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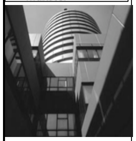

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Valvular Stenosis and Regurgitation: Assessment of Severity

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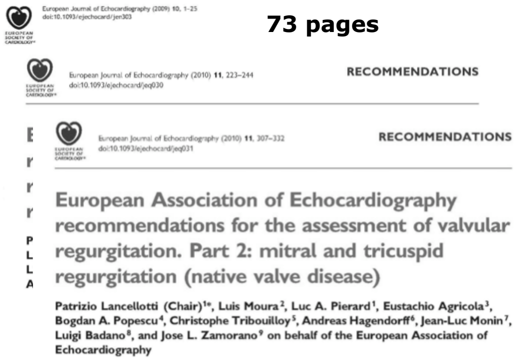

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RECOMMENDATIONS

European Journal of Echocardiography (2010) **11**, 307–332
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RECOMMENDATIONS

European Association of Echocardiography recommendations for the assessment of valvular regurgitation. Part 2: mitral and tricuspid regurgitation (native valve disease)

Patrizio Lancellotti (Chair)[1*], Luis Moura[2], Luc A. Pierard[1], Eustachio Agricola[3], Bogdan A. Popescu[4], Christophe Tribouilloy[5], Andreas Hagendorff[6], Jean-Luc Monin[7], Luigi Badano[8], and Jose L. Zamorano[9] on behalf of the European Association of Echocardiography

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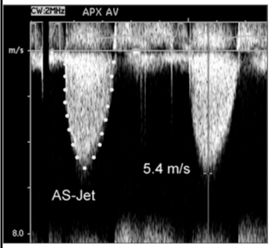
Assessment of valvular stenosis severity

- Peak velocity / peak gradient
- Mean gradient
  (rest / exercise / dobutamine)
- Valve area
  planimetry (MS, AS)
  continuity equation (AS)
  pressure half-time (MS)
- Indirect signs
  LVH (AS), RVH (PS)
  PAP (MS), RVP (PS)

Assessment of Valvular Stenosis Severity



CW Doppler: Measurement of transvalvular velocity

Calculation of peak gradient
$\Delta P_{peak} = 4v^2$

Calculation of mean gradient
$\Delta P_{mean} = \Sigma 4v^2 / N$

Doppler Assessment of Transvalvular Gradient

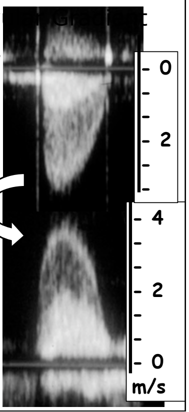
Sources of Error

(1) Underestimation of Catheter Gradient:

- Inappropriate recording angle
- Poor signal quality
- Recording „wrong vel.“ (LVOT)
- Lack of technical expertise or appropriate equipment

Doppler Assessment of Transvalv

Technical Aspects



Try all approaches!
Right parasternal!
Suprasternal!

Doppler Assessment of Transvalvular Gradient

Sources of Error

(2) Overestimation of Catheter Gradient:

- Failure to account for an increased subvalvular velocity

Gradient Calculation by CW-Doppler

BERNOULLI EQUATION

$$p_1 - p_2 = \underbrace{\frac{1}{2}\rho\left(v_2^2 - v_1^2\right)}_{\text{Convective acceleration}} + \underbrace{\rho\int_1^2 \frac{dv}{dt}\,\mathrm{ds}}_{\text{Flow acceleration}} + \underbrace{R\left(\mu v\right)}_{\text{Viscous friction}}$$

$$\Delta p = \frac{1}{2}\rho\left(v_2^2 - v_1^2\right)$$

$$\Delta p = 4\left(v_2^2 - \cancel{v_1^2}\right)$$

V_1: subv. velocity (LVOT) ≈1m/s

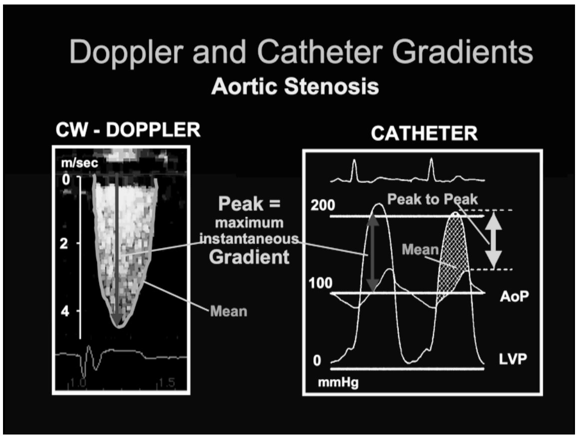
$$\boxed{\Delta p = 4v^2}$$

Doppler Assessment of Transvalvular Gradient

Sources of Error

(2) Overestimation of Catheter Gradient:

- Failure to account for an increased subvalvular velocity
- Inappropriate comparison of different gradients



Doppler and Catheter Gradients

Aortic Stenosis

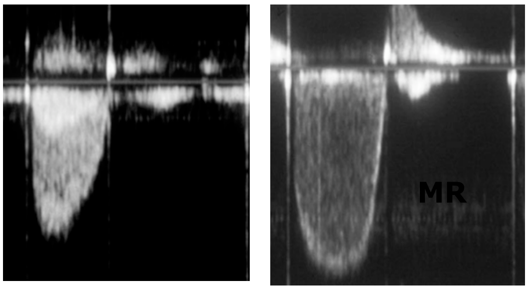
Doppler Assessment of Transvalvular Gradient

Sources of Error

(2) Overestimation of Catheter Gradient:

- Failure to account for an increased subvalvular velocity
- Inappropriate comparison of different gradients
- Recording the wrong velocity (f.e. mitral regurgitation / aortic stenosis)

Recording the Wrong Signal (Aortic Stenosis - Mitral Regurgitation)



Different shape and timing!

