Anatomy of the Mitral Valve and Quantification of Mitral Regurgitation

Sunil Mankad, MD, FACC, FCCP, FASE
Associate Professor of Medicine
Mayo Clinic College of Medicine
Director, Transesophageal Echocardiography
Associate Director, Cardiology Fellowship
Mayo Clinic, Rochester, MN
mankad.sunil@mayo.edu
DISCLOSURE

Relevant Financial Relationship(s)
None

Off Label Usage
None
Pre-Test Questions
What is the specific abnormality of the mitral valve shown on this pre-operative TEE?

3D TEE

"Surgeon’s View"

0° View

60° View
What is the specific mitral valve abnormality?

1. Flail P2
2. Flail P1
3. Flail P3
4. Barlow’s Disease
5. Flail A3
41 y/o woman: Dyspnea on exertion
PISA Radius = 1.1 cm

Aliasing velocity 49 cm/sec

MR Peak Velocity 570 cm/sec

TVI = 161 cm
**What is the calculated ERO?**

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45 cm²</td>
</tr>
<tr>
<td>2</td>
<td>0.55 cm²</td>
</tr>
<tr>
<td>3</td>
<td>0.35 cm²</td>
</tr>
<tr>
<td>4</td>
<td>0.65 cm²</td>
</tr>
<tr>
<td>5</td>
<td>0.75 cm²</td>
</tr>
</tbody>
</table>

- **PISA Radius** = 1.1 cm
- **Aliasing velocity** = 49 cm/sec
- **MR Peak Velocity** = 570 cm/sec
- **TVI** = 161 cm
Mitral Valve Prolapse: Evolution of Echo
Mitral Valve Posterior Leaflet Prolapse
Mitral Valve Anatomy:
View from the Left Atrium

Carpentier Nomenclature
3D Transthoracic Echo: View from the Left Atrium
Transesophageal 3D Echocardiography

- Allows visualization of mitral valve leaflets, orifice, and subvalvular apparatus in a manner that is not possible using conventional 2D echo
- "En face" views of the MV from atrial and ventricular perspective
- Fully sampled volume, not mechanically rotated
Feasibility of Mitral Repair

1. **Surgeon’s skill and experience**

2. Accurate identification the anatomic lesions of the mitral valve

- Echocardiography is pivotal in defining the functional anatomy of the mitral valve
- Surgeon and Echocardiographer
  - Speaking a common language
  - Mutual respect and honesty
- Knowing when to send the patient to a “Surgical Centers of Excellence”
Etiology of Mitral Regurgitation

- Ischemic mitral regurgitation – 27%
- Endocarditis – 5%
- Rheumatic valve disease – 1%
- Other – 2%
- Degenerative mitral disease (MVP) – 65%

Waller BF et al: Clin Cardiol 17:395, 1994
Imaging Depth: 2D TEE

A2-P2

A1-P1
Mitral Valve Scallops

2-chamber: Commissural view at 60 degrees
Mitral Valve Scallops
Commissural view at 60 degrees
Flail MV Scallops
Identification of Mitral Valve Scallop


Zero Degree View

Commisural View
TEE Commissural View

TEE 90° View

Flail A2

- Courtesy Pravin Shah MD
Transgastric Imaging

- Courtesy of Dr. Pravin Shah, MD, MACC

Adapted from Carpenter Classification
Limitation of 2D TEE

- P1, P2, P3, A2 Prolapse
- P2 and P3 Flail
- Multiple Torn Chordae Tendineae
- Were you 100% confident on the 2D TEE Images?
What’s wrong with the mitral valve?
What’s wrong with the mitral valve?

1. Flail posterior lateral scallop (P1)
2. Flail posterior middle scallop (P2)
3. Flail posterior medial scallop (P3)
4. Flail anterior middle scallop (A2)
5. Mitral valve cleft
View from LA Perspective

View from LV Perspective
Surgical Note

Diagnosis:
1. Severe mitral valve regurgitation.
2. Flail middle scallop posterior leaflet.
3. Cleft between lateral and middle scallops of the posterior leaflet.
4. New York Heart Association class II.
5. Moderate right ventricular dysfunction.
6. Pulmonary hypertension.
7. Medial scallop posterior leaflet prolapse.

Procedure:
1. Robotic-assisted minimally invasive mitral valve repair.
2. Triangular resection of the middle scallop of the posterior leaflet.
3. Closure of cleft between the lateral and middle scallops of the posterior leaflet.
What’s wrong with the mitral valve?

