Essential tools for Clinical Cardiovascular MRI

Raja Muthupillai, PhD, DABMP, DABR
Director of Imaging Research
Department of Diagnostic and Interventional Radiology
Baylor St Luke’s Medical Center,
Houston, TX 77030
Outline

- Cardiovascular Disease and Non-Invasive Imaging
- Clinical Cardiovascular MRI
  - Cardiac Gating
  - Anatomy
  - Function
  - Flow
  - Perfusion
  - Viability
- Why CMR?
- Summary
Cost of Heart Disease: Lives

610,000 deaths per year; 1 in 4 deaths; ~50% due to CAD; 109 Billion USD
The 22 leading diagnoses for direct health expenditures, United States, 2010 (in billions of dollars).

Percentage breakdown of deaths attributable to cardiovascular disease (United States: 2010).

What we need to see?
- Congenital Anomalies
- Coronaries
- Coronary Blood Flow
- Perfusion
- Myocardium
- Infections
- Viability
- Infiltrative Processes
- Cardiac vessels
- Valves
- Functional Information
- ...

Cardiac Imaging Modalities: Echo

Echocardiography

**Strengths:**
- Real-time
- Inexpensive
- Wall motion
- Valvular function
- Blood flow velocity

**Limitations:**
- Need for acoustic windows
- Limited coverage
- Single contrast mechanism
X-ray Angiography

**Strengths:**
- Exquisite spatial resolution
- Exquisite contrast resolution
- Vascular Morphology
- Potential for therapy

**Limitations:**
- Invasive; Non-negligible risk
- Lack of tissue structure information
- Radiation dose
- Contrast agent dose
x-ray computed tomography

**X-ray CT**

**Strengths:**
- High Spatial resolution
- Exquisite contrast resolution
- Cardiac Anatomy
- Calcifications
- Surgical Planning
- Fast

**Limitations:**
- Cardiac Function
- Valve Function
- Radiation dose
- Contrast agent dose
Nuclear Scintigraphy

**Strengths:**

- Exquisite sensitivity
- Functional Imaging method
- Perfusion and Viability

**Limitations:**

- Modest Spatial Resolution
- Lack of tissue structure information
- Radiation dose
# Cardiac Imaging

<table>
<thead>
<tr>
<th>Parameter</th>
<th>US</th>
<th>XRA</th>
<th>x-ray CT</th>
<th>NM</th>
<th>MRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventricular Function</td>
<td>☑☑☑</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Valvular Function</td>
<td>☑☑☑</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Tissue Characterization</td>
<td>?</td>
<td>?</td>
<td>☑</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Ischemia/Viability</td>
<td>☑</td>
<td>☑☑☑</td>
<td>?</td>
<td>☑☑☑</td>
<td></td>
</tr>
<tr>
<td>Coronary Arteries</td>
<td>☑</td>
<td>☑☑☑</td>
<td>☑☑</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Congenital Anomalies</td>
<td>??</td>
<td>??</td>
<td>☑☑</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
Simplified Outline of an MR Experiment

- The patient or the object is placed within a *homogeneous* magnetic field.
- A radio-frequency wave is sent in for a short duration.
- RF signal from the patient is picked up using a coil.
- The received signal is used for forming an image.

Å Creates a net magnetization due to the slight excess of protons aligning parallel to \( B_o \).
Å Energy Deposition: Creates measurable transverse magnetization.
Å Reconstruction: The received signal is used for forming an image.
Conventional 2DFT MR imaging

Simple 2DFT Imaging:

Time between phase encoding steps: $\text{TR}$
($\sim$ of 100s of ms; $T_1$ relaxation time)

Time from excitation to Readout: $\text{TE}$
($\sim$ of 10s of ms; $T_2$ relaxation time)

Repeat the experiment over several $\text{TR}$
(Allows for longitudinal relaxation between phase encoding steps)
Assumption: Consistency of Data
Outline

Å Cardiovascular Disease and Non-Invasive Imaging
Å Clinical Cardiovascular MRI
  í Cardiac Gating
  í Anatomy
  í Function
  í Flow
  í Perfusion
  í Viability
Å Why CMR?
Å Summary

CHI St. Luke’s Health
Traditional Radiology Department
1. Cardiac Synchronization

Heart moves substantially with

Cardiac Pulsation (~ 1 Hz)

and

Respiration (0.05 Hz)

$T_1$ relaxation rates ~ 1 Hz

Time scale of MR is on the order of **seconds to minutes**
Prospectively Triggered CMR Acquisition

\[ \text{# shots} = \frac{\text{Total PE}}{\text{PE_per_shot}} \]

- Good Image Quality
- Long Scan time
- Linear profile order
ECG Synchronization: Gating

- Maintains Steady State - Continuous RF excitation
- No flashing artifact
- Single or Multi-phase images
- Low SNR / Time consuming (often used in FQ studies)
Retrospective ECG Gating

- Large number of phases
- No flashing artifact
- RR Interval > 1 beat
- Flow Quantification Studies
- Time Consuming
Outline

Cardiovascular Disease and Non-Invasive Imaging

Clinical Cardiovascular MRI
  - Cardiac Gating
  - Anatomy / Tissue Characterization
  - Function
  - Flow
  - Perfusion
  - Viability

Why CMR?

