Quantification of MR

• *Defining the size of the “hole” in the valve is key, along with the regurgitant volume (leak/beat)*

• **What is severe MR?**
  - Regurgitant orifice area > 0.4 cm²
  - Regurgitant volume > 60 mL

• **As of March, 2017, we use the same standard for organic MR and functional MR but recognize that lesser degrees of FMR adversely impact survival than in primary MR.**
We Now Have Détente Between the Guidelines
Organic and Functional MR Graded the Same

• Does this mean that etiology doesn’t matter anymore?

**NOT AT ALL**

Organic vs Functional MR
Critical to Proper Management

Organic MR: The valve makes the ventricle sick

Flail PML, severe anteriorly-directed MR
Organic vs Functional MR
Critical to Proper Management

Functional MR: The ventricle makes the valve sick

Large IPMI, severe posteriorly-directed MR
Look for the PML pointing to the apex

Integrative approach to chronic mitral regurgitation
Quantifying Mitral Regurgitation

What are the Alternatives?

- **Color jet area**
  - **Pro:** Easy, fast, helps assess mechanism
  - **Con:** Impacted by BP, jet eccentricity, instrumentation factors, only 3 or 4 grades

- **Pulsed Doppler and 2D difference methods**
- **Pulmonary veins**
- **Vena contracta**
- **Proximal flow convergence (PISA)**

Factors Effecting Color Doppler Jet Size

- **Jet momentum**
  - Flow rate x velocity
  - Record BP during examination
- **Chamber constraint**
  - Eccentric jets only 40% the size of free jets
- **Instrumentation**
  - Jet size *directly* related to gain, transmit power, ensemble length
  - *Inversely* related to pulse repetition frequency and wall filter
  - Transducer frequency has variable effect
Quantification of Jet Flow by Momentum Analysis

An In Vitro Color Doppler Flow Study

Circulation 1990; 81: 247-259

James D. Thomas, MD, Chun-Ming Liu, MD, Frank A. Flachskampf, MD,
John P. O'Shea, MB, BS, Ravin Davidoff, MB, BCh, and Arthur E. Weyman, MD

Determinants of Jet Size

Wall jets are 58% smaller than equivalent central jets

Central jets
y = .254x - .7
r = 0.74, p<0.001

Wall jets
y = .054x + 2.6
r = 0.42, p = NS

MR fraction [%]

Chen, et al., Circulation 1991; 84; 712-720
Color Doppler Instrumentation

Changes that Increase Jet Size

- ↑ Gain and power
- ↓ Pulse repetition frequency
- ↑ Transducer frequency
  - Frequency effect
- ↓ Transducer frequency
  - Attenuation effect
- ↓ Wall filter
- ↑ Ensemble length

Impact of Color Gain

CD Gain = 25

CD Gain = 56
Impact of Velocity Scale

Nyquist Limit = 69 cm/sec  \( V_{\text{min}} \approx 4 \text{ cm/sec} \)

Nyquist Limit = 17 cm/sec  \( V_{\text{min}} \approx 1 \text{ cm/sec} \)

How We Usually Grade Regurgitation

Trace  Mild  Moderate  Severe

Can’t we do better????
How Leaky IS That Valve?

Key Quantitative Concept

• Regurgitant orifice area (ROA)
  • Actual size of the regurgitant lesion
  • Fundamental parameter of valve integrity

PISA??

What are the Alternatives?

• Color jet area

• Pulsed Doppler and 2D difference methods
  – Pro: Well validated, quantitative
  – Con: Complex, multiple windows and measurements, propagation of errors compounded by subtraction

• Pulmonary veins
• Vena contracta
• Proximal flow convergence (PISA)
Quantification of Stroke Volume
2D or 3D Volumetric Assessment

LVEDV
150 ml
LVESV
59 ml

Stroke volume = 91 ml; ejection fraction = 61%
Quantification of Stroke Volume

2D or 3D Volumetric Assessment

Calculation of Mitral Inflow
By Biplane Transesophageal Echocardiography

Annular area = \( \frac{\pi ab}{4} \)

Stroke volume = \( TVI_{MA} \times A_{MA} \)
Why Aren’t Volumetric Methods Always Used?

