Optimizing Pediatric Cardiovascular MRI

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Aug 4th, 2016

Disclosure

• Research agreement with Siemens Medical Solutions

Outline

• Challenges in pediatric MRI (specifically cardiovascular MRI)
• Cardiovascular (CV) MRI applications and techniques
  - CV MRI artifacts and solutions
  - Optimizations of pediatric CV protocols
  - Advanced CV MRI techniques
Challenges in Pediatric MRI

- General challenges
  - Small anatomy
  - Size varies
  - Patient motion
  - Irregular respiratory pattern
  - Sedation / general anesthesia

- Specific challenges in CV MRI
  - Appropriate coils
  - Faster heart rate and blood flow
  - Complexity of imaging exams and long imaging protocols
  - Contrast agent

To Optimize Pediatric CV MRI

- Size-based, heart-rate-based protocols
- Appropriate coil setup
- Improve spatial resolution
- Improve temporal resolution
- Optimize imaging contrast
- Motion insensitive protocols
- Non-contrast MRA

Coil Setup

- Special coil for neonates and infants <10 kg
  - Clamshell configuration
- Special coil for large infants
  - Both anterior with posterior spine matrix
- Small Flex for toddlers
- Large Flex for small children
- Body matrix for large children and adults
Artifacts due to Coils

- Sagittal scout – correct centering of the coils around heart
- Alignment between anterior and posterior coils
- Scanned at the iso-center

ECG Triggering

- Clean and dry skin, hair shaving
- Stabilize patient in a comfortable position
- Ensure good electrode contact
- Wireless 2 channel VCG system

Prospective vs. Retrospective ECG gating

Prospective
- Acquire data throughout part of the cardiac cycle
- If of cardiac frames must fit into the acquisition window
  - Discard end diastolic information
  - More used in patients with highly variable R-R intervals

Retrospective
- Data are acquired continuously throughout the cardiac cycle
- Data from several different cardiac cycles are combined to yield a cine sequence
Segmented vs. Single-shot cine

Segmented Cine

Multiple k-space lines are measured and time stamped per cardiac phase.

Single-Shot Cine

All k-space lines are acquired in one cardiac cycle.

CV MRI Applications and Techniques

- Function
- Morphology
- Flow
- Perfusion and Viability
- Angiography

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Applications

- Cine imaging is used to visually assess wall motion and valve function.

Long-axis 4 chamber  |  Short-axis 2 chamber  |  Aortic outflow tract  |  Aortic valve

Applications

- Ejection fraction, stroke volume, and cardiac output
  - Short axis stack cine imaging to assess the cardiac function of left and/or right ventricles

Cine Acquisition Techniques

- Single-shot cine imaging
  - Very sick patients with extreme arrhythmias or cannot hold breath.

Segmented Cine
- Requires breath-hold (10-15 sec per slice)
- Temporal resolution: 48 ms
- Spatial resolution: 1.8 x 1.8 mm²

Single-shot Cine
- Free breathing
- Acquired in one heartbeat
- Temporal resolution: 128 ms
- Spatial resolution: 5.0 x 5.0 mm²
Segmented Cine with Free breathing

- Free breathing with multiple signal averages
- Longer imaging time
- Higher temporal and spatial resolution compared with single-shot imaging
- Imaging blurring due to motion

2 yo, NEX = 3
16 yo, NEX = 3

Radial Imaging

- Less sensitive to motion
- No phase wrap at smaller FOV
- Isotropic in-plane spatial resolution
- High temporal resolution

Cartesian k-space
Radial k-space

Radial GRAPPA

- Non-ECG-gated, free breathing
- Radial imaging combined with advanced parallel imaging k-t-GRAPPA
  - Through-time calibration using multiple calibration frames allows estimation of the weights of the GRAPPA kernel.
  - Missing k-space points are calculated by convolving acquired points with GRAPPA kernel.
- Comparable temporal resolution and spatial resolution as Cartesian segmented cine.
Segmented Cine (BH)

<table>
<thead>
<tr>
<th>Age</th>
<th>HR</th>
<th>Time (ms)</th>
<th>Slice Thickness (mm)</th>
</tr>
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<tbody>
<tr>
<td>12 yo</td>
<td>45 bpm</td>
<td>37</td>
<td>1.7</td>
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<td>13 yo</td>
<td>92 bpm</td>
<td>24</td>
<td>2.0</td>
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<tr>
<td>2 yo</td>
<td>97 bpm</td>
<td>22</td>
<td>1.3</td>
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Radial-GRAPPA (FB)

