CARDIAC VOLUME AND FLOW MEASUREMENTS

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FINANCIAL DISCLOSURE

- None

"How come we never complicate equations?"

"Ohhhhhhh . . . Look at that, Schuster . . . Dogs are so cute when they try to comprehend quantum mechanics."
K-SPACE

\[ W(k) = \int_V w(r) \exp[2\pi i (k \cdot (r + d))] \, dr = \exp[2\pi i (k \cdot d)] W(k). \]

Fig.1. K-space image of a simple phantom

\[ q(r) = \int Q(k) \exp[-2\pi i (k \cdot r)] \, dk \approx q(r) = \sum_q Q(q) \exp[-2\pi i (q \cdot r)] \]

\[ dS(t) = q(r) \exp(-R_2^* t) \exp[2\pi i \Phi(t)] \, dr, \text{ where } \Phi(t) = (\Delta f)t. \]
“If you don’t know where you’re going, you might end up some place else.” – Yogi Berra
LEARNING OBJECTIVES

• Prescribe scan for flow and functional analysis

• Perform flow analysis for vessel and valve stenosis and regurgitant valves

• Perform functional analysis of the left ventricle

• List at least 3 clinical use cases for flow and functional analysis
PHASE CONTRAST IMAGING

- Exploit moving blood acquires phase shift in presence of velocity encoding gradients
- Phase shift (signal) is directly proportional to velocity of blood
- 2 measurements: positive and negative bipolar gradients
  - Subtract- only moving objects result in signal
- Reliability
  - Not limited by acoustic windows like US
  - Regular calibration with flow phantom advisable
GATING

• Prospective- triggered
  • Advantage- minimize effects of mild arrhythmia
  • Disadvantage- Excludes some data at end diastole

• Retrospective- continuous
  • Advantage- No portion of cycle excluded
  • Disadvantage- More sensitive to arrhythmia- software minimize effect
BREATH-HOLD VS FREE BREATHING

• Breath-hold
  • Advantages- Removes motion artifacts and Shorter acquisition time
  • Disadvantage- May compromise temporal resolution (≥50 msec)

• Free breathing
  • Advantage- Higher temporal resolution (≤50 msec)
  • Disadvantages- Motion artifact from breathing and Longer acquisition time
VELOCITY ENCODING

- $V_{\text{enc}}$ - maximum velocity that produces a $180^\circ$ phase shift

- Closer the $V_{\text{enc}}$ is to the actual velocity the more accurate the measurement
  - $V_{\text{enc}}$ too low results in aliasing
    - High flow in one direction erroneously encoded as fast flow in the opposite direction
VELOCITY ENCODING

- **In-plane**
  - $V_{\text{enc}}$ direction is encoded within the plane
  - Useful for determining flow direction

- **Through-plane**
  - $V_{\text{enc}}$ encoded through the plane of the slice
  - Commonly used for accurate measurement of velocity and flow
  - Plane of imaging must be directly orthogonal to region of interest
IN-PLANE FLOW

Aortic coarctation
THROUGH-PLANE FLOW

Magnitude

Phase
MEASURING FLOW
TIPS

• Set spatial resolution appropriately for vessel size
  • Prevent underestimation due to partial volume

• Temporal resolution set appropriately
  • Higher temporal resolution for high flow

• Aortic regurgitant jets best assessed with a slice just below aortic valve
VOLUME AND MASS

- MRI is reference standard for volume and mass
  - Accurate, highly reproducible and without geometric assumption

- Limitations
  - Relatively poor depiction at base because of slice thickness 8-10 mm
  - Significant through plane motion at base - for normal ventricles the through-plane motion exceeds the typical section thickness

- Global RV function - axial slices has advantages over short-axis

AUTO OR SEMI-AUTO SEGMENTATION

- Methods based on geometric (2D or 3D) or statistical models
  - Geometric model may fail when pathology results in odd shape of ventricle

- Epicardial border detection more complex than endocardial
  - Varying intensity of the adjacent structures
    - Lung, diaphragm, RV blood, or epicardial fat
  - Model-based segmentation methods most successful

- Volumetric and EF measurements by MRI and CT shown very comparable
FUNCTION
FULL FUNCTIONAL ANALYSIS
MYOCARDIAL MASS

