Clinical MRI: From Physical Principles to Practical Protocols

Cardiovascular Methods

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Disclaimers/Disclosures

1. The use of contrast media has not been approved by the FDA for use in Cardiovascular MR. Off label use of contrast media will be discussed in this presentation.
2. The information in this presentation is strictly educational and is not intended to be used for instruction as to the practice of medicine.
3. The speaker is an employee of Siemens Corporate Research

Outline

Physiology and cardiac MR acquisitions
Morphology
Function
Flow
Perfusion
Late enhancement

Motion in Cardiovascular MR

Cardiac
Respiratory

Motion Compensation Methods

- ECG Triggering
  - synchronize data acquisition over multiple heartbeats
- Respiratory gating
  - restrict acquisition to quiet periods of cycle
  - breath-holding
- Real time imaging
  - freeze motion
Electromechanical Activity in the Heart

ECG
Pressure (Aortic, LV, LA)
LV Volume

ECG Triggering

R Wave Detection
Trigger Delay (TD)
k-Space

MRI-Related ECG Noise Sources
- $B_0$ related (main static field)
  - magnetohydrodynamic effect
  - flux change due to motion (respiratory and cable)
- $B_1$ related (radio-frequency field)
  - RF pulses
  - electrode and ECG amplifier effects
- $G$ related (gradient switching)

Magnetohydrodynamic Effect (Flow Artifact)

not the T-wave anymore!

Diagnostic Value of ECG in MR Environment
- Not Diagnostic
  - P-wave, ST-segment, T-wave, T-axis, J-point
  - PQ interval, QT-interval, P duration
- Diagnostic
  - heart rate (accurate QRS detection required, or manual evaluation)
  - electrical axis of the heart
- Heart rate changes due to $B_0$

Skin Preparation
- Remove chest hair if needed
- Clean and roughen skin surface
  - Remove oil and perspiration to allow better contact of electrodes
  - Clean with abrasive prep pad or gel (NuPrep)
  - Dry area completely!!!
Use MR Compatible ECG Equipment

- MR compatible ECG system
  - Bruker
  - InVivo
  - Medrad
- MR compatible ECG pads
  - check with MR vendor for recommendation
  - check expiration date
  - do not leave pads exposed to air - will dry out (baseline noise)
- Non MR pads
  - worst case = burns
  - RF interference = unable to scan!

Lead Placement Tips: Standard ECG

- The R wave with the highest amplitude will be attained by placing the positive and negative electrodes, parallel to the electrical axis of the heart
- The reference electrode can be placed in any position

Principle of the VCG (Vectorcardiogram)

- Two-channel ECG system
- Signals from two pairs of electrodes plotted against each other to remove time
- Resulting graph is spatial representation of electrical activity in the heart.

VCG Triggering Principle

- R-wave is spatially separate from artifacts
- 2D direction of R-waves is determined during learning-phase, while patient is outside magnet bore.
- Direction information is used to differentiate R-waves from artifacts.

2D VCG Lead Setup

Philips Medical Systems

Wireless VCG System

Siemens Medical Solutions
Summary: ECG Triggering

- Don't start scanning unless ECG is good
- Skin preparation is important for signal quality
- For non-VCG systems, placement of electrodes based on patient characteristics can greatly influence quality of ECG signal

Electromechanical Activity in the Heart

Filling k-space Using ECG Triggering

ECG Triggered Acquisition with Respiratory Gating

Navigator Gated Imaging Sequences

Navigator Technique: Prospective Mode

- Detect respiratory motion
- Accept data only in expiration
- Compensate by adjusting slice position (slice following)
Outline

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Imaging Heart Anatomy

- Clinical goals
  - Determine relationship between various structures in the heart and in the thorax
  - Identify and characterize tumors, thrombus, fatty infiltration of myocardium, etc.
  - Identify and characterize vessel wall abnormalities
- Sequence requirements
  - Good contrast between blood and myocardium
  - Ability to have T1 or T2 weighting to characterize fat, tumors, etc.
  - Moderate spatial resolution 1 x 1 mm in plane, 5-7 mm through plane
  - Good suppression of artifacts

Examples of Anatomic Imaging

Spin Echo Based Black-blood Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Lines acquired per beat</th>
<th>Temporal resolution</th>
<th>Scan time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin echo</td>
<td>1</td>
<td>10 – 40 ms</td>
<td>128 – 384 heartbeats</td>
</tr>
<tr>
<td>Turbo spin echo</td>
<td>32</td>
<td>30 – 300 ms</td>
<td>4 – 32 heartbeats</td>
</tr>
<tr>
<td>Turbo Haste</td>
<td>64-128</td>
<td>200 – 400 ms</td>
<td>1 heartbeat</td>
</tr>
</tbody>
</table>

Breath-hold Black-blood Turbo Spin Echo

- Breath-hold to reduce respiratory artifacts.
- Diastolic gating to reduce cardiac motion artifacts.
- Double-inversion blood effectively eliminates signal from flowing blood.