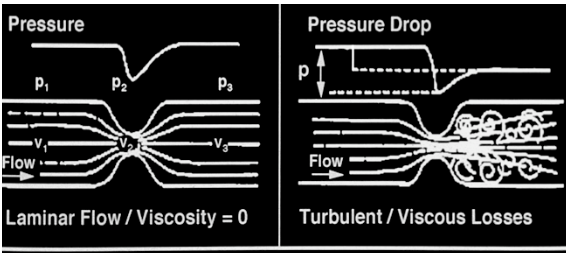
Doppler Assessment of Transvalvular Gradient

Sources of Error

(2) Overestimation of Catheter Gradient:

- Failure to account for an increased subvalvular velocity
- Inappropriate comparison of different gradients
- Recording the wrong velocity (f.e. mitral regurgitation / aortic stenosis)
- Nonrepresentative selection of velocity recording (arrhythmias - tendency to select highest velocities)
- Pressure recovery

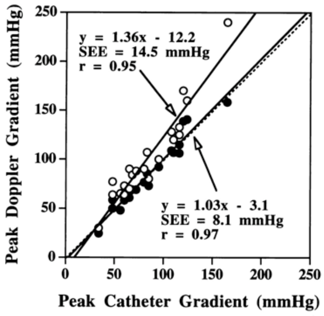
Pressure Recovery



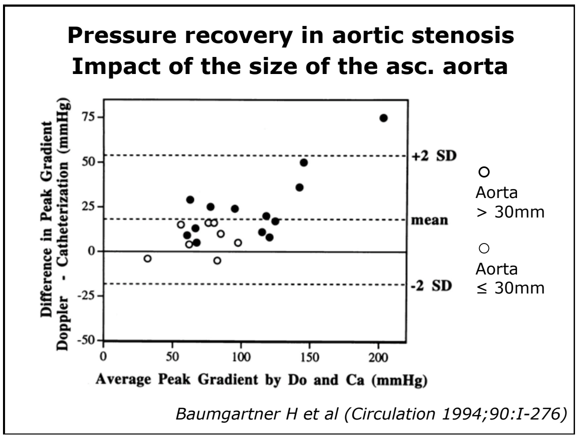
Pressure recovery in aortic stenosis

$$p3 - p2 = 1/2\ \rho v^2 .\ 2AVA/AoA\ .\ (1 - AVA/AoA)$$

Aortic Stenosis: Doppler and Corrected Doppler Gradients vs. Catheter Gradients



Baumgartner H et al (Circulation 1994;90:I-276)

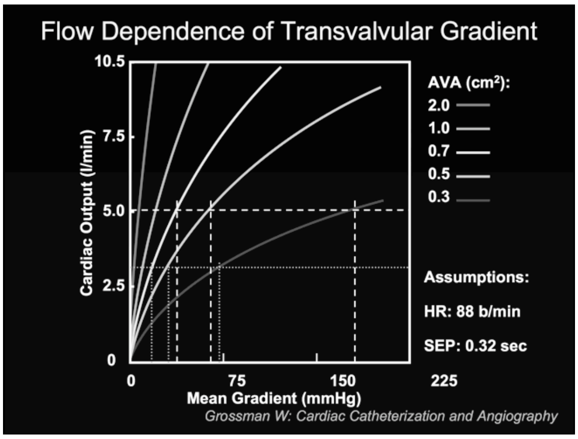


Pressure recovery in aortic stenosis
Impact of the size of the asc. aorta

○ Aorta > 30mm

○ Aorta ≤ 30mm

Baumgartner H et al (Circulation 1994;90:I-276)



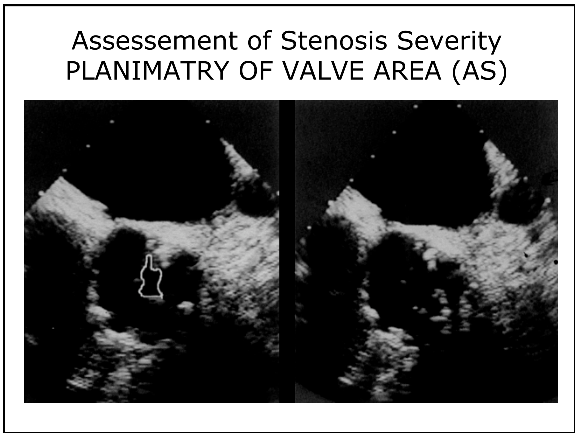
Flow Dependence of Transvalvular Gradient

Assumptions:

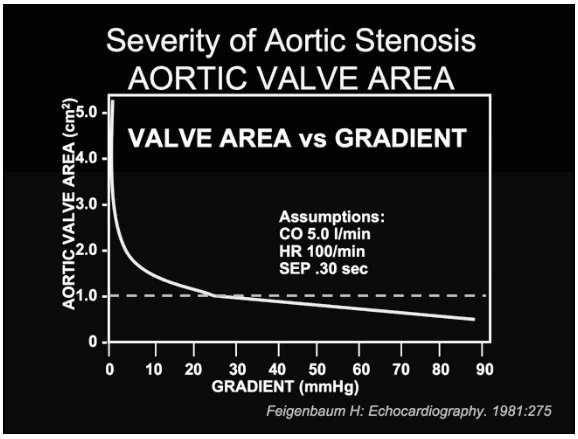
HR: 88 b/min

SEP: 0.32 sec

Grossman W: Cardiac Catheterization and Angiography

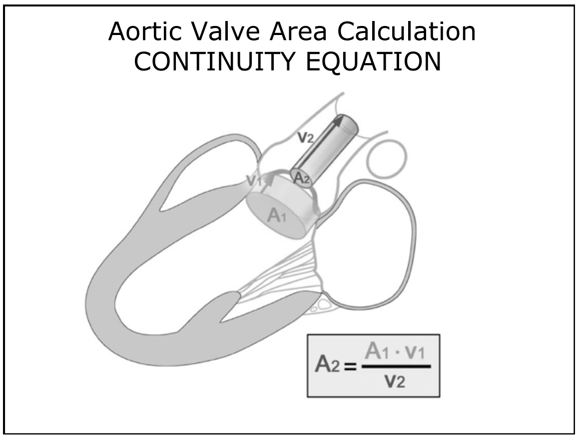


Assessement of Stenosis Severity
PLANIMATRY OF VALVE AREA (AS)