• Measure LV myocardial volume and multiply by specific gravity of 1.05 g/ml

• Myocardial volume = sum of the area of myocardium x slice thickness
  • Area is between the endocardial and epicardial tracings
  • Papillary muscles usually included in chamber volume not myocardial mass
    • Hypertrophic cardiomyopathy- consider papillary muscles
      • Prevent underestimation of myocardial mass
      • Prevent overestimation of LV diastolic volume
      • Prevent underestimation of LV EF
“Algebra class will be important to you later in life because there’s going to be a test six weeks from now.”
FUNCTION FORMULAS

- Ventricular ejection fraction (EF) = $\frac{EDV - ESV}{EDV}$
  - Ventricular length (base to apex) is shorter at end-systole
    - Draw on more SA slices at end-diastole then end-systole

- Stroke volume (SV) = EDV – ESV

- Cardiac Output (CO) = SV x heart rate

- Cardiac Index (CI) = CO/body surface area (BSA)
CLINICAL APPLICATIONS
CLINICAL APPLICATIONS

• Pressure gradient across vessel or valve stenosis
• Regurgitant fractions for cardiac valves
• Cardiomyopathies- myocardial mass and function
• Diastolic dysfunction/heart failure- E/A ratio
• Pericardial disease- function
• Pulmonary hypertension- RV function
• Congenital- shunts (Qp/Qs)
  • Qp/Qs >1- left to right shunt
  • Qp/Qs <1- right to left shunt
  • Moderate >1.5 or large >2.2
STENOSIS WITH GRADIENT
AORTIC COARCTATION
# Aortic Coarctation

**Slice Position:** SP H23.8  
**Region:** 1  
**Range, ms:** 0 to 798  
**Venc Adjustment:** -550 cm/sec 550 cm/sec  
**Body Surface Area (BSA):** 1.72 m²

### Velocity

- **Peak Velocity:** 396.49 cm/sec  
  **Average Velocity:** 21.25 cm/sec  

### Flow

- **Average Flow Over Range:** -115.05 ml/sec  
- **Average Flow Per Minute:** -6.51 l/min  
- **Forward Volume:** 0.000 ml  
- **Reverse Volume:** 91.70 ml  
- **Net Forward Volume:** -91.70 ml  
- **Net Forward Volume / BSA:** -53.39 ml/m²

### Area

- **Average Area:** 5.41 cm²  
- **Minimum Area:** 4.40 cm²  
- **Maximum Area:** 7.70 cm²

**Gradient**  
\[ \text{Gradient} = 4V^2 = 4(16) = 64 \text{ mmHg} \]
AORTIC STENOSIS
AORTIC STENOSIS

Venc = 150 cm/sec

Venc = 300 cm/sec
STENOSIS CLASSIFICATION

- **Aorta**
  - **Velocity**
    - Mild- 2.6-2.9 m/sec
    - Moderate- 3.0-4.0 m/sec
    - Severe- >4.0 m/sec
  - **Opening area**
    - Mild- >1.5 cm²
    - Moderate- 1.0-1.5 cm²
    - Severe- <1.0 cm²

- **Pulmonary**
  - **Velocity**
    - Mild- <3 m/sec
    - Moderate- 3-4 m/sec
    - Severe- >4 m/sec
REGURITANT VALVE CLASSIFICATION

- Mild- <30%
- Moderate- 30-49%
- Severe- ≥ 50%
PULMONIC REGURGITATION
Regurgitant Fraction = \[ \frac{\text{Reverse Flow}}{\text{Forward Flow}} = \frac{64}{113} = 57\% \]
MITRAL REGURGITATION
MITRAL REGURGITATION

• SV = aortic forward flow + mitral regurgitation

• SV – aortic forward flow = mitral regurgitant volume

• Mitral regurgitant fraction = $\frac{\text{Mitral regurgitant volume}}{\text{Stroke volume}}$
CARDIOMYOPATHY
HYPERTROPHIC CARDIOMYOPATHY

<table>
<thead>
<tr>
<th>Cardiac Function</th>
<th>Normal Range (M MRI)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ejection Fraction EF</td>
<td>56.00 ... 78.00</td>
<td>%</td>
</tr>
<tr>
<td>End Diastolic Volume EDV</td>
<td>77.00 ... 195.00</td>
<td>ml</td>
</tr>
<tr>
<td>End Systolic Volume ESV</td>
<td>19.00 ... 72.00</td>
<td>ml</td>
</tr>
<tr>
<td>Stroke Volume SV</td>
<td>51.00 ... 133.00</td>
<td>ml</td>
</tr>
<tr>
<td>Cardiac Output CO</td>
<td>----</td>
<td>l/min</td>
</tr>
<tr>
<td>Myocardial Mass (at ED)</td>
<td>118.00 ... 238.00</td>
<td>g</td>
</tr>
<tr>
<td>Myocardial Mass (Avg)</td>
<td>118.00 ... 238.00</td>
<td>g</td>
</tr>
</tbody>
</table>

