Optimizing Pediatric Cardiovascular MRI

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Aug 4th, 2016

Disclosure

- Research agreement with Siemens Medical Solutions

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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

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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

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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

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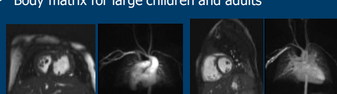
Coil Setup

- 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



3 mo special coil 16 mo Small Flex coil

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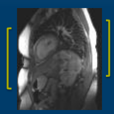
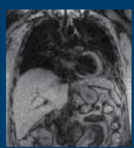
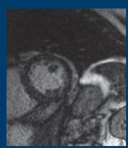
Artifacts due to Coils



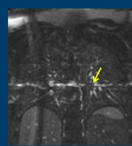
- Sagittal scout - correct centering of the coils around heart
- Alignment between anterior and posterior coils
- Scanned at the iso-center



Anterior coil too low



Anterior coil not connected



Coil Malfunction

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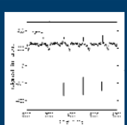
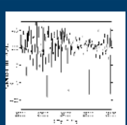
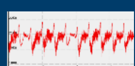
ECG Triggering



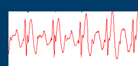
Poor skin prep
Electrode contact



Patient motion



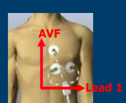
Gradient & RF pulse noise



magneto-hydrodynamic effect

Poor ECG signals result in missing R-wave trigger, miscalculated heart rate and bad image quality.

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



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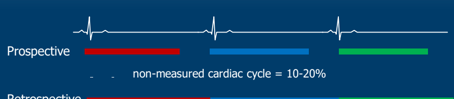
Prospective vs. Retrospective ECG gating



- Prospective gating
  - Acquire data throughout part of the cardiac cycle
  - # of cardiac frames must fit into the acquisition window
  - Discard the end diastole information
  - More used in patients with highly variable R-R intervals
- Retrospective gating
  - Data are acquired continuously throughout the cardiac cycle
  - Data from several different cardiac cycles are combined to yield a cine sequence.

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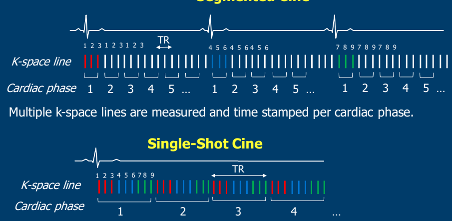
Segmented vs. Single-shot cine



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

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

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CV MRI Applications and Techniques

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

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CV MRI Applications and Techniques

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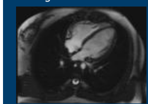
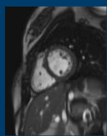
Applications

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

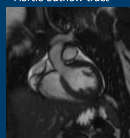
Long-axis 4 chamber



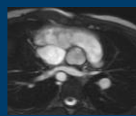
Short-axis 2 chamber



Aortic outflow tract



Aortic valve



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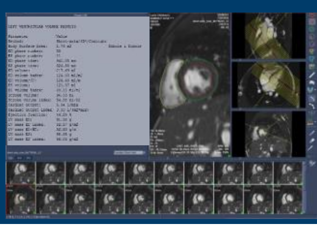
Applications

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



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Cine Acquisition Techniques

Segmented Cine

Require breath-hold
(10-15 sec per slice)

Temporal resolution 40 ms
Spatial resolution 1.8 x 1.8 mm^2

Single-shot Cine

Free breathing
Acquired in one heartbeat

Temporal resolution 120 ms
Spatial resolution 5.0 x 5.0 mm^2

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

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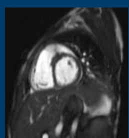
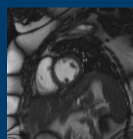
Segmented Cine with Free breathing

- 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

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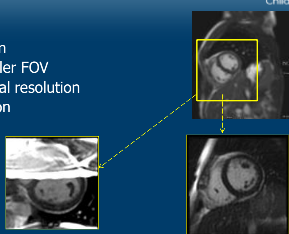
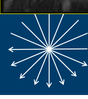
Radial Imaging

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



Cartesian k-space

Radial k-space



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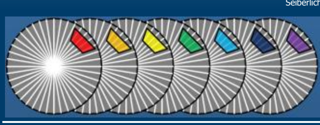
Radial GRAPPA

Seiberlich N. Magn Reson in Med 65:492–505 (2011)



GRAPPA Kernel

time

- 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.