Summary
(2) Myocardial Morphology: Black Blood Imaging Techniques

- Blood Appears Black / Dark
- High Anatomic Detail
- Typically Spin Echo Methods
  - Spin Echo
  - Turbo Spin Echo (TSE)
  - Inversion Recovery TSE
- Diastolic Images (Diastole)
- Cardiac Triggered Sequences
- Rely on blood flow (Outflow)
Simple Spin-Echo and BB contrast

<table>
<thead>
<tr>
<th>Direction and rate of flow</th>
<th>After 90° pulse</th>
<th>Before 180° pulse</th>
<th>Resulting signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td></td>
<td></td>
<td>Bright</td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast</td>
<td></td>
<td></td>
<td>Dark</td>
</tr>
</tbody>
</table>

TR: Time to Repetition
TE: Time to Echo
Simple SE Characteristics:

- Cardiac Triggered Scans
- Free breathing scans
- Quick BB Survey of Anatomy
- Use Multiple NSA (with EPI/TSE)

Tips:
- Use Systolic Acquisitions (for T₁ wtd scans)
- Use Proper Excitation Order (Ascending or Descending)
- Use Saturation pulses (to minimize inflow or fat ghosting)
- Both T₁ and T₂ weighting is possible
Simple SE Limitations

- Blood Signal Suppression depends on Spin Velocity
  - Incomplete suppression of slow flow
  - In-plane flow is problematic
- Simple SE is time consuming
  - Faster Acquisition Techniques - TSE, EPI
- SE-EPI sequence
  - Can introduce artifacts
- Alternative: T₁ based suppression (akin to STIR)
Double Inversion BB Imaging

The first non-selective inversion inverts everything

The second selective inversion pulse re-inverts the signal within slice
BB Pre-pulse ï  A recap
Double Inversion BB : Summary

Â Null the blood based on its $T_1$ (like conventional IR)
Â Retain the full signal for the stationary tissue
Â Minimized the dependency on flow dynamics
Â $T_1$ and $T_2$ weighting is possible (1 or 2 heart beats)
Â Blood Signal within slice still gives signal out of plane
Edema Weighted Imaging Vs $T_2$ mapping in AMI

Acute Myocardial Infarction Model
Evaluation of stem cell therapy
Quantitative Imaging: $T_2$ Analysis

Å The histogram of $T_2$ has:

- A well defined normal myocardium with a Gaussian distribution with a mean of $51 \pm 4.8$ ms at all cut offs, and at all TE

- The AAR had a broad range of $T_2$ values, with a well defined $T_2$ peak at a $T_2$ of $57.3 \pm 6.7$ ms, and another broad peak located at $83.5 \pm 9$ ms
Cardiac Mass - Tissue Characterization:

Lipomatous Hypertrophy of the Interatrial Septum/Right Atrium
Fat Suppression - Triple IR

Double IR

Triple IR
BB Imaging and Tissue Characterization: Inflammation

- Dual IR Prep + STIR
- Inflammation Imaging
  - Vasculitis
  - Takayasu's Arteritis
CMR Morphologic Assessment

- Size/Shape of heart and vessels
- Freely angulated field of view; Large field of view
- Soft tissue contrast:
  - Tumor Characterization
  - Inflammation, Edema
  - Quantitative imaging
Outline

Â Cardiovascular Disease and Non-Invasive Imaging

Â Clinical Cardiovascular MRI
  - Cardiac Gating
  - Anatomy / Tissue Characterization
  - Function
  - Flow
  - Perfusion
  - Viability

Â Why CMR?

