depends on the relative concentration of aliphatic and water protons and on the T1 and T2 values. The margarine is faint because it is fairly solid and so has a short fat T2 value, and it contains little water. In three of the images of the egg, both the yolk and white are visible, but in the fat image only the yolk is visible, showing that egg white does not contain fat but the yolk does.

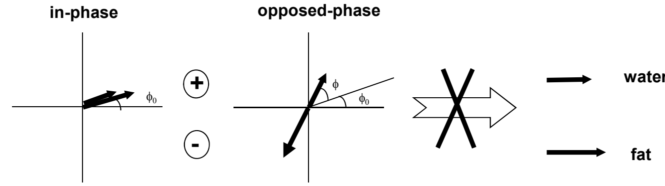
Dixon, Radiology 1984

The Dixon technique



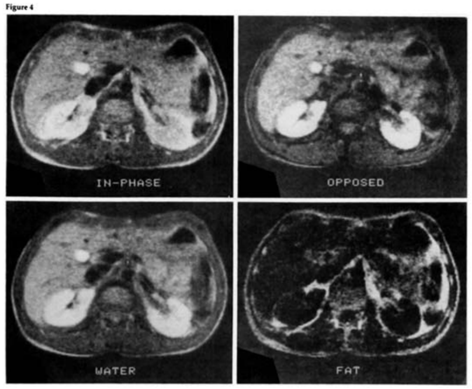


• it is a 2-term Fourier Transform and the simplest case of the general spectroscopic imaging
• water-only image can serve the purpose of fat-suppression
• fat-only image is "free" and may be useful for certain applications



Like FatSat, the Dixon technique is also sensitive to magnetic field inhomogeneity

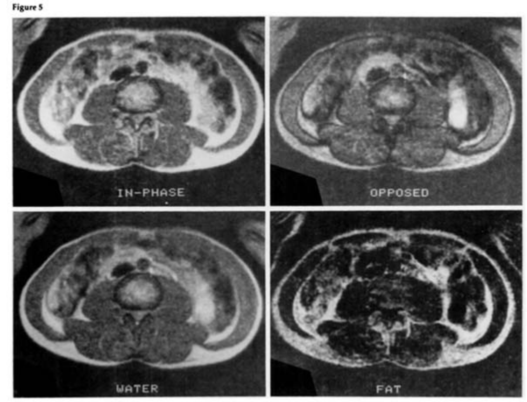
Figure 4



Transverse images of a normal volunteer after a 20-hour fast. In the opposed image the boundaries between most organs are clearly delineated by dark lines of fat. The parenchyma of the kidneys seems brighter in the opposed image than in the conventional image. The left kidney is much easier to see in the opposed than in the in-phase image. Note that the gallbladder has visible intensity in the fat image, even though bile should be 90% water. The spinal canal is more easily seen in the opposed than in the conventional image.

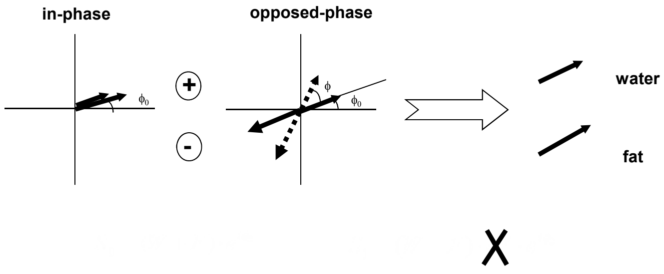
Dixon, Radiology 1984

Figure 5

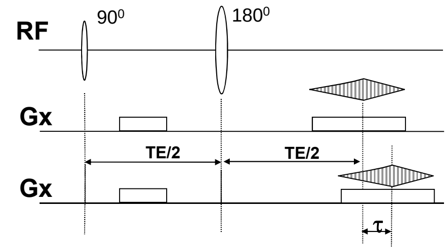


Images of a plane 40 mm caudal to Figure 4. Both sets of images were made at the same time using multiple section capability. Note that in both figures the subcutaneous fat in the back is not dark in the opposed image and appears in the water image rather than the fat image. In the front this is not a problem.

Dixon, Radiology 1984



Phase correction is feasible but a major challenge!