<table>
<thead>
<tr>
<th>Age</th>
<th>HR</th>
<th>Time (ms)</th>
<th>Slice Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 yo</td>
<td>37 ms</td>
<td>52</td>
<td>2.5</td>
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<tr>
<td>13 yo</td>
<td>42 ms</td>
<td>43</td>
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<tr>
<td>2 yo</td>
<td>24 ms</td>
<td>36</td>
<td>2.0</td>
</tr>
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Techniques – Sequence Type

**Balanced SSFP**
- T2/T1 contrast
- High SNR and CNR
- Wall motion better seen
- Off-resonance artifacts

**GRE (gradient recalled echo with spoiling)**
- T1 contrast
- Flow jets better seen
- Less off-resonance and flow artifacts
- Lower SNR and CNR

Off-Resonance Artifacts in bSSFP

- Dark band: caused by the dephasing of spins with loss of the steady-state signal.
- Minimize TR
  - Increase bandwidth
  - Decrease readout matrix
- Perform better local shimming around heart
Shimming Method

- Shimming: To estimate B0 field map and apply compensatory shim currents to reduce field inhomogeneity

  - GRE shimming
    - Adapt field map acquisition based on GRE double echo acquisition

Flow Artifacts in bSSFP

- In regions with fast blood flow, e.g., at the base of the heart or the aorta, off-resonance artifact fluctuates with the flow profile, resembling a pulsating jet.

  - Off-resonance artifact is worse on 3T.

Frequency Scout

- To determine the off resonance frequency and compensate for the center frequency offset.
  - Imaging location and plane dependent.
**CV MRI Applications and Techniques**

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- **Morphology**
- **Flow**
- **Perfusion and Viability**
- **Angiography**

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**Morphology – Dark Blood Techniques**

- Blood signal is suppressed for better delineation of myocardium and vessel wall.
- ECG trigger, double inversion pulses (DIR) followed by fast spin echo acquisition during mid-late diastole.

![Double Inversion Pulse](http://limpeter-mriblog.blogspot.com/2009/09/pulse-sequences-for-cardiac-mri.html)

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**Dark Blood Images**

- **Dark blood T1w**
  - Short TR (1R-R)
  - Short TE
  - Short echo train length (~7)
- **Dark blood T2w**
  - Long TR (2-3 R-R)
  - Long TE
  - Longer echo train length (~11)
- **Triple IR (Dark blood STIR)**
  - Dark blood T2w
  - 3rd inversion pulse for fat saturation
DIR Sequence Diagram

- Null time is directly related to effective R-R (heart rate dependent)

Null time too short: Systolic motion reduces myocardial signal
Null time optimal
Null time too long: Blood signal recovers

Null Time Optimization

- Calculate optimal null time based on Recovery Time and T1_{blood}:
  - Recovery Time (RT) = R-R x Trigger pulse
  - T1_{blood} ~1200ms
  - Null Time = Temporal distance between the double inversion pulses and the excitation pulse

Dark Blood Imaging post-contrast

- T1_{blood} is shortened → Null time pre-contrast does not apply
- Re-estimate T1_{blood} after contrast injection using T1 mapping sequence

Null time = T1_{blood,post} \cdot \log \left( \frac{1}{2} \right)
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Flow Quantification – Clinical applications

- Cardiac output
- Stroke volume
- Shunt fraction
- Regurgitant fraction
- Peak velocity
- Pressure gradient

Phase Contrast (PC) Technique

- Moving proton through a gradient field produces a phase shift.
  - The phase shift is proportional to flow velocity and direction.
- Stationary proton produces no phase shift.
- Phase contrast: measure the difference in phase shift between moving and stationary protons.
- Data Acquisition:
  - Magnitude and phase images
  - Flow compensated acquisition
  - Flow encoded acquisition
Velocity ENCODing (VENC)
- VENC is the velocity when phase angle reaches +/-180 degrees
- Entire range of velocity is assigned a phase shift between +/-180°
  - Maximum forward velocity – maximum bright intensity
  - Maximum reverse velocity – maximum black intensity
- VENC has both magnitude and direction
  - Be applied along flow direction (in-plane, through-plane)

\[ \text{Velocity} = \frac{\Delta \phi \cdot \text{VENC}}{180°} \]

Flow Aliasing
- VENC represents the maximum encoded velocity
- When a velocity > VENC, it will be assigned an opposite phase – flow aliasing.
- VENC should be adjusted slightly above peak velocity.
Pediatric PC MRI Challenges

- High spatial resolution for accurate flow/velocity measurements.
  - Sufficient number of pixels (>6) across the lumen of the vessels
  - Multiple signal averages to compensate for SNR
- High temporal resolution in segmented PC
  - # of segments needs to be reduced (1 or 2)
- Free breathing is more common due to
  - Physiology reasons
  - Long acquisition time

Real-time PC Techniques

- No ECG synchronization
- Single-shot EPI acquisition (EPI factor >7)
- K-t acceleration parallel imaging
- Two-sided and shared velocity encoding → double the frame rate
- Temporal resolution ~40 ms

Examples of Real-time PC

- Preliminary study of aortic flow
  - Cardiac output was not significantly different (real-time vs. standard segmented).
  - Peak systolic velocity was significantly different (real-time vs. standard segmented).
  - Heart rate may influence real-time PC measurements.
  - Further validation for measurement accuracy is warranted.
Time-resolved phase contrast (4D flow)

- Pathlines indicative of flow patterns in the aorta throughout the cardiac cycle.
- Aortic valve leaflet fusion patterns.