1. Flail posterior lateral scallop (P1)
2. Flail posterior middle scallop (P2)
3. Flail posterior medial scallop (P3)
4. Flail anterior middle scallop (A2)
5. Mitral valve cleft
Objectives

CLINICAL INVESTIGATIONS
VALVULAR HEART DISEASE


Real-Time Three-Dimensional Transesophageal Echocardiography in the Intraoperative Assessment of Mitral Valve Disease

Jasmine Grewal, MD, Sunil Mankad, MD, William K. Freeman, MD, Roger L. Click, MD, PhD, Rakesh M. Suri, MD, Martin D. Abel, MD, Jae K. Oh, MD, Patricia A. Pellikka, MD, Gillian C. Nesbitt, MD, Imran Syed, MD, Sharon L. Mulvagh, MD, and Fletcher A. Miller, MD, Rochester, Minnesota

pathologic anatomy of the MV leaflets and apparatus
Detection of Pathology with 2D and Live 3D TEE  

\[ n = 42 \text{ patients} \]

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2D</td>
<td>3D</td>
<td>2D</td>
</tr>
<tr>
<td>P1</td>
<td>83</td>
<td>100</td>
<td>88</td>
</tr>
<tr>
<td>P2</td>
<td>93</td>
<td>100</td>
<td>76</td>
</tr>
<tr>
<td>P3</td>
<td>67</td>
<td>100</td>
<td>76</td>
</tr>
<tr>
<td>A1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>A2</td>
<td>86</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>A3</td>
<td>0</td>
<td>100</td>
<td>89</td>
</tr>
<tr>
<td>Bileaflet disease</td>
<td>66</td>
<td>100</td>
<td>86</td>
</tr>
<tr>
<td>Chord rupture</td>
<td>88</td>
<td>93</td>
<td>93</td>
</tr>
<tr>
<td>Ischemic Disease</td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
</tbody>
</table>

\*p <0.05 versus 2D TEE; BL = bileaflet involvement

- The predominant MV pathology was correctly identified in 98\% vs. 90\% of patients for 3D TEE vs. 2D TEE (p < 0.05)
Flail Posterior Leaflet (P2)
Flail Anterior Leaflet (A2)
Confusion: Unclear Terminology

1) Trivial
2) Trace
3) Mild
4) Mild to moderate
5) Moderate
6) Moderate to severe
7) Moderately Severe
8) Severe
9) Industrial Strength
10) Torrential

Semi-Quantification

- 1+
- 1-2+
- 2+
- 2-3+
- 3+
- 3-4+
- 4+
Mitral Regurgitation Has Four Hallmarks

- Flow Convergence
- Flow Acceleration
- Turbulence
- Downstream Jet Area

Adapted from Echo in Context. Kisslo et al.
MR Jet Area Semi-Quantification

Adapted from Echo in Context – Kisslo et al.

Nanda N. Textbook of Color Doppler
## Quantification of MR by Jet Area

<table>
<thead>
<tr>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Central Jet (usually &lt; 4 cm(^2))</td>
<td>20-40% of LA Area</td>
<td>Large Central Jet (usually &gt; 10 cm(^2))</td>
</tr>
<tr>
<td>&lt; 20% of LA Area</td>
<td></td>
<td>&gt; 40% of LA Area</td>
</tr>
</tbody>
</table>

Problems with Jet Area

• Affected by instrumental factors
  • Pulse Repetition Frequency
    • Nyquist limit should be > 50-60 cm/sec
  • Color Gain
    • Gain set so that random color speckling does not occur in non-moving regions
How Much Mitral Regurgitation?: Eccentric Mitral Regurgitation Jet

Coanda Effect
Regurgitation Has Four Hallmarks

Flow Convergence
Flow Acceleration
Turbulence
Downstream

Adapted from Echo in Context. Kisslo et al.
Vena Contracta

• Narrowest portion of a jet that occurs at or just downstream from the orifice

• Vena Contracta Width
  • Mild < 0.3 cm
  • Moderate 0.3-0.69 cm
  • Severe > 0.7 cm

Mitral Regurgitation
Transesophageal Echo Long Axis

Vena Contracta vs Angiographic Grade

Jet width by multiplane long-axis view (mm)

Angiographic grade

Vena Contracta vs Regurgitant Volume

Regurgitation volume (mL)