Another challenge is the increased acquisition time:

- ***a minimum of 2 or more acquisitions, even though SNR is largely preserved***
- ***acquisition shift can be a major factor, especially for fast sequences.***

The three-point Dixon technique

Glover GH.
J. Magn. Reson. Imaging
1991

- ***now requires three acquisitions, tripling the scan time***
- ***phase calculation is only determined with $-\pi$ to $+\pi$***
- ***phase wrapping will swap the water and fat***

Two-point Dixon revisited

Coombs et. al. MRM 1997

Skinner et. al. MRM 1997

- ***original two-point acquisitions***
- ***the second in-phase image is redundant except for pixels with equal amounts of water and fat and assuming relaxation is negligible***

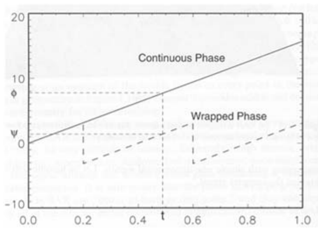
However,

- ***phase calculation is only determined with $-\pi$ to $+\pi$***
- ***phase wrapping will swap the water and fat***
- ***it was generally believed that 2-point Dixon is less reliable than 3-point Dixon***

Phase unwrapping

- *a well-studied problem, particularly in Synthetic Aperture Radar*
- *also a long-standing problem still with no general solution*
- *mathematically can be stated as:*

Where:

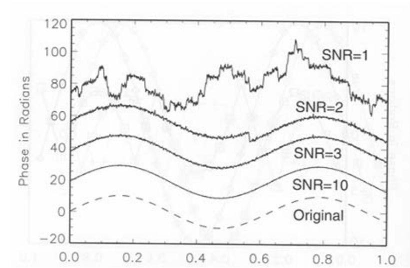


From: Ghiglia and Pritt, 2D Phase Unwrapping: theory, algorithms and software

Ito's method for 1-D phase unwrapping:
1. *Compute the phase difference*
2. *Compute the wrapped phase difference*
3. *Initialize a first phase value*
4. *Unwrap by summing the wrapped phase difference*

Phase unwrapping

Unwrappability Criterion:

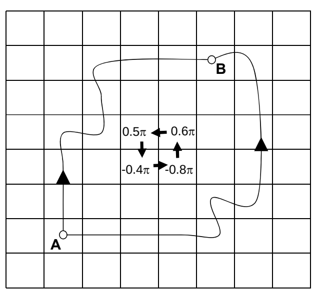


From: Ghiglia and Pritt, 2D Phase Unwrapping: theory, algorithms and software

Other common sources of non-unwrappability are undersampling, artefacts.

2D phase unwrapping

Violation of the unwrappability criterion leads to phase poles or residues



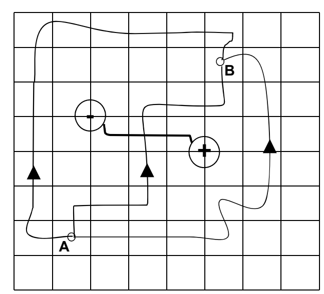
W(-0.8+0.4) + W(0.6+0.8)
 + W(0.5-0.6) + W(-0.4-0.5)

= (-0.4-0.6-0.1-0.9)

= 2

Existence of poles and residues leads to a dilemma that phase unwrapping may be path-dependent.

The "cutline" approach for phase unwrapping



what "cutlines" are correct?

Chavez et. al. IEEE TMI 2002

- *Identify all the poles*
- *Construct "cutlines" that pair up or annihilate the "poles"*
- *Phase unwrapping is path-independent as long as it does not cross the "cutlines".*

The minimum norm approach

- *The goal is to find unwrapped phase whose local derivatives match the measured derivatives "as closely as possible"*
- *L^p-norm formulation:*

When p = 2, this leads to the familiar Poisson equation:

Song et. al. IEEE TIP 1995

Requires segmentation to exclude noise regions and specification of proper boundary conditions

The quality-guided path following approach

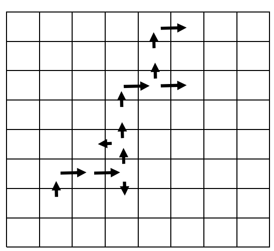
- *works under the assumption that a good quality map will guide the phase unwrapping path without encircling unbalanced poles*
- *there are many potential candidates for quality maps:*
  - *first or second derivatives of the phase*
  - *some measure of SNR*
  - *any combinations of SNR and phase variations*
- *it has produced some remarkably good results*
- *implementation-wise, it requires a huge dynamic array to store the quality map*

Ching et. al. IEEE TIP 1992

An et. al. IEEE TMI 2000

Minimum spanning tree

A similar traveling salesman problem: given a number of cities and costs of traveling from any city to any city, what is the least cost round trip route that visits each city exactly once and then returns to the starting city?