Filling and Ejection Data

<table>
<thead>
<tr>
<th></th>
<th>Normal Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Ejection Rate</td>
<td>n.a.</td>
<td>ml/sec</td>
</tr>
<tr>
<td>Peak Ejection Time</td>
<td>n.a.</td>
<td>msec</td>
</tr>
<tr>
<td>Peak Filling Rate</td>
<td>n.a.</td>
<td>ml/sec</td>
</tr>
<tr>
<td>Peak Filling Time from ES</td>
<td>n.a.</td>
<td>msec</td>
</tr>
</tbody>
</table>
SEPTAL HYPERTROPHY
SUBVALVULAR FLOW

Venc = 300 cm/sec
## SUBVALVULAR FLOW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient Height</td>
<td>66.93 in</td>
</tr>
<tr>
<td>Patient Weight</td>
<td>220.26 lbs</td>
</tr>
<tr>
<td>Heart Rate</td>
<td>59 Beats/min</td>
</tr>
<tr>
<td>Slice Position</td>
<td>SP F52.7</td>
</tr>
<tr>
<td>Region</td>
<td>1</td>
</tr>
<tr>
<td>Range, ms</td>
<td>0 to 967</td>
</tr>
<tr>
<td>Vena Adjustment</td>
<td>-300 cm/sec</td>
</tr>
<tr>
<td>300 cm/sec</td>
<td></td>
</tr>
<tr>
<td>Body Surface Area (BSA)</td>
<td>2.11 m²</td>
</tr>
<tr>
<td>Velocity</td>
<td></td>
</tr>
<tr>
<td>Peak Velocity</td>
<td>252.07 cm/sec</td>
</tr>
<tr>
<td>Average Velocity</td>
<td>7.34 cm/sec</td>
</tr>
<tr>
<td>Flow</td>
<td></td>
</tr>
<tr>
<td>Average Flow Over Range</td>
<td>66.95 ml/sec</td>
</tr>
<tr>
<td>Average Flow Per Minute</td>
<td>3.82 l/min</td>
</tr>
<tr>
<td>Forward Volume</td>
<td>85.33 ml</td>
</tr>
<tr>
<td>Reverse Volume</td>
<td>20.65 ml</td>
</tr>
<tr>
<td>Net Forward Volume</td>
<td>64.68 ml</td>
</tr>
<tr>
<td>Net Forward Volume / BSA</td>
<td>30.71 ml/m²</td>
</tr>
<tr>
<td>Area</td>
<td></td>
</tr>
<tr>
<td>Average Area</td>
<td>9.12 cm²</td>
</tr>
<tr>
<td>Minimum Area</td>
<td>8.26 cm²</td>
</tr>
<tr>
<td>Maximum Area</td>
<td>9.53 cm²</td>
</tr>
</tbody>
</table>
PULMONARY HYPERTENSION
CONGENITAL SHUNT
CONGENITAL WITH SHUNT

Aortic Flow (S)

Pulmonary Flow (P)
### Congenital with Shunt

#### Aortic Flow (S)
- Peak Velocity: 144.02 cm/sec
- Average Velocity: 15.44 cm/sec
- Average Flow Over Range: 122.13 ml/sec
- Average Flow Per Minute: 6.97 l/min
- Forward Volume: 103.68 ml
- Reverse Volume: 1.23 ml
- Net Forward Volume: 102.45 ml
- Net Forward Volume / BSA: 45.03 ml/m²