Black-blood Turbo Spin Echo

Blood signal artifacts in turbo spin echo can be severe without blood nulling.
Turbo Spin Echo Black-blood Sequence

- Spatially non-selective excitation
  - Blood and tissue signal inverted
- Section selective excitation
  - Tissue signal re-inverted
  - i.e. no net change in magnetization
  - Systole follows
  - i.e. blood outside section only sees first pulse

Black-blood Imaging: Preparation

Wait Acquire

= Dark blood preparation

Simonetti et al., Radiology 1996; 199:49-57

Black-blood Imaging

Wait Acquire

= Blood null point

Fleckenstein et al., Radiology 1991; 179:499-504

Blood Null Point Varies with HR

<table>
<thead>
<tr>
<th>Heart Rate BPM</th>
<th>RR msec</th>
<th>Blood Null Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>750</td>
<td>530</td>
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<tr>
<td>60</td>
<td>1000</td>
<td>625</td>
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</table>

Timing: Delay Too Short

- Slice A ≠ Slice B
- Blood at null point
Timing: Delay Just Right

- Slice A = Slice B
- Blood signal zero

Timing: Delay Too Long

- Slice A = Slice B
- Blood signal recovering

Getting the Timing Right

- Delay 790 ms: OK for LV, not for RV
- Delay 840 ms: OK for both RV and LV

“T1” and “T2”-Weighting

- Short TE values
- Long TE values
- Triggering every beat
- Triggering every other beat

Variations Of Anatomical Imaging

- White blood single-shot imaging
- Dark blood single shot imaging (HASTE)
- Non-BH spin echo with long TE and no flow compensation
- Contrast enhanced MR angiography

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Functional Imaging In The Heart

Clinical goal
- View and quantitate left and right ventricular function, wall motion, and wall thickening

Sequence Requirements
- Moderate spatial resolution (1-2 mm in-plane, 6-8 mm through plane)
- High temporal resolution (< 50 ms/frame)
- Suppression of respiratory motion (breathhold, real-time, respiratory gating)
- High contrast between blood and myocardium

Examples: Functional imaging in the Heart

- Standard BH acquisition
- Real-time acquisition

Multiple Phase ECG Triggered Imaging (Cine Imaging)

- Collect more than one k-space line per phase per beat (segmentation)
- Share collected k-space lines between phases (segmentation with echo sharing)
- Collect fewer lines than in full matrix and use properties of k-space or sensitivity maps to 'fill in' the rest
  - partial Fourier
  - parallel imaging (SENSE, SMASH, GRAPPA)
  - undersampled radial imaging
- Go really fast…get all lines at once (real time imaging)

Improvement in Scan Time

Cardiovascular MR:

<table>
<thead>
<tr>
<th>Year</th>
<th>Scan Time (sec)</th>
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<tbody>
<tr>
<td>1985</td>
<td>600</td>
</tr>
<tr>
<td>1988</td>
<td>200</td>
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<td>1992</td>
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<td>2003</td>
<td>15</td>
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<tr>
<td>2005</td>
<td>10</td>
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Penalties for Shorter Scan Times

- Less spatial resolution
- Less temporal resolution
- Artifacts
Variations: Segmented Imaging with Echo Sharing

Lines shared to fill k-space of multiple phases

Example: 3 phases

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Principle of Phase Contrast Flow Imaging

- Protons moving in the presence of a gradient field produce a phase shift
- The phase shift is directly proportional to velocity
- To compensate for imperfections, flow compensated and flow encoded acquisitions are used in combination

Flow Quantification Cine Sequences

- Retrospective triggering to include entire cardiac cycle preferred
- Temporal resolution depends on number of directions encoded (half of normal cine temporal resolution if 1 direction encoded)
- Same approaches to reducing scan time as for functional cine acquisition can be used (segmentation, parallel imaging, etc)
Phase Contrast Cine Images

- rephased
- magnitude of flow compensated signal $S_1$
- flow bright background visible
- phase of difference signal $\gamma$
- forward flow bright (reverse flow black)
- background midgray

Typical Peak Velocities (cm/sec)

- Pulmonary Artery: 70-130
- Aorta: 100 – 175
- Carotid Artery: 80 – 120
- External Iliac Artery: 81 – 120
- Common Femoral Artery: 115
- Basilar Artery: 40
- Superficial Femoral Artery: 90
- Vertebal Artery: 40
- Popliteal Artery: 70
- Sagittal Sinus Vein: 10
- Peripheral Veins: 5 – 10

What Happens If The VENC Is Wrong?