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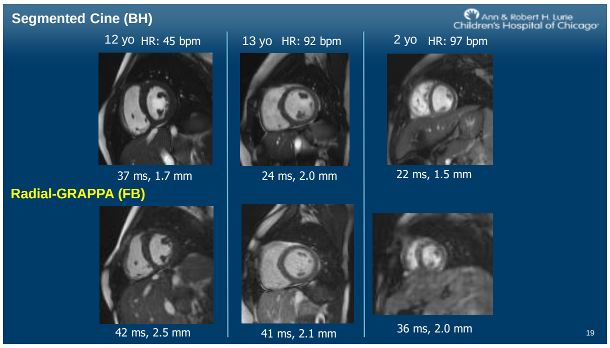
Segmented Cine (BH)
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12 yo HR: 45 bpm
13 yo HR: 92 bpm
2 yo HR: 97 bpm
37 ms, 1.7 mm
24 ms, 2.0 mm
22 ms, 1.5 mm
Radial-GRAPPA (FB)
42 ms, 2.5 mm
41 ms, 2.1 mm
36 ms, 2.0 mm
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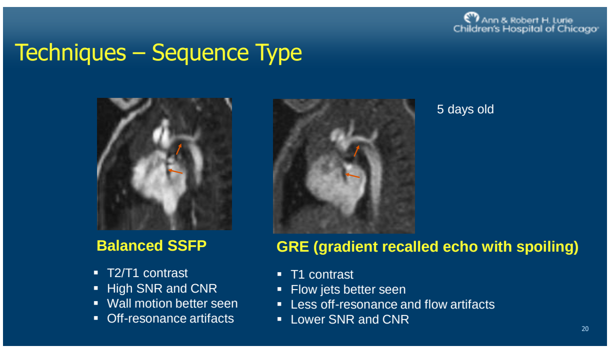
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Techniques – Sequence Type
5 days old
Balanced SSFP
T2/T1 contrast
High SNR and CNR
Wall motion better seen
Off-resonance artifacts
GRE (gradient recalled echo with spoiling)
T1 contrast
Flow jets better seen
Less off-resonance and flow artifacts
Lower SNR and CNR
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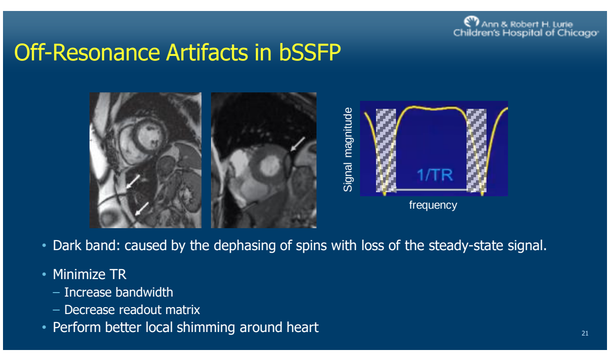
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Off-Resonance Artifacts in bSSFP
Signal magnitude
1/TR
frequency
Dark band: caused by the dephasing of spins with loss of the steady-state signal.
Minimize TR
Increase bandwidth
Decrease readout matrix
Perform better local shimming around heart
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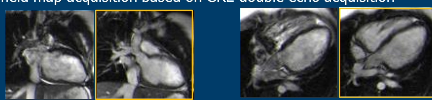
Shimming Method

- 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



standard GRE shimming standard GRE shimming

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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.

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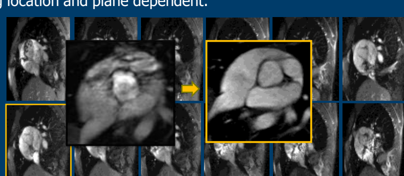
Frequency Scout

- To determine the off resonance frequency and compensate for the center frequency offset.
- Imaging location and plane dependent.



