Peak Velocity and Valve Regurgitation

Comparison of Catheterization, Echocardiography, and Phase Contrast MRI
Objectives

1. Compare catheterization, echocardiography, and phase contrast MRI

2. Review methodologies for grading stenosis and regurgitation

3. Identify common assumptions and limitations of each technique

4. Describe several situations where these assumptions are misleading
General Principles

Vena Contracta

- Narrow jet immediately distal to a stenosis containing the peak velocities
- Best sampled with continuous wave Doppler
- MRI measurements are challenged by small size, temporal resolution, and adjacent turbulence
General Principles
Peak Velocity

• Peak and mean gradients can be calculated from velocities using the simplified Bernoulli equation

  • \( \Delta P = 4v^2 \)

  • Assumption - Proximal velocity < 1 m/sec

  • If proximal velocity > 1.5 m/sec, or distal velocity < 3 m/sec, then full Bernoulli equation is appropriate

  • \( \Delta P = 4(v_{distal}^2 - v_{proximal}^2) \)
General Principles
Cardiac Catheterization

• How does one determine peak velocity? - You don’t
• Measure pressure gradients directly
  • Velocity is derived from Torricelli law;
    • Velocity = $\sqrt{2gh}$, where;
      • $g =$ velocity of acceleration from gravity
      • $h =$ pressure gradient
• Peak to peak gradient ideal, but not physiologically simultaneous during cardiac cycle
• Mean gradient is often calculated instead

General Principles
Cardiac Catheterization

- Assessment of valvular stenosis relies on:
  - Trans-valvular pressure gradient
  - Cardiac output
  - Gorlin formula;
    - Valve Area = Flow/(C_c \times C_v \times \sqrt{2gh})
      - C_c = coefficient of orifice contraction - physiologic < anatomic
      - C_v = coefficient of velocity loss - kinetic energy lost to friction
General Principles
Cardiac Catheterization

Cardiac Output

- Gold standard is the Fick principle;
  
  \[ CO = \frac{\text{Oxygen consumption}}{(\text{concentration of } O_2 \text{ arterial} - \text{concentration of } O_2 \text{ venous})} \]

- Cumbersome to measure in practice

- Standard values are often assumed instead (125 ml/min/m²; potential error of up to 40%)

- Thermodilution/Indicator methods often substituted instead;
  
  - But inaccurate with;
    
    - Low CO
    
    - Dysrhythmias
    
    - Significant tricuspid regurgitation
Comparison of PC MRI to Conventional Oximetry

- 30 patients with single ventricle and superior cavopulmonary connection
- Compared pulmonary and systemic blood flow as calculated by the Fick equation and measured via PC MRI
- Using PC MRI as the reference;
  - Qp:Qs as derived from Fick did not correlate to results from PC CMR - did not account for systemic to pulmonary collaterals
  - Oximetry underestimated Qp by 32%
  - Oximetry overestimated Qs by 15%
  - Concluded that Fick-derived flow estimates are inherently unreliable due to lack of true mixed venous saturation

Limitations of Phase Contrast MRI

Spatial Resolution

• Typically 1.0-2.0 mm in-plane resolution
• Slice thickness often 5-7 mm; minimum ~ 3.5 mm
• Intrinsic averaging of intra-voxel velocities limits ability to detect peak velocities
• Through plane vessel motion also intrinsically limits resolution
Limitations of Phase Contrast MRI

Temporal Resolution

- Temporal resolution typically 20-50 msec
  - \((R-R = 500-1000 \text{ msec with 20 frames/cycle})\)
- Voxels are acquired over multiple heart beats with segmented acquisition
- Velocities will vary from beat to beat
- Resulting measured velocities represent an average
- This also effectively dampens peak velocities
Limitations of Peak Velocity Assessment with MRI Phase Contrast

• Intravoxel dephasing
  • Spatial resolution
    • Reduces partial volume effects
    • Limitations:
      • S/N
      • Temporal resolution
• Higher order turbulence
  • Minimize $T_E$

Limitations of Peak Velocity Assessment with MRI Phase Contrast

Vectorial alignment with jet

• 3 dimensional vector

• Inaccuracies of up to 20 degrees usually considered acceptable

• Potential for multiple jets
Limitations of Phase Contrast MRI

- Background noise
  - Phase offset errors
    - Eddy currents - exaggerated away from isocenter
    - Gradient field effects
  - Correction methods:
    - Repeat scans on phantoms with identical parameters and slice orientation
      - Time consuming
    - Automated background correction:
      - Little significant effect on Qp:Qs
      - Still some error as compared to SSFP measurements

