Contrast-Manipulation Techniques for Steady-State Magnetic Resonance Imaging

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Magnetic Resonance Imaging

Clinical benefits:
- No radiation exposure
- Arbitrary slice plane
- Flexible contrast between soft tissues
- Contrast can be tailored to the organ or pathology being studied

Early scans required several minutes due to hardware limitations

Since then, higher-performance MR hardware has become available
- Faster scans
- Higher resolution

High-Performance Imaging

Steady-state free precession (SSFP) acquisition: (Carr 1958)
- Signal grows as imaging time decreases
- More susceptible to hardware imperfections

As imaging time decreases, it becomes increasingly worthwhile to use SSFP acquisitions

Example: Real-Time Cardiac MR

Conventional SSFP

24 images/sec
1.85-mm resolution

Steady-State Contrast

Conventional techniques for manipulating image contrast are not directly applicable to steady-state acquisitions

This work provides:
- Specific techniques for generating steady-state images with
  - Angiographic contrast
  - Fat-suppressed contrast
- A mathematical framework for developing other contrast-manipulated steady-state imaging techniques
Overview

- Physics of MRI
  - Image formation
  - Steady-state imaging
- Steady-state contrast manipulation
  - Flow-based contrast
  - Angiography
  - Spectral contrast
  - Banding artifact reduction
  - Lipid suppression
- Conclusion

Overview

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Nuclear Spins

Nuclei that possess spin angular momentum ("spins"):
- Small magnetic dipole
- Rotates on its axis
- For MRI, we use hydrogen nuclei because of the abundance of water molecules in the body

Spins in a Magnetic Field

When placed in a magnetic field, spins align such that
\[ M \parallel B_0 \]

\[ B_0 : \text{Magnetic field} \]
\[ M : \text{Net nuclear magnetization} \]

Spin Diagram

Precession

- Magnetization precesses about the z axis
- Frequency \( f \) is linearly proportional to \( B_0 \)
\[ f = \gamma B_0 \]

\( f : \text{Larmor rate} \)
\( \gamma : \text{Gyromagnetic ratio} \)
**RF Excitation**

- To move magnetization away from longitudinal, we define a second magnetic field ($B_2$).
- Perpendicular to $B_1$.
- Rotating at the Larmor rate.

**Rotating Reference Frame**

- To simplify the motion of $M$.
- Rotating coordinate system.
- xy plane rotates at the Larmor rate.
- Excitation is simplified to a pure rotation.

**Relaxation**

- Magnetization returns to longitudinal by two mechanisms:
  - Transverse Decay ($T2$)
  - Longitudinal Recovery ($T1$)

**Steady-State Pulse Sequence**

- $TR$: RF repetition time.
- After a transient, the magnetization evolves toward a steady state.

**Magnetic Field Gradients**

- For imaging:
  - Spatially varying magnetic fields are used.
  - Spins at different positions precess at different rates.

**Steady-State Image Formation**

- MRF signal represents samples of multidimensional Fourier transform spaces ($k$-space).
- Gradient amplitude equals the rate of motion through $k$-space.

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Steady-State Image Formation

- MR signal represents samples of multidimensional Fourier transform space (k-space)
- Gradient amplitude equals the rate of motion through k-space

Free Precession

- Free precession if:
  - Unknown
  - Spatially varying
  - Due to:
    - $B_0$ inhomogeneity
    - Incomplete gradient refocusing
    - Resonant frequency differences
    - Lipid spins precess 200 Hz slower than water spins

Oscillating Steady-State Sequences

- Sequence repeats with period $N \times TR$
- Magnetization $M_0$ occurs every $N^k \times TR$
- Alters steady-state signal profile

Example: FEMR (Vosman et al. 1999)

- $N=2$
- RF phase alternates between x and y axes
**Physics of MRI: Summary**

- Main field \( B_0 \) generates net magnetization \( M \)
- RF field \( B_1 \) rotates magnetization away from longitudinal
- Gradients encode position through magnetization phase
- Relaxation returns magnetization to longitudinal
- SSFP sequence consists of a train of RF tips with all intervening gradients fully refocused

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**Flow Encoding**

A bipolar gradient can be used to encode a spin's velocity:

- No Velocity
- Constant Velocity

No Effect
Phase Offset
Induces a phase that is linearly proportional to velocity:

\[ \theta = \text{Velocity} \]

**Flow-Sensitive Steady State**

A bipolar gradient is included every other TR:

- Moving spins: \( \uparrow \neq \text{\( B_1 \)} \)
- Stationary spins: \( \uparrow = \text{\( B_1 \)} \)

\[ \uparrow = \text{\( B_1 \)} \] Angiographic contrast
- Signal only from moving spins
- "Oscillating Dual-Equilibrium Steady-State Angiography" (ODESSA)

\[ \uparrow \neq \text{\( B_1 \)} \] Anatomic contrast

**ODESSA Pulse Sequence**

- Two TR intervals are shown

- Bipolar gradient occurs during odd TR intervals
- Before or after readout
**ODESSA Pulse Sequence**

- Triphasic pulse occurs during even TR intervals
- No effect on spins moving with constant velocity
- Compensates for imaging imperfections:
  - Maxwell gradients
  - Eddy currents

**Steady State: No Flow**

- After accounting for RF phase, signal is equal in odd and even echoes
- Subtraction results in zero signal

**Steady State: Flow**

- Odd echo "1":
  - Position does not change with precession
  - Low signal
- Even echo "2":
  - Enhanced signal
- Subtraction results in large signal difference

**Sum & Difference vs. Velocity**

- ODESSA difference:
  - Signal null at zero velocity
  - Uniformly high signal for all nonzero velocities
- Echo sum:
  - High signal for zero velocity
  - Small signal loss for nonzero velocities
- Free precession causes:
  - No change in signal null
  - Less passband uniformity
**ODESSA vs. PCA**

Compared with conventional phase contrast angiography:
- 3x signal increase in the same scan time
- Uniform phase eliminates signal loss due to intra-voxel velocity dispersion

**Alternating Bipolar Gradients**

When used with PCA:
- Minimizes signal loss from phase dispersion
- Reduces the size of each bipolar pulse

When used with ODESSA:
- Changes the steady state
- No region of constant signal

**Phantom Validation**

Velocity encoding:
- 25 cm/s → 180°
- ODESSA measurements match theory

**Phantom Images**

Total scan time: 3 sec

**Axial Knee: 2D Slice**

Total scan time: 3 sec

**Lower Leg: 3D Slice**

3D scan time: 3 min., 11 sec
2 NEX
**Lower Leg: MIP**

Targeted Maximum Intensity Projection

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**ODESSA: Summary**

Utilizes an oscillating steady state to generate non-contrast MR angiograms:
- Fast
- Large, uniform signal from all moving spins
- More than 3x the signal of PCA
- Acquires anatomic image simultaneously

Technical challenges:
- Free precession can change signal uniformity
- Eddy currents and Maxwell gradients can cause residual signal from stationary tissue

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**Sequence Synthesis**

Modifying the oscillating-SSFP tips ($\alpha_n$) alters the steady-state magnetization profile:
- ODESSA
- FEMR

The inverse problem (sequence synthesis):
- Given a desired magnetization profile, can we determine the set of oscillating-SSFP tips that best approximates it?

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**Oscillating Steady State**

Neglecting relaxation:
- $R_{xy}(t) = \prod R_{xy}(\alpha_n) R_{xy}(\theta_0)$
- $d(\theta)$: axis of rotation
- $\phi(\theta)$: angle of rotation

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**Steady-State Solution**

Steady-state magnetization is unchanged after rotation:
- $M_{ss}$ must lie along the axis of rotation:
  - $M_{ss}(\theta) = k\theta(0)$
- Rotation angle $\phi$ is not specified by the desired $M_{ss}$
**Steady-State Solution**

The sequence-synthesis problem:
- Design a set of tips $a_n$ whose composite rotation $R_n(t)$ has an axis of rotation $d(t)$ that best approximates $M_j(0)$

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**Sequence Synthesis: Possible Solutions**

Analytic solution:
- Equations are nonlinear & noninvertible
- Brute-force search over all tips
- Computation time increases exponentially with $N$
- Unacceptably long even for $N=3$

Nonlinear optimization (gradient descent; N-M simplex):
- Needs a very good initial guess

SLR Transform:
- Can produce results quickly
- Provides intuition into steady-state signal formation

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**SLR Design**

(From 1994)

Originally developed to design shaped RF pulses for:
- Slice-selective excitation
- Frequency selection

Steps:
- Translate a desired tip profile into parameters $A_2$ and $B_2$
- $z = 0$
- Approximate $A_2(t)$ and $B_2(t)$ with polynomials in $z$: $A_2(t)$ and $B_2(t)$
- Use the inverse SLR transform to generate an RF pulse that matches the approximated profile