Propagation of Errors

Subtracting two large numbers with an error that is magnified as the root sum square of the individual errors

\[
\text{SV}_{\text{LV}} = 100 \pm 10 \text{ mL}
\]
\[
\text{SV}_{\text{LVOT}} = 60 \pm 10 \text{ mL}
\]
\[
\text{RV}_{\text{MV}} = 40 \pm 14 \text{ mL}
\]

95% CI for \( \text{RV}_{\text{MV}} = (10, 70) \text{ mL} \)

Automated Calculation of Cardiac Output

Sun et al, *Circulation* 1997; 95: 932-939
Accuracy of ACM
Quantification of MR

Sun et al. JACC 1998; 32:1074-82.
Assessment of Regurgitation
Pulmonary Venous Flow

Mild MR

Severe MR

Quantification of MR
Limitations of Pulmonary Vein Patterns

Regurgitant Orifice Area (cm²)

Normal = mild; reversed = severe; blunted = anything

Pu et al. JASE 1999; 12: 736-743
Quantification of MR
Vena Contracta Diameter

Limited by lateral resolution of echo
Flow thru any isovelocity shell is equal to instantaneous orifice flow
Quantification of Regurgitation

Proximal Convergence Method

Practical Implementation

Aliasing velocity: \( v \) (= 42 cm/s)
Aliasing radius: \( r \)

Flow: \( Q \)
Orifice vel: \( v_0 \)

Q = 2\( \pi r^2 v \)
ROA = \( Q / v_0 \)

Comprehensive, but there’s an easier way.

Assessment of MR by Proximal Convergence

![Image](Freq: 1.6 MHz/3.2 MHz
FPS: 23:2
Depth: 11.0 cm
Scale: 4.00 kHz
Freq.: 2.5 MHz)
Assessment of MR by Proximal Convergence

\[ Q = 2\pi r^2 v = 6.28 \times (1.0)^2 \times 62 = 389 \text{ ml/sec} \]
\[ \text{ROA} = \frac{Q}{v_0} = \frac{389}{550} = 0.7 \text{ cm}^2 \]
Measurement of Mitral ROA
*Simplified PISA Formula*

- Assume $LV-LA \Delta p$ is 100 mmHg
- Set aliasing velocity to (near) 40 cm/sec
- Then $ROA = r^2/2$

$ROA = 9^2/2 = 40 \text{ mm}^2$

Pu et al., JASE 2001;14:180-5

---

**ROA by Simplified PISA Method: $r^2/2$**

Pu et al., JASE 2001;14:180-5
72 yo Man with MR post IPMI

How Bad is the MR??

Simplified PISA Method

5 Easy Steps

1. Optimize view of proximal convergence zone from apex
2. Baseline shift to ~40 cm/sec
3. Zoom on valve
4. Measure first aliasing radius
5. ROA = r^2/2
Simplified PISA Method
5 Easy Steps

2. Baseline shift to ~40 cm/sec

Simplified PISA Method
5 Easy Steps

3. Zoom on valve
5. \( \text{ROA} = \frac{r^2}{2} = \frac{9^2}{2} = 40 \text{ mm}^2 \)

**PISA Adjustments**

*Pitfalls and Refinements to Keep in Mind*

1. Nonholosystolic MR
2. Contour flattening near orifice
3. Proximal constraint distorting hemisphere
4. Noncircular orifice
PISA Adjustments

Pitfalls and Refinements to Keep in Mind

1. Nonholosystolic MR
2. Contour flattening near orifice
3. Proximal constraint distorting hemisphere
4. Noncircular orifice

Dynamics of Mitral Regurgitant Flow and Orifice Area

Physiologic Application of the Proximal Flow Convergence Method: Clinical Data and Experimental Testing

_Circulation_ 1994; 90: 307-322

Ehud Schwammenthal, MD; Chunguang Chen, MD; Frank Benning, BS; Michael Block, MD; Günter Breithardt, MD, FESC, FACC; Robert A. Levine, MD, FACC

How Bad is this Regurgitation??

46 Year Old Woman Referred for Surgery

Large jet, large proximal convergence zone

ROA ~ 0.6 cm²
But Only Briefly!