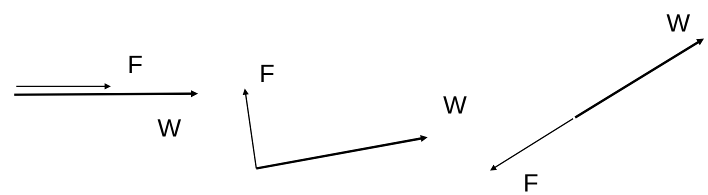


"NP-hard": considered one of the deepest, most perplexing open research problems in theoretical computer science!

Cormen et al, Introduction to Algorithms, 2nd Edition

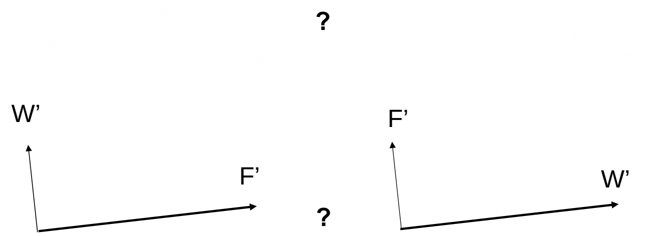
Direct Phase Encoding (DPE)

data sampling at (0, α, 2α), *where* $\alpha \neq 180^o$



Xiang, An. J. Magn. Reson. Imaging, 1997

Direct Phase Encoding (DPE)



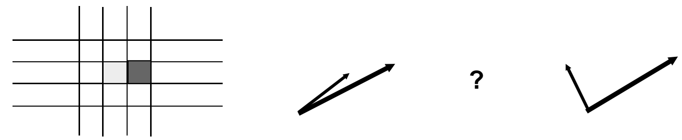
No ambiguity because fat has lower Larmor frequency than water (so fat must be leading in phase)!

Xiang, An. J. Magn. Reson. Imaging 1997

Direct Phase Encoding (DPE)

Relative phase may be poorly defined:
- ***single component pixels***
- ***low SNR or artifact-contaminated pixels***

Region-growing based on orientation filters:



Xiang, An. J. Magn. Reson. Imaging 1997

IDEAL: iterative decomposition of water and fat with echo asymmetry

Reeder et. al. MRM 2004
Reeder et. al. MRM 2005
Yu et. al. MRM 2005

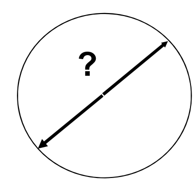
- ***solve for ρ_i iteratively, starting with $\psi = 0$ and until $\Delta\psi < 1Hz$.***
- ***a minimum of three acquisitions with flexible time shifts***
- ***a set of acquisitions with ($-\pi/6$, $\pi/2$, $7\pi/6$) produces “IDEAL” SNR that is independent of relative water and fat ratio***
- ***pixel based processing unable to resolve pixels of single peak and the cost function in general may have local minima***
- ***region-growing IDEAL helps reduce the processing failures***

Back to a two-point Dixon technique

$$\phi$$

$$e^{i\phi}$$

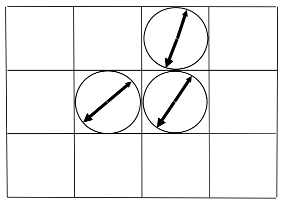
$$\phi = \widehat{\phi} + k \cdot 2\pi$$



multiple vs. binary choices

Back to two-point Dixon technique

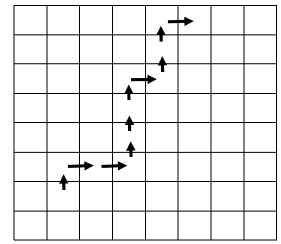
$e^{i\phi}$



- *indeterminate on a pixel basis*
- *however, we expect directional smoothness because the underlying field is slowly varying*
- *the spatial distribution can thus be determined in a region growing or other algorithms*