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**Tip Representation**

Shaped-pulse SLR design:
- Heat-pulse approximation converts continuous waveforms into alternating samples of RF and gradient

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**Tip Representation**

Shaped-pulse SLR design:
- Heat-pulse approximation converts continuous waveforms into alternating samples of RF and gradient

Steady-state design:
- This arrangement exists without approximation

Both are described by:

$$R_n(t) = \prod R_{n_k} a_n R_i(0)$$
**Designing for Multiple Echoes**

- Algorithm designs signal profile for only one of \( N \) echoes
- If signal is desired over a particular range, \( \{d_i\} \) = drivers magnetization close to zero for all \( N \) echoes
- Can also perform multiple optimizations for any number of \( T_1 \) subgroups

**SSFP Without Bands**

**Goal:** Uniform signal profile

**Applications:**
- Long-TR SSFP imaging
- Spectrally selective RF pulses
- More-efficient k-space trajectories

**SSFP Without Bands: Sequence**

- Pulse sequence resembles a driven-equilibrium experiment (Iwaoia 1984)
- Increasing T1 makes recovery time

**Filter Design**

**Goal:** Square magnitude filter

**Applications:**
- Spectrally selective excitation
- Solvent-suppressed spectroscopy
- Fat-suppressed imaging

**Filter Design**

**Goal:** Square magnitude filter

**Solutions:**
- As \( N \) increases,
- Transition is sharpened
- Stopband remains suppressed in all echoes

Notches in B1p solution:
- Locations where least-square weights \( w_j \) =
Design for Fat Suppression

- **Design constraints:**
  - \( N = 4 \)
  - Relatively large \( |G(z)| \) is persistently for strong T2 contrast
  - Stopband is suppressed in all echoes
  - Echoes occur in equal-magnitude pairs
  - Design algorithm is flexible

Solution:
- Echo pairs are virtually identical
- “Fat-Water” region is fully suppressed in all echoes
- Signal phase is very similar at resonance

“Fat-Suppressed, Oscillating SSFP” (FS-SSFP)

Tip Sequence

Echo Behavior

- On-resonance:
  - Magnitudes equal
  - Signal related by
    \[
    \frac{\cos(10\text{o})}{\cos(60\text{o})} = 2.3
    \]
  - Independent of T1 or T2

Echo Acquisition

- Ratio between echo amplitudes is known
- Echoes can be equalized to the same magnitude
- Each phase-encoding line is acquired only once
- Central k-space lines are acquired in high-amplitude echoes
- Maximizes SNR

Comparison with Other Techniques

- FS-SSFP
- PEMR
- LCSFP

- FS-SSFP requires the least scan time for a given resolution
- Similar normalized SNR in k-space
- More complete stopband suppression, over a broader range
Phantom Results

- Water signal peak corresponds to lipid null
- Echo signal corresponds well with theory
- Stopband suppressed in all echoes
- Peak signal within 5% of desired ratio

Equalization Results

- All 4 Echoes Averaged
- Equalized (1/4 Scan Time)
- Equalization Error

Results: Knee

FS-OSSFP
SSFP

FS-OSSFP: Summary

A technique has been developed for fat-suppressed SSFP imaging with:
- Scan time equal to that of standard SSFP
- Normalized SNR comparable to other techniques

Echo equalization:
- Allows efficient scans
- Introduces minimal image artifacts

Potential applications:
- Cartilage imaging
- Abdominal imaging
- Cardiac imaging

Synthesis Algorithm: Summary

Steady states can be designed quickly and reliably using an iterative technique
- Uniform-magnitude sequences resemble driven-equilibrium imaging
- Filters with arbitrary passbands and stopbands can also be generated

Important criterion for specifying SSFP contrast is the elevation angle of $M_w(0)$

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Contributions

ODESSA:
A new technique for rapid non-contrast MR angiography
- United States patent pending.

Steady-state sequence synthesis:
A new algorithm for designing steady-state sequences with arbitrary signal profiles
- United States patent pending.

Contributions

Steady-state phase contrast (SSPC):
A new technique for flow quantification using SSFP
- Spin velocity encoded as image phase

Genetic-algorithm catalyzation:
A new technique for quickening the approach to steady state
- Can generate sequences of arbitrary length

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- Tom Andreacci
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Other:
- [Insert your name here]

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