Â Summary
Gradient Echo Basics

- After one RF pulse, FID
- After two or more RF pulses, we get an FID + Spin Echo
- When the transverse magnetization is spoiled or destroyed, we get $T_1$-FFE or spoiled gradient echo
- When it is preserved carefully we get TrueFISP, or bFFE.
- The preservation is done by carefully balancing the gradient areas along all axis to be zero for each TR.
Steady State Free Precession Vs $T_1$-FFE

Transverse magnetization spoiled after each RF pulse.
They do not contribute any signal in subsequent excitations

$T_1$-FFE

Transverse magnetization coherence is carefully preserved after each RF pulse - by unwinding the phase encoding gradient, balancing the read and slice-select gradients, and with short TR

b-FFE
Bright Blood Imaging - Function

- **TFE**
  - FLASH, SPGR
  - Short TE/Short TR
  - Routine Evaluation

- **FFE-EPI**
  - Modest TE
  - High Temporal Res

- **SSFP**
  - bFFE/TrueFISP/FIESTA
  - High Blood/Tissue Contrast
  - High Temporal Resolution
  - Flow “Independent”
Myocardial Function: Bright Blood Imaging

**T₁-TFE:**
1. Flashing (HR)
2. Robust
3. Suitable for 3.0 T
4. Inflow-dependent

**T₁-wtd EPI:**
1. Flow Sensitive (Long TE)
2. Valvular Assessment
3. High Frame Rate
4. Prone to EPI Artifacts

**SSFP:**
1. High Bld/Myo contrast (T₂/T₁ ratio difference)
2. Sequence of choice
3. Flow insensitive
4. Challenging for 3.0T
SSFP Field Homogeneity Requirements

- SNR independent of TR
- Shortest possible TR
- Requires high field homogeneity
- Autoshim / Use shim volumes if necessary!
- Typical TR $\leq 4$ msec
LV function Evaluation

- End Diastolic Volume (EDV)
- End Systolic Volume (ESV)
- Stroke Volume (SV)
- Ejection Fraction (EF (%))
- Cardiac Mass

Regional Wall motion information
Why is this important?

- CMR is highly reproducible;
- Devoid of geometric assumptions
- Both RV and LV volumes

<table>
<thead>
<tr>
<th>To detect</th>
<th>n req. for Echo</th>
<th>n req. for MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 ml change in EDV</td>
<td>66</td>
<td>13</td>
</tr>
<tr>
<td>10 ml change in ESV</td>
<td>82</td>
<td>12</td>
</tr>
<tr>
<td>10 gm change in LV mass</td>
<td>194</td>
<td>20</td>
</tr>
<tr>
<td>3% change in EF</td>
<td>73</td>
<td>7</td>
</tr>
</tbody>
</table>

In heart failure patients; power = 0.9

p < 0.05
Outline

Cardiovascular Disease and Non-Invasive Imaging

Clinical Cardiovascular MRI
  • Cardiac Gating
  • Anatomy / Tissue Characterization
  • Function
  • Flow
    • Perfusion
    • Viability

Why CMR?

Summary
Myocardial Ischemia ï Overview

Myocardial Function

Normal Resting Mechanical Function

Is it ischemic? Stress Test?

Reversible Injury

Stunning and Hibernation

Irreversible Injury

Mechanical Dysfunction
Some Definitions

**Ischemia**: Impaired blood supply; inducible defect with stress

**Stunning**: Transient Mechanical Dysfunction due to acute ischemic insult

**Hibernation**: Adaptation to chronic ischemia via downregulation.

**Cell death**: Loss of cell membrane integrity; irreversible injury either via apoptosis or necrosis.
Myocardial Blood Flow Reserve

Stress Perfusion

Qualitative Analysis

Viability

% Lumen narrowing ->

Myocardial Blood Flow Reserve

0 1 2 3 4

Stress

Rest

0 50 100

Myocardial Blood Flow Reserve

CHI St. Luke’s Health
MR Perfusion Measurement

- Changes in $T_1$ caused by Gd-DTPA during first pass indicate microvascular flow.

- At low concentrations, $T_1$ changes are linearly related to concentration of Gd-DTPA.

- The SI in a $T_1$ weighted sequence can therefore be linked to the concentration of Gd-DTPA.
Perfusion Analysis:

\[ RMU = \frac{\frac{MU}{S0}}{\frac{LVMU}{LVS0}} \times 100\% \]

- Mean upslope
- Relative mean upslope
- Time to arrival
- Time to peak
- Peak enhancement
- Relative peak enhancement

MR signal

LVMU

Bloodpool

Myocardial signal

LVS0
S0

T0
TTP
Myocellular matrix: Before Injury

Intact Myocytes

Distribution volume For Extracellular agent (0.3)
Irreversible Injury: Distribution volume ($V_d$) for Gd goes up

- Intact Myocytes
- Injured Myocytes
- Distribution volume for Extracellular agent
Myocellular Injury and $V_d$

- Loss of cell membrane integrity
  - Increased Distribution volume for Gadolinium
- Chronic Case
  - Increased deposition of fibrous tissue
    - Collagen matrix
  - Increased distribution volume for an extracellular contrast medium
- Differential Accumulation of Extravascular agent
Delayed-Enhancement MRI
Myocardial Viability MRI

- High Contrast Resolution
- Transmurality of Infarction
- Well validated
- Clinically Simple to Use
Why assess myocardial viability?