Grayburn PA: AJC 74, 1994

\[ y = 0.07x + 0.6 \]
\[ r^2 = 0.63 \]
SEE = 0.4 cm
Problems with Vena Contracta
Valvular Regurgitation
Quantitation

• Regurgitant volume (RV)
• Effective regurgitant orifice (ERO)
• Regurgitant fraction (RF)
Continuity Equation

Quantitative Hemodynamics
(Conservation of Mass Principle)

\[ \text{Stroke volume} \times A = \text{Area} \times X \times \text{TVI} \]
Four Measurements

- LVOT Diameter
- LVOT TVI
- Mitral annulus diameter
- Mitral annulus TVI

\[ SV_{LVOT} \]

\[ SV_{MV} \]
Diastole

\[ \text{Diastole} = \text{MV Stroke Volume} \]
Systole

LVOT Stroke Volume

MR Volume
MV Stroke Volume = LVOT Stroke Volume + MR Volume
MV Stroke Volume = LVOT Stroke Volume - MR Volume
Step 1: Calculate LVOT Stroke Volume

LVOT diameter = 2.6 cm

LVOT Stroke Volume = \pi \left(\frac{D}{2}\right)^2 \times 18 \text{ cm}

= 0.785 \times (2.6 \text{ cm})^2 \times 18 \text{ cm}

= 96 \text{ cm}^3
Step 2: Calculate MV Stroke Volume

MV diameter = 4.1 cm
MV Annular TVI = 12 cm

MV Stroke Volume

\[ = 0.785 \times (4.1 \text{ cm})^2 \times 12 \text{ cm} \]

\[ = 158 \text{ cm}^3 \]
Step 3: Calculate MR Volume

MV Stroke Volume - LVOT Stroke Volume = MR Volume

158 cm$^3$ - 96 cm$^3$ = 62 cm$^3$
Step 4: Calculate Regurgitant Fraction (RF)

Mitral RF = \frac{MR Volume}{MV Stroke Volume} = \frac{62 \text{ cm}^3}{158 \text{ cm}^3} = 40\%
Step 5: Calculate MR ERO

Effective Regurgitant Orifice

$$\text{ERO} = \frac{62 \text{ cm}^3}{163 \text{ cm}} = 0.38 \text{ cm}^2$$

MR Volume
62 cm$^3$

MR TVI
(163 cm)
# Quantitation of Mitral Regurgitation

<table>
<thead>
<tr>
<th></th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MR Volume</strong></td>
<td>&lt;30</td>
<td>30 - 44</td>
<td>45 - 59</td>
</tr>
<tr>
<td><strong>Regurgitant Fraction (%)</strong></td>
<td>&lt;30</td>
<td>30 - 39</td>
<td>40 - 49</td>
</tr>
<tr>
<td><strong>ERO (cm²)</strong></td>
<td>&lt;0.20</td>
<td>0.20-0.29</td>
<td>0.30-0.39</td>
</tr>
</tbody>
</table>

Quantitation of Valvular Regurgitation Continuity Method: Potential Pitfalls

- Incorrect Doppler alignment to flow ($\theta > 20^\circ$)
- Incorrect sample volume placement:
  - Place at annulus, not leaflet tips
- Incorrect annular measurement: $(\text{error})^2$
  - Mitral annular calcification (MAC)
- Failure to trace modal velocity (especially MV)
- Geometric assumptions of circular annulus
  - (LVOT – excellent, MV - good, TV - poor)
- Aortic regurgitation > mild  (use RVOT instead)
- Arrhythmia; inadequate data averaged
Regurgitation Has Four Hallmarks

- Flow Convergence → PISA
- Flow Acceleration
- Turbulence
- Downstream

Adapted from Echo in Context. Kisslo et al.
What is PISA?

- Derived from the hydrodynamic principle stating that, as blood approaches a regurgitant orifice, its velocity increases forming concentric, roughly hemispheric shells of increasing velocity and decreasing surface area.
Flow Convergence

Proximal
Isovelocity Surface
Area

\[ V = 20 \text{ cm/sec} \]
\[ V = 50 \text{ cm/sec} \]
\[ V = 100 \text{ cm/sec} \]

\[ V_{MR} = 500 \text{ cm/sec} \]
PISA Calculations
(Proximal Isovelocity Surface Area)

• Flow (cc/sec)
  \[ \text{Flow (cc/sec)} = 6.28 \times [r \ (\text{cm})]^2 \times V_a \ (\text{cm/sec}) \]

• ERO (cm²) = \underline{\text{Flow (cc/sec)}} \times \frac{V}{\text{cm/sec}}

• RV (cc) = ERO (cm²) \times TVI (cm)
Locating the Color Flow Convergence

• Zoom region of interest
  (Decreases error of radius measurement)

• Shift color Doppler baseline in the direction of the regurgitant jet

• Baseline shift to obtain an optimal hemispheric flow convergence signal for PISA measurement
Zoom In As Tight As You Can

- Larger zoom box
- Smaller zoom box

- Courtesy of Leslie Elvert, B.S., R.D.C.S.
What is the best aliasing velocity?