Ma. MRM 2004

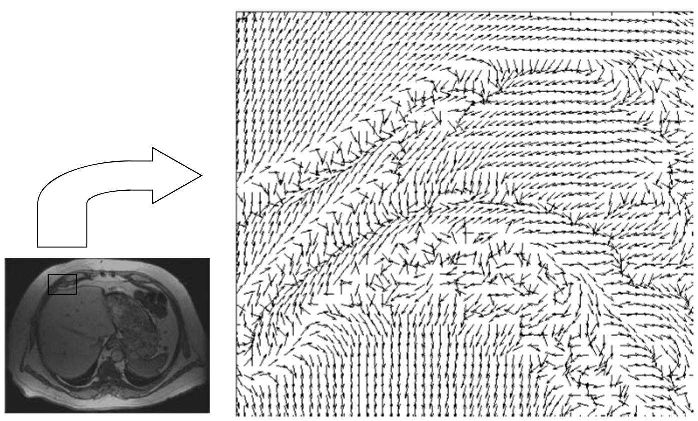
Region growing



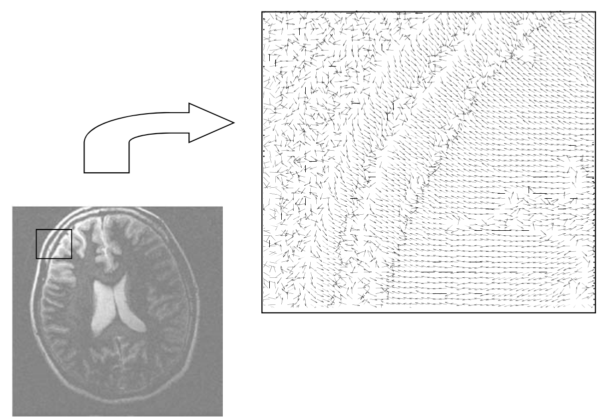
- *selection of an initial seed*
- *selection of growth paths*
- *selection of growth criteria*

Often empirical and results are unreliable due to noise, artifacts, image shading