Death Rates in Patients +/- Revascularisation

- **NON-VIABLE**
  - MEDICAL: 6.2%
  - REVASC: 7.7%
  - P = 0.23 (Δ 23%)

- **VIABLE**
  - MEDICAL: 3.2%
  - REVASC: 16%
  - P < 0.0001 (Δ 80%)

Meta-analysis > 3000 pts
PET, TI SPECT, ECHO


Courtesy: Dr. Cheong, MD, BSLMC
SLEH MV Trial: Segmental Wall Motion

Accepted for publication, JACC 2013
Non-Ischemic CM

TI: 200  TI: 250  TI: 300
CMR and Viability

- Simple technique to use
  - IV line and MR contrast
- High contrast resolution
- Transmurality of Infarction
  - Guides clinical decision making
- Ischemic Cardiomyopathy
  - Acute and Chronic MI
- Non-ischemic cardiomyopathy
  - Comprehensive Evaluation ($T_2$, $T_1$, $T_{1\rho}$ etc.)
Outline

- Cardiovascular Disease and Non-Invasive Imaging
- Clinical Cardiovascular MRI
  - Cardiac Gating
  - Anatomy / Tissue Characterization
  - Function
  - Flow
  - Perfusion
  - Viability
- Why CMR?
- Summary
# Cardiac Imaging

<table>
<thead>
<tr>
<th>Parameter</th>
<th>US</th>
<th>XRA</th>
<th>x-ray CT</th>
<th>NM</th>
<th>MRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV Function</td>
<td>✅✅✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅✅✅</td>
</tr>
<tr>
<td>Valvular Function</td>
<td>✅✅✅</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>✅✅</td>
</tr>
<tr>
<td>Tissue Characterization</td>
<td>?</td>
<td>?</td>
<td>✅</td>
<td>?</td>
<td>✅✅✅</td>
</tr>
<tr>
<td>Ischemia/Viability</td>
<td>✅</td>
<td>✅✅</td>
<td>?</td>
<td>✅✅✅</td>
<td>✅✅✅</td>
</tr>
<tr>
<td>Coronary Arteries</td>
<td>✅</td>
<td>✅✅✅</td>
<td>✅✅</td>
<td>?</td>
<td>✅</td>
</tr>
<tr>
<td>Congenital Anomalies</td>
<td>??</td>
<td>??</td>
<td>✅✅</td>
<td>?</td>
<td>✅✅</td>
</tr>
</tbody>
</table>
CMR : Clinical Outcomes

Å Multitude of soft-tissue contrast manipulations:
  - Tissue characterization; Tumors; Structure; Freely Angulated FOV

Å Ventricular Function: Global and Regional
  - Devoid of geometrical assumptions; Accurate/Precise; Both RV and LV

Å Flow : Evaluation of Valvular Function
  - Assessment of regurgitation and stenosis

Å Perfusion
  - Non-invasive assessment of ischemia; Quantitation; No-radiation

Å Myocardial Viability
  - High contrast resolution; Non-transmural infarction; Patient mgt.
CMR: Impediments

- Cumbersome technology; Time consuming
- Not suitable for claustrophobic patients
- Not suitable (at the moment) for patients with pacemakers
- Requires Expertise: Technologist / Clinician / Physics
- Radiology / Cardiology Practice Cultures
Thank you!
Phase contrast MRA: Principles

\[ \omega \propto B_0 \]

Precessional Frequency is proportional to field gradient.
Phase Velocity Mapping: Principle - I

A Static Spins and magnetic field gradients
A Static Spins and magnetic field gradients
Phase Velocity Mapping: Principle - 2
Static spins do not accrue phase in the presence of bipolar gradients (or any other gradient with a zero net area)!
Phase Velocity Mapping: Principle - 3
Phase Velocity Mapping: Principle - 3
Spins moving in the direction of a bi-polar gradient do accumulate a net phase shift.
Concept of Velocity Aliasing

-45 cm/s
-90 cm/s
-135 cm/s
0 cm/s
+45 cm/s
+90 cm/s
+135 cm/s
+210 cm/s
180 cm/s
Or
-150 cm/s?
Phase Contrast MRA
Qflow analysis on console
Phase Contrast: Key Points

- **Amplitude of Velocity (Speed)**
  - MR Angiography, Peak Velocity, Pressure gradient

- **Direction of Velocity (Vector)**
  - Regurgitation, Flow shunts, etc.

- **Strength of Velocity Encoding: \( V_{\text{enc}} \)**
  - Aliasing, Visualization of arteries/veins

- **Shape of flow waveform**
  - Wall-shear stress; Systemic Physiology

[CHI St. Luke’s Health]
Functional MRI for pre-surgical planning

Foot Movement

Visual System
Diffusion Tensor Imaging
Thank you!