

Chapter 4: Basics of echocardiography for transcatheter interventions

Adrian DaSilva-DeAbreu, MD¹, Catalin Loghin, MD²

¹Resident, Department of Internal Medicine, McGovern Medical School, The University of Texas Health Science Center at Houston, TX.

²Professor, Division of Cardiovascular Medicine, Department of Internal Medicine, McGovern Medical School, The University of Texas Health Science Center at Houston, TX.

Introduction

Echocardiography plays a fundamental role within the rapid evolution of transcatheter technologies. Patients evaluated for structural heart disease interventions require an initial transthoracic echocardiogram (TTE), which establishes an anatomical and functional diagnosis. TTE, as a widely available bedside study, is complemented by a dedicated three dimensional (3D), transesophageal echocardiogram (TEE), which provides detailed anatomical information. During transcatheter procedures, TTE or 3D TEE are used to guide in real time the interventional cardiologist, to monitor for complications and to assess results. TTE, and occasionally TEE, are required for procedural follow-up.

As a fundamental imaging modality, echocardiography remains highly operator dependent, and lacks fully standardized acquisition protocols. Image quality can be affected by many factors: body habitus, chest deformities, inability to assume adequate examinations positions, difficulty in holding respiration, breast implants and gross artifacts or “shadowing” in the presence of valvular prostheses and calcifications. It is imperative to follow a standardized, comprehensive imaging protocol when evaluating patients as potential candidates for transcatheter interventions. This reduces the wide variability of study interpretation resulting from different levels of interpretation proficiency, and from rapidly changing hemodynamic conditions. Moreover, 3D TEE operator experience may be limited outside large volume centers.

Transcatheter Aortic Valve (AoV) Replacement (TAVR)

TTE represents the gold standard for the diagnosis and severity quantification of aortic stenosis (AS). As per PARTNER Trial,⁽¹⁾ patients considered for TAVR must meet the following criteria: valve area (AVA) <0.8 cm²; transaortic peak velocity >4 m/s, or mean pressure gradient >40 mm Hg, as measured by continuous wave Doppler.

Common pitfalls in TTE grading of AS severity result from: errors in measuring left ventricular (LV) outflow tract (LVOT) diameter, LVOT time velocity integral (TVI), or sampling LVOT TVI from an area different from where the LVOT diameter measurement was taken (Figures 1, 2, 3).