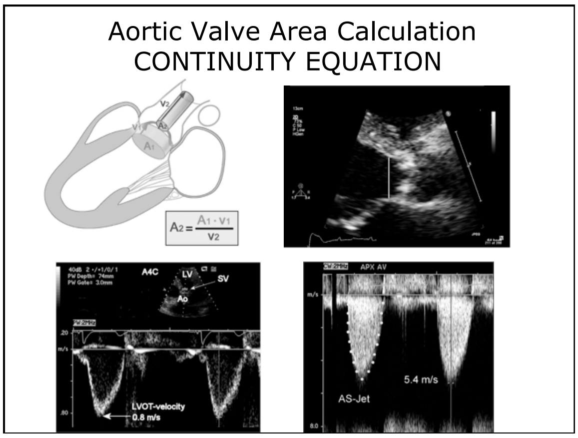
Severity of Aortic Stenosis
AORTIC VALVE AREA

Feigenbaum H: Echocardiography. 1981:275



Aortic Valve Area Calculation
CONTINUITY EQUATION

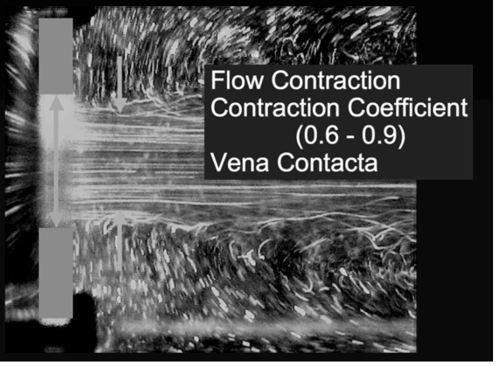
$$A_2 = \frac{A_1 \cdot v_1}{v_2}$$



Aortic Valve Area Calculation
CONTINUITY EQUATION

$$A_2 = \frac{A_1 \cdot v_1}{v_2}$$

Anatomic Orifice vs Effective Orifice



Flow Contraction
Contraction Coefficient
(0.6 - 0.9)
Vena Contacta

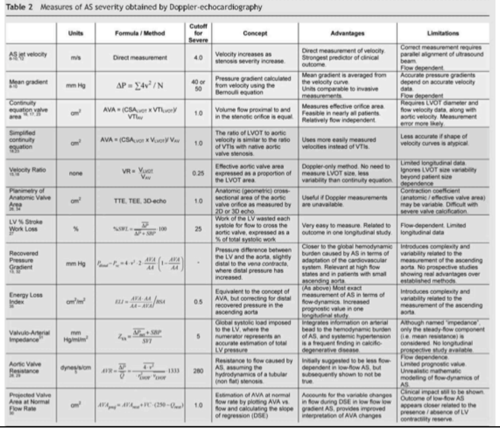
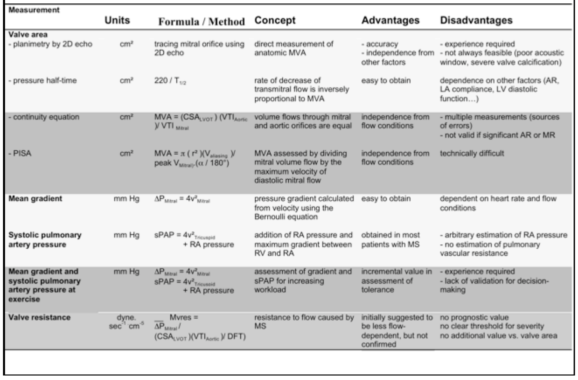