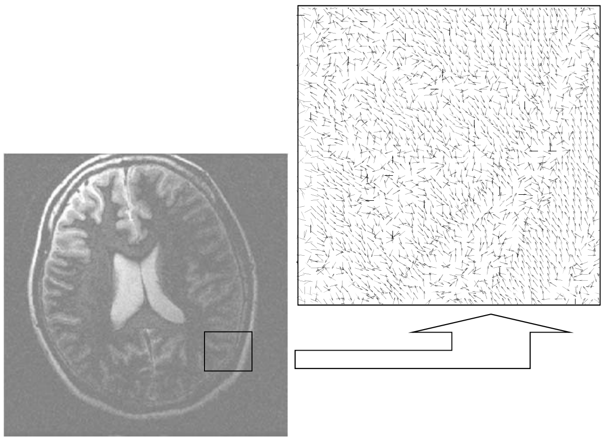
Noise and phase stability



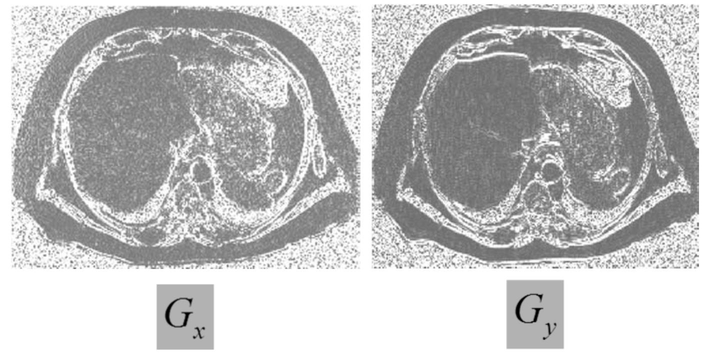
Noise and phase stability



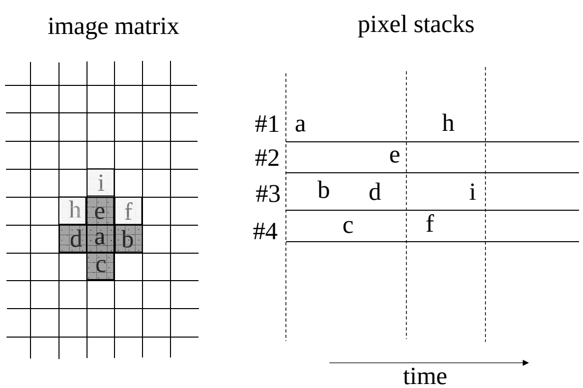
Noise and phase stability



Phase gradients

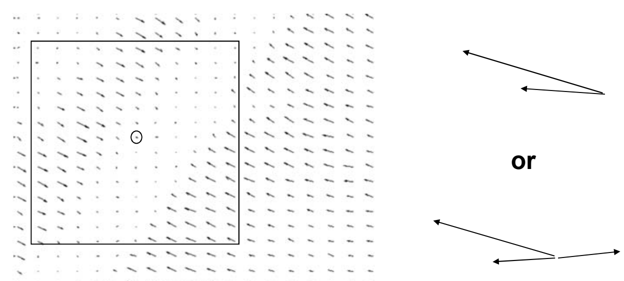


Region growing

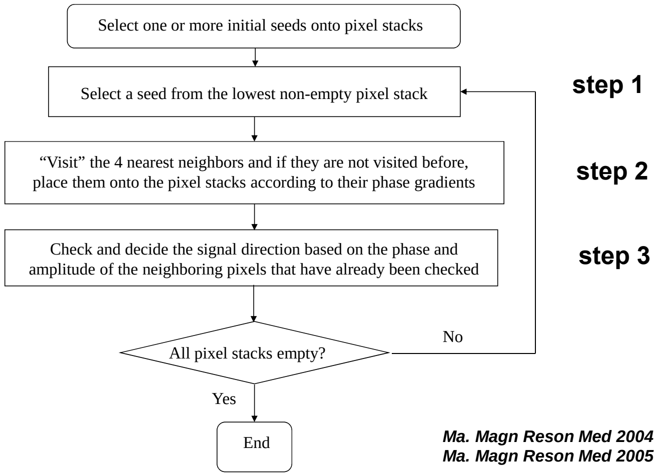


Ma. Magn Reson Med 2004

phase vector vs. phasor



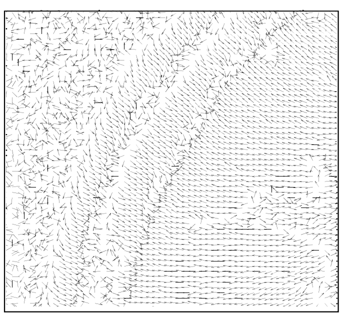
Information on both amplitude and phase is incorporated in phase vector



Ma. Magn Reson Med 2004
Ma. Magn Reson Med 2005

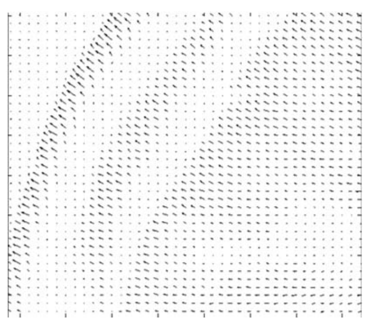
Region growing

- ***"optimal" growth paths facilitated by phase gradients/pre-established pixel stacks***
- ***the grown region can be viewed as islands surrounded by a sea of to-be-grown regions. As the water is drained, the islands grow in the order of the heights and eventually join together***
- ***a "greedy solution" to the more general minimum spanning tree or traveling salesman problems***



Before

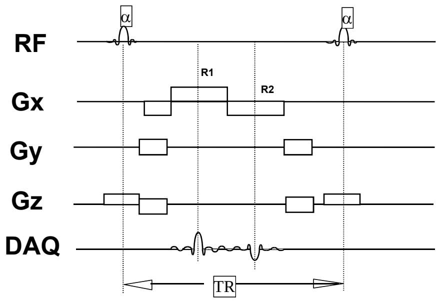
After



Advantages of 2-point Dixon

- ***At least 1/3 less acquisition time relative to a 3-point Dixon***
  - ***less susceptibility to motion***
  - ***less signal decay***
- ***SNR can be optimal independent of water and fat ratio***
- ***Other effects such as from eddy current can be taken care of***

