Managing fat in MRI: a technical perspective

Jingfei Ma, PhD, DABR
Department of Imaging Physics

Disclaimer

The speaker is an inventor of US patents or patent applications that are licensed to GE Healthcare Technologies.

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**

- 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

Frahm et al, Radiology 1985
**Chemical shift selective saturation**

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

---

**Selective excitation**

**Binomial RF pulses:**

Water

\[ \alpha \quad 2\alpha \quad \alpha \]

Fat

\[ \alpha \quad 2\alpha \quad \alpha \]

---

**Selective excitation**

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 2009
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)

- 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.

Bydder and Young, J. Comput Assist Tomogr 1985

FatSat STIR

Other variants: spectral inversion

Figure 6: Images of a healthy volunteer, obtained with fat and water B0 suppression with 110° angle FT pulse with the imaging of the coronary pulse set to the 110° and a short time after the inversion. Note the good suppression of both T1 and T2. The minimal signal changes with fat suppression. The signal intensity of fat is greater than that of the FT pulse. The STIR pulse is more effective in reducing the signal intensity of fat compared with the FT pulse. 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

- Almost 1000 citations
- Dixon, Radiology 1984
• 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.
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:

\[ \text{Ito's method for 1-D phase unwrapping:} \\
1. Compute the phase difference \\
2. Compute the wrapped phase difference \\
3. Initialize a first phase value \\
4. Unwrap by summing the wrapped phase difference \]

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

2D phase unwrapping

Violation of the unwrappability criterion leads to phase poles or residues

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

The “cutline” approach for phase unwrapping

- 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”.

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

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

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

Chavez et. al. IEEE TMI 2002
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 \((0, \alpha, 2\alpha)\), where \(\alpha \neq 180^\circ\)

**Direct Phase Encoding (DPE)**

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


---

**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:


---

**IDEAL: iterative decomposition of water and fat with echo asymmetry**

- solve for $\rho$ iteratively, starting with $\phi = 0$ and until $\Delta \phi < 1$ Hz.
- 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

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

---

**Back to a two-point Dixon technique**

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

multiple vs. binary choices
Back to two-point Dixon technique

- 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

Region growing

phase vector vs. phasor

Information on both amplitude and phase is incorporated in phase vector.
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

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

- 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

- 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

20 slices in 20 seconds without parallel imaging

patient with hepatic steatosis

F/W = 0.03

F/W = 0.2
1a) 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

T2-weighted head and neck imaging

FatSat  
Dixon

Ma, Jackson, Kumar, Ginsberg, AJNR 2009

Large 3D volume imaging (breast cancer)

An entire abdomen-pelvis acquisition in less than 20 seconds

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

---

**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:

---

Xiang MRM, 2006
Eggers et al, MRM, 2011
Berglund et al MRM, 2011
Ma, ISMRM 2011
Single point Dixon

Ma, JMRI, 2008

Fat suppression using MT effects

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

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.