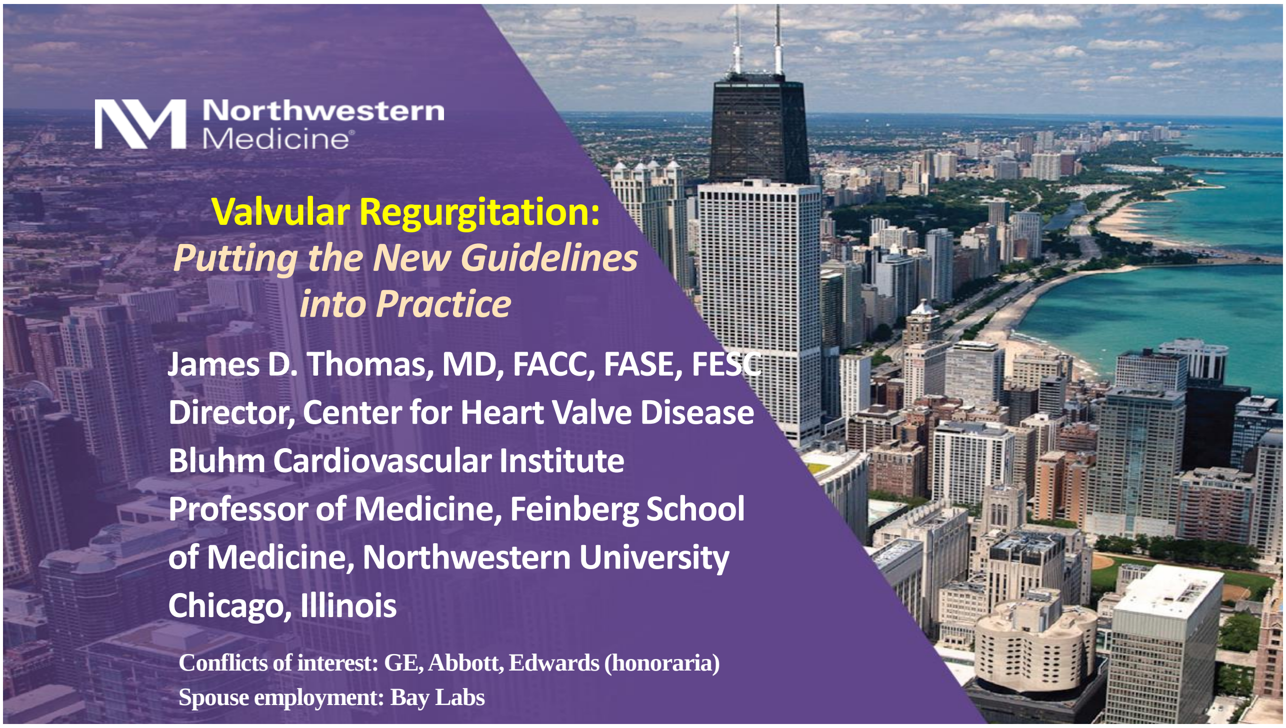
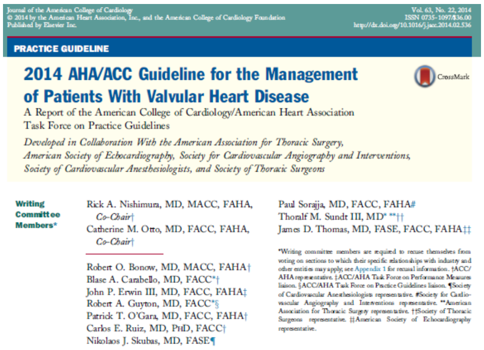


Quantification of MR

- ***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.***


Journal of the American College of Cardiology
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Vol. 63, No. 22, 2014
ISSN 0735-1097/$36.00
http://dx.doi.org/10.1016/j.jacc.2014.02.536

PRACTICE GUIDELINE

2014 AHA/ACC Guideline for the Management of Patients With Valvular Heart Disease

A Report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines

Developed in Collaboration With the American Association for Thoracic Surgery, American Society of Echocardiography, Society for Cardiovascular Angiography and Interventions, Society of Cardiovascular Anesthesiologists, and Society of Thoracic Surgeons

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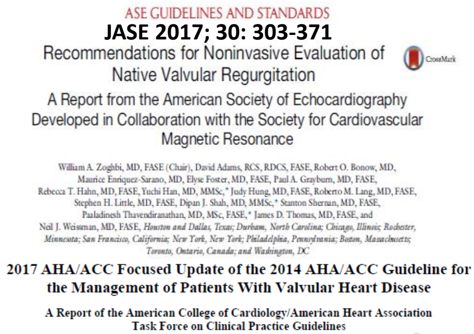

ASE GUIDELINES AND STANDARDS

JASE 2017; 30: 303-371

Recommendations for Noninvasive Evaluation of Native Valvular Regurgitation

A Report from the American Society of Echocardiography Developed in Collaboration with the Society for Cardiovascular Magnetic Resonance

William A. Zoghbi, MD, FASE (Chair), David Adams, RCS, RDCS, FASE, Robert O. Bonow, MD, Maurice Enriquez-Sarano, MD, Elyse Foster, MD, FASE, Paul A. Grayburn, MD, FASE, Rebecca T. Hahn, MD, FASE, Yuchi Han, MD, MMSc,* Judy Hung, MD, FASE, Roberto M. Lang, MD, FASE, Stephen H. Little, MD, FASE, Dipan J. Shah, MD, MMSc,* Stanton Shernan, MD, FASE, Paaladinesh Thavendiranathan, MD, MSc, FASE,* James D. Thomas, MD, FASE, and Neil J. Weissman, MD, FASE, *Houston and Dallas, Texas; Durham, North Carolina; Chicago, Illinois; Rochester, Minnesota; San Francisco, California; New York, New York; Philadelphia, Pennsylvania; Boston, Massachusetts; Toronto, Ontario, Canada; and Washington, DC*

2017 AHA/ACC Focused Update of the 2014 AHA/ACC Guideline for the Management of Patients With Valvular Heart Disease

A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines

We Now Have Détente Between the Guidelines

Organic and Functional MR Graded the Same

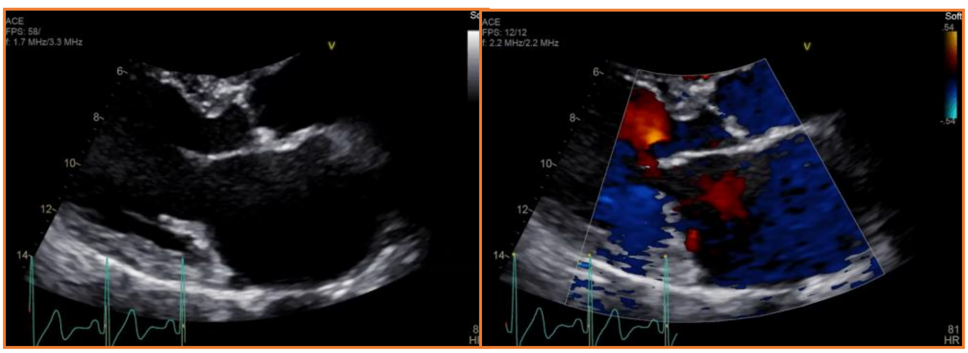
- **Does this mean that etiology doesn't matter anymore?**

NOT AT ALL

Organic vs Functional MR

Critical to Proper Management

Organic MR: The valve makes the ventricle sick

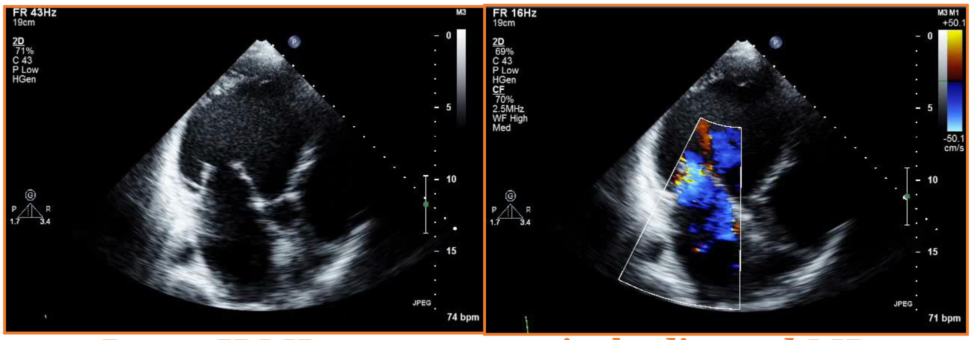


Flail PML, severe anteriorly-directed MR

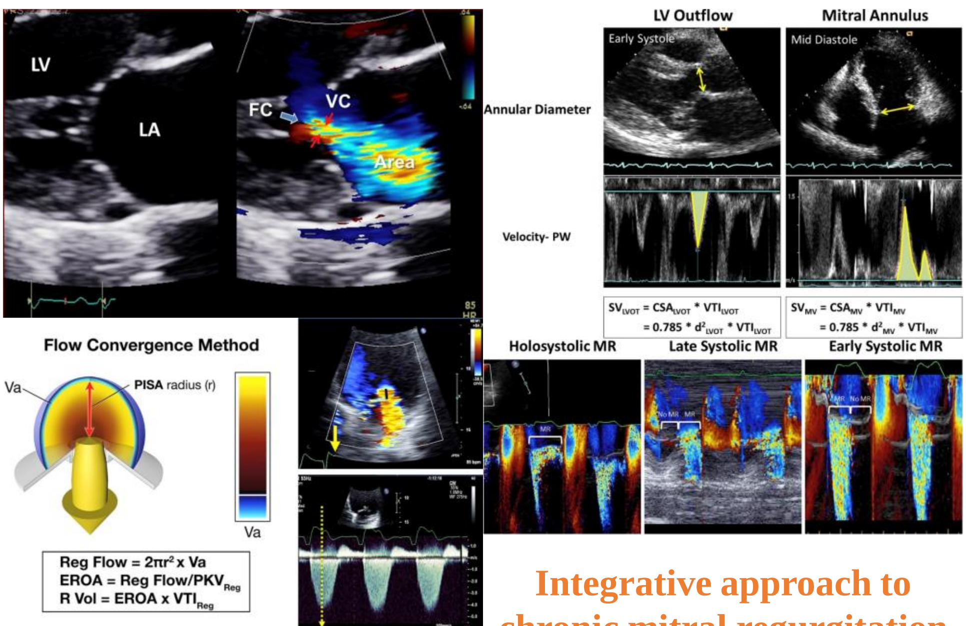
Organic vs Functional MR

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



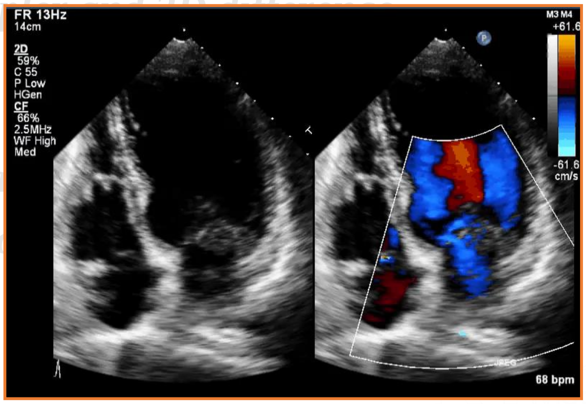
Integrative approach to chronic mitral regurgitation

JASE 2017; 30: 303-371

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 Dopp*
  methods
- *Pulmonary*
- *Vena contra*
- *Proximal fl*



Factors Effecting Color Doppler Jet Size

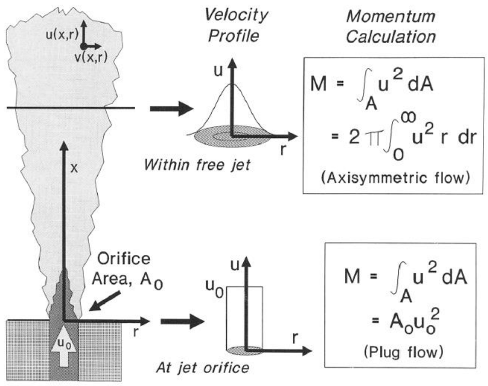
- Jet momentum
  - Flow rate x velocity
  - Record BP during examination
- Chamber constraint
  - Eccentric jets only 40% the size of free jets
- Instrumentation
  - Jet size directly related to gain, transmit power, ensemble length
  - Inversely related to pulse repetition frequency and wall filter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



$$JA(M,x_c,u_c)=2\int_0^{x_c} \frac{x}{9.7}\left(\ln\frac{7.8\sqrt{M}}{u_c x}\right)^{1/2} dx$$

This integral is expressible in closed form through a series of substitutions. First, let $\xi=u_c x/7.8\sqrt{M}$ yielding

$$JA=K\int_0^{\xi_c} \xi\sqrt{\ln(1/\xi)}\, d\xi$$

where $K=(2\times 7.8^2 M)/(9.7 u_c^2)=12.5M/u_c^2$ and $\xi_c=u_c x_c/7.8\sqrt{M}$ that ranges from 0 to 1. Next, let $\nu=\sqrt{\ln(1/\xi)}$ yielding

$$JA=2K\int_{\nu_c}^{\infty} \nu^2 e^{-2\nu^2}\, d\nu$$

where $\nu_c=\sqrt{\ln(1/\xi_c)}$, which ranges from 0 for unconstrained jets to ∞ for infinitesimally small receiving chambers. This expression may be integrated by parts ($\int u\, dv=uv-\int v\, du$) with $u=\nu$ and $dv=\nu e^{-2\nu^2} d\nu$:

$$JA=K[\tfrac{1}{2}\nu_c e^{-2\nu_c^2}+(\sqrt{\pi}/4\sqrt{2})\,\mathrm{erfc}(\sqrt{2}\nu_c)]^*$$

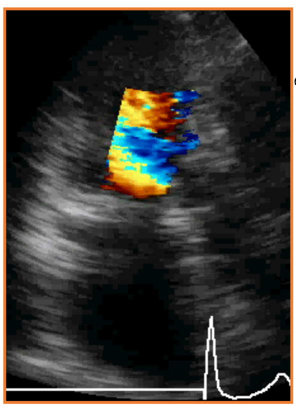
Backsubstituting for ν, ξ, and K yields

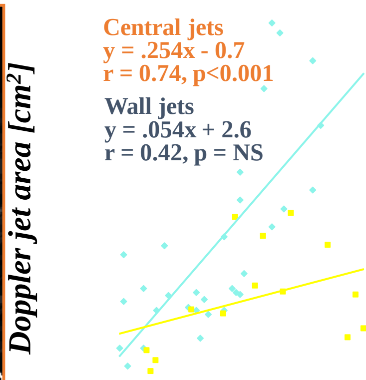
$$JA(M,x_c,u_c)=\frac{x_c^2}{9.7}\left(\ln\frac{7.8\sqrt{M}}{u_c x_c}\right)^{1/2} + \frac{3.93M}{u_c^2}\,\mathrm{erfc}\left[\sqrt{2}\left(\ln\frac{7.8\sqrt{M}}{u_c x_c}\right)^{1/2}\right] \quad (A3)$$

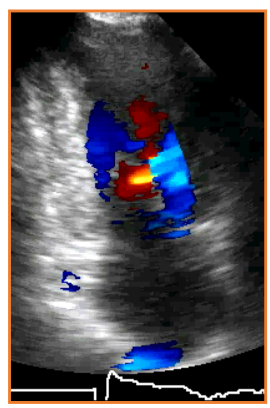
This function is displayed graphically in Figure 7 and discussed in the text.