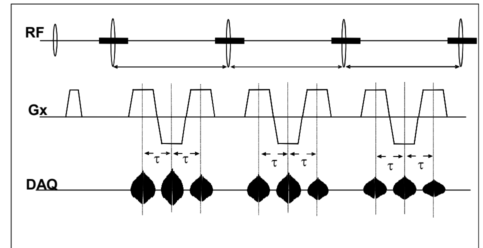
Dual echo acquisition



Ma, Vu, Son, Choi, Hazle.
J. Magn. Reson. Imaging 2006

- *dual echo acquisition substantially reduces the total scan time*
- *minimizes motion and other artefacts*
- *higher bandwidth improves image sharpness and chemical shift misregistration is always sub-voxel*
- *true steady state acquisition by removing intermittent prep pulses*

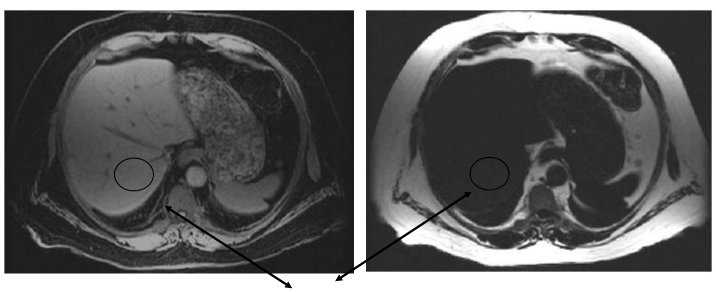
Fast spin echo triple echo Dixon (FTED) sequence



Ma, Son, Zhou, Le-Petross, Choi. Magn Reson Med 2007

- *maximum efficiency for fast spin echo acquisition*
- *minimal increase to echo spacing*
- *inter-echo phase errors can be dealt with independent of the sources and without any reference scan*
- *can be used for both T2 and T1-weighted imaging*

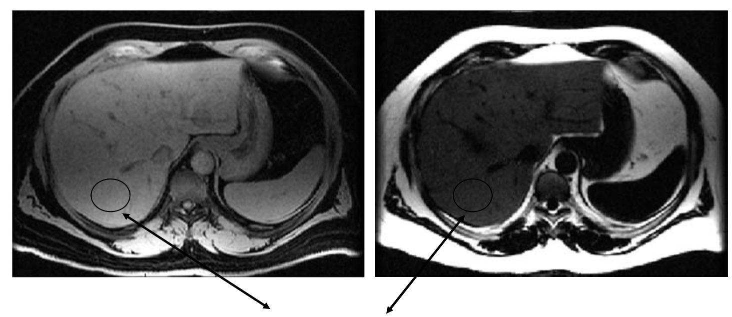
Breath hold 2D gradient echo



F/W = 0.03

20 slices in 20 seconds without parallel imaging

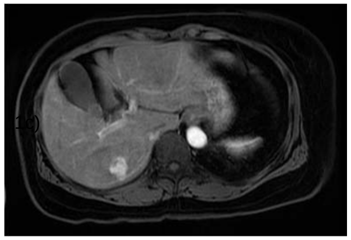
patient with hepatic steatosis

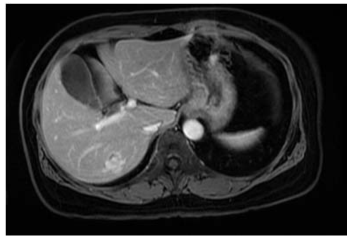


F/W = 0.2

1a) 1b)

Contrast enhanced triphasic study with 3D fast spoiled gradient echo dual echo Dixon

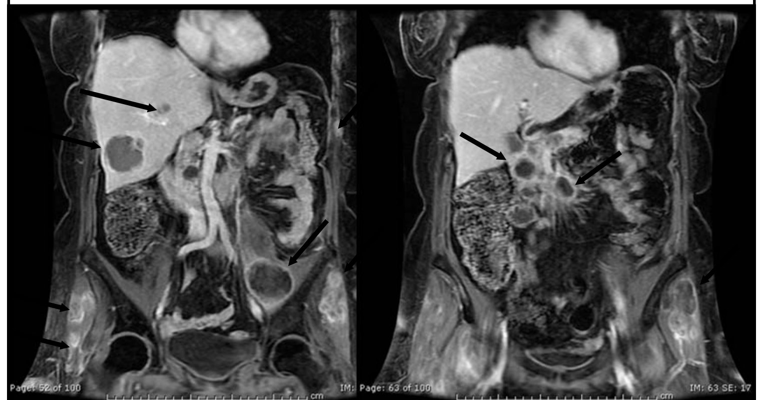




Arterial **Delayed**

Courtesy Russell Low, MD, Sharp and Children's MRI Center

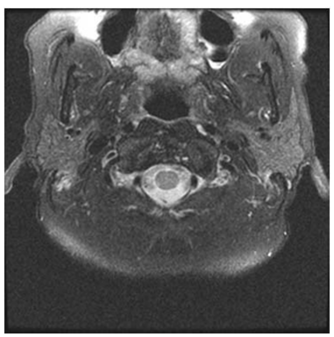
Large 3D volume imaging (breast cancer)