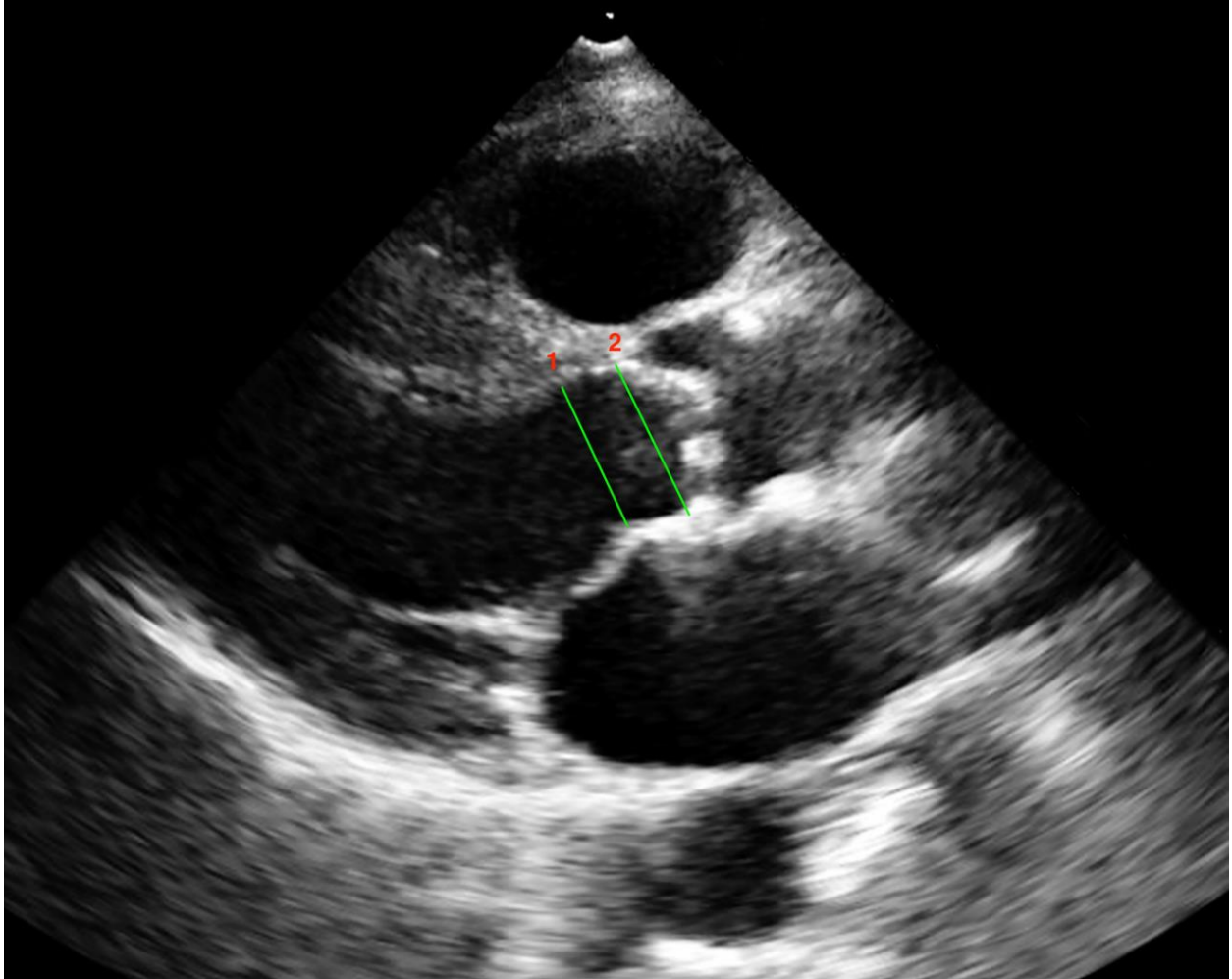


Figure 1: AS – TTE parasternal long axis view.

Notice the limited peak systolic opening, and calcification of the aortic cusps, with supra-valvular calcified atheroma. Measurements: 1 - LVOT diameter, 2 - AV annulus.

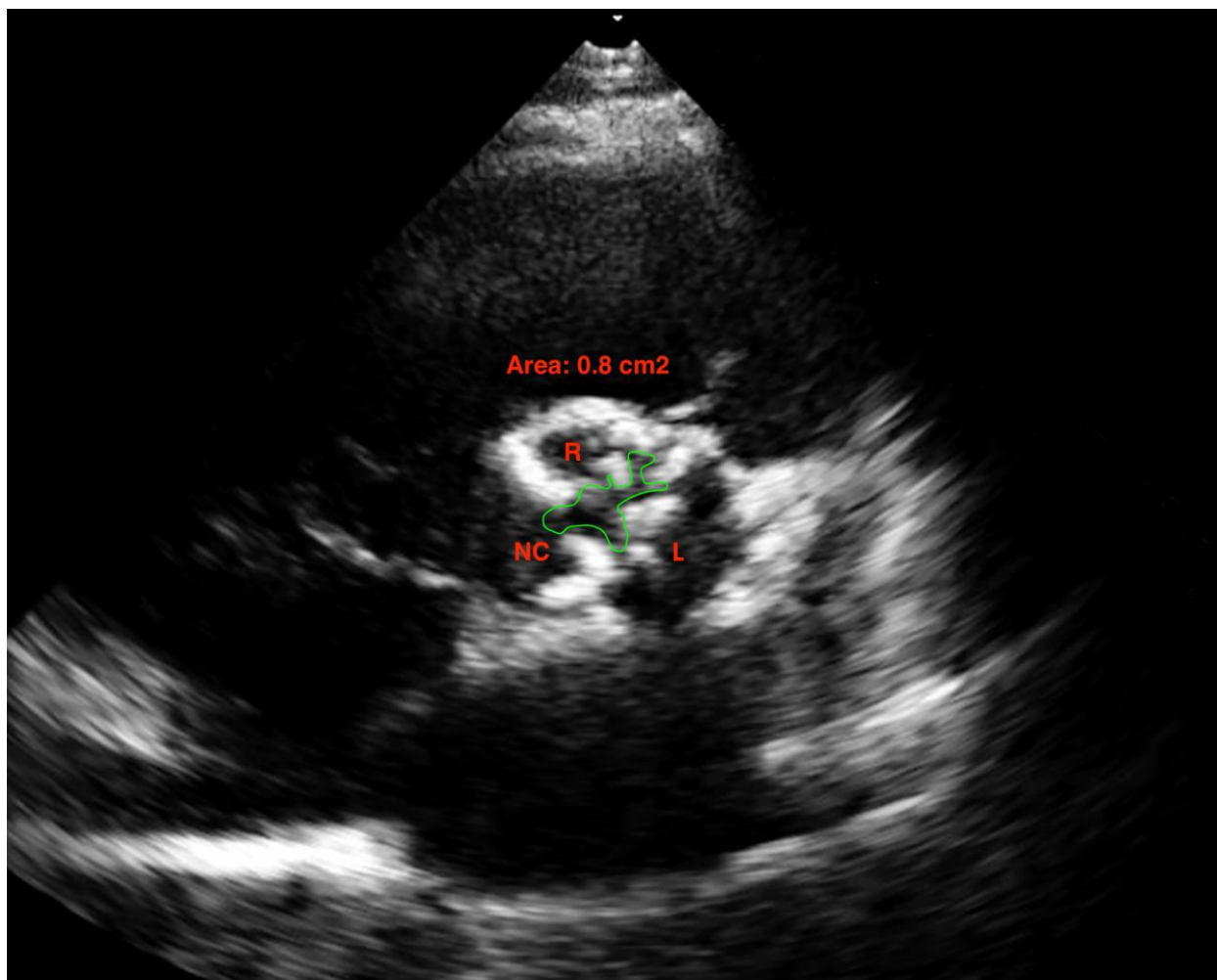


Figure 2: AS – TTE parasternal short axis view

Notice AVA measurement by planimetry at the tips of the cusps, in peak systole, and within the cusp contour. The shape of the stenotic orifice is highly irregular. L: left cusp; R: right cusp; NC: non-coronary cusp.