# Aortic Stenosis

## Echocardiographic Assessment

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Mild Aortic Stenosis</th>
<th>Moderate Aortic Stenosis</th>
<th>Severe Aortic Stenosis</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak velocity (m/sec)</td>
<td>&lt; 2.6</td>
<td>2.6 - 3</td>
<td>3-4</td>
<td>&gt; 4</td>
<td>Requires correct US beam alignment Flow dependent</td>
</tr>
<tr>
<td>Mean gradient</td>
<td>&lt; 25</td>
<td>25-40</td>
<td>&gt;40</td>
<td></td>
<td>Peak to Peak Gradients are not simultaneous. Pressure Recovery. Flow dependent</td>
</tr>
<tr>
<td>Indexed Ao V Area</td>
<td>&gt; 0.85</td>
<td>0.6 - 0.85</td>
<td>&lt; 0.6</td>
<td></td>
<td>Requires flow velocity data and LVOT diameter</td>
</tr>
<tr>
<td>(cm²/m² BSA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simplified Continuity</td>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td>Less accurate with atypical velocity curves</td>
</tr>
<tr>
<td>Equation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>&gt; 0.5</td>
<td>0.25 - 0.50</td>
<td>&lt; 0.25</td>
<td></td>
<td>Ignores LVOT diameter effects</td>
</tr>
<tr>
<td>Anatomic Valve Planimetry (cm²)</td>
<td>&gt; 1.5</td>
<td>1.0 - 1.5</td>
<td>1.0</td>
<td>Valvular calcifications Variable contraction coefficient</td>
<td></td>
</tr>
</tbody>
</table>

* Circulation (2006), 118(15), e523–e661.*
Pressure Recovery

- The increase in pressure downstream from a stenosis due to a reconversion of kinetic energy into potential energy
- The result is that continuous wave Doppler ultrasound will overestimate pressure gradients across a stenosis relative to catheter-derived pressures
- The magnitude of pressure recovery effect is determined by transvalvular velocity and the ratio between the cross sectional areas of the stenotic valve and downstream vessel
- Can often represent the difference between a diagnosis of “severe” and “moderate” stenosis

# Aortic Regurgitation

## Echocardiographic Assessment

<table>
<thead>
<tr>
<th></th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color Doppler Jet Width</td>
<td>Central jet, &lt; 25% of LVOT width</td>
<td>Greater than mild, but no severe signs</td>
<td>Central jet greater than 65% LVOT width</td>
<td></td>
</tr>
<tr>
<td>Doppler Vena Contracta (mm)</td>
<td>&lt; 3</td>
<td>3 - 6</td>
<td>&gt; 6</td>
<td>Can be multiple, eccentric, elliptical</td>
</tr>
<tr>
<td>Left Ventricular Size</td>
<td>Normal</td>
<td>Normal</td>
<td>Increased</td>
<td></td>
</tr>
<tr>
<td>Descending Aortic Diastolic Flow Reversal</td>
<td>Brief</td>
<td>Holodiastolic, &gt; 20 cm/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure T(1/2) Index (msec)</td>
<td>&gt; 500</td>
<td>200-500</td>
<td>&lt; 200</td>
<td>Dependent on LV diastolic pressure, compliance, peripheral arterial resistance, aortic dilation</td>
</tr>
</tbody>
</table>

LVOT: Left Ventricular Outflow Tract

Dependent on LV diastolic pressure, compliance, peripheral arterial resistance, aortic dilation.
Aortic Regurgitation

Asc Ao
RF = 33%

Ao Sinus
RF = 35%
Aortic Valve Regurgitation

- 59 adult patients status post TAVI with Edwards SAPIEN
- Compared aortic regurgitation as assessed by TTE and CMR
- TTE underestimated AR in 81% of patients with moderate AR by CMR
- TTE overestimated ~33% of cases with absent to mild AR by CMR

Valvular Regurgitation

Accurate LV volumes with CMR can aid clinical assessment of the impact of AR, and the high reproducibility is particularly useful for serial assessment, which is important for the management of a condition that has a long asymptomatic phase. CMR-derived LV end-diastolic volumes have also shown some ability to predict the onset of symptoms or other indications for valve surgery [43], and although less strong than quantifying the regurgitation itself, it can provide a useful adjunct in predicting outcome. CMR can also provide a detailed assessment of aortic root anatomy, which can assist in identifying the cause of the regurgitation, and/or whether the root needs replacing at the time of valve replacement surgery.