- **VENC too low**
  - aliasing
  - can correct to some extent, recommended to re-acquire with appropriate higher venc

- **VENC too high**
  - loss of "velocity" resolution (poor dynamic range)

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Myocardial Perfusion Imaging

**Clinical goals**
- Detect deficits in blood flow to the heart muscle at rest or under stress

**Sequence requirements**
- At least 1 image per heartbeat per slice
- Slices to cover relevant segments of the heart (3-5)
- High T1 sensitivity
- Good SNR
- Good spatial resolution (at least 2 x 2 in plane)
- Resistance to motion artifacts and variations in heart cycle length

**Contrast Enhanced MR**

- Normal Myocardium
- Infarcted Myocardium
- Ischemic Myocardium

**First Pass Myocardial Perfusion**

- Saturation recovery TurboFLASH with parallel imaging, GRAPPA rate 2; 1-4 slices/heart beat

**Ischemic Heart Disease – Ischemic Region versus Infarct**

- (a) Rest perfusion
- (b) Stress perfusion
- (c) Infarct

**Current Pulse Sequences for Myocardial Perfusion with MR**

- T1 weighted gradient echo sequences
- Steady State sequences
- Segmented echo planar sequences
Magnetization Preparation

- **Inversion Recovery** (180° pulse)
  - Very strong T1 contrast.
  - Multi-slice imaging difficult.
  - Sensitive to arrhythmia.

- **Saturation Recovery** (90° pulse)
  - Weaker T1 contrast.
  - Multi-slice capabilities.
  - Insensitive to arrhythmia.

Dynamic First-Pass Perfusion

Saturation Recovery Preparation

ECG Trigger

R

<table>
<thead>
<tr>
<th>0,00</th>
<th>0,20</th>
<th>0,40</th>
<th>0,60</th>
<th>0,80</th>
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<tr>
<td>0</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>400</td>
</tr>
</tbody>
</table>

Ischemic Myocardium (long T1)

Non-Ischemic Myocardium (short T1)

Mz evolution period

acquisition period

90°

\[\text{weaker T1 contrast} \]

\[\text{Insensitivity to Arrhythmia} \]

\[\text{Multi-slice capabilities} \]

\[\text{CNR & SNR depend on TI} \]

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Late Enhancement Imaging

- **Clinical goals**
  - Identify locations of the myocardium that are 'dead' or injured, including infarcts, fibrous tissue due to myocarditis, intentional ablation, cardiomyopathies, etc
  - Identification from kinetic behavior of Gd-DTPA

- **Sequence requirements**
  - Highly T1 sensitive
  - High spatial resolution
  - Short acquisition time (obtain images in a BH)

Contrast Enhanced MR

Normal Myocardium

Contrast injection

Infarcted Myocardium

Ischemic Myocardium

Rest --- Stress

Shorter T1 of contrast-enhanced infarcted region results in faster signal recovery following inversion.

Nulling of signal from longer T1 viable myocardium results in maximum contrast ratio.
Basic Imaging Approach: Inversion Recovery

ECG Trigger

Non-selective 180° inversion trigger delay

Gated to diastole of every other cardiac cycle.
TI adjusted to null normal myocardium post-Gd.

Non-selective 180° inversion

Mz Infarct
Mz Normal

Effect of TI on Image Quality

- Imaging at the null-point of viable myocardium
- TI depends on:
  - Contrast dosage
  - Time between injection and imaging
  - Relaxation time between IR pulses (e.g., 2D versus 3D breathhold imaging)
- And TI is time dependent …
  - Contrast in myocardium washes out with time

Effect of TI on Late Enhancement Imaging

Magnitude

TI = 175 200 225 250 275 300 ms

PSIR

Inversion Time Scout

- Inversion Time Scout Sequence
  - Segmented IR-SSFP cine
  - Quickly identify correct inversion time (TI).
  - May be useful for TI mapping

Phase Sensitive IR Pulse Sequence

TI Insensitivity of Phase Sensitive IR

Phase Sensitive IR
Works over broader range of TI

Summary

And for slide contributions…. Thank you!
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