Table 2 Measures of AS severity obtained by Doppler-echocardiography

	Units	Formula / Method	Cutoff for Severe	Concept	Advantages	Limitations
AS jet velocity [8-10, 12]	m/s	Direct measurement	4.0	Velocity increases as stenosis severity increase.	Direct measurement of velocity. Strongest predictor of clinical outcome.	Correct measurement requires parallel alignment of ultrasound beam. Flow dependent.
Mean gradient [8-10]	mm Hg	$\Delta P = \sum 4v^2 / N$	40 or 50	Pressure gradient calculated from velocity using the Bernoulli equation	Mean gradient is averaged from the velocity curve. Units comparable to invasive measurements.	Accurate pressure gradients depend on accurate velocity data. Flow dependent
Continuity equation valve area [16, 17, 23]	cm^2	$AVA = (CSA_{LVOT} \times VTI_{LVOT}) / VTI_{AV}$	1.0	Volume flow proximal to and in the stenotic orifice is equal.	Measures effective orifice area. Feasible in nearly all patients. Relatively flow independent.	Requires LVOT diameter and flow velocity data, along with aortic velocity. Measurement error more likely.
Simplified continuity equation [18,23]	cm^2	$AVA = (CSA_{LVOT} \times V_{LVOT}) / V_{AV}$	1.0	The ratio of LVOT to aortic velocity is similar to the ratio of VTIs with native aortic valve stenosis.	Uses more easily measured velocities instead of VTIs.	Less accurate if shape of velocity curves is atypical.
Velocity Ratio [15,18]	none	$VR = \frac{V_{LVOT}}{V_{AV}}$	0.25	Effective aortic valve area expressed as a proportion of the LVOT area.	Doppler-only method. No need to measure LVOT size, less variability than continuity equation.	Limited longitudinal data. Ignores LVOT size variability beyond patient size dependence
Planimetry of Anatomic Valve Area [26, 34]	cm^2	TTE, TEE, 3D-echo	1.0	Anatomic (geometric) cross-sectional area of the aortic valve orifice as measured by 2D or 3D echo.	Useful if Doppler measurements are unavailable.	Contraction coefficient (anatomic / effective valve area) may be variable. Difficult with severe valve calcification.
LV % Stroke Work Loss [27]	%	$\%SWL = \frac{\overline{\Delta P}}{\overline{\Delta P} + SBP} \cdot 100$	25	Work of the LV wasted each systole for flow to cross the aortic valve, expressed as a % of total systolic work	Very easy to measure. Related to outcome in one longitudinal study.	Flow-dependent. Limited longitudinal data
Recovered Pressure Gradient [13, 32]	mm Hg	$P_{distal} - P_{vc} = 4 \cdot v^2 \cdot 2 \cdot \frac{AVA}{AA}\left(1 - \frac{AVA}{AA}\right)$	-	Pressure difference between the LV and the aorta, slightly distal to the *vena contracta*, where distal pressure has increased.	Closer to the global hemodynamic burden caused by AS in terms of adaptation of the cardiovascular system. Relevant at high flow states and in patients with small ascending aorta.	Introduces complexity and variability related to the measurement of the ascending aorta. No prospective studies showing real advantages over established methods.
Energy Loss Index [35]	cm^2/m^2	$ELI = \frac{AVA \cdot AA}{AA - AVA} \Big/ BSA$	0.5	Equivalent to the concept of AVA, but correcting for distal recovered pressure in the ascending aorta	(As above) Most exact measurement of AS in terms of flow-dynamics. Increased prognostic value in one longitudinal study.	Introduces complexity and variability related to the measurement of the ascending aorta.
Valvulo-Arterial Impedance [31]	mm Hg/ml/m²	$Z_{VA} = \frac{\overline{\Delta P_{net}} + SBP}{SVI}$	5	Global systolic load imposed to the LV, where the numerator represents an accurate estimation of total LV pressure	Integrates information on arterial bead to the hemodynamic burden of AS, and systemic hypertension is a frequent finding in calcific-degenerative disease.	Although named "impedance", only the steady-flow component (i.e. mean resistance) is considered. No longitudinal prospective study available.
Aortic Valve Resistance [28, 29]	dynes/s/cm⁵	$AVR = \frac{\overline{\Delta P}}{\overline{Q}} = \frac{\overline{4 \cdot v^2}}{\pi r_{LVOT}^2 \cdot v_{LVOT}} \cdot 1333$	280	Resistance to flow caused by AS, assuming the hydrodynamics of a tubular (non flat) stenosis.	Initially suggested to be less flow-dependent in low-flow AS, but subsequently shown to not be true.	Flow dependence. Limited prognostic value. Unrealistic mathematic modelling of flow-dynamics of AS.
Projected Valve Area at Normal Flow Rate [30]	cm^2	$AVA_{proj} = AVA_{rest} + VC \cdot (250 - Q_{rest})$	1.0	Estimation of AVA at normal flow rate by plotting AVA vs. flow and calculating the slope of regression (DSE)	Accounts for the variable changes in flow during DSE in low flow low gradient AS, provides improved interpretation of AVA changes	Clinical impact still to be shown. Outcome of low-flow AS appears closer related to the presence / absence of LV contractility reserve.

Approaches to evaluation of mitral stenosis



Measurement	Units	Formula / Method	Concept	Advantages	Disadvantages
Valve area					
- planimetry by 2D echo	cm²	tracing mitral orifice using 2D echo	direct measurement of anatomic MVA	- accuracy - independence from other factors	- experience required - not always feasible (poor acoustic window, severe valve calcification)
- pressure half-time	cm²	$220 / T_{1/2}$	rate of decrease of transmitral flow is inversely proportional to MVA	easy to obtain	dependence on other factors (AR, LA compliance, LV diastolic function…)
- continuity equation	cm²	$MVA = (CSA_{LVOT})(VTI_{Aortic}) / VTI_{Mitral}$	volume flows through mitral and aortic orifices are equal	independence from flow conditions	- multiple measurements (sources of errors) - not valid if significant AR or MR
- PISA	cm²	$MVA = \pi (r^2)(V_{aliasing}) / \text{peak } V_{Mitral} \cdot (\alpha / 180°)$	MVA assessed by dividing mitral volume flow by the maximum velocity of diastolic mitral flow	independence from flow conditions	technically difficult
Mean gradient	mm Hg	$\Delta P_{Mitral} = 4v^2_{Mitral}$	pressure gradient calculated from velocity using the Bernoulli equation	easy to obtain	dependent on heart rate and flow conditions
Systolic pulmonary artery pressure	mm Hg	$sPAP = 4v^2_{Tricuspid} + \text{RA pressure}$	addition of RA pressure and maximum gradient between RV and RA	obtained in most patients with MS	- arbitrary estimation of RA pressure - no estimation of pulmonary vascular resistance
Mean gradient and systolic pulmonary artery pressure at exercise	mm Hg	$\Delta P_{Mitral} = 4v^2_{Mitral}$ $sPAP = 4v^2_{Tricuspid} + \text{RA pressure}$	assessment of gradient and sPAP for increasing workload	incremental value in assessment of tolerance	- experience required - lack of validation for decision-making
Valve resistance	dyne. sec⁻¹ cm⁻⁵	$Mvres = \overline{\Delta P}_{Mitral} / (CSA_{LVOT})(VTI_{Aortic}) / DFT)$	resistance to flow caused by MS	initially suggested to be less flow-dependent, but not confirmed	no prognostic value no clear threshold for severity no additional value vs. valve area