Taken together, the many CMR techniques useful in AR, including regurgitation quantification, LV volumetric assessment and aortic root anatomy, make CMR the optimal tool for comprehensive assessment.

Mitral regurgitation

As for aortic regurgitation, the main advantages of CMR in mitral regurgitation are in quantitative assessment of both the regurgitation, and ventricular volume and function. CMR can also assess leaflet morphology and valve function, particularly utilising the free choice of image planes to characterise the aetiology of the regurgitation in this complex valve. CMR has good agreement with trans-oesophageal echocardiography for assessing mitral valves for repair [46], though the slice thickness can result in partial volume errors more frequently than echocardiography, which has a very narrow beam width. A good method is to place multiple cine images perpendicular to the mitral valve commissure, facilitating assessment of the individual scallops/coaption, and can identify the site of localised prolapse/regurgitation [47]. This technique can be modified by placing three slices specifically across the commissure, perpendicular to the edge of the leaflet at each of the scallops (Figure 9). This results in reduced partial volume effects in the A1/P1 and A3/P3 views particularly, while also being marginally quicker. Despite these good techniques, transoesophageal echocardiography is likely to remain the optimal investigation for leaflet assessment, due to its

Sources of error

- Downward motion of valve plane toward ventricular apex during systole
- Dilation of aortic sinuses in systole accommodates greater volume without passing through PC slice
- Exacerbated by aortic root dilation and hyperdynamic left ventricle

Aortic Valve Regurgitation

- Assessed aortic regurgitation at three levels
  - Aorta - \textit{ascending}
  - Aortic valve hinge point - \textit{diastole}
  - Aortic valve hinge point - \textit{systole}
- Compared direct measurements of systolic FFlow, diastolic RFlow at each level
- Compared to LV cardiac index (cine SSFP volumetry)
- Compared to pulmonary flow ($Q_{\text{right}} + Q_{\text{left}}$)

Aortic Valve Regurgitation

Conclusions

• Direct measurement of aortic regurgitant volumes and fractions is inaccurate with wide variations in forward, retrograde, and net flows

Recommendation

• Ao R Volume = Ao systolic FFlow_{aov\, diastolic} - Q_{pulmonary}

• Ao R Fraction = (Ao systolic FFlow_{aov\, diastolic} - Q_{pulmonary})/Ao systolic FFlow_{aov\, diastolic}

• Avoids the turbulent regurgitant aortic jet

• Use of the branch pulmonary arteries minimizes motion artifacts $Q_p = (Q_{right} + Q_{left})$

# Pulmonary Regurgitation by Echocardiography

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary Valve</td>
<td>Normal</td>
<td>Normal or abnormal</td>
<td>Abnormal</td>
</tr>
<tr>
<td>RV size</td>
<td>Normal*</td>
<td>Normal or dilated</td>
<td>Dilated</td>
</tr>
<tr>
<td>Jet size by color Doppler§</td>
<td>Thin (usually &lt; 10 mm in length) with narrow origin</td>
<td>Intermediate</td>
<td>Usually large, with a large origin; may be brief in duration</td>
</tr>
<tr>
<td>Jet density and deceleration rate - CW †</td>
<td>Soft; Slow deceleration</td>
<td>Dense, variable deceleration</td>
<td>Dense; steep deceleration; early diastolic flow termination</td>
</tr>
<tr>
<td>Pulmonic systolic flow compared to systemic flow - PW φ</td>
<td>Slightly increased</td>
<td>Intermediate</td>
<td>Greatly increased</td>
</tr>
</tbody>
</table>

*J Am Soc Echocardiogr 2003;16:777-802*
### Pulmonary Regurgitation by Phase Contrast MRI

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regurgitant Fraction</td>
<td>0 - 20%</td>
<td>20 - 40%</td>
<td>&gt; 40%</td>
</tr>
</tbody>
</table>

Results are generally more reliable than for aortic regurgitation:
- Wider orifice
- Smaller pressure gradient

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Regurg Fr 44%  
Regurg Fr 23%
### Mitral Valve - Regurgitation Grading with Echocardiography

<table>
<thead>
<tr>
<th>Grade</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Jet</td>
<td>Small</td>
<td></td>
<td>Large; wall-impinging, swirling in LA</td>
</tr>
<tr>
<td>Vena Contracta Width (mm)</td>
<td>&lt; 3</td>
<td></td>
<td>&gt; 7</td>
</tr>
<tr>
<td>Flow convergence</td>
<td>None or minimal</td>
<td></td>
<td>Large</td>
</tr>
<tr>
<td>Pulmonary veins</td>
<td>None</td>
<td></td>
<td>Systolic reversal</td>
</tr>
<tr>
<td>Left Ventricular Size</td>
<td>Normal</td>
<td></td>
<td>Enlarged</td>
</tr>
<tr>
<td>Mitral Inflow</td>
<td>A wave dominant</td>
<td></td>
<td>E wave dominant</td>
</tr>
</tbody>
</table>
Severe Mitral Regurgitation
# Mitral Valve - Regurgitation Grading with Cardiac Catheterization

<table>
<thead>
<tr>
<th>Grade</th>
<th>Left Atrial Opacification</th>
<th>Left Atrial Enlargement</th>
<th>Timing</th>
<th>Clearance</th>
<th>Pulmonary veins</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+</td>
<td>Brief</td>
<td>None</td>
<td>Several cycles</td>
<td>Rapid</td>
<td>None</td>
</tr>
<tr>
<td>2+</td>
<td>Moderate</td>
<td>None</td>
<td>Every cycle</td>
<td>Intermediate</td>
<td>None</td>
</tr>
<tr>
<td>3+</td>
<td>Equal to left ventricular opacification</td>
<td>Significant</td>
<td>Every cycle</td>
<td>Delayed</td>
<td>None</td>
</tr>
<tr>
<td>4+</td>
<td>Greater than left ventricular opacification</td>
<td>Severe</td>
<td>Every cycle</td>
<td>Slow</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Catheterization Quantitation** = \((\text{SV}_{\text{area-length}} - \text{SV}_{\text{COFick}})/\text{SV}_{\text{area-length}}\)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricuspid Valve Morphology</td>
<td>Normal/Abnormal</td>
<td>Normal/Abnormal</td>
<td>Abnormal/flail/large coaptation defect</td>
</tr>
<tr>
<td>Color Flow TR Jet (cm$^2$)</td>
<td>Small, central, &lt; 5</td>
<td>Intermediate, 5-10</td>
<td>Large or eccentric, &gt; 10</td>
</tr>
<tr>
<td>CW Signal of TR Jet</td>
<td>Faint/parabolic</td>
<td>Dense/variable</td>
<td>Dense/triangular with early perak</td>
</tr>
<tr>
<td>Vena Contracta Width (mm)</td>
<td>Not defined</td>
<td>&lt; 7 mm</td>
<td>&gt; 7 mm</td>
</tr>
<tr>
<td>PISA Radius (mm)</td>
<td>&lt; 5</td>
<td>6-9</td>
<td>&gt; 9</td>
</tr>
<tr>
<td>Hepatic Vein Flow</td>
<td>Systolic dominance</td>
<td>Systolic blunting</td>
<td>Systolic flow reversal</td>
</tr>
<tr>
<td>Tricuspid Inflow</td>
<td>Normal</td>
<td>Normal</td>
<td>E wave dominant</td>
</tr>
<tr>
<td>EROA (mm$^2$)</td>
<td>Not defined</td>
<td>Not defined</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>R Vol (ml)</td>
<td>Not defined</td>
<td>Not defined</td>
<td>&gt; 45</td>
</tr>
<tr>
<td>RA/RV/IVC Dimension</td>
<td>Normal</td>
<td>Normal or dilated</td>
<td>Usually dilated</td>
</tr>
</tbody>
</table>

Atrioventricular Valves - Grading Regurgitation with Phase Contrast MRI

Methods:
  • Through-plane phase contrast MRI
  • Regurgitant fraction = \( (SV_{SSFP} - \text{Outflow } SV_{PC})/SV_{SSFP} \)
Tricuspid Valve Regurgitation in Repaired Tetralogy of Fallot

TV RF (Direct PC) = 3% vs.
TV RF (RV SV-MPA FF)/RV SV = 11.2%

Tricuspid Valve Regurgitation in Repaired Tetralogy of Fallot

- 56 school-aged (mean 11.6 y) children with repaired tetralogy of Fallot
- Found moderate or severe TR in 32% of patients
  - 44% - Normal tricuspid morphology
  - 55% - Tethered, prolapsing, or flail leaflet
  - 47% had moderate TR within 1st post-operative year; most of these had structural TV abnormalities potentially relating to surgical repair
- Presence of TR did not always correlate with RV dilation

Summary

• Reviewed methodologies for measuring peak velocities and valvular regurgitation with echocardiography, catheterization, and MRI

• Addressed assumptions and sources of error for each modality

• Identified situations where the observed results do not match expectations

• Proposed several modifications to MRI techniques to mitigate the effects of flow turbulence