Determinants of Jet Size

Wall jets are 58% smaller than equivalent central jets







Central jet (Cardiomyopathy)

MR fraction [%]

Wall jet (AML override)

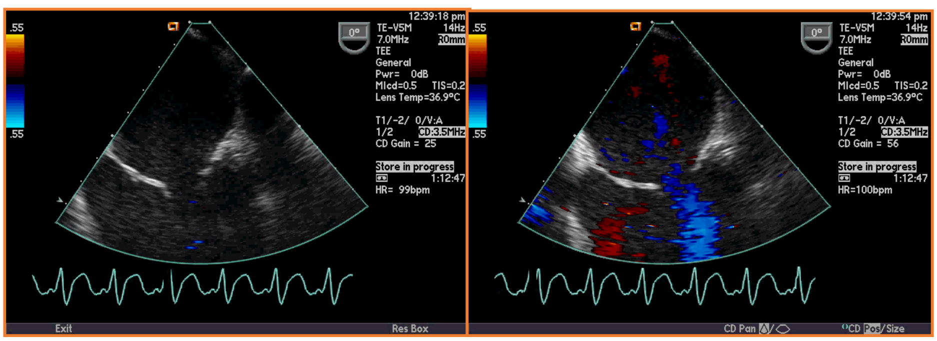
Chen, et al., Circulation 1991; 84; 712-720

Color Doppler Instrumentation

Changes that Increase Jet Size

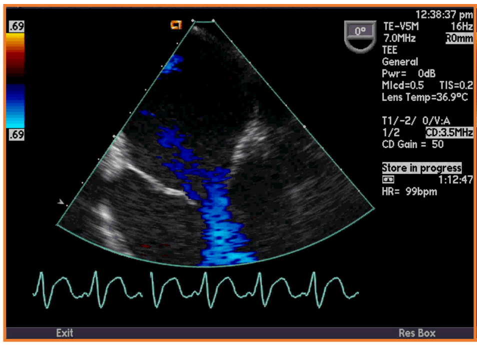
- ⇑ Gain and power
- ⇓ Pulse repetition frequency
- ⇑ Transducer frequency
  - *Frequency effect*
- ⇓ Transducer frequency
  - *Attenuation effect*
- ⇓ Wall filter
- ⇑ Ensemble length

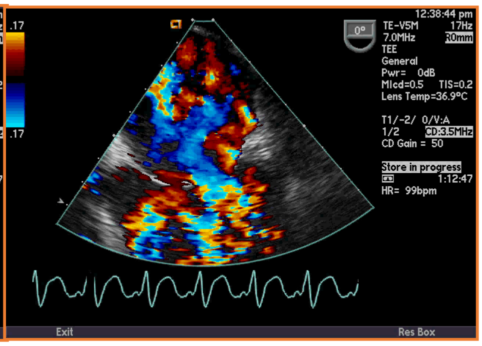
Impact of Color Gain



CD Gain = 25 *CD Gain = 56*

Impact of Velocity Scale

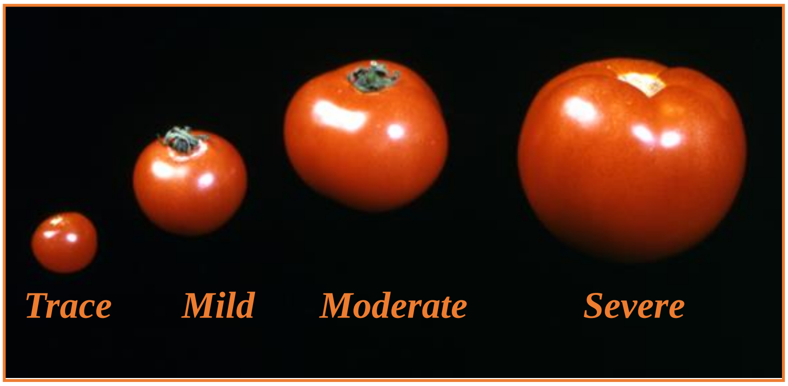




Nyquist Limit = 69 cm/sec *Nyquist Limit = 17 cm/sec*

$V_{min} \approx 4$ *cm/sec* $V_{min} \approx 1$ *cm/sec*

How We Usually Grade Regurgitation

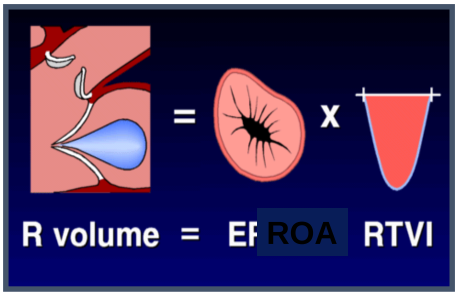


Can't we do better????

How Leaky IS That Valve?

Key Quantitative Concept

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

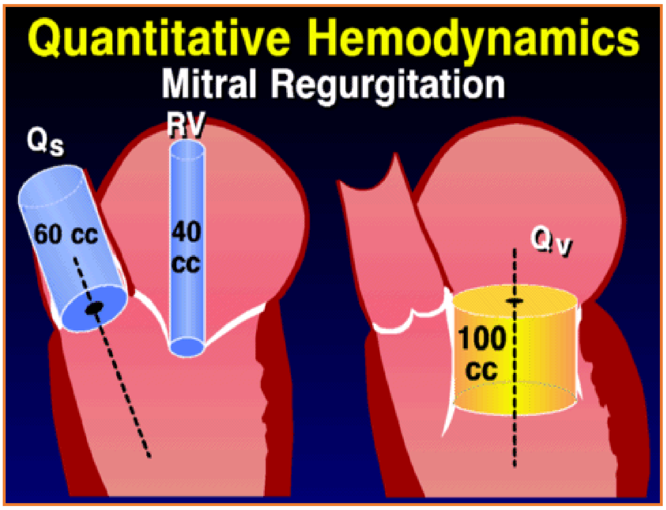


Mild: 0 - 20 mm^2
Moderate: 20 - 40 mm^2
Severe: > 40 mm^2

PISA??

What are the Alternatives?

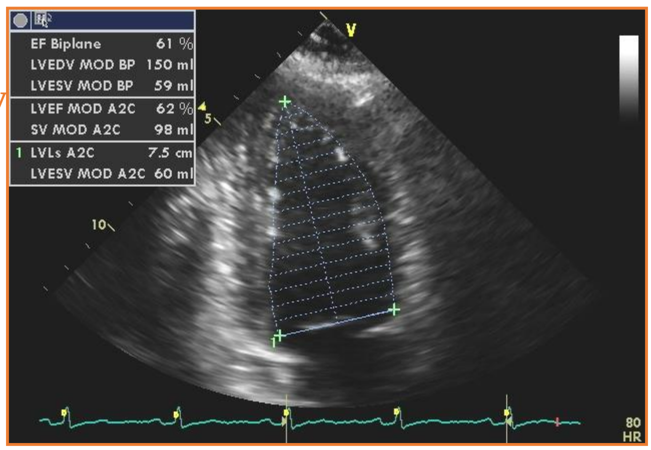
- *Color jet area*
- ***Pulsed Doppler and 2D difference methods***
  - **Pro: Well validated, quantitative**
  - **Con: Complex, multiple windows and measurements, propagation of errors compounded by subtraction**
- *Pulmonary veins*
- *Vena contracta*
- *Proximal flow convergence (PISA)*



Quantification of Stroke Volume

2D or 3D Volumetric Assessment

LVEDV 150 ml

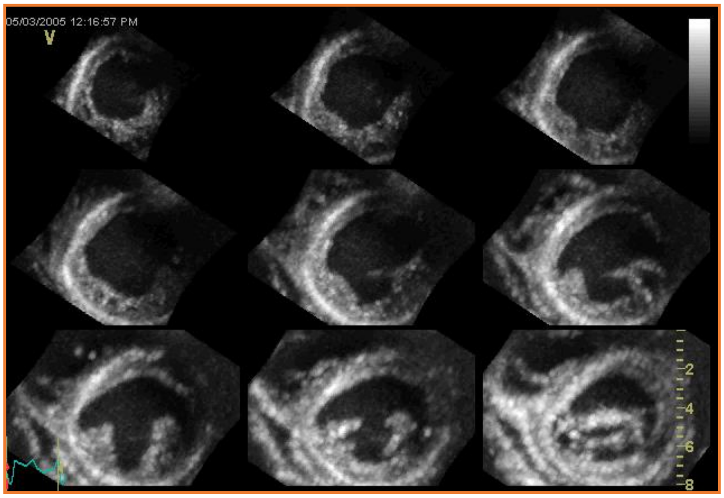


LVESV 59 ml

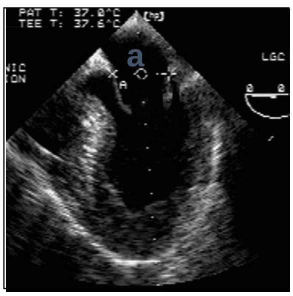
Stroke volume = 91 ml; ejection fraction = 61%

Quantification of Stroke Volume

2D or 3D Volumetric Assessment

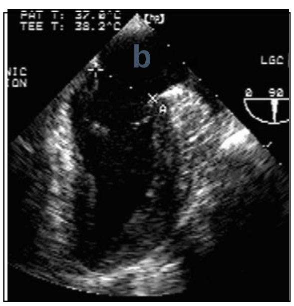


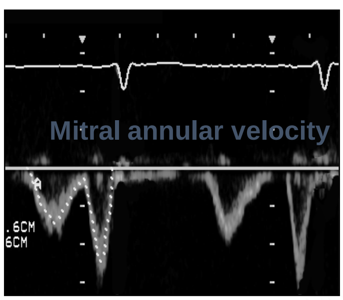
Calculation of Mitral Inflow By Biplane Transesophageal Echocardiography



Annular area = $\pi ab/4$

Stroke volume = $TVI_{MA} \times A_{MA}$





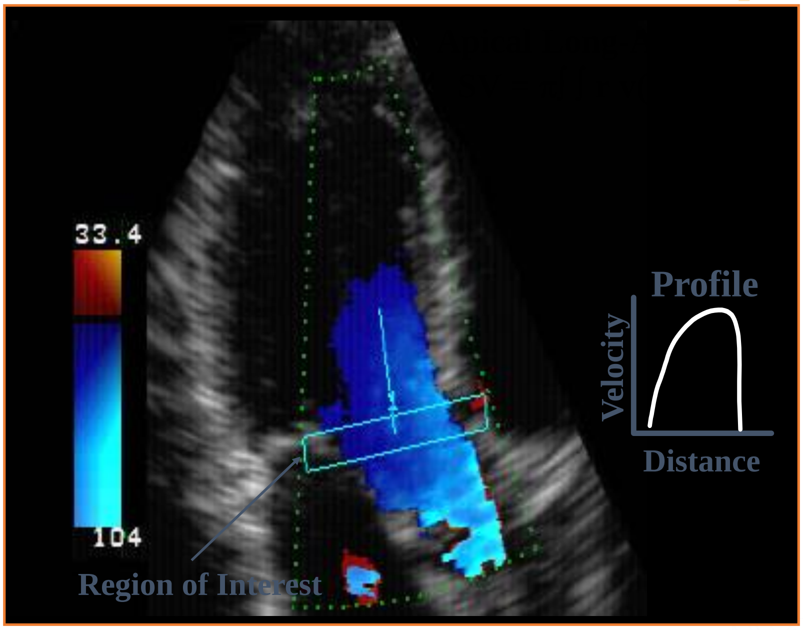
Why Aren't Volumetric Methods Always Used?