- **Alias Vel.** 25 cm/s
- **Radius** 0.99 cm
- **ERO** 0.32 cm²
- **Reg Vol** 44 cc

- **Alias Vel.** 38 cm/sec
- **Radius** 0.83 cm
- **ERO** 0.35 cm²
- **Reg Vol** 47 cc

- Courtesy of Leslie Elvert, B.S., R.D.C.S.
Advantages of PISA Method

• Can be used in presence of other valvular regurgitation or shunts
• Can be used in presence of valve stenosis or prosthetic valves
• Uses fewer variables
Quantitation of Mitral Regurgitation

<table>
<thead>
<tr>
<th></th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MR Volume (cm³/beat)</strong></td>
<td>&lt;30</td>
<td>30 - 44</td>
<td>45 - 59</td>
</tr>
<tr>
<td><strong>ERO (cm²)</strong></td>
<td>&lt;0.20</td>
<td>0.20 - 0.29</td>
<td>0.30 - 0.39</td>
</tr>
<tr>
<td><strong>Vena Contracta Width (cm)</strong></td>
<td>&lt; 0.3</td>
<td>0.3 - 0.69</td>
<td>≥ 0.7</td>
</tr>
</tbody>
</table>

Simplified Approach to PISA (ERO)

- ERO = \(2\pi \cdot r^2 \cdot \frac{V}{V_{\text{max}}} \text{ of MR}\)
  
  = \(6.28 \cdot r^2 \cdot \frac{V}{V_{\text{max}}} \text{ of MR}\)

- If \(\frac{V}{V_{\text{max}}} \text{ of MR}\) can be adjusted to 1/12, then ERO = \(6.28/12 \times r^2\)
  
  = 0.5 \times r^2

Aliasing velocity set at 40 cm/sec assuming MR maximum velocity \(\approx 500\) cm/sec

Simplified PISA (ERO)

• Examples

- \( r = 0.4 \text{ cm}; \ r^2 = 0.16 \text{ cm}^2; \ \text{ERO} = 0.08 \text{ cm}^2 \)
- \( r = 0.6 \text{ cm}; \ r^2 = 0.36 \text{ cm}^2; \ \text{ERO} = 0.18 \text{ cm}^2 \)
- \( r = 0.8 \text{ cm}; \ r^2 = 0.64 \text{ cm}^2; \ \text{ERO} = 0.32 \text{ cm}^2 \)
- \( r = 0.9 \text{ cm}; \ r^2 = 0.81 \text{ cm}^2; \ \text{ERO} = 0.4 \text{ cm}^2 \)
- \( r = 1.0 \text{ cm}; \ r^2 = 1.0 \text{ cm}^2; \ \text{ERO} = 0.5 \text{ cm}^2 \)
48 y/o Housewife: Heart murmur, dyspnea
Apical Color Views: Mayo Clinic Format (ASE Type B Format)
Mayo Clinic Format
(ASE Type B Format)
PISA R = 0.5 cm; Aliasing velocity 61 cm/sec
Step 1: Calculate proximal MR flow

\[
\text{Flow}_{\text{MR}} = \text{Area}_{\text{PISA}} \times \text{Velocity}_{\text{Alias}}
\]

\[
= 2\pi \times R^2 \times V_{\text{Alias}}
\]

\[
= 6.28 \times (0.5\text{cm})^2 \times 61 \text{ cm/sec}
\]

\[
\text{Flow}_{\text{MR}} = 96 \text{ cm}^3/\text{sec}
\]
MR Peak Velocity 570 cm/sec; TVI = 179 cm
Color M-Mode: MVP and MR
MR Peak Velocity 570 cm/sec; TVI = 127 cm
Step 2: Calculate the mitral ERO

\[
ERO = \frac{\text{Flow}_{\text{MR}}}{\text{Velocity}_{\text{MR}}}
\]

