Ultrashort and Zero Echo Time MRI

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Semi-solid Tissues

Examples:
- Cortical Bone
- Tendons
- Lung Tissue
- Myelin

Data Acquisition

Cortical bone

Tendons

Meniscus
Ultra-short/Zero Echo Time Imaging

Potential Clinical Applications:
Bone mapping
Tendinopathy
Cancerous Lung Nodules
Fibrotic Lung Disease
Demyelination/dysmyelination
Dipole Field

Magnetic dipole produces local (~nm) magnetic field variations, $\Delta B_0$
Dipolar Coupling

\[ \omega_0 \]

Frequency

\[ \omega_0 \]
Dipoles couple, which induces resonance frequency shifts, $\Delta \omega$
Dipoles couple, which induces resonance frequency shifts, $\Delta \omega$
Spins precess around $B_0$ at their resonance frequency, $\omega$
Rotating Frame: Demodulate precession at Larmor frequency $\omega_0 = \gamma B_0$
- "on-resonance" – $\omega = \omega_0$, acquires no phase
- "off-resonance" – $\omega = \omega_0 + \Delta \omega$, dephases from resonant spins
Net magnetization is reduced over time by varying precession rates.
$T_2$ relaxation is caused by local **field shifts** from dipolar coupling → Dephasing and reductions of the transverse magnetization ($M_{XY}$)
$T_2$ for Mobile Spins

Long $T_2$ relaxation time

Number of Spins

Frequency

$M_{xy}$

$\omega_0$
**T₂ for Spins in Solids**

Short $T₂$ relaxation time

$M_{XY}$ vs. $t$

Number of Spins vs. Frequency

$ω₀$
2D Ultrashort TE Pulse Sequence

Full-pulse excitation

Half-pulse excitation

Conventional

UTE
Conventional Excitation

Always ends at center of excitation $k$-space
2D UTE Excitation

Half-pulses
Half-pulse Slice Profile

Positive Gradient

Negative Gradient

$M_{XY}$

$M_{XY}$

Position (cm)

Position (cm)

$M_X$

$M_Y$

$M_{XY}$

Position (cm)
UTE Acquisitions

Start at k-space origin for minimum TE

Ultra-short echo
3D UTE Excitation

Hard Pulse

- Excites everything
- Short
- Minimum TE = 0

Minimum-phase Slab Pulse

- Excites a slab
- Minimum TE and duration increased (~100 µs)
- Limits FOV and artifacts (gradient non-linearity)

Images courtesy of Paul Gurney
3D UTE Acquisition

3D Radial Trajectory

3D Cones Trajectory
Gurney et al. MRM 2006.
Slice profile blurs as $T_2$ decreases and as RF duration increases.
T₂ Decay during Acquisition

- **Lose Resolution with T₂ decay**
- **Tread ≪ T₂** requires massive gradients and lowers SNR ($\sqrt{\text{Tread}}$)
- **Use Tread ≈ T₂** for optimal SNR

\[
\text{Signal} = \exp(-t / T₂)
\]
Varying TE Ankle Images

3D UTE image, TE=229 µs

TE=2.2 ms

Achilles’ tendon
($T_2 \approx 1 \text{ ms}$)

Varying TE

Signal

Achilles’ tendon
($T_2 \approx 1 \text{ ms}$)