Propagation of Errors

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

SV_{LV} = 100±10 mL
SV_{LVOT} = 60±10 mL
RV_{MV} = 40±14 mL
95% CI for RV_{MV} = (10, 70) mL

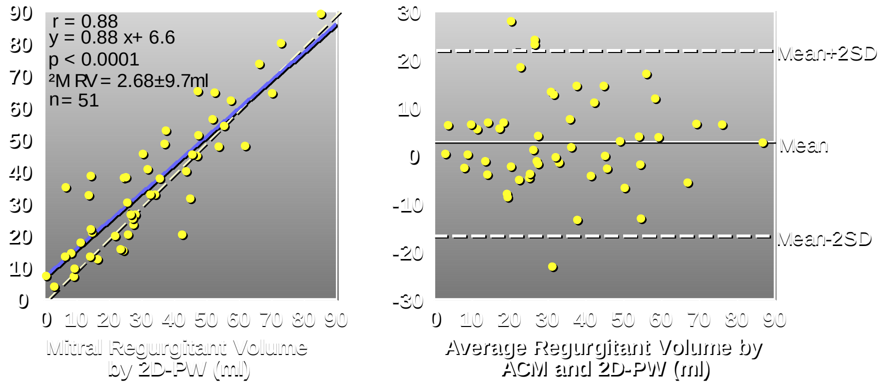
Automated Calculation of Cardiac Output



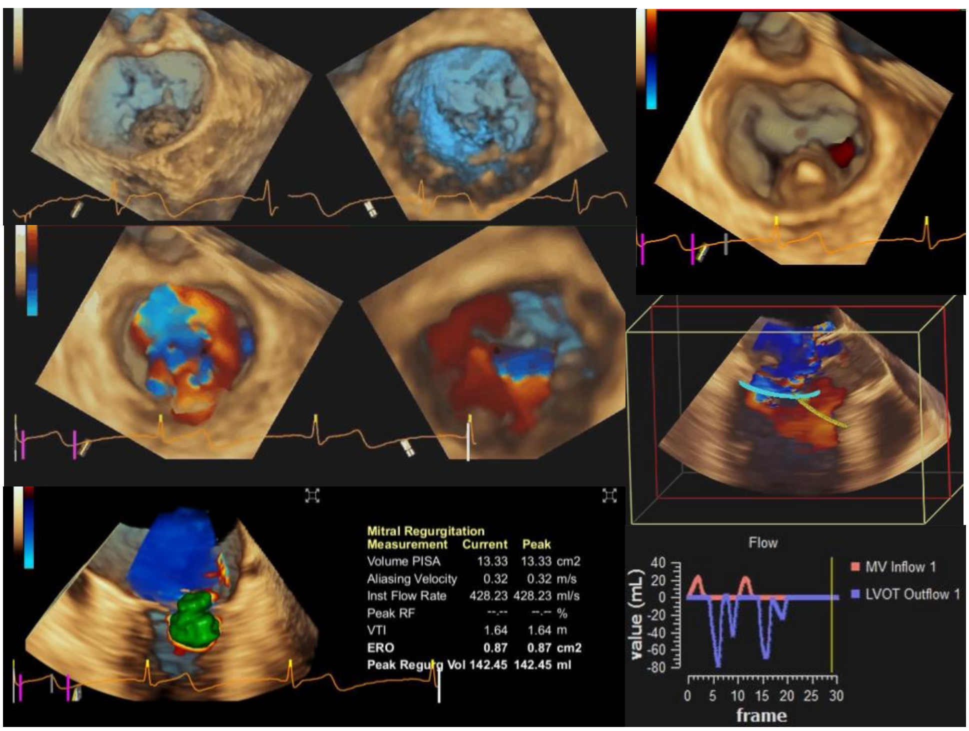
Sun et al, *Circulation* 1997; 95: 932-939

Accuracy of ACM

Quantification of MR

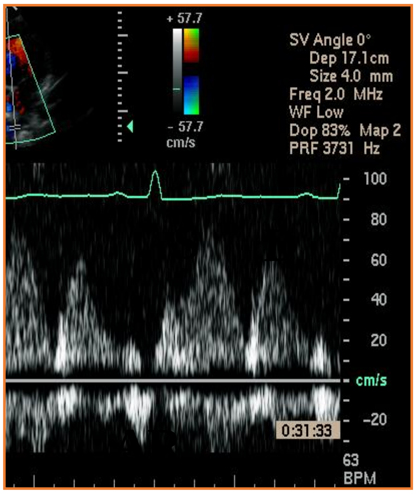


Sun et al. JACC 1998; 32:1074-82.

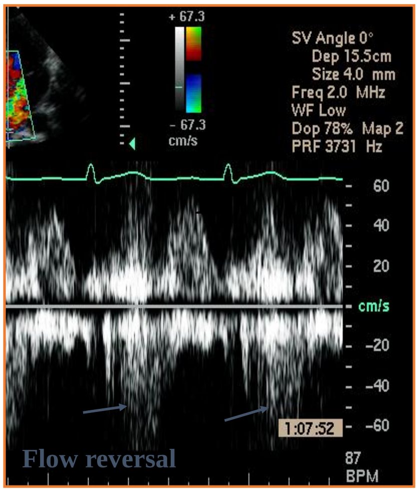


Assessment of Regurgitation

Pulmonary Venous Flow



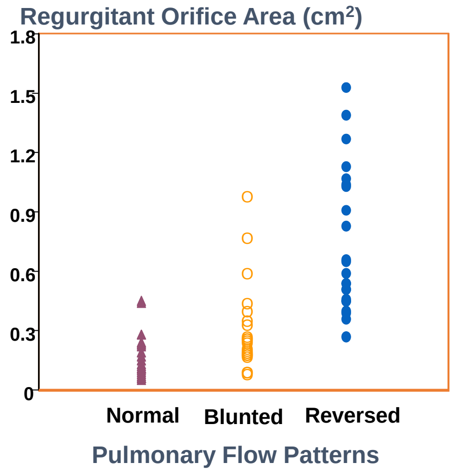
Mild MR



Severe MR

Quantification of MR

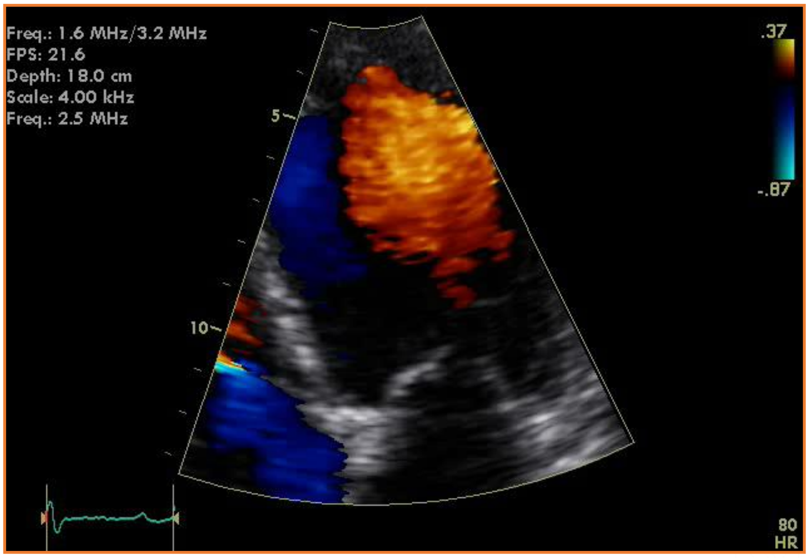
Limitations of Pulmonary Vein Patterns



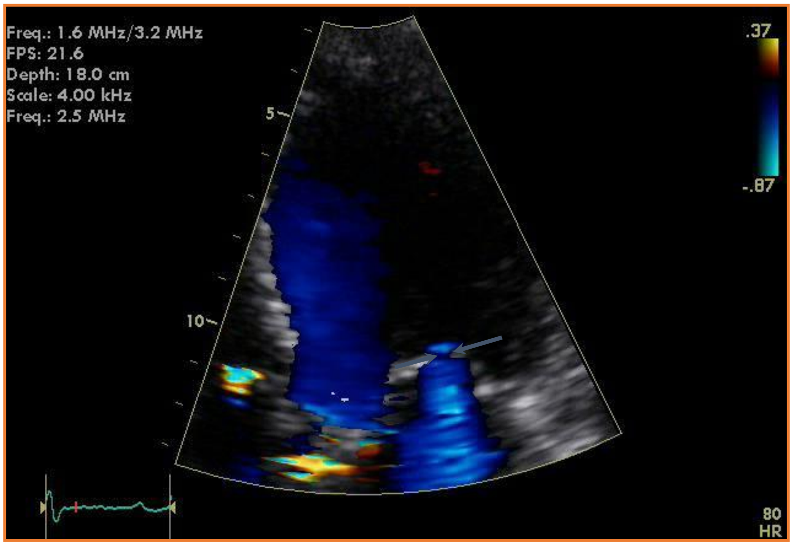
Normal = mild; reversed = severe; blunted = anything

Pu et al. JASE 1999; 12: 736-743

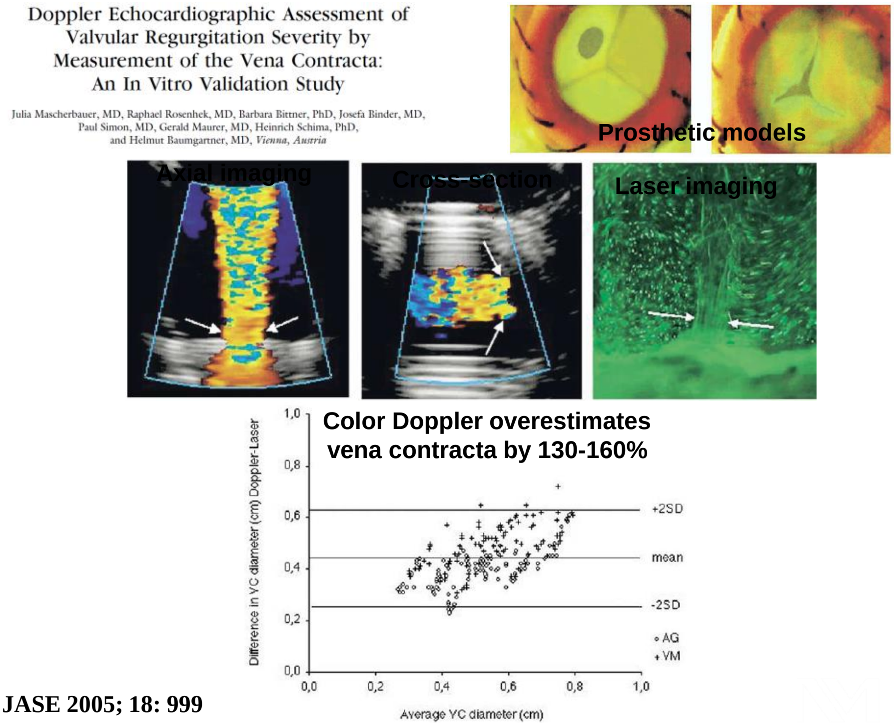
Quantification of MR
Vena Contracta Diameter



Quantification of MR
Vena Contracta Diameter



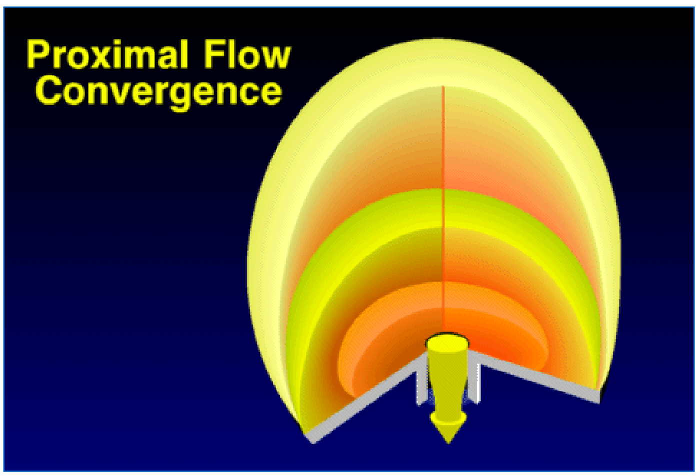
Limited by lateral resolution of echo



JASE 2005; 18: 999

Proximal Convergence Method

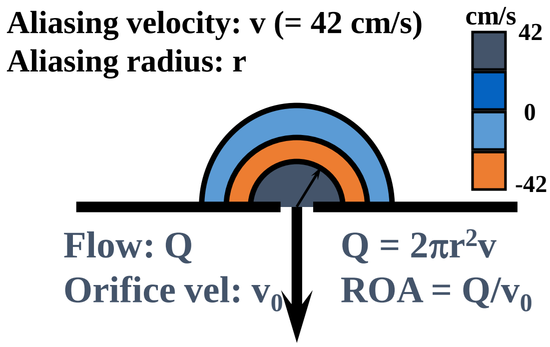
Underlying Principle



Flow thru any isovelocity shell is equal to instantaneous orifice flow

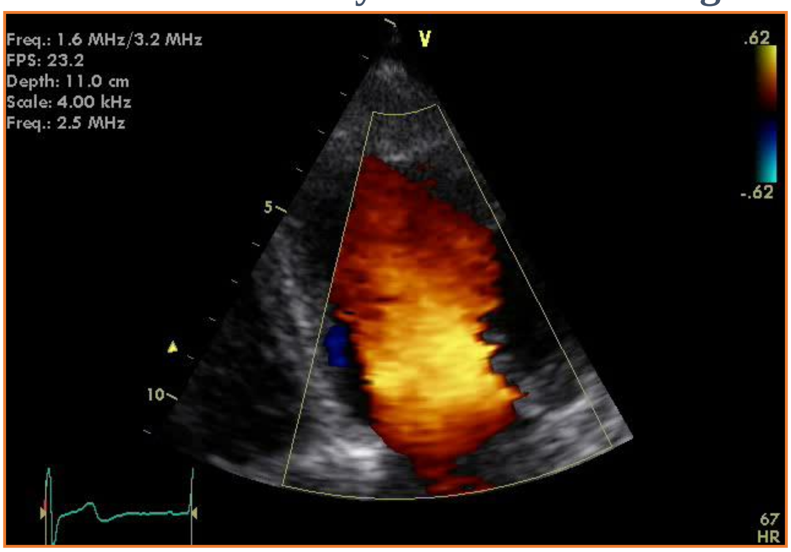
Proximal Convergence Method

Practical Implementation

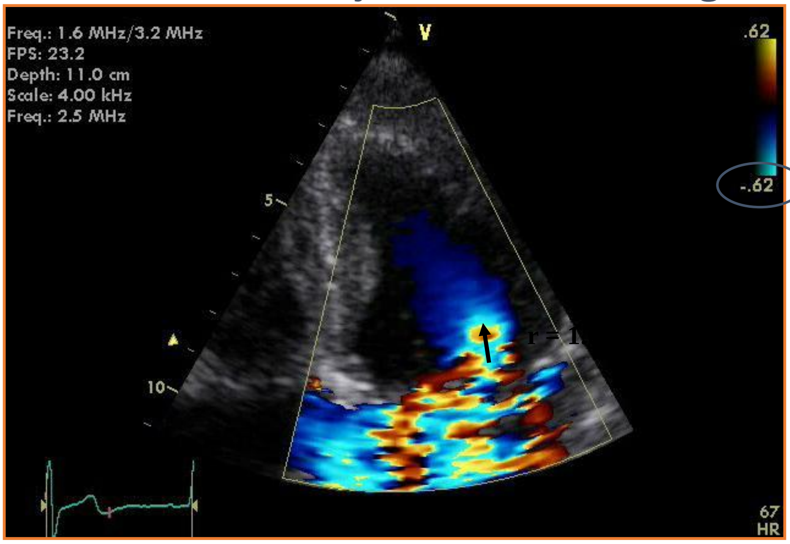


Comprehensive, but there's an easier way.