#### Pulmonary Flow (P)
- Peak Velocity: 108.47 cm/sec
- Average Velocity: 18.15 cm/sec
- Average Flow Over Range: 185.74 ml/sec
- Average Flow Per Minute: 10.50 l/min
- Forward Volume: 144.25 ml
- Reverse Volume: 0.444 ml
- Net Forward Volume: 143.81 ml
- Net Forward Volume / BSA: 63.20 ml/m²

\[
\frac{Q_p}{Q_s} = \frac{144}{104} = 1.4
\]
LEARNING OBJECTIVES

“IT’S LIKE DEJA VU ALL OVER AGAIN.” - YOGI BERRA

• Prescribe scan for flow and functional analysis

• Perform flow analysis for vessel and valve stenosis and regurgitant valves

• Perform functional analysis of the left ventricle

• List at least 3 clinical use cases for flow and functional analysis
Thank You

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WALL MOTION

• Various quantitative methods but visual assessment remains the standard
  • Normal, hypokinetic, akinetic, or dyskinetic
AORTIC REGURGITATION

Magnitude Image

Phase Image
Regurgitant Fraction = \frac{Reverse Flow}{Forward Flow} = \frac{51}{143} = 36\%
## POOR FUNCTION

### Left Ventricle - Absolute

<table>
<thead>
<tr>
<th>Cardiac Function</th>
<th>Normal Range (M) (MRI)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ejection Fraction</strong></td>
<td>EF 29.2</td>
<td>%</td>
</tr>
<tr>
<td>End Diastolic Volume</td>
<td>EDV 166.9</td>
<td>ml</td>
</tr>
<tr>
<td>End Systolic Volume</td>
<td>ESV 118.1</td>
<td>ml</td>
</tr>
<tr>
<td>Stroke Volume</td>
<td>SV 48.8</td>
<td>ml</td>
</tr>
<tr>
<td>Cardiac Output</td>
<td>CO</td>
<td>l/min</td>
</tr>
<tr>
<td>Myocardial Mass (at ED)</td>
<td>144.6</td>
<td>g</td>
</tr>
<tr>
<td>Myocardial Mass (Avg)</td>
<td>148.9 ± 6.1</td>
<td>g</td>
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### Right Ventricle - Absolute

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<tr>
<td><strong>Ejection Fraction</strong></td>
<td>EF 44.7</td>
<td>%</td>
</tr>
<tr>
<td>End Diastolic Volume</td>
<td>EDV 106.8</td>
<td>ml</td>
</tr>
<tr>
<td>End Systolic Volume</td>
<td>ESV 59.1</td>
<td>ml</td>
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<td>Stroke Volume</td>
<td>SV 47.8</td>
<td>ml</td>
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SEGMENTAL WALL MOTION

- Evaluate myocardial thickness and motion over the complete cycle

VOLUMES FOR FUNCTION

End Diastole

End Systole
PERFORMING FLOW ANALYSIS

Estimate pressure gradient using Modified Bernoulli Equation
Pressure \( P \) = 4\( V^2 \) where velocity \( V \) = m/sec
VELOCITY ENCODING

- $V_{\text{enc}}$ is commonly encoded in single direction
- $V_{\text{enc}}$ encoded in three directions
  - Longer time so temporal resolution can be compromised especially if performing breath hold acquisition
  
- $V_{\text{enc}}$ is inversely proportional to amplitude of gradient
  - Lower the velocity ($V_{\text{enc}}$) the higher the gradient strength
STRAIN

- Tagged cine MRI images
  - Apply special radio-frequency pre-pulse immediately after detection of the R wave
  - Pre-pulse oriented perpendicular to imaging plane- local saturation- lines
  - Short-axis and long-axis 2D images allow the determination of 3D strain
  - Tags usually fade in early diastole due to T1 relaxation
  - Very limited for RV evaluation- thinness and strain orientation
- New inherent tissue tracking methods
  - HARP, DENSE, SENC
PERFUSION

- T1-sensitive imaging sequence during first pass of gadolinium agent
  - Most robust and studied
  - Main issue is trade off between spatial and temporal resolution
    - Image several slices (3-5 SA) every or every other heart beat (over 60 s after contrast)
    - In-plane resolution of 2-3 mm- separate endocardial and epicardial layers
    - Pharmacologic stress with adenosine or dipyridamole
  - Visual assessment validated and most commonly used
  - Semi-quantitative- upslope of the signal intensity curve most widely adopted and improves over visual assessment
  - Absolute blood flow- mL/min/gram
    - Requires registration of the images due to patient motion over time of acquisition
    - Important with multi-vessel disease
DELAYED ENHANCEMENT

- Accurately quantify acute and chronic infarcts
- Size of scar can be derived from pixels with increased signal expressed in grams or % of myocardium
- Transmurality can be derived as the thickness of scar relative to local wall thickness