Mitral CW Doppler

Significant MR only in latter half of systole

Impact of Duration of Mitral Regurgitation on Outcomes in Asymptomatic Patients With Myxomatous Mitral Valve Undergoing Exercise Stress Echocardiography

Peyman Naji, MD; Fadi Asfahan, MD; Tyler Barr; L Leonardo Rodriguez, MD; Richard A. Grimm, MD; Shikhar Agarwal, MD, MPH; James D. Thomas, MD; A. Marc Gillinov, MD; Tomislav Mihaljevic, MD; Brian P. Griffin, MD; Milind Y. Desai, MD

- 609 pts w/ ≥ 3+ MR (122 late systolic)
- All underwent stress echocardiography
- Late MR pts were younger and more likely female
- Endpoints: death and CHF
- HS vs LS: 4.99x more likely endpoints

Naji et al., JAHA 2015; 4: e001348
PISA Adjustments

Pitfalls and Refinements to Keep in Mind

1. Nonholosystolic MR
2. Contour flattening near orifice
3. Proximal constraint distorting hemisphere
4. Noncircular orifice

Impact of Finite Orifice Size on Proximal Flow Convergence
Implications for Doppler Quantification of Valvular Regurgitation

Leonardo Rodriguez, Joseph Anconina, Frank A. Flachskampf, Arthur E. Weyman, Robert A. Levine, and James D. Thomas
Circ Res 1992; 70: 923-30

Computational Fluid Dynamics Aids Analysis
Contour Flattening Near the Orifice

Contour velocity: \( v_a \)
Orifice velocity: \( v_0 \)
Conventional PISA
\[ Q = 2\pi r^2 v_a \]
Flow underestimated by \( \frac{v_a}{v_0} \)
(e.g., 8% for 40 cm/sec contour and 5 m/sec jet)

Corrected PISA
\[ Q = 2\pi r^2 \frac{v_0}{v_0 - v_a} \]
PISA Adjustments
Pitfalls and Refinements to Keep in Mind

1. Nonholosystolic MR
2. Contour flattening near orifice
3. Proximal constraint distorting hemisphere
4. Noncircular orifice

Pu et al., *Circulation* 1995; 92: 2169-2177.

Quantification of Mitral Regurgitation by the Proximal Convergence Method Using Transesophageal Echocardiography


PISA Pitfalls
Constraint by Surrounding Structures

Flail posterior leaflet leads to constraint by posterolateral wall

Pu et al., *Circulation* 1995; 92: 2169-2177.
Angle Correction for Constrained Flow

Regurgitant Orifice Area

\[ Q = 2\pi r^2 v(\alpha/180) \]

Proximal Convergence (cm²)

Uncorrected
Corrected

\[ y_1 = 1.41x + 0.30 \quad r = 0.87 \]
\[ \Delta \text{ROA} = 0.54 \pm 0.31 \text{ cm}^2 \]

\[ y_2 = 0.92x + 0.18 \quad r = 0.92 \]
\[ \Delta \text{ROA} = 0.14 \pm 0.14 \text{ cm}^2 \]

PISA Adjustments

Pitfalls and Refinements to Keep in Mind

1. Nonholosystolic MR
2. Contour flattening near orifice
3. Proximal constraint distorting hemisphere
4. Noncircular orifice

Pu et al., Circulation 1995; 92: 2169-2177.
Valvular and Congenital Heart Disease

Geometry of the proximal isovelocity surface area in mitral regurgitation by 3-dimensional color Doppler echocardiography: Difference between functional mitral regurgitation and prolapse regurgitation

Yoshikil Matsumura, MD, Shota Fukuda, MD, Hung Tran, RDCS, Neil L. Greenberg, PhD, Deborah A. Agler, RDCS, Nozomi Wada, MD, Manato Toyono, MD, James D. Thomas, MD, and Takahiro Shiota, MD Cleveland, OH

Functional mitral regurgitation

Prolapse regurgitation

ROA highly elongated in FMR, more focal in MVP


What is the impact of orifice shape on PISA accuracy?
Flow Through 5:1 Ellipse

New Work at Northwestern

AHA abstract, 2015
Manuscript under review

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Impact of Noncircular Orifices

Underestimation vs Circular Orifice

Minor impact to 3:1 shape
What’s New in MR Quantification?

3D PISA Analysis!

Proximal Isovelocity Surface Area

Thavendiranathan et al, JACC 2012, 60(16): 1470-83
Proximal Isovelocity Surface Area

Thavendiranathan et al. Circulation cardiovascular imaging 2013, 6(1): 125-33


Biblical degree of accuracy?

Practical Approach to Quantifying MR

Chronic Mitral Regurgitation by Doppler Echocardiography

Yes, mild

Yes, severe

Does MR meet specific criteria for mild or severe MR?

Intermediate Results

MR Probability Moderate

Specific Criteria for Mild MR
- Small regurgitant jet
- PSV of aortic valve ≤ 3 m/s
- Presence of aortic stenosis
- Absence of infective endocarditis
- Normal LV and LVOT

2-3 criteria

Specific Criteria for Severe MR
- Full systolic failure
- PSV of aortic valve ≥ 3.5 m/s
- Presence of bicuspid aortic valve
- Presence of infective endocarditis
- Dilated LV and LVOT

Indeterminate MR

Consider further testing.