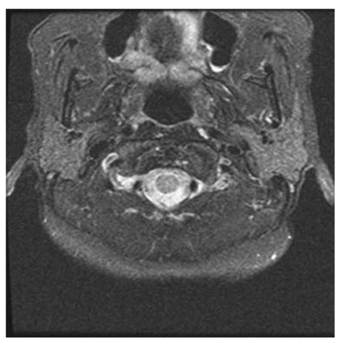


An entire abdomen-pelvis acquisition in less than 20 seconds

Courtesy Russell Low, MD, Sharp and Children's MRI Center

T2-weighted head and neck imaging

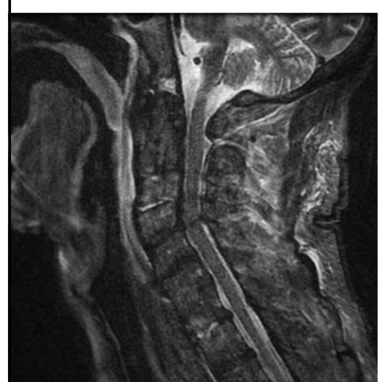


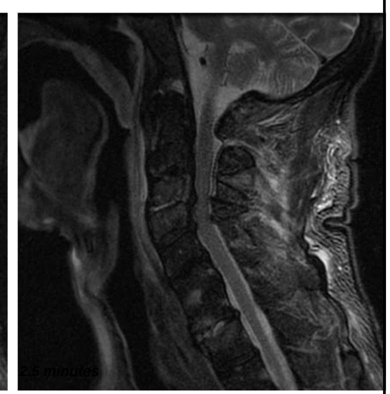


FatSat ***Dixon***

Ma, Jackson, Kumar, Ginsberg. AJNR 2009

T2-weighted C-Spine Trauma





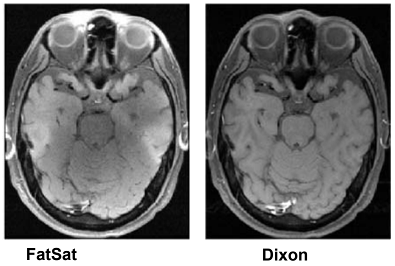
IRFSE Dixon

Courtesy Russell Low, MD, Sharp and Children's MRI Center

Spin echo Dixon sequence

Existing T1-weighted sequence for head and neck imaging:

- severely degraded image quality (T1-contrast and fat suppression) at 3T



Dixon sequence:

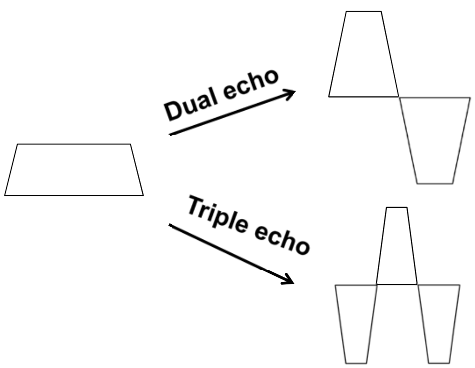
- substantially better contrast and overall image quality
- approximately 40% shorter scan time for identical scan parameters

Two-point Dixon with flexible echo times

- *in-phase and opposed-phase images can be relaxed to somewhat arbitrary phases*
- *complex fat spectrum can be included assuming fat spectrum is identical for different subjects and different anatomy*

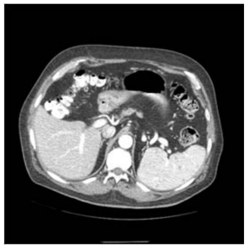
Xiang MRM, 2006
Eggers et al, MRM, 2011
Berglund et al MRM, 2011
Ma, ISMRM 2011