Problem with UTE Imaging

Poor short-$T_2$ component contrast
Signal from all tissues

cortical bone
($T_2 \approx 500 \mu s$)

tendons
($T_2 \approx 1 \text{ ms}$)

meniscus
($T_2 \approx 4 \text{ ms}$)
Long-$T_2$ Suppression

Fat
$T_2 \approx 80 \text{ ms}$

Muscle
$T_2 \approx 50 \text{ ms}$
RF Pulse $T_2$ Contrast

**Short-$T_2$**

**Long-$T_2$**

- $z$
- $x-y$

**Number of Spins**

**Frequency**

**RF Pulse**
RF Pulse $T_2$ Contrast

- Short-$T_2$
- Long-$T_2$

Frequency

Number of Spins

RF Pulse

x-y

z
Long-T$_2$ Suppression Pulses

Suppression pulse: \textit{contrast preparation}

Dephasing gradient: \textit{destroys} $M_{XY}$

Half-pulse excitation

$RF$

$G_Z$

$G_X, G_Y$

$DAQ$

Contrast in $M_Z$

Signal = $M_{XY}$
Improved Suppression Pulses

- Precisely match desired spectral profile
- Time-bandwidth (TBW) - controls sharpness of profile

\[ TBW = 2.0 \]

\[ TBW = 3.0 \]

Rectangular (TBW ≈ 1.0)

RF

\[ \frac{M_z}{\text{Off-resonance Frequency}} \]

\[ 0 \sim 1 \]
Suppression Results

No Suppression

Rectangular Suppression Pulse

SLR-designed Suppression Pulse

Consistent white matter contrast (likely Myelin)

Rectangular pulse failures

TE = 80 us, TR = 500 ms, flip = 60 degrees, 5 mm slice thickness, 1 mm in-plane resolution, transmit/receive head coil, 1.5T GE Scanner 4:15 min acquisition

Falx Cerebri

Dura Matter
Adding Fat Suppression

Short-T₂

Fat Long-T₂

Water Long-T₂

Number of Spins

ω₀ - Δω_{fat} (fat)

ω₀ (water)

Frequency

z

x-y
Dual-Band Suppression Pulses

Using SLR pulse design

+ Fat suppression band
- Additional short-$T_2$ signal loss

RF

real
imag

TBW = 3.4

$M_z$

Off-resonance Frequency
3D Ankle Images (1.5T, 2005)

No Suppression

Dual-band Long-T$_2$ Suppression Pulse

Achilles’ tendon

Fat
3D Ankle Images (1.5T, 2005)

No Suppression

Dual-band Long-$T_2$ Suppression Pulse
3D Ankle Images (7T, 2014)

**FIGURE 5.** Internal structural analysis of the Achilles tendon. A to C, Axial, sagittal, and coronal reformatted slices. The positions of the slices are denoted as dashed lines in A to B. A fascicular pattern is observed in the tendon. C, The orientations of the fascicles can be characterized, allowing for distinguishing different groups of fascicles as denoted by arrows. Numerous other tendons in the ankle are also well depicted, indicated in A.
UTE Lung Imaging

1.25mm resolution, Resolved over 5 respiratory phases

Zero Echo Time (ZTE) MRI

- Zero echo time: cross center of k-space during RF pulse
- But don’t acquire center of k-space
  - Algebraic reconstruction
  - Fill in with single point acquisitions
  - Fill in with low-resolution projections
Zero Echo Time (ZTE) MRI

- Silent scan due to slow ramping of gradients
- Limited flip angle and volumetric coverage due to “slice selection” during RF pulse
- “Slice” changes every TR! Blurring artifacts
ZTE Bone Imaging

ZTE  -log(ZTE)  Pseudo-CT

ZTE Tendon Imaging

- Excellent tendon visualization, including fascicular structure of Achilles’ tendon
- 0.7mm isotropic resolution
- 4:45 scan time

Larson et al. MAGMA 2015.
ZTE Knee Imaging

- Excellent tendon, ligament, cartilage, and meniscus visualization
- 0.6 mm isotropic resolution
- 4:45 scan time

Larson et al. MAGMA 2015.
Other UTE Images
3D UTE Violin Images

3D PR acquisition with FOV tailored to the violin shape

TE = 64 us, TR = 5.2 ms, 1.3-1.8 mm in-plane resolution, 3" surface coil, transmit/receive head coil, 1.5T GE Scanner

*1 min 43 s and 19 min acquisition*