\[
= \frac{96 \text{ cm}^3/\text{sec}}{570 \text{ cm/sec}}
\]

\[
= 0.17 \text{ cm}^2
\]
Step 3: Calculate MR volume

Volume_{MR} = ERO \times TVI_{MR}

= 0.17 \text{ cm}^2 \times 127 \text{ cm}

= 22 \text{ cm}^3

TVI_{MR} = 127 \text{ cm}
Step 1: Calculate LVOT Stroke Volume

LVOT Diameter = 2.2 cm
LVOT TVI = 20 cm

LVOT Stroke Volume = 0.785 \times (2.2 \text{ cm})^2 \times 20 \text{ cm} = 76 \text{ cm}^3
Step 2: Calculate MV Stroke Volume

MV Stroke Volume = 0.785 (3.6 cm)² × 10 cm

= 102 cm³
Step 3: Calculate MR Volume

\[ \text{MV Stroke Volume} - \text{LVOT Stroke Volume} = \text{MR Volume} \]

\[ 102 \text{ cm}^3 - 76 \text{ cm}^3 = 26 \text{ cm}^3 \]
Step 4: Calculate Regurgitant Fraction (RF)

Mitral RF = \frac{MV Stroke Volume}{MR Volume} = \frac{26 \text{ cm}^3}{102 \text{ cm}^3} = 25\%
Step 5: Calculate MR ERO

Effective Regurgitant Orifice (ERO) = \( \frac{26 \text{ cm}^3}{127 \text{ cm}} \) = 0.20 cm²
Problems with PISA

- Sub-optimal flow convergence
  - Non-hemispheric flow
  - Not useful in large orifices
- Multiple MR jets
- Some eccentric jets may impinge on hemisphere
- LVOT obstruction may distort the isovelocity convergence zone
- PISA is dynamic during systole, timing is crucial
- PISA is too complicated for routine clinical use
  - Simplified PISA
- PISA just doesn’t work
Sub-optimal Flow Convergence
Non-Hemispheric Flow Convergence: Wall Impingement

\[
ERO = \frac{\pi \times r^2 \times Av}{MR \text{ Vmax}} \times \frac{\alpha}{180}
\]
Severe Mitral Regurgitation
- Supportive Signs

Pulmonary Vein Systolic Reversal of Flow

- Enlarged LA
- Enlarged LV
Final Points

• Mild, well visualized, central jet = MILD
• If suspect more that mild, analyze
• Use **all** available info, no method is perfect
• Learn to quantify
• Responsibility to patients and colleagues to produce a report closest to the truth
To dare is to lose one’s footing momentarily, not to dare is to lose oneself

- Soren Kierkegaard
Post-Test Questions
What is the specific abnormality of the mitral valve shown on this pre-operative TEE?

**3D TEE**

- **View from LA**
- **Surgeon’s View**

**View from**

- **0° View**
- **60° View**
What is the specific mitral valve abnormality?

1. Flail P2
2. Flail P1
3. Flail P3
4. Barlow’s Disease
5. Flail A3
Mitral Valve Anatomy: View from the Left Atrium
41 y/o woman: Dyspnea on exertion
PISA Radius = 1.1 cm

Aliasing velocity 49 cm/sec

MR Peak Velocity 570 cm/sec

TVI = 161 cm
What is the calculated ERO?

1. 0.45 cm\(^2\)
2. 0.55 cm\(^2\)
3. 0.35 cm\(^2\)
4. 0.65 cm\(^2\)
5. 0.75 cm\(^2\)

PISA Radius = 1.1 cm

Aliasing velocity 49 cm/sec

MR Peak Velocity 570 cm/sec

TVI = 161 cm
Step 1: Calculate proximal MR flow

\[ \text{Flow}_{MR} = \text{Area}_{PISA} \times \text{Velocity}_{Alias} \]

\[ = 2\pi \times R^2 \times V_{Alias} \]

\[ = 6.28 \times (1.1\text{cm})^2 \times 49 \text{ cm/sec} \]

\[ \text{Flow}_{MR} = 372 \text{ cm}^3/\text{sec} \]
Step 2: Calculate the mitral ERO

\[
ERO = \frac{\text{Flow}_{\text{MR}}}{\text{Velocity}_{\text{MR}}}
\]

\[
\text{Velocity}_{\text{MR}} = 570 \text{ cm/sec}
\]

\[
\frac{372 \text{ cm}^3/\text{sec}}{570 \text{ cm/sec}} = 0.65 \text{ cm}^2
\]