Terms and Conditions

JASE 2017; 30: 303-371
What About AR???
Quantification of AR
What are the Alternatives?

- Color jet area
- Vena contracta
  - AR pressure half-time
  - Aortic flow reversal
- Pulsed Doppler and 2D difference methods
- ACOM methods
- Proximal convergence method

Many parameters similar to MR
AR Pressure Half-Time

Chronic Moderate AR

AR Pressure Half-Time

Acute Severe AR (endocarditis)
AR Halftime vs RF
Contrasting Effect of ROA and SVR

Quantification of AR
What are the Alternatives?

- Color jet area
- Vena contracta
- AR pressure half-time
- Aortic flow reversal
- Pulsed Doppler and 2D difference methods
- ACOM methods
- Proximal convergence method

Apical Five-Chamber View

AR of Unclear Severity

Aortic Arch Doppler

Moderately severe AR
Apical Five-Chamber View

AR of Unclear Severity

Aortic Arch Doppler

Severe AR
If I could have only one piece of data regarding AR severity……

……it would be an aortic arch pulsed Doppler recording.
How About TR?

Incomplete TV closure with severe functional TR

Tricuspid regurgitation
Carcinoid

TV fixed in systole and diastole with severe mixed TR/TS

Apical 4-Chamber
Tricuspid Valve CW

Severe TR

Conservation of energy:

$$\Delta p = \frac{1}{2} \rho (v_1^2 - v_2^2) + M \frac{dv}{dt} + R(v)$$

Convective Acceleration
Inertial Component
Viscous Dissipation

Early peaking, triangular flow profile
Invalidates the simplified Bernoulli equation
Hepatic Vein Flow

Can PISA be used in TR???

Yes, but...

- Limited validation and experience
- Contour flattening a bigger issue
- Orifices can be bizarrely shaped
PISA in TR

\[ Q = 2\pi r^2 v = 6.28 \times (1.3)^2 \times 37 = 393 \text{ ml/sec} \]

\[ \text{ROA} = Q/v_0 = 393/300 = 1.3 \text{ cm}^2 \]

But 37/300 is 0.12, so we’re underestimating by 12%

3D PISA in TR?

Again, biblical degree of accuracy?

De Augustin et al. JASE 2013; 28: 1063-72
3D Tools are Progressing Rapidly

Clip courtesy of Helene Houle, Siemens

What about systolic flow reversal in the hepatic veins?

“Usually” a pretty specific sign of severe TR
So how bad’s the TR here?

Not so bad

How come?
Baseline EKG: SR

EKG on day of echo: Junctional Retrograde P-waves Cannon A-waves

Chronic Tricuspid Regurgitation by Doppler Echocardiography

Specific Criteria for Mild TR
- Thin, small central vena cava
- YCA width <0.3 cm
- PISA radius <0.4 cm at Nyquist 30-40 cm/s
- Incomplete or blunt CW jet
- Systolic-dominant tricuspid inflow
- Normal RV:RA

Specific Criteria for Severe TR
- Dilated annulus with no valve septation or flail leaflet
- Large central jet >50% of RA
- YCA width <0.7 cm
- PISA radius <0.9 cm at Nyquist 30-40cm/s
- Dense, triangular CW jet or sine wave pattern
- Systolic reversal of hepatic vein flow
- Dilated RV with preserved function

Minority of criteria or Intermediate Values: TR Probably Moderate

Perform VC measurement, and May perform quantitative PISA method, whenever possible

- YCA width < 0.3 cm
- *EROA < 0.2 cm²
- *Rv' < 30 mL

- YCA width 0.3-0.6 cm
- *EROA 0.2-0.4 cm²
- *Rv' 30-44 mL

- YCA width > 0.6 cm
- *EROA > 0.4 cm²
- *Rv' > 45 mL

Mild TR
Moderate TR
Severe TR

Indeterminate TR
Consider further testing TEE or CMR for quantitation

* Clinical experience in quantification of TR is much less than that with mitral and aortic regurgitation

JASE 2017; 30: 303-371
And What of PR?

Actually, no one cares about PR
With ONE exception

Severe PR s/p ToF Repair

The most severe PR is virtually inapparent by
color Doppler. Look at the CW Doppler
PR So Severe You Can’t See It!!

PISA

Is It the Best Way to Quantify Regurgitation??

Of Course!!