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CV MRI Applications and Techniques

- Function
- **Morphology**
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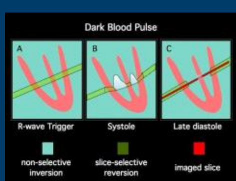
Morphology – Dark Blood Techniques

- 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

http://limpeter-mriblog.blogspot.com/2009/09/pulse-sequences-for-cardiac-mri.html

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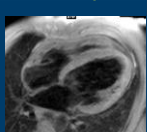
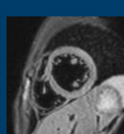
Dark Blood Images



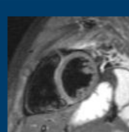
Dark blood T1w

- 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

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DIR Sequence Diagram

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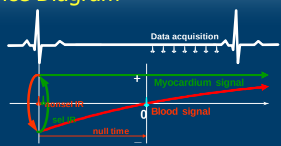
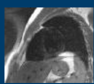
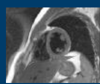
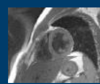


- Null time is directly related to effective R-R (heart rate dependent)


Null time too short: Systolic motion reduces myocardial signal


Null time optimal


Null time too long: Blood signal recovers

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Null Time Optimization

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Null Time = Temporal distance between the double inversion pulses and the excitation pulse

- Calculate optimal null time based on Recovery Time and $T1_{blood}$
  - Recovery Time (RT) = R-R x Trigger pulse
  - $T1_{blood}$ ~1200ms

$$Null\ time = -T1_{blood} \cdot \log\left(\frac{1+e^{-RT/T1_{blood}}}{2}\right)$$

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Dark Blood Imaging post-contrast

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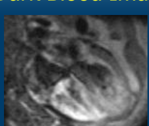
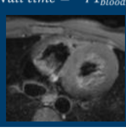
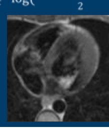


- $T1_{blood}$ is shortened → Null time pre-contrast does not apply
- Re-estimate $T1_{blood}$ after contrast injection using T1 mapping sequence

$$Null\ time = -T1_{blood,post} \cdot \log\left(\frac{1+e^{-RT/T1_{blood,post}}}{2}\right)$$





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CV MRI Applications and Techniques

- Function
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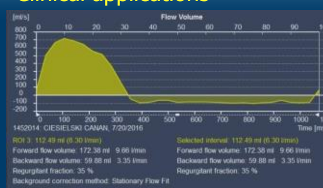
Flow Quantification – Clinical applications

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



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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

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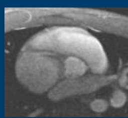
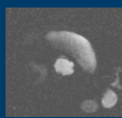


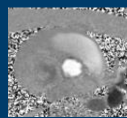
Flow-comp Image

- Flow bright
- Anatomy



Magnitude Image

- Flow bright
- Background suppressed



Phase Image

- Forward flow bright
- Reverse flow black
- Background gray

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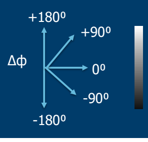
Velocity ENCoding (VENC)

- VENC is the velocity when phase angle reaches +/-180 degrees
- Entire range of velocity is assigned a phase shift between +/-180º
  - 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)



Velocity = $\Delta\phi \cdot$ VENC/180º

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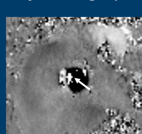
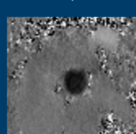
Flow Aliasing

- 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.



VENC too low



VENC too high

- SNR drops
- Inaccurate velocity measurement

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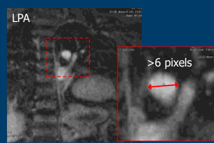
Pediatric PC MRI Challenges

- 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



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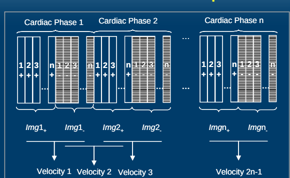
Real-time PC Techniques



Hung-Yu Lin et al. Shared Velocity Encoding: A Method to Improve the Temporal Resolution of Phase-Contrast Velocity Measurements. Magn Reson Med 2012;68:703-710

- 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

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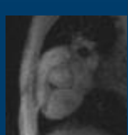
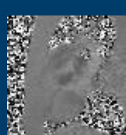
Examples of Real-time PC





- 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.