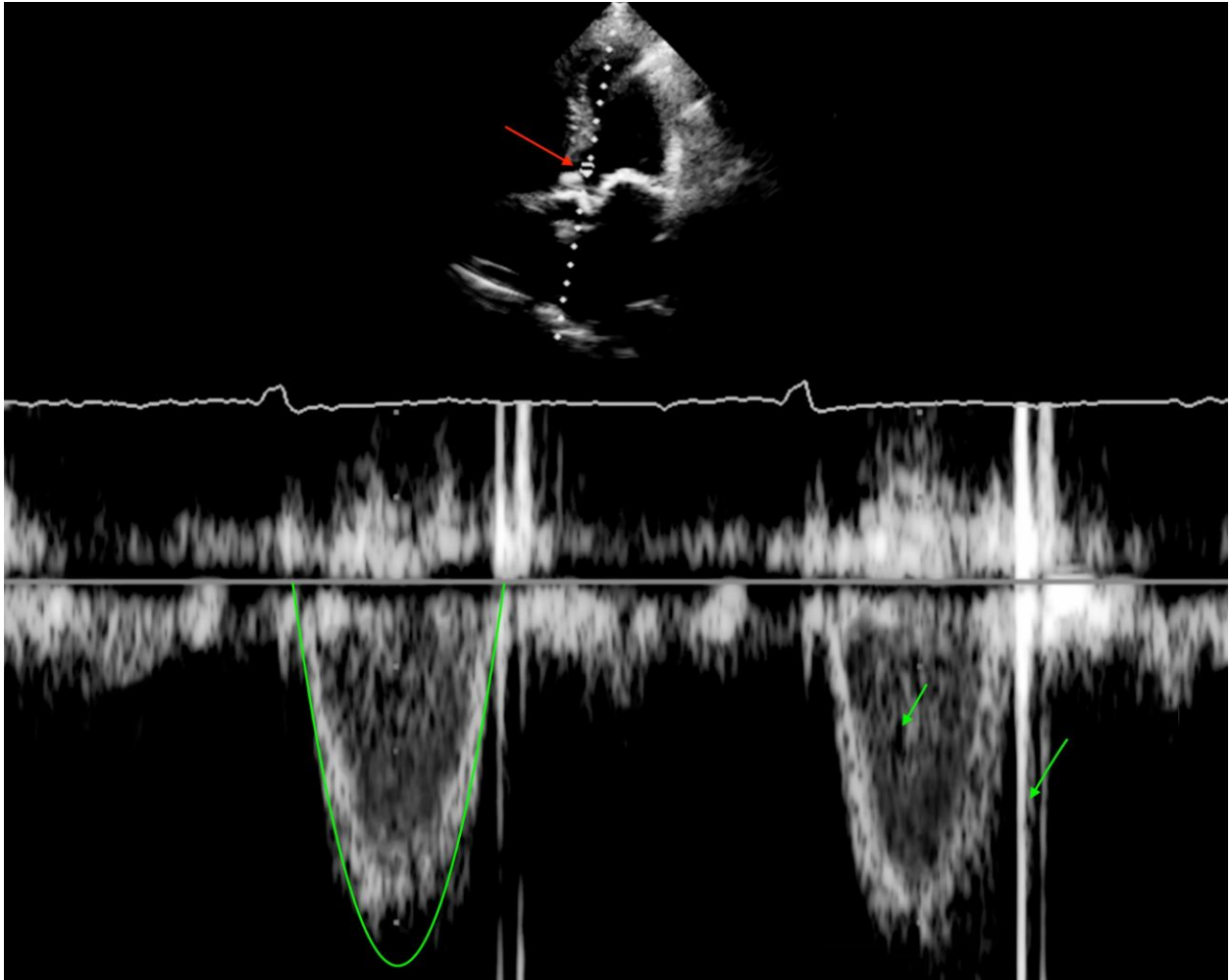


Figure 3: AS – TTE five chamber view, pulsed wave Doppler (PW), LVOT TVI measurement. PW is used to measure only the blood velocity at the LVOT level. Notice the PW sample volume (red arrow) placed at the same distance from the AV where the LVOT diameter was measured in Figure 1. LVOT TVI area is traced by hand. A correct LVOT TVI recording demonstrates a hollow spectral envelope (modal velocities) and the presence of the AV closing (green arrows)