Findings indicative for hemodynamcally significant tricuspid stenosis

Specific Findings	
Mean pressure gradient	≥ 5 mm Hg
Inflow time velocity integral	> 60 cm
T½	≥ 190 ms
Valve area by continuity equation*	≤ 1 cm^{2*}
Supportive Findings	
Enlarged right atrium ≥ moderate	
Dilated inferior vena cava	

Pulmonic Stenosis

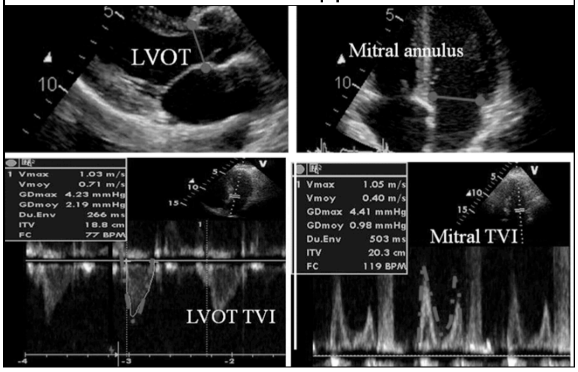
	Mild	Moderate	Severe
Peak Velocity (m/s)	< 3	3-4	>4
Peak gradient (mm Hg)	< 36	36 to 60	>60

Mean Gradient
Right ventricular pressure (TR velocity)

Assessment of valvular regurgitation severity

- Qualitative
  - Valve morphology (flail, caoptation)
  - Color flow jet (size)
  - CW signal of regurgitant jet
- Semi-quantitative
  - VC width
  - Flow convergence zone size
  - PW flow pattern: PV (MR), desc. Ao (AR), PA (PR), HV (TR)
  - CW signal shape (PHT in AR....)
- Quantitative
  - EROA, R Vol (PISA, volumetric)
- Secondary signs: LV/RV volume load, atria, PAP

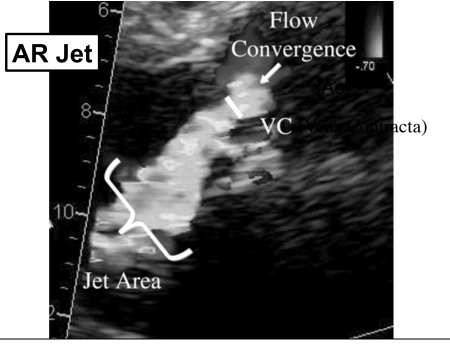
Quantitative assessment of regurgitation: Volumetric approach

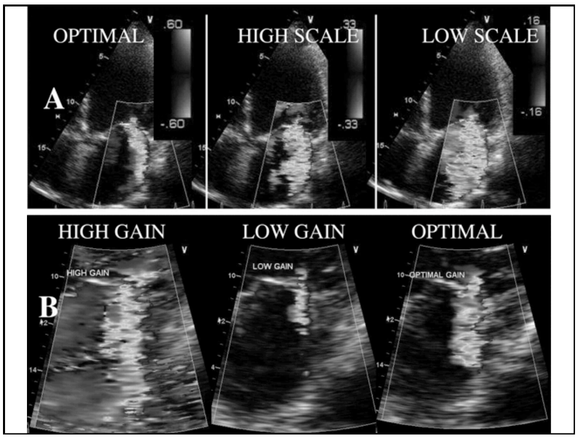


```
1 Vmax     1.03 m/s
  Vmoy     0.71 m/s
  GDmax  4.23 mmHg
  GDmoy  2.19 mmHg
  Du.Env    266 ms
  ITV      18.8 cm
  FC       77 BPM
```

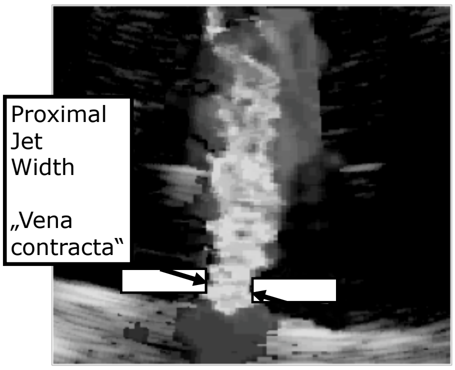
```
1 Vmax     1.05 m/s
  Vmoy     0.40 m/s
  GDmax  4.41 mmHg
  GDmoy  0.98 mmHg
  Du.Env    503 ms
  ITV      20.3 cm
  FC      119 BPM
```

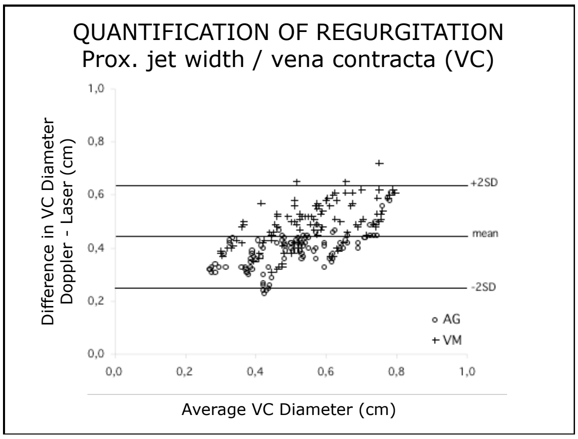
Color Doppler assessment of regurgitation severity