Assessment of MR by Proximal Convergence



Assessment of MR by Proximal Convergence



$Q = 2\pi r^2 v = 6.28\ (1.0)^2\ 62 = 389$ ml/sec

$ROA = Q/v_0 = 389/550 = 0.7\ cm^2$

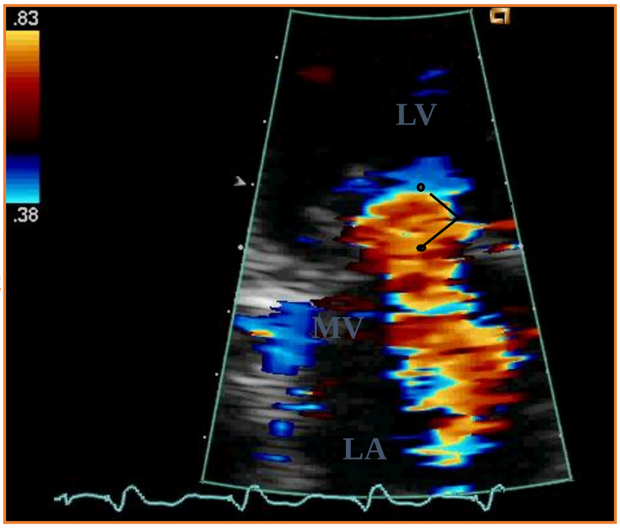
PISA for **Pinheads!**

"Are we having fun, yet??"

Measurement of Mitral ROA
Simplified PISA Formula

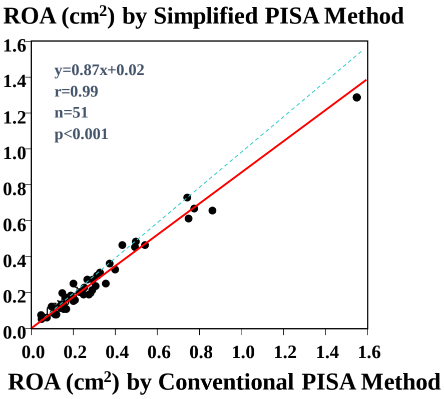
- *Assume LV-LA Δp is 100 mmHg*
- *Set aliasing velocity to (near) 40 cm/sec*
- *Then ROA = $r^2/2$*

ROA = $9^2/2$ = 40 mm^2



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

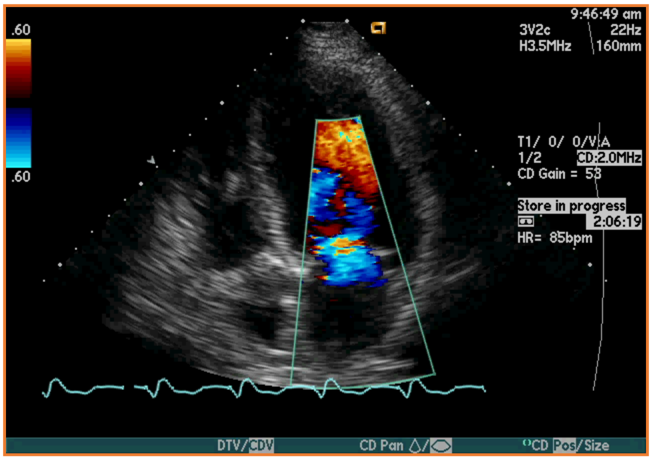
ROA by Simplified PISA Method: $r^2/2$



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

72 yo Man with MR post IPMI

How Bad is the MR??



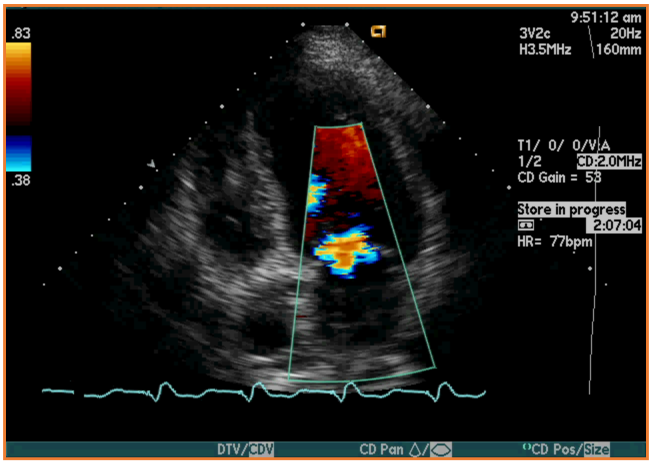
Simplified PISA Method

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

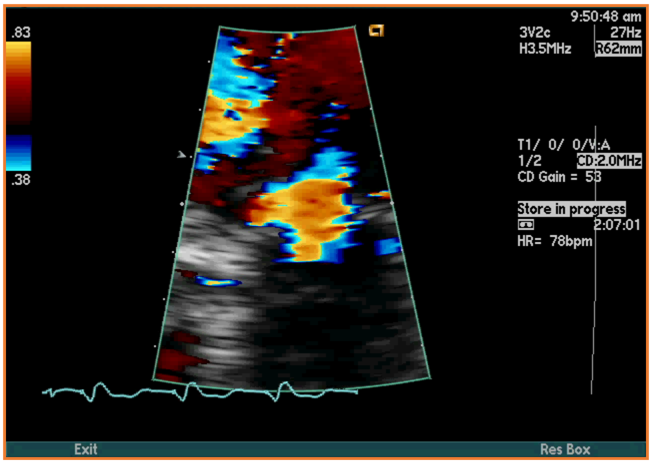
5 Easy Steps



2. Baseline shift to ~40 cm/sec

Simplified PISA Method

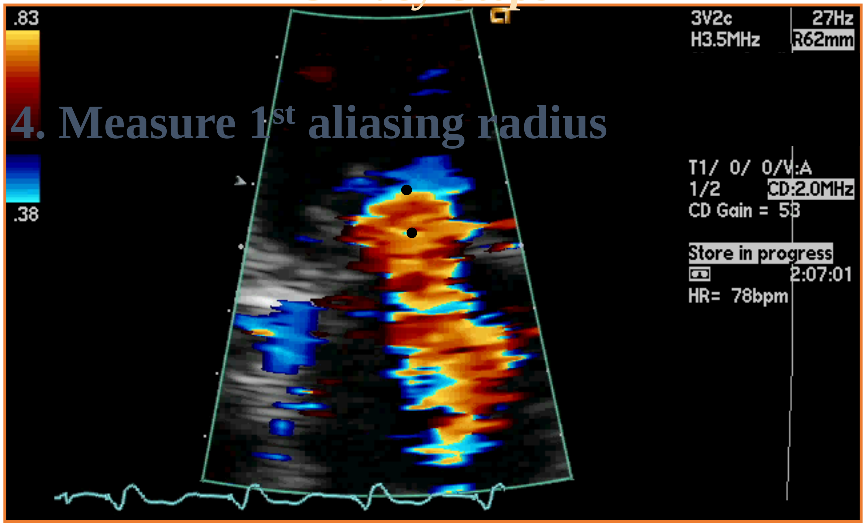
5 Easy Steps



3. Zoom on valve

Simplified PISA Method

5 Easy Steps



4. Measure 1st aliasing radius

5. ROA = $r^2/2 = 9^2/2 = 40\ mm^2$

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

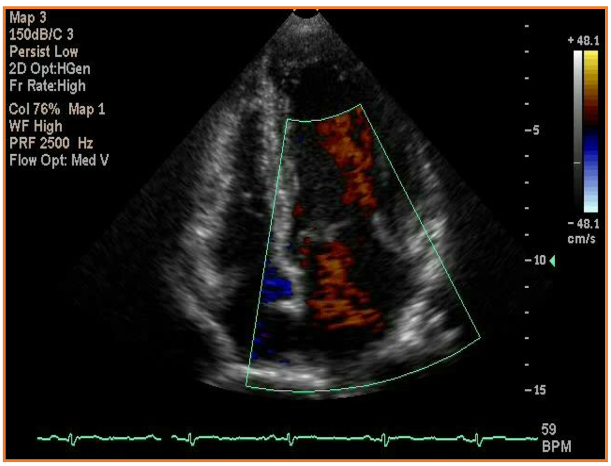
Physiologic Application of the Proximal Flow Convergence Method: Clinical Data and Experimental Testing

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

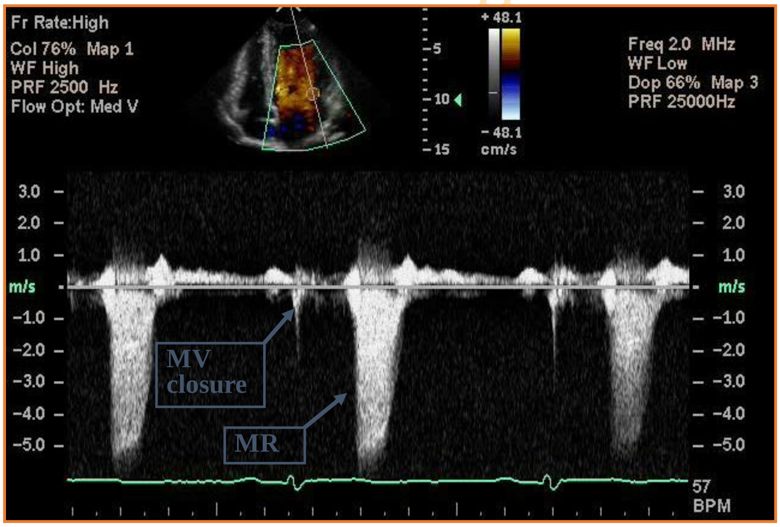


Large jet, large proximal convergence zone

ROA ~ 0.6 cm²

But Only Briefly!

Mitral CW Doppler



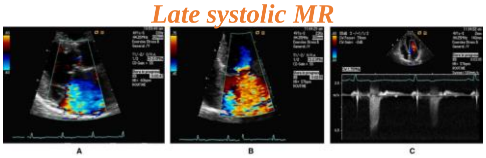
Significant MR only in latter half of systole

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

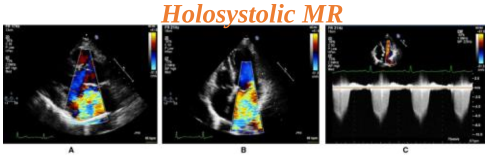
Peyman Naji, MD; Fadi Asfahan, MD; Tyler Barr; L. Leonardo Rodriguez, MD; Richard A. Grimm, MD; Shikhar Agarwal, MD, MPH; James D. Thomas, MD; A. Marc Gillinov, MD; Tomislav Mihaljevic, MD; Brian P. Griffin, MD; Milind Y. Desai, MD

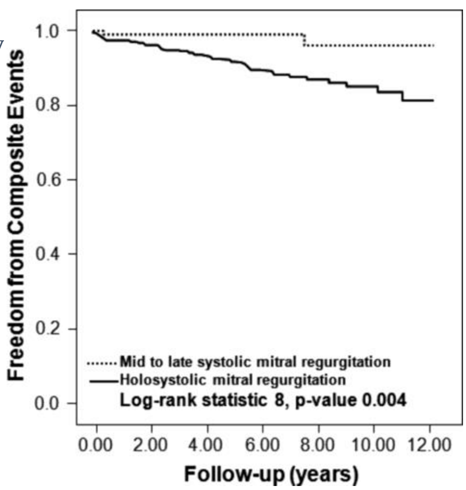
- **609 pts w/ ≥ 3+ MR (122 late systolic)**
- **All underwent stress echocardiography**
- **Late MR pts were younger and more likely female**
- **Endpoints: death and CHF**
- **HS vs LS: 4.99x more likely endpoints**

Late systolic MR



Holosystolic MR





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

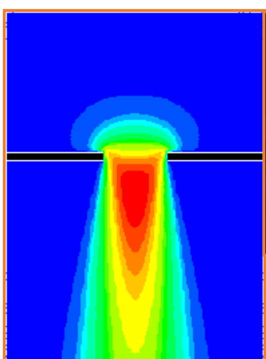
Implications for Doppler Quantification of Valvular Regurgitation

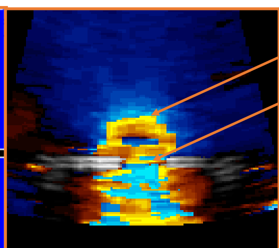
Leonardo Rodriguez, Joseph Anconina, Frank A. Flachskampf, Arthur E. Weyman, Robert A. Levine, and James D. Thomas

Circ Res **1992; 70: 923-30**

Computational Fluid Dynamics Aids Analysis

Contour Flattening Near the Orifice





Contour velocity: v_a

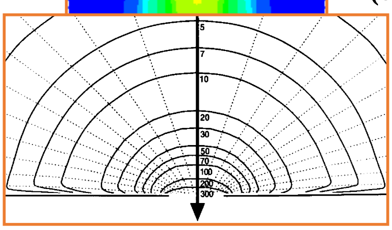
Orifice velocity: v_0

Conventional PISA

$Q = 2\pi r^2 v_a$

Flow underestimated by v_a/v_0

(e.g., 8% for 40 cm/sec contour and 5 m/sec jet)



Corrected PISA

$$Q = 2\pi r^2 v_a \frac{v_0}{v_0 - v_a}$$

Rodriguez et al. Circ Res 1992; 70: 923-30

PISA Adjustments

Pitfalls and Refinements to Keep in Mind

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

Validation of the Proximal Flow Convergence Method

Calculation of Orifice Area in Patients With Mitral Stenosis

Leonardo Rodriguez, MD; James D. Thomas, MD; Victor Monterroso, MD; Arthur E. Weyman, MD; Pamela Harrigan, RDCS; Licia N. Mueller, RDCS; Robert A. Levine, MD

Rodriguez et al. *Circulation*. 1993;88:1157-65.