- *increased flexibility and efficiency*
- *more accurate water and fat decomposition*

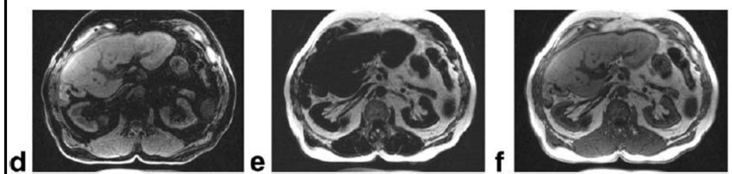


Phase correction remains the underlying challenge

There is hope because a radiologist can tell fat before Dixon invented the Dixon technique, even on a CT image:



Single point Dixon



Ma, JMRI, 2008

Fat suppression using MT effects

Fat-Free MRI Based on Magnetization Exchange 717

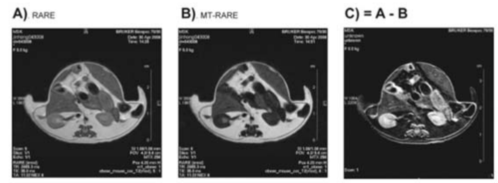


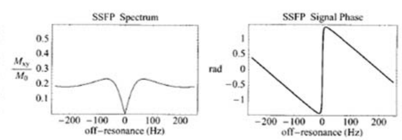
FIG. 4. Images acquired on an obese mouse. **a:** Image acquired using RARE and with the presaturation power off. **b:** Image acquired using RARE and with the saturation power on. **c:** Fat-free image consisting of the subtraction of **(b)** from **(a)** with adjustment of the image brightness/contrast level. The distorted external shape of the mouse resulted from using an undersized support structure to contain the oversized obese mouse in the imaging magnet.

Chen et al, MRM, 2010

Balanced SSFP

- ***The balanced SSFP sequence has completely balanced gradient in all three axes***
- ***The signal profile as a function of resonance offset (or chemical shift) can be modified by***
  - ***RF phase cycling. Vasanawala et al MRM 1999***
  - ***alternating TRs. Leupold et al, MRM 2006; Curkur et al, MRM 2009***
- ***Combination of the signals can produce water-only and fat-only images as well as removing the banding artefacts***
- ***Manipulates both incoming signals and processing***

FIG. 2. SSFP equilibrium transverse magnetization magnitude (left) and phase (right) for a species with T_1 of 900 ms and T_2 of 200 ms (TR = 2.5 ms, 25° flip angle). Spins near the resonance frequency are saturated, so by shifting the RF frequency, a particular chemical species can be suppressed. The width of the passband and stopband inversely scale with the sequence repetition time.



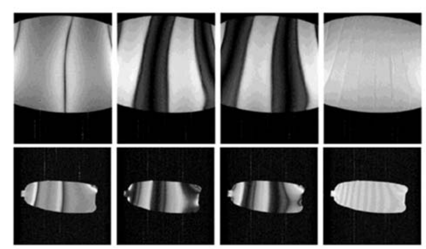


FIG. 3. Images of water (top) and lipid (bottom) phantoms acquired with a constant gradient field from the left to the right of the images. From left to right, images were acquired with data from an SSFP sequence, $D_{0-0} + iD_{0-180}$, $D_{0-0} - iD_{0-180}$, and $D_{0-0-0-0} + D_{0-90-180-270} + D_{0-180-0-180} + D_{0-270-180-90}$. For all sequences, a 45° excitation and 3.3 ms TR were employed. Note the relatively thin band of suppression with SSFP in the lipid image (left bottom image), and a broad region of high intensity just left of it. The high intensity band may be due to decoupling of methyl protons in lipid, and the consequent increase in T_2 relaxation time. The two-phase images (middle two) have much broader bands of signal suppression, as predicted by theoretical off-resonance equilibrium magnetization profiles, whereas the four-phase images have no suppression bands.

Vasanawala et al MRM, 2000

Summary

- ***Fat suppression is widely used in clinical MRI and in different pulse sequences***
- ***Many fat suppression techniques have been developed and continued to be developed***
- ***they may all have their intrinsic pros and cons***
- ***Further development of these techniques can substantially improve the current image quality, improve the scan efficiency, and enable new clinical applications in MRI***

Thank you for your attention.