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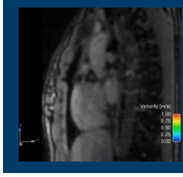
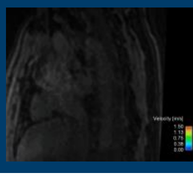
Time-resolved phase contrast (4D flow)

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

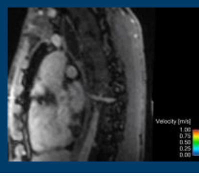
Tricommissural valve



Right-left leaflet fusion



Right non leaflet fusion



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CV MRI Applications and Techniques

- **Function**
- **Morphology**
- **Flow**
- **Perfusion and Viability**
  - First-pass Perfusion
  - Delayed Enhancement
- **Angiography**

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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 90º saturation pulse for T1 weighting preparation
  - Followed by data acquisition (spoiled GRE, bSSFP, EPI)
  - 3-6 slices (heart rate dependent)

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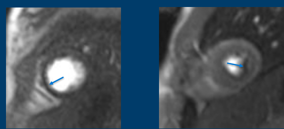
Dark Rim artifacts



- 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.

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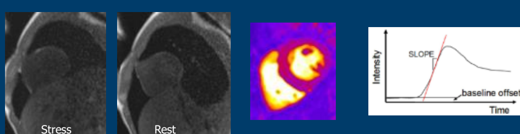
Motion Corrected Perfusion



- 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$_{rest}$

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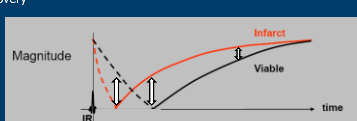
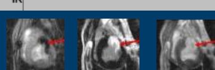
Delayed Enhancement

- Concentration of contrast agent reaches an equilibrium 5 minutes after contrast injection.
- Delayed enhancement is used to assess myocardium viability.
- Acute necrosis or chronic fibrosis has greater concentration of remaining contrast agent.
  - Fast T1 recovery





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Inversion Time (TI) Scout

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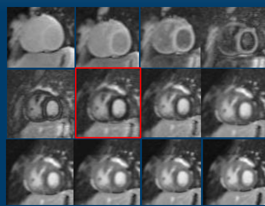
- TI is dependent upon
  - Contrast dose
  - Contrast agent wash-out time
  - Heart rate
- Technique:
  - IR pulse followed by cine data acquisition
  - Each cardiac phase has a different TI due to T1 recovery
  - Trigger pulse of TI scout should match that of delayed enhancement sequence.



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Phase Sensitive Inversion Recovery (PSIR)

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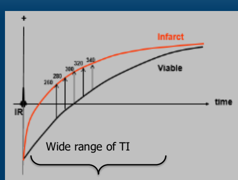

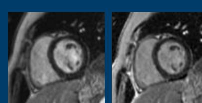

magnitude　phase-sensitive

- 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.

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Motion Artifacts in Delayed Enhancement Imaging

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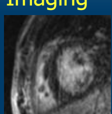
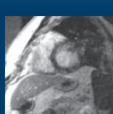
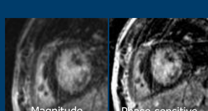


Respiratory motion



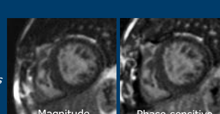
Defective ECG gating

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



Segmented PSIR

vs



Single-shot PSIR

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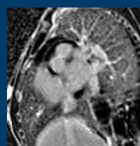
Motion Corrected PSIR

- 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


Segmented PSIR BH


MOCO Segmented PSIR FB

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CV MRI Applications and Techniques

- Function
- Morphology
- Flow
- Perfusion and Viability
- **Angiography**
    - Contrast-enhanced MRA
    - Non-contrast MRA

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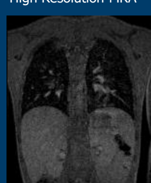
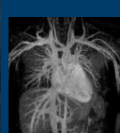
Contrast Enhanced MRA

- 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: 1.1 mm

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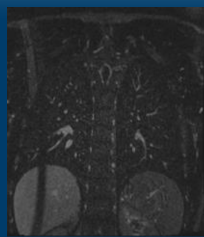
Steady-state MRA

- 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 minutues
  - Not limited to the timing/window of acquisition
  - Isotropic high spatial resolution
    - 0.9-1.5 mm^3



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 = 14º
  - Isotropic high spatial resolution
    - 1.3 mm^3

Non-contrast Enhanced MRA

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

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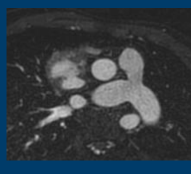
Non-contrast Enhanced MRA

- **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



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Thank you!