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

Clinical Validation of a Geometric Correction for Proximal Flow Constraint

Min Pu, MD, PhD; Pieter M. Vandervoort, MD; Brian P. Griffin, MD; Dominic Y. Leung, MBBS, MRCP, FRACP; William J. Stewart, MD; Delos M. Cosgrove III, MD; James D. Thomas, MD

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

Impact of Wall Constraint on Velocity Distribution in Proximal Flow Convergence Zone

Implications for Color Doppler Quantification of Mitral Regurgitation

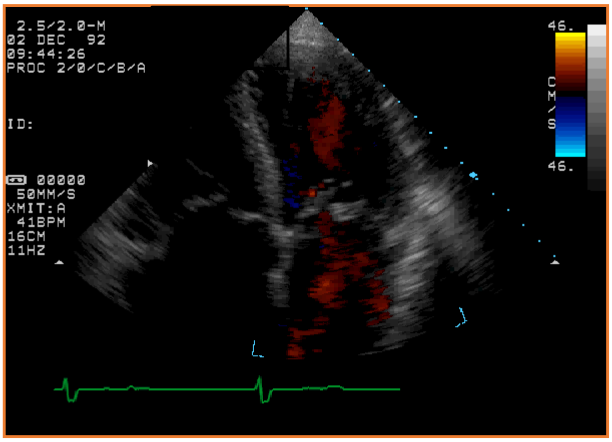
MIN PU, MD, PIETER M. VANDERVOORT, MD, NEIL L. GREENBERG, MS, KIMERLY A. POWELL, PhD, BRIAN P. GRIFFIN, MD, FACC, JAMES D. THOMAS, MD, FACC

Cleveland, Ohio

Pu et al., *JACC* 1996; 27: 706-13.

PISA Pitfalls

Constraint by Surrounding Structures

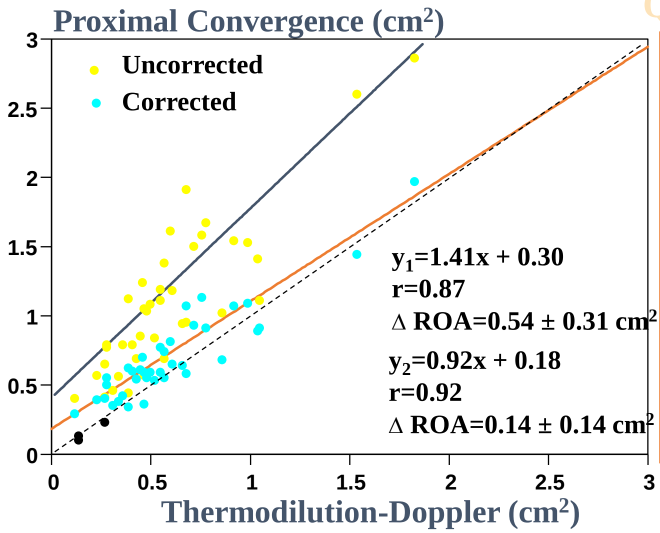


Flail posterior leaflet leads to constraint by posterolateral wall

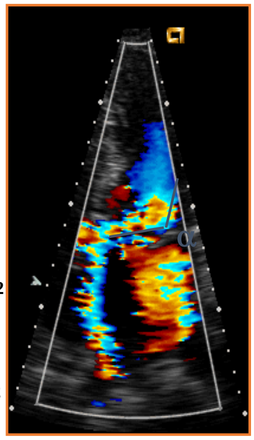
Pu et al., *Circulation* 1995; 92: 2169-2177.

Angle Correction for Constrained Flow

Regurgitant Orifice Area



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



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

PISA Adjustments

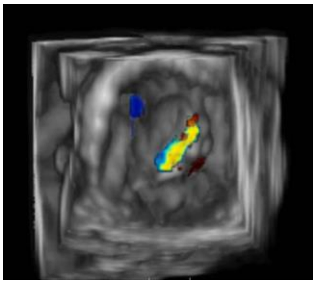
Pitfalls and Refinements to Keep in Mind

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

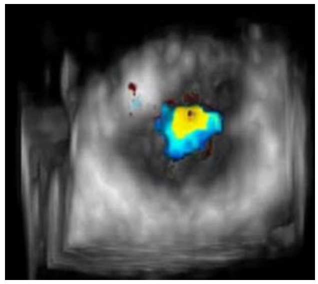
Valvular and Congenital Heart Disease

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

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



Functional mitral regurgitation



Prolapse regurgitation

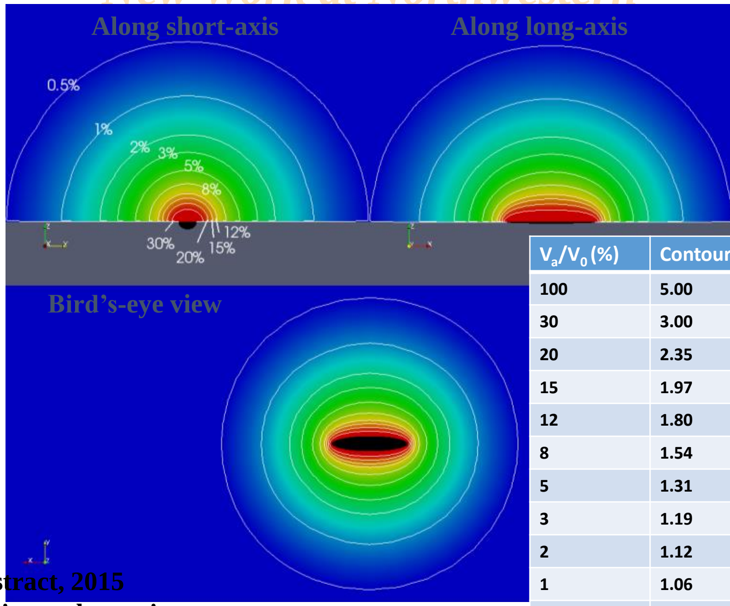
ROA highly elongated in FMR, more focal in MVP

Matsumura Y, et al. ***Am Heart J*** **2008;155:231-8**

What is the impact of orifice shape on PISA accuracy?

Flow Through 5:1 Ellipse

New Work at Northwestern

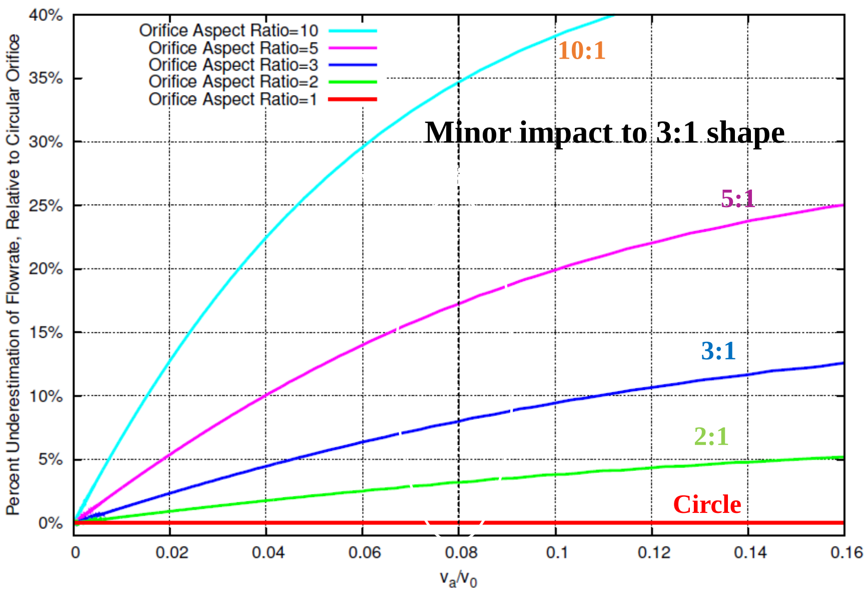


V_a/V_0 (%)	Contour Ratio
100	5.00
30	3.00
20	2.35
15	1.97
12	1.80
8	1.54
5	1.31
3	1.19
2	1.12
1	1.06
0.5	1.02

AHA abstract, 2015
Manuscript under review

Impact of Noncircular Orifices

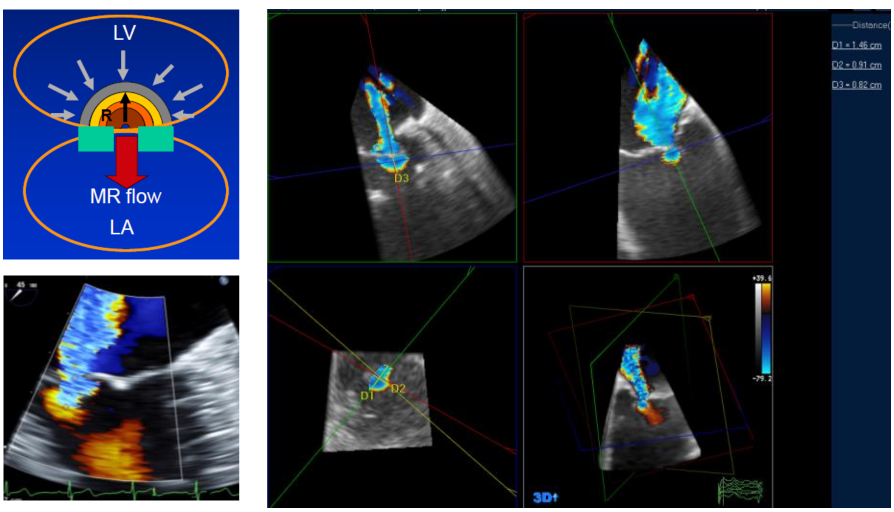
Underestimation vs Circular Orifice



What's New in MR Quantification?

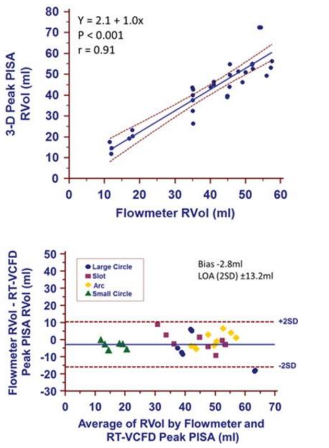
3D PISA Analysis!

Proximal Isovelocity Surface Area

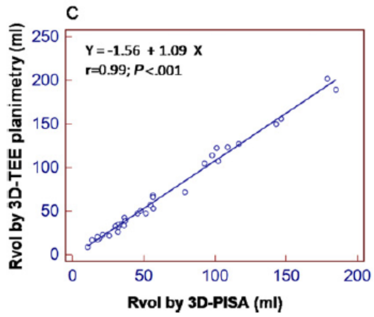


Thavendiranathan et al, JACC Cardiovascular Imaging, 2012, 5(11):1161-75.
Thavendiranathan et al, JACC 2012, 60(16): 1470-83

Proximal Isovelocity Surface Area



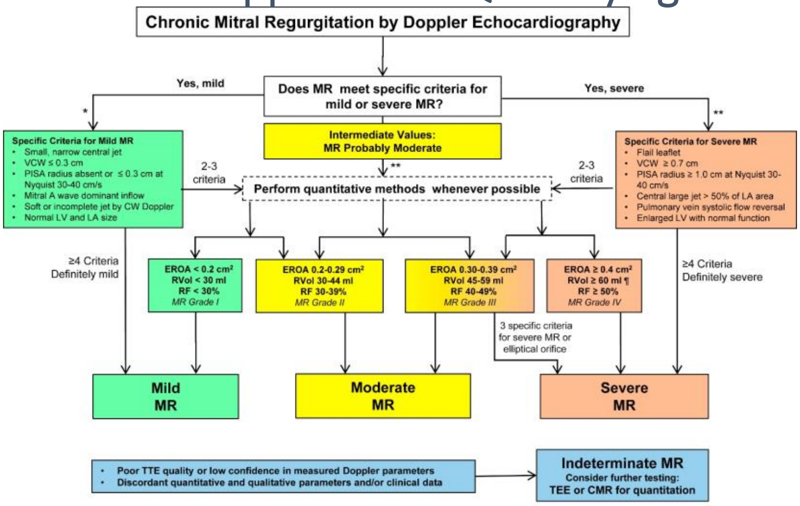
Thavendiranathan et al. Circulation cardiovascular imaging 2013, 6(1): 125-33



De Augustin JA et al, J Am Soc Echocardiogr. 2012 Aug;25(8):815-23

Biblical degree of accuracy?

Practical Approach to Quantifying MR

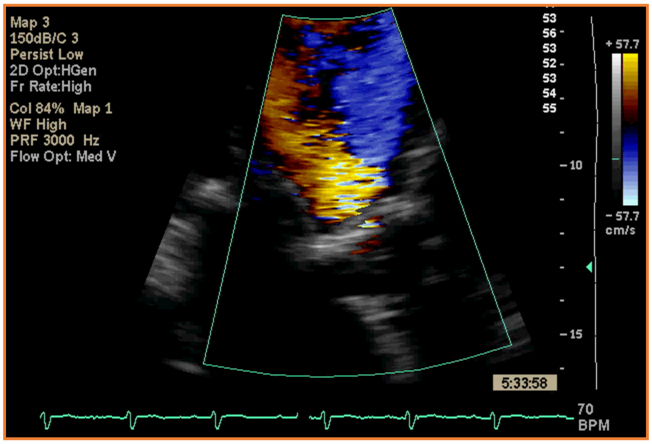


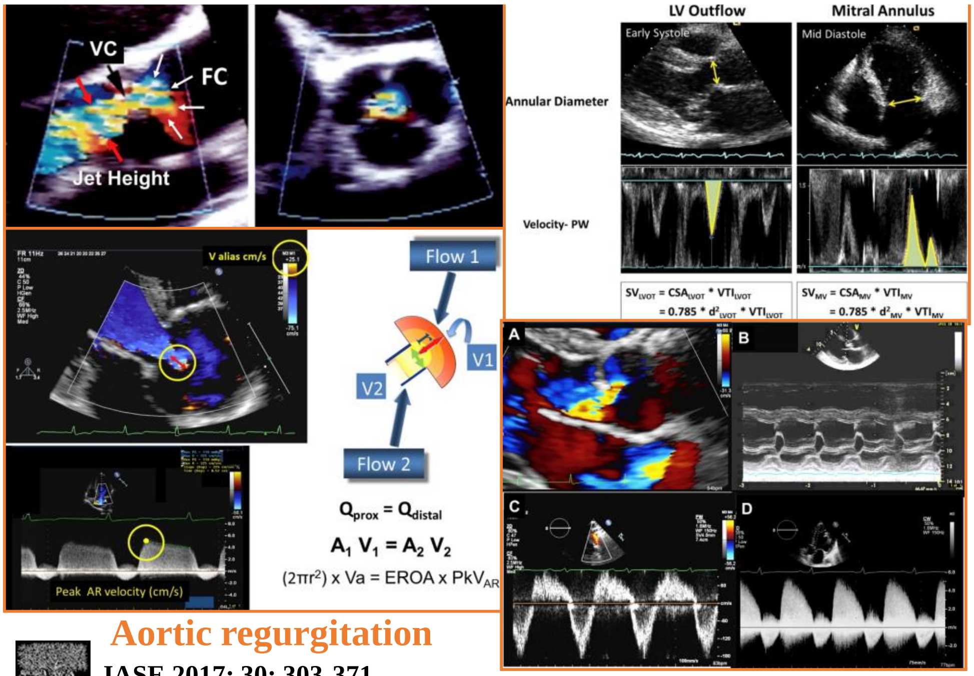
*	Beware of underestimation of MR severity in eccentric, wall impinging jets; quantitation is advised
**	All values for EROA by PISA assume holosystolic MR; single frame EROA by PISA and VCW overestimate non-holosystolic MR
¶	Regurgitant volume for severe MR may be lower in low flow conditions.

ELSEVIER

JASE 2017; 30: 303-371

What About AR???





Aortic regurgitation

ELSEVIER JASE 2017; 30: 303-371

Quantification of AR
What are the Alternatives?

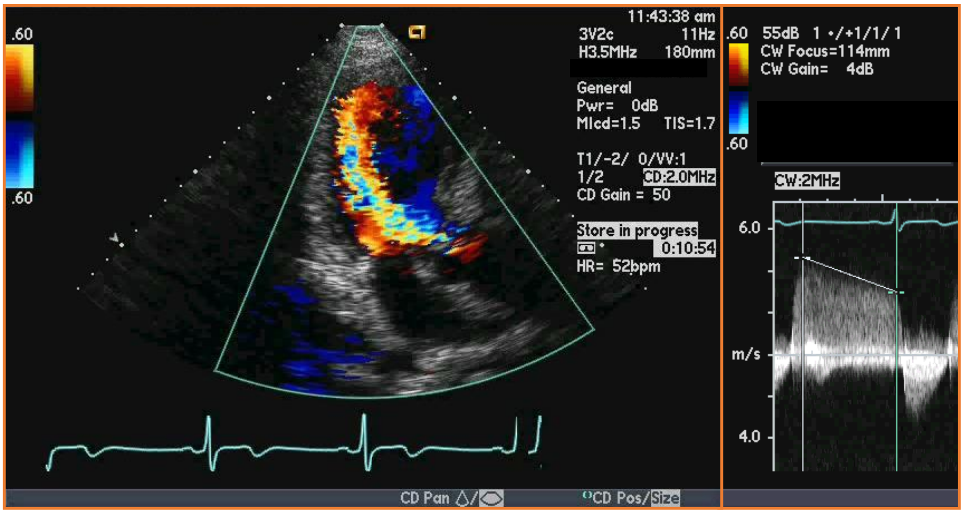
- *Color jet area*
- *Vena contracta*
- *AR pressure half-time*
- *Aortic flow reversal*
- *Pulsed Doppler and 2D difference methods*
- *ACOM methods*
- *Proximal convergence method*

Many parameters similar to MR

Quantification of AR
What are the Alternatives?

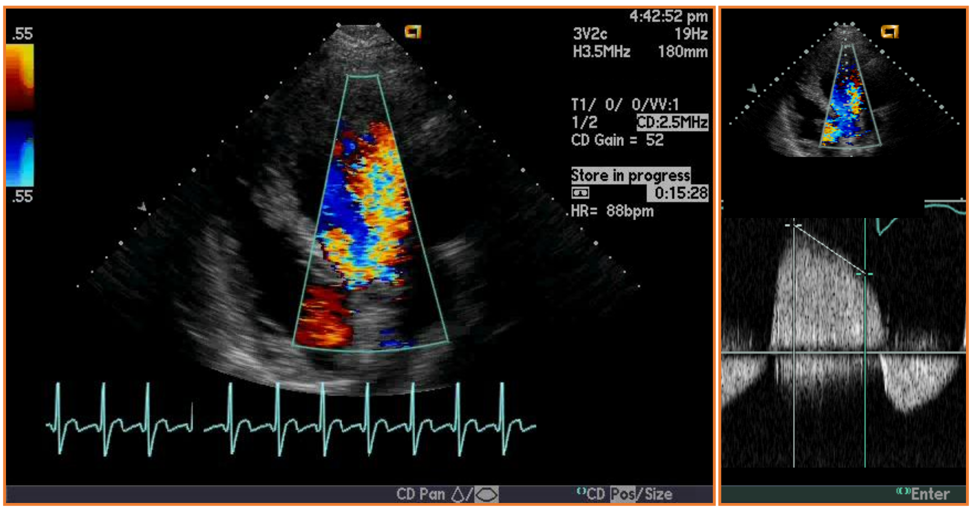
- *Color jet area*
- *Vena contracta*
- *AR pressure half-time*
- *Aortic flow reversal*
- *Pulsed Doppler and 2D difference methods*
- *ACOM methods*
- *Proximal convergence method*

AR Pressure Half-Time



Chronic Moderate AR

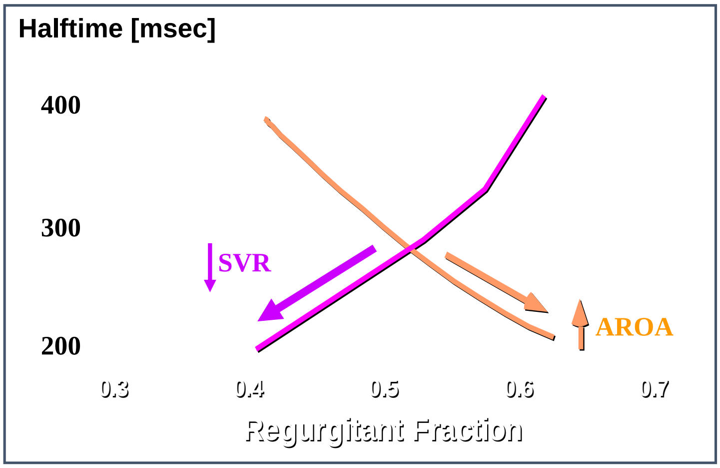
AR Pressure Half-Time



Acute Severe AR (endocarditis)

AR Halftime vs RF

Contrasting Effect of ROA and SVR



Griffin et al *Am Heart J* 1991;122:1049-1056, *Eur Heart J* 1994; 15: 681-685.

Quantification of AR

What are the Alternatives?

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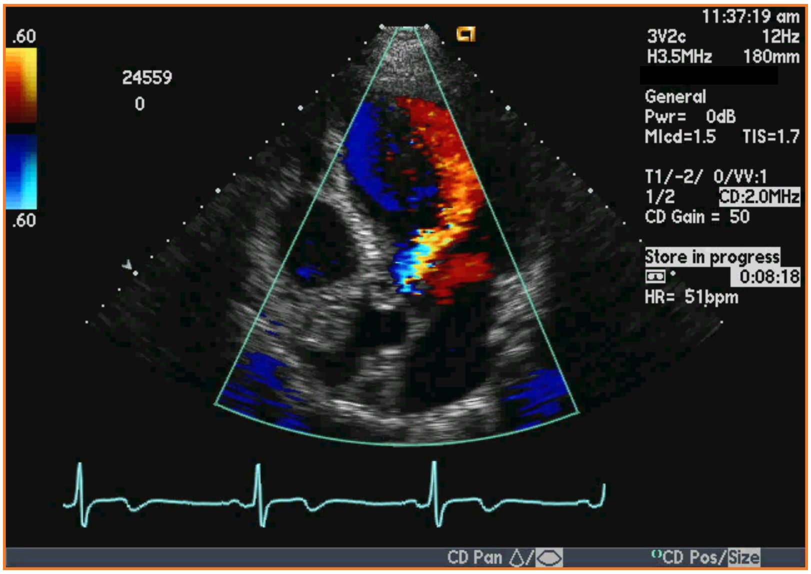
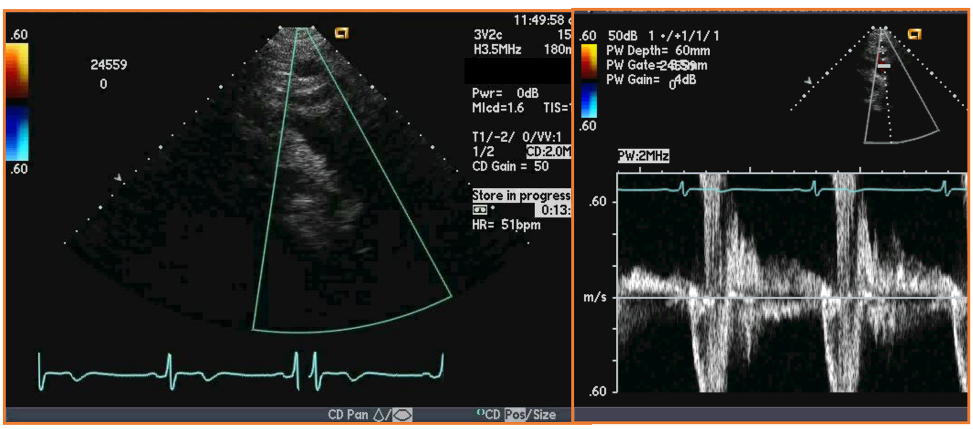
- ***Aortic flow reversal***
- *Pulsed Doppler and 2D difference methods*
- *ACOM methods*
- *Proximal convergence method*

Apical Five-Chamber View



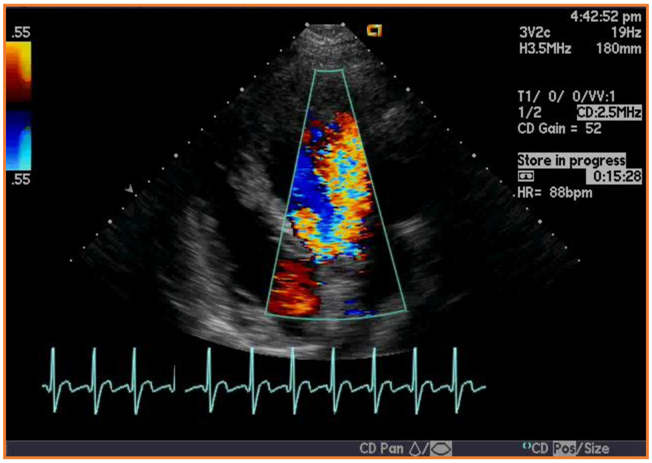
AR of Unclear Severity

Aortic Arch Doppler



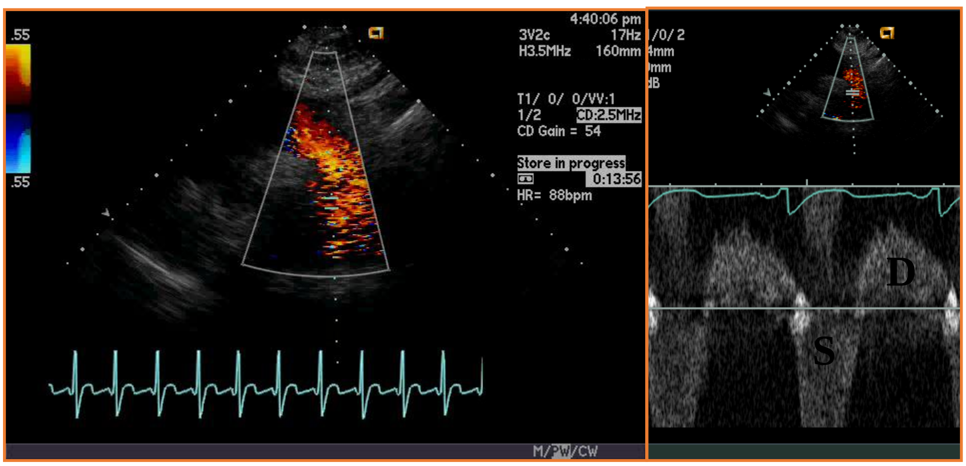
Moderately severe AR

Apical Five-Chamber View



AR of Unclear Severity

Aortic Arch Doppler

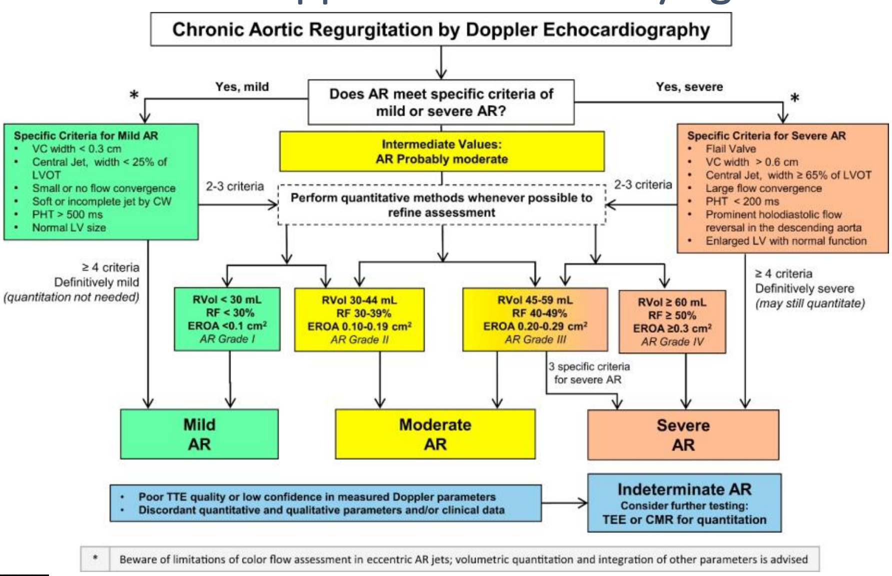


Severe AR

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

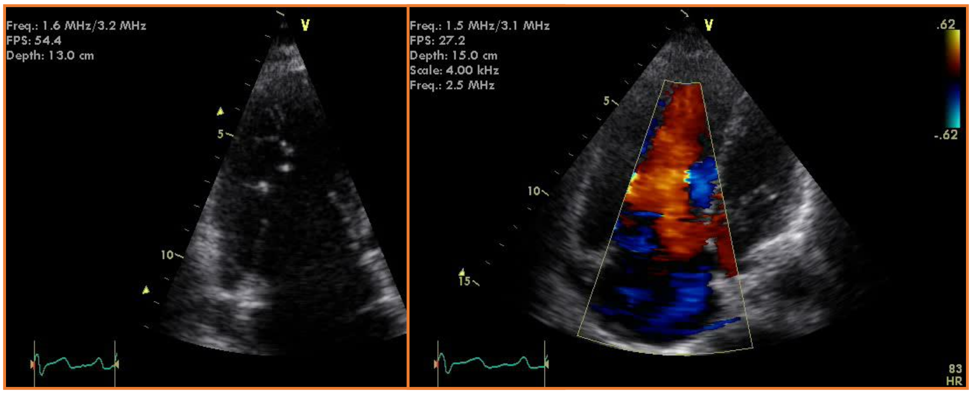
…….it would be an aortic arch pulsed Doppler recording.

Practical Approach to Quantifying AR

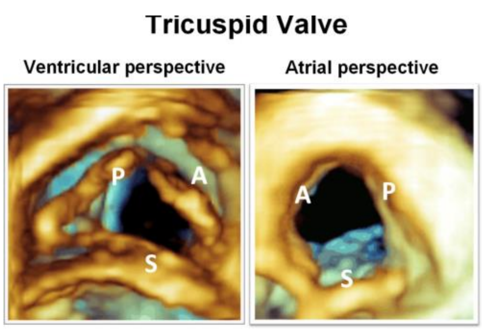


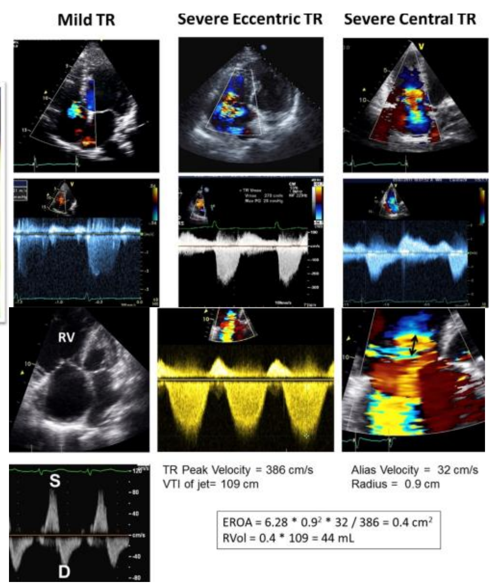
JASE 2017; 30: 303-371

How About TR?



Incomplete TV closure with severe functional TR



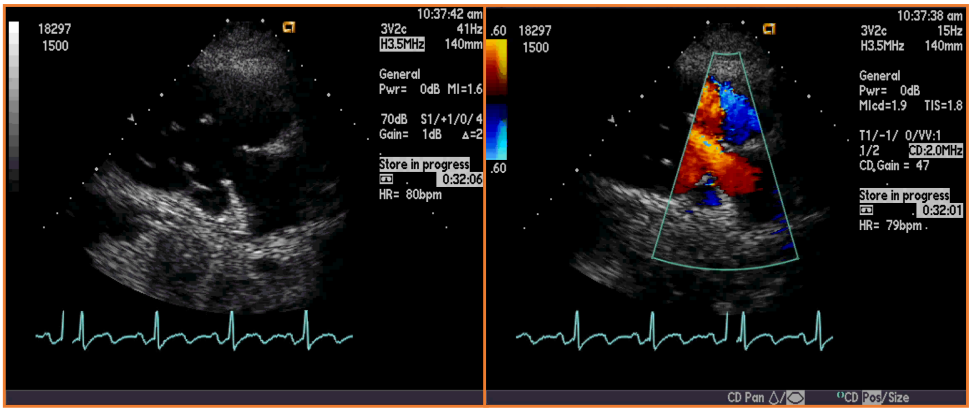


Tricuspid regurgitation

JASE 2017; 30: 303-371

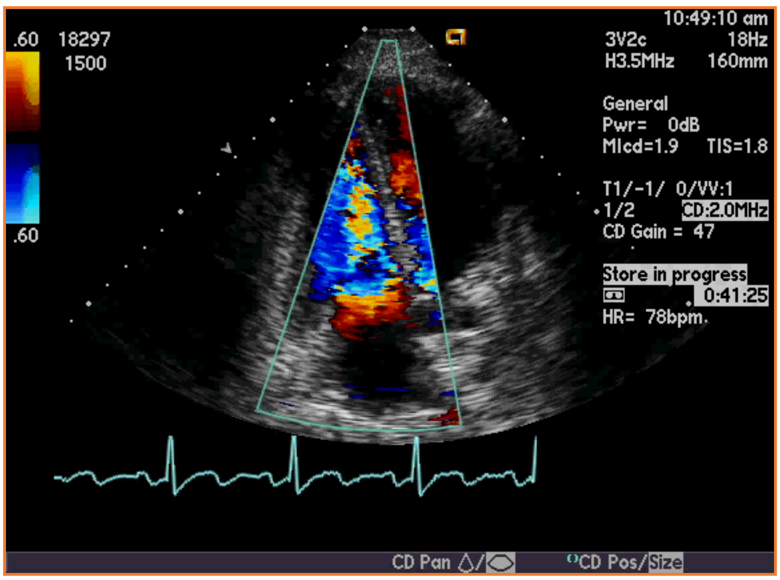
Terms and Conditions

Carcinoid



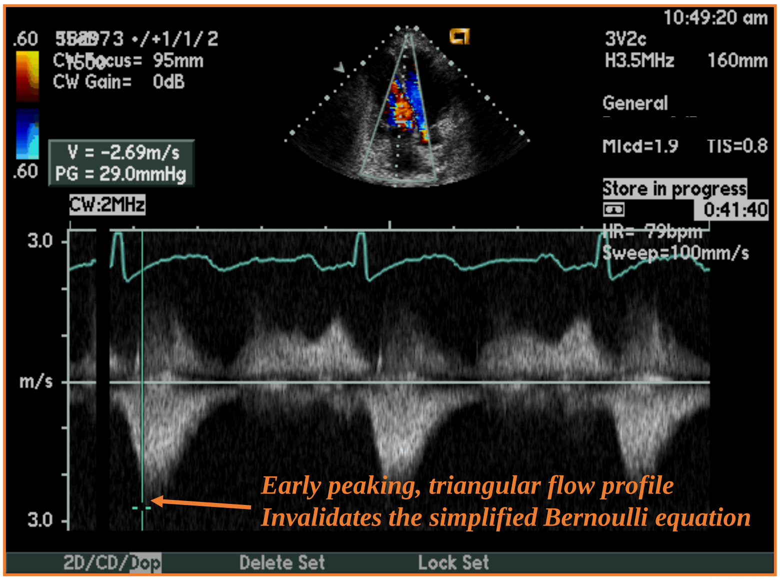
TV fixed in systole and diastole
with severe mixed TR/TS

Apical 4-Chamber



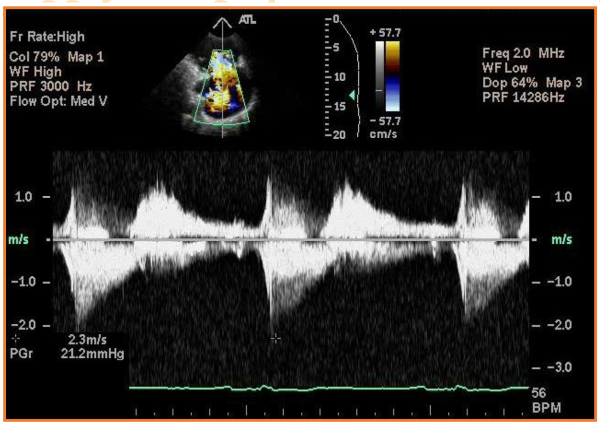
Tricuspid Valve CW

Severe TR



Severe TR

Cannot Apply Simplified Bernoulli Equation

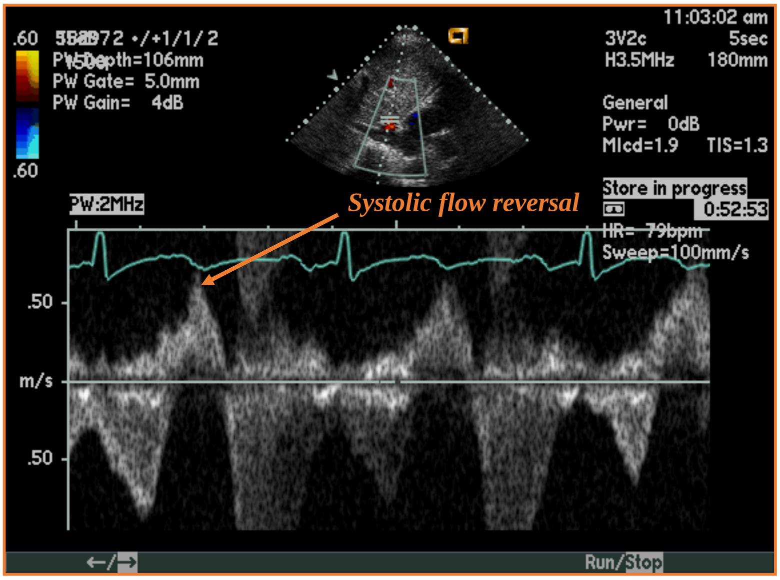


Conservation of energy: ***Bernoulli equation***

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

Convective Acceleration | Inertial Component | Viscous Dissipation

Hepatic Vein Flow



Can PISA be used in TR???

Yes, but…

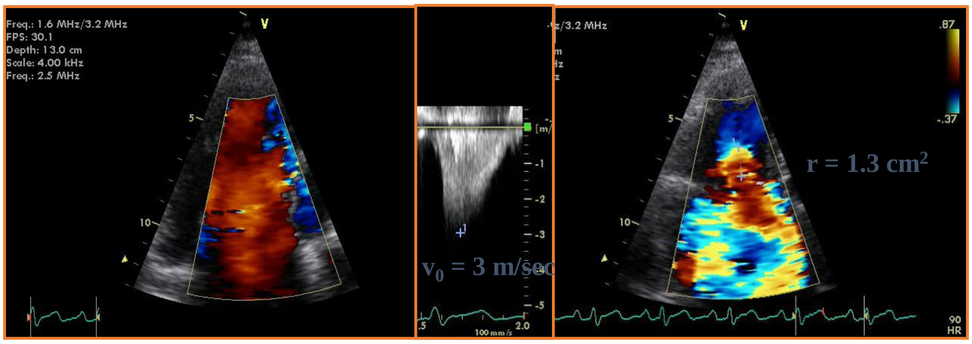
American Heart Journal
Volume 127, Issue 5, May 1994, Pages 1354-1362

Quantification of tricuspid regurgitation by means of the proximal flow convergence method: A clinical study

J.Miguel Rivera, MD [a, b, c, 1], Pieter M. Vandervoort, MD [a, b, c], Donato Mele [a, b, c], Samuel Siu, MD [a, b, c], Eleanor Morris [a, b, c], Arthur E. Weyman, MD [a, b, c], James D. Thomas, MD [a, b, c, 2]

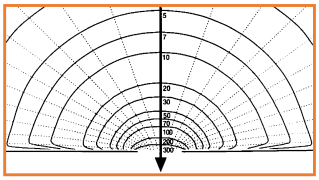
- **Limited validation and experience**
- **Contour flattening a bigger issue**
- **Orifices can be bizarrely shaped**

PISA in TR



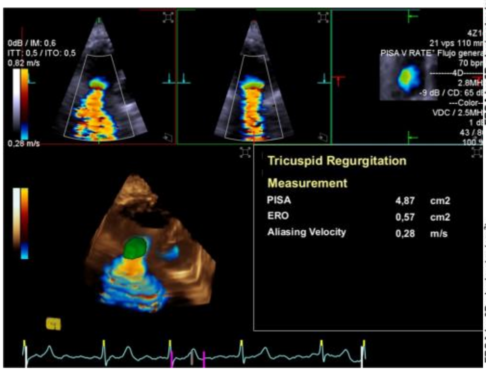
$Q = 2\pi r^2 v = 6.28\ (1.3)^2\ 37 = 393$ ml/sec

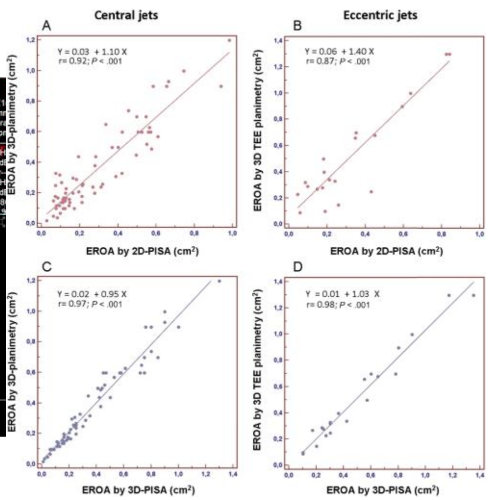
$ROA = Q/v_0 = 393/300 = 1.3$ cm^2



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

3D PISA in TR?

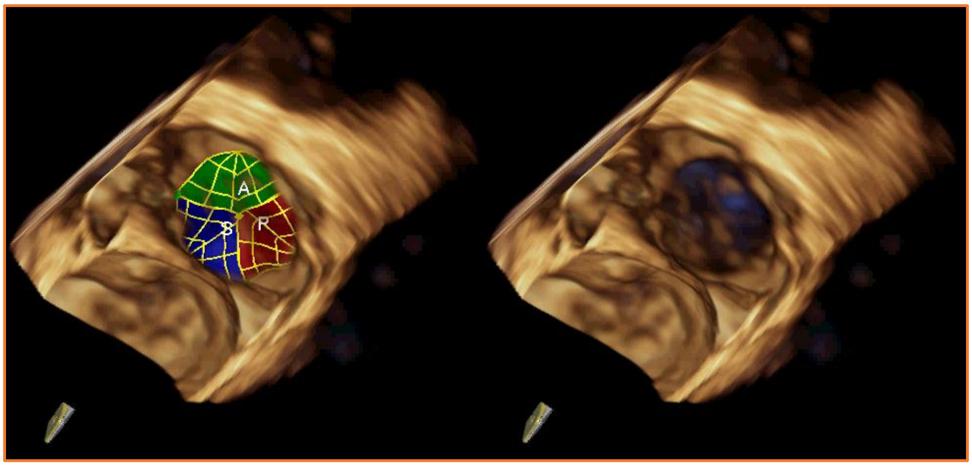




Again, biblical degree of accuracy?

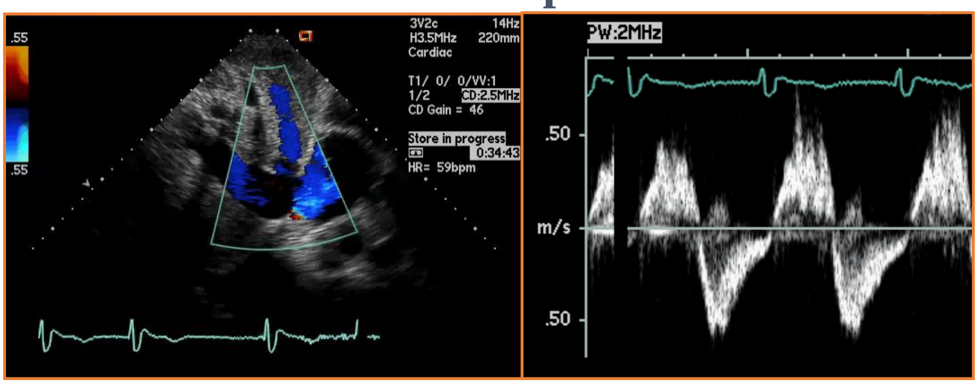
De Augustin et al. JASE 2013; 28: 1063-72

3D Tools are Progressing Rapidly



Clip courtesy of Helene Houle, Siemens

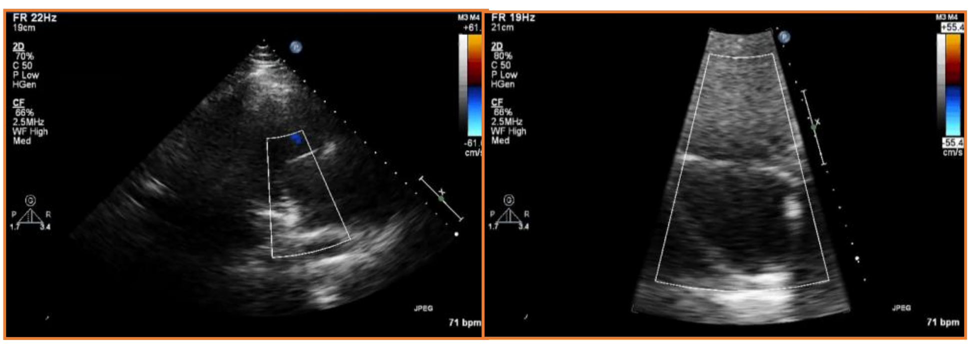
What about systolic flow reversal in the hepatic veins?



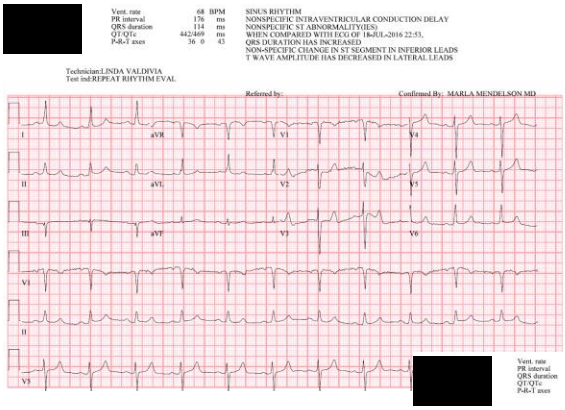
"Usually" a pretty specific sign of severe TR

So how bad's the TR here?

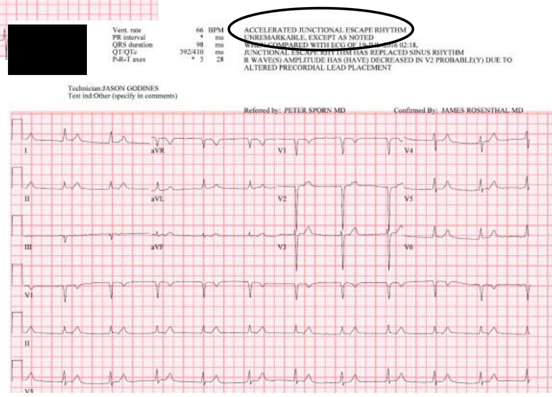
Not so bad



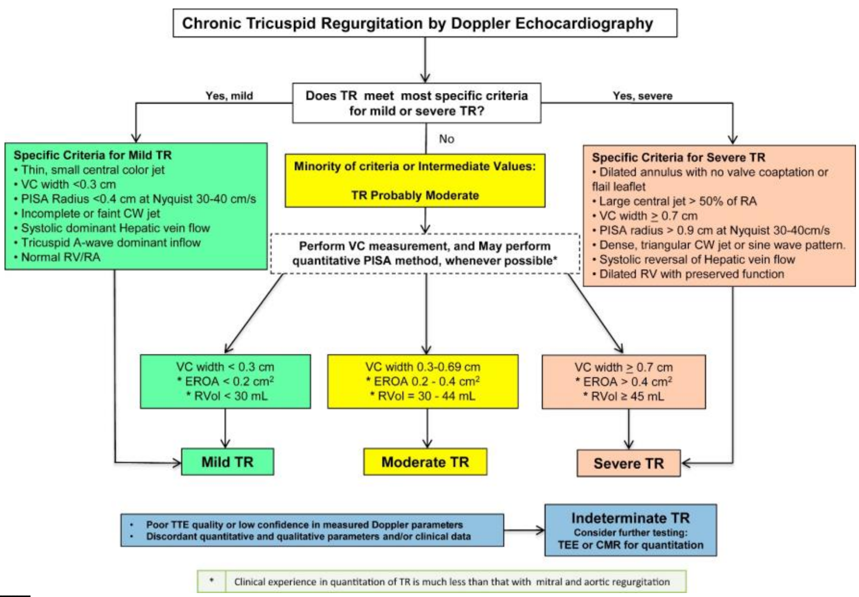
How come?



Baseline EKG: SR

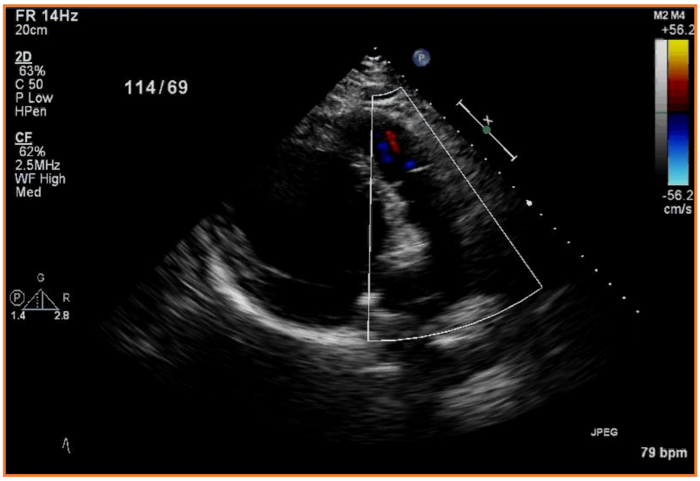


EKG on day of echo: Junctional
Retrograde P-waves
Cannon A-waves



JASE 2017; 30: 303-371

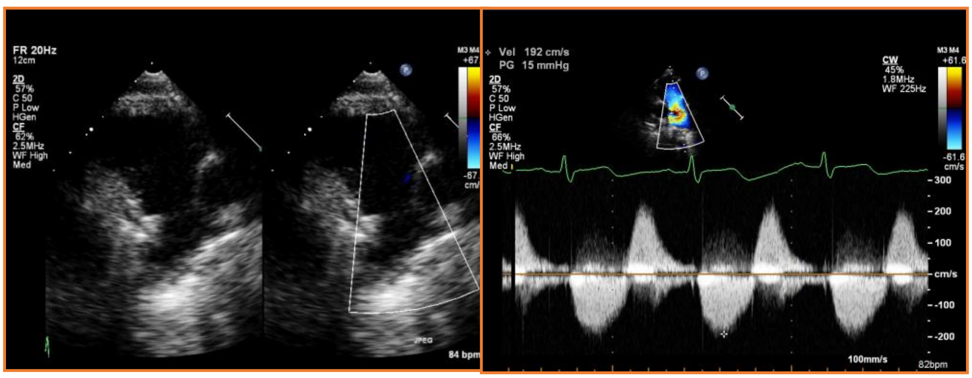
And What of PR?



Actually, no one cares about PR

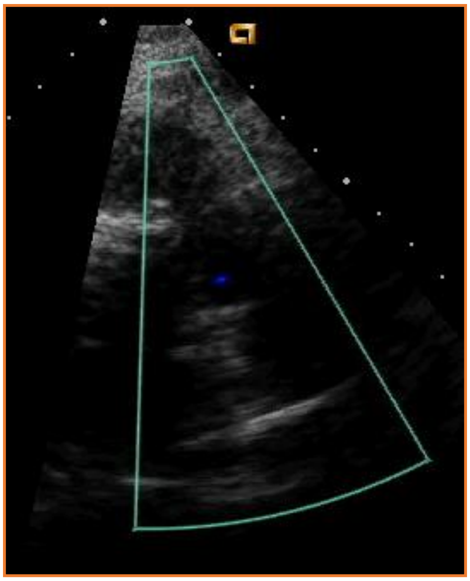
With ONE exception

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!!