CV MRI Applications and Techniques

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- First-pass Perfusion
- Delayed Enhancement

First Pass Perfusion

- Wash-in and wash-out of extra-vascular, extra-cellular contrast agent.
- Signal acquisition for ~1min after contrast injection, usually requires breath-hold.
- Transient signal differences in the myocardium indicate ischemia.

- Technique
  - ECG triggered
  - Non-selective 90° saturation pulse for T1 weighting preparation
  - Followed by data acquisition (spoiled GRE, bSSFP, EPI)
  - 3-6 slices (heart rate dependent)
Dark Rim artifacts

- Most prominent at the blood-myocardium interface, confused with myocardial perfusion defects.
- In phase-encoding direction with lower spatial resolution.
- Peak gadolinium concentration, myocardial motion and partial volume averaging.
- Improve SNR, increase spatial resolution, less dose of contrast agent.

Motion Corrected Perfusion

- Free breathing acquisition.
- Non-rigid registration, spatial and temporal denoising.
- Semi-quantitative parametric map of the slope of first pass signal changes.
- If both stress and rest scans are acquired:
  - Perfusion reserve index = up-slope_{stress} / up-slope_{rest}
Inversion Time (TI) Scout

- TI is dependent upon:
  - Contrast dose
  - Contrast agent wash-out time
  - Heart rate

- Technique:
  - IR pulse followed by cine data acquisition
  - Each cardiac phase has a different TI due to T1 recovery
  - Trigger pulse of TI scout should match that of delayed enhancement sequence.

Phase Sensitive Inversion Recovery (PSIR)

- Preserves the positive and negative polarity of the signal as it recovers from the inversion pulse.
- Infarcted tissue always has a higher signal than viable tissue, regardless of the chosen TI.
- Reconstructs both phase-sensitive and magnitude images.

Motion Artifacts in Delayed Enhancement Imaging

- Single-shot PSIR
  - For uncooperative or arrhythmic patients
  -Insensitive to motion, free breathing
  -bSSFP is used due to speed advantage
  -Lower spatial resolution
Motion Corrected PSIR

- Multiple measurements of cardiac-triggered single-shot acquisition, under free breathing
- Motion-corrected single shot images are averaged to form the final image
- Improved SNR and spatial resolution compared with single-shot PSIR
- Insensitive to motion compared with segmented PSIR

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- Contrast-enhanced MRA
- Non-contrast MRA

Contrast Enhanced MRA

- Time Resolved MRA
  - Temporal resolution: 2-3 sec
  - In-plane resolution: 1-1.3 mm
  - Through-plane resolution: 2-2.5 mm

- High Resolution MRA
  - Arterial phase
  - In-plane resolution: <0.9 mm
  - Through-plane resolution: 1.3 mm
Steady-state MRA

- Intravascular contrast agent
  - Gadofosveset trisodium (Ablavar®, 0.03 mmol/kg)
  - Whole heart imaging with all vasculature
- Inversion recovery T1 gradient echo with ECG triggering and respiratory navigator gating
- 5-10 minutes
- Not limited to the timing/window of acquisition
- Isotropic high spatial resolution
  - 0.9-1.5 mm³

Slow Infusion MRA

- Extracellular contrast agent
  - Gadoterate meglumine (Dotarem®, 0.4 ml/kg)
  - Injection rate: 0.3 ml/s
  - Start acquisition 60 sec after injection
  - Whole heart imaging with all vasculature
- T2-prep gradient echo with ECG triggering and respiratory navigator gating
  - TE = 40 ms, centric encoding, FA = 14°
  - Isotropic high spatial resolution
  - 1.3 mm³

Non-contrast Enhanced MRA

- 3D T2-prep bSSFP
  - Image quality not reliably sufficient
  - Coronary imaging
  - Limited utility for extracardiac vascular anatomy evaluation
Non-contrast Enhanced MRA

- **QISS** (Quiescent-interval slice selective angiography)
  - 2D, ECG-gated, flow dependent
  - Single shot
  - In-plane saturation and tracking venous saturation, followed by bSSFP
  - Quiescent interval for maximal enhancement of inflowing blood signal

Thank you!