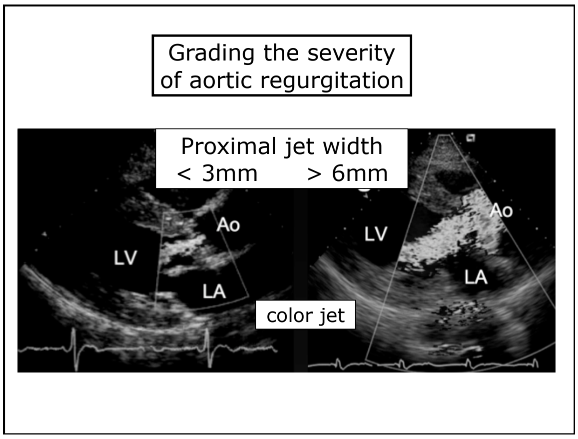


COLOR DOPPLER REGURGITANT JET





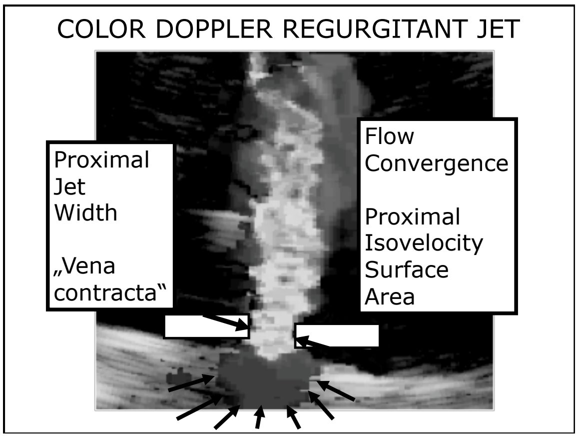
QUANTIFICATION OF REGURGITATION
Prox. jet width / vena contracta (VC)



Grading the severity of aortic regurgitation

Proximal jet width
< 3mm > 6mm

color jet



COLOR DOPPLER REGURGITANT JET

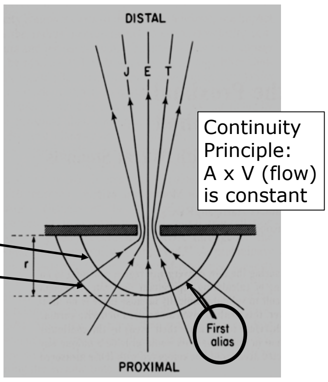
Proximal Jet Width

„Vena contracta“

Flow Convergence

Proximal Isovelocity Surface Area

Flow convergence zone

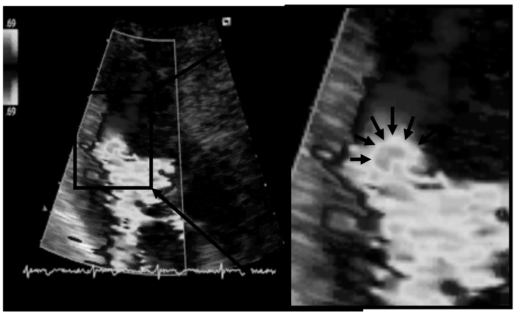


Continuity Principle:
A x V (flow) is constant

Proximal Isovelocity Surface Area

Rodriguez et al, Circulation 1993

Proximal Flow Convergence



PISA method for quantification of regurgitant flow and effective regurgitant orifice area (EROA), regurgitant volume (R vol)

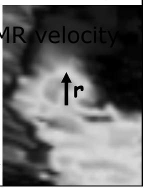
Hemispheric surface = $2 \times r^2 \times \pi$

Regurgitant flow Q = $(2 \times r^2 \times \pi) \times$ alias velocity

$(2 \times r^2 \times \pi) \times$ alias velocity = EROA $\times$ MR velocity

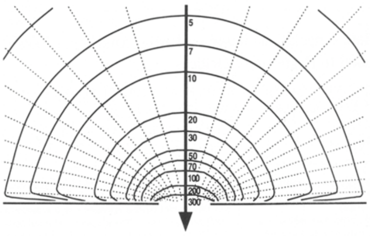
$$\text{EROA} = \frac{2 \times r^2 \times \pi \times \text{alias velocity}}{\text{MR velocity}}$$

Regurgitant volume = EROA $\times$ VTI_{MR}



Limitations of PISA method:

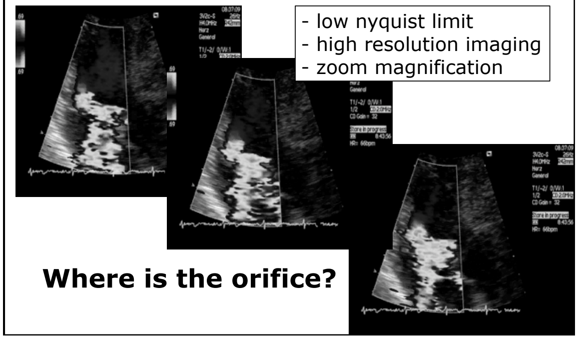
1) Position for PISA estimation



Vandervoort et al, JACC 1993

Limitations of PISA method:

2) Accurate radius measurement



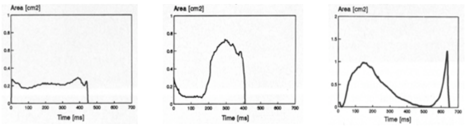
- low nyquist limit
- high resolution imaging
- zoom magnification

Where is the orifice?

Limitations of PISA method:

3) Dynamic changes of the anatomic regurgitant orifice area

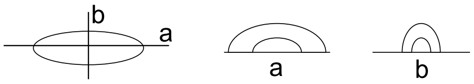
- decrease in dilated cardiomyopathy
- increase in mitral valve prolaps
- constant in rheumatic mitral regurgitation

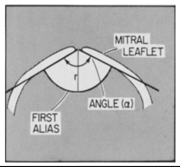


Schwammenthal et al, Circulation 1994

Limitations of PISA method:

4) Effect of orifice geometry (multiple orifices!)and inlet angle of the valve cusps





Surface can in general not be assumed to be flat
(particularly in MV prolapse/flail)
This angle is normally ignored!!!

Limitations of PISA metod

5) Movement of the regurgitant orifice

Doppler measures the velocity relative to the transducer

Regurgitant orifice may be moving away from or towards the transducer

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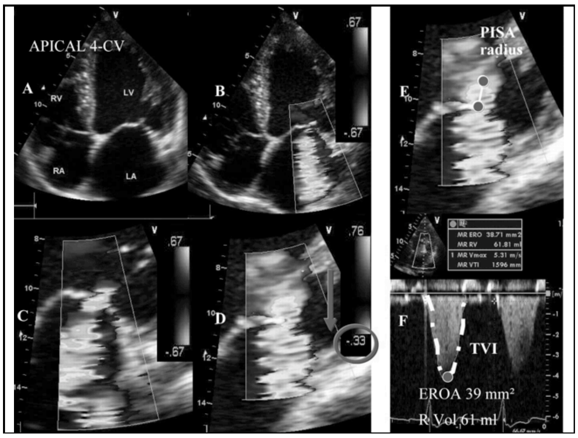
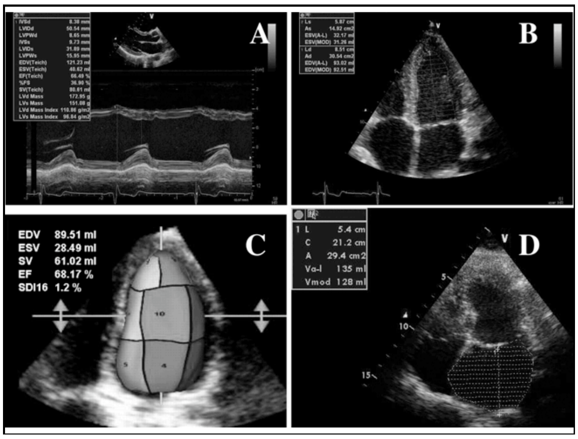
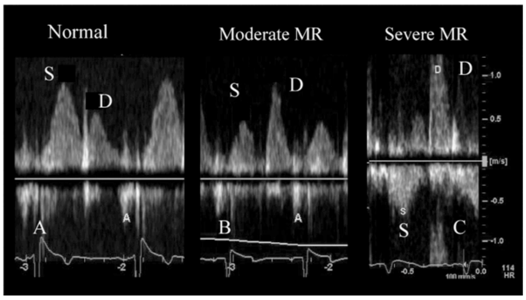
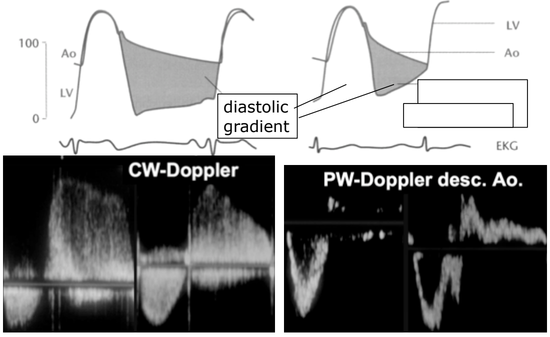




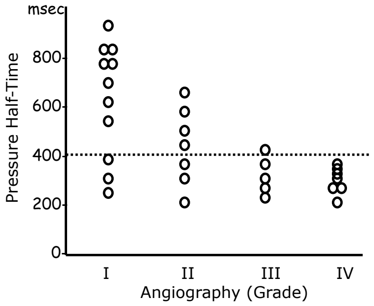
Mitral regurgitation
Pulmonary venous flow



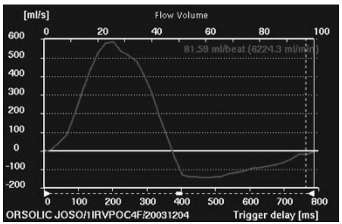
Grading the severity of aortic regurgitation

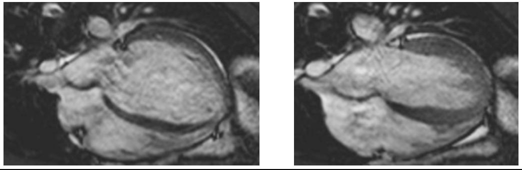


CW-Doppler in AR

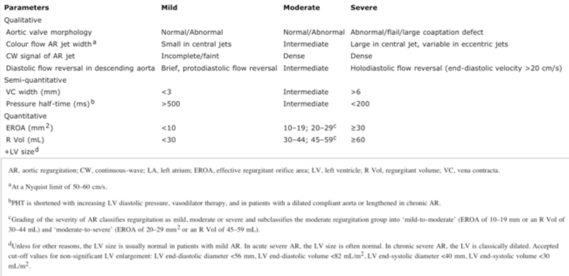


Quantification of Valvular Regurgitation





Grading the severity of aortic regurgitation



Parameters	Mild	Moderate	Severe
Qualitative			
Aortic valve morphology	Normal/Abnormal	Normal/Abnormal	Abnormal/flail/large coaptation defect
Colour flow AR jet width[a]	Small in central jets	Intermediate	Large in central jet, variable in eccentric jets
CW signal of AR jet	Incomplete/faint	Dense	Dense
Diastolic flow reversal in descending aorta	Brief, protodiastolic flow reversal	Intermediate	Holodiastolic flow reversal (end-diastolic velocity >20 cm/s)
Semi-quantitative			
VC width (mm)	<3	Intermediate	>6
Pressure half-time (ms)[b]	>500	Intermediate	<200
Quantitative			
EROA (mm^2)	<10	10–19; 20–29[c]	≥30
R Vol (mL)	<30	30–44; 45–59[c]	≥60
+LV size[d]			

AR, aortic regurgitation; CW, continuous-wave; LA, left atrium; EROA, effective regurgitant orifice area; LV, left ventricle; R Vol, regurgitant volume; VC, vena contracta.

[a] At a Nyquist limit of 50–60 cm/s.

[b] PHT is shortened with increasing LV diastolic pressure, vasodilator therapy, and in patients with a dilated compliant aorta or lengthened in chronic AR.

[c] Grading of the severity of AR classifies regurgitation as mild, moderate or severe and subclassifies the moderate regurgitation group into 'mild-to-moderate' (EROA of 10–19 mm or an R Vol of 30–44 mL) and 'moderate-to-severe' (EROA of 20–29 mm^2 or an R Vol of 45–59 mL).

[d] Unless for other reasons, the LV size is usually normal in patients with mild AR. In acute severe AR, the LV size is often normal. In chronic severe AR, the LV is classically dilated. Accepted cut-off values for non-significant LV enlargement: LV end-diastolic diameter <56 mm, LV end-diastolic volume <82 mL/m^2, LV end-systolic diameter <40 mm, LV end-systolic volume <30 mL/m^2.

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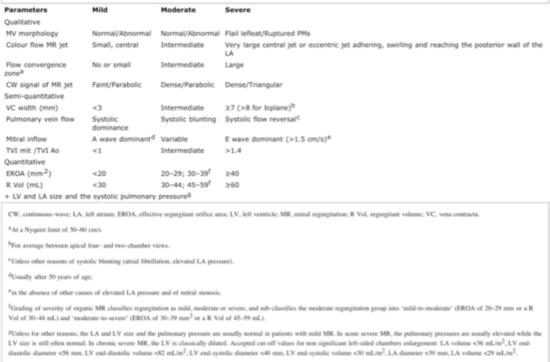
Grading the severity of mitral regurgitation



Parameters	Mild	Moderate	Severe
Qualitative			
MV morphology	Normal/Abnormal	Normal/Abnormal	Flail lefleat/Ruptured PMs
Colour flow MR jet	Small, central	Intermediate	Very large central jet or eccentric jet adhering, swirling and reaching the posterior wall of the LA
Flow convergence zone[a]	No or small	Intermediate	Large
CW signal of MR jet	Faint/Parabolic	Dense/Parabolic	Dense/Triangular
Semi-quantitative			
VC width (mm)	<3	Intermediate	≥7 (>8 for biplane)[b]
Pulmonary vein flow	Systolic dominance	Systolic blunting	Systolic flow reversal[c]
Mitral inflow	A wave dominant[d]	Variable	E wave dominant (>1.5 cm/s)[e]
TVI mit /TVI Ao	<1	Intermediate	>1.4
Quantitative			
EROA (mm^2)	<20	20–29; 30–39[f]	≥40
R Vol (mL)	<30	30–44; 45–59[f]	≥60
+ LV and LA size and the systolic pulmonary pressure[g]			

CW, continuous-wave; LA, left atrium; EROA, effective regurgitant orifice area; LV, left ventricle; MR, mitral regurgitation; R Vol, regurgitant volume; VC, vena contracta.

[a] At a Nyquist limit of 50–60 cm/s

[b] For average between apical four- and two-chamber views.

[c] Unless other reasons of systolic blunting (atrial fibrillation, elevated LA pressure).

[d] Usually after 50 years of age;

[e] in the absence of other causes of elevated LA pressure and of mitral stenosis.

[f] Grading of severity of organic MR classifies regurgitation as mild, moderate or severe, and sub-classifies the moderate regurgitation group into 'mild-to-moderate' (EROA of 20–29 mm or a R Vol of 30–44 mL) and 'moderate-to-severe' (EROA of 30–39 mm^2 or a R Vol of 45–59 mL).

[g] Unless for other reasons, the LA and LV size and the pulmonary pressure are usually normal in patients with mild MR. In acute severe MR, the pulmonary pressures are usually elevated while the LV size is still often normal. In chronic severe MR, the LV is classically dilated. Accepted cut-off values for non significant left-sided chambers enlargement: LA volume <36 mL/m^2, LV end-diastolic diameter <56 mm, LV end-diastolic volume <82 mL/m^2, LV end-systolic diameter <40 mm, LV end-systolic volume <30 mL/m^2, LA diameter <39 mm, LA volume <29 mL/m^2.

EAE recommendations 2010

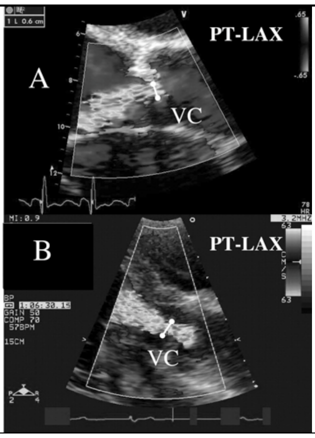
Thank you for your attention

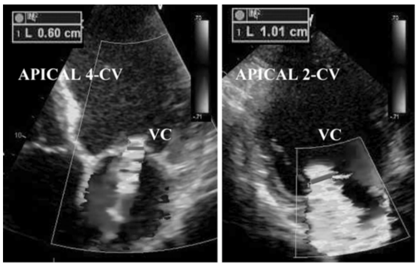
Assessment of Valvular Stenosis Severity

CW Doppler: Measurement of transvalvular velocity

Calculation of peak gradient
$\Delta P_{peak} = 4v^2$

Calculation of mean gradient
$\Delta P_{mean} = \Sigma 4v^2 / N$





Grading the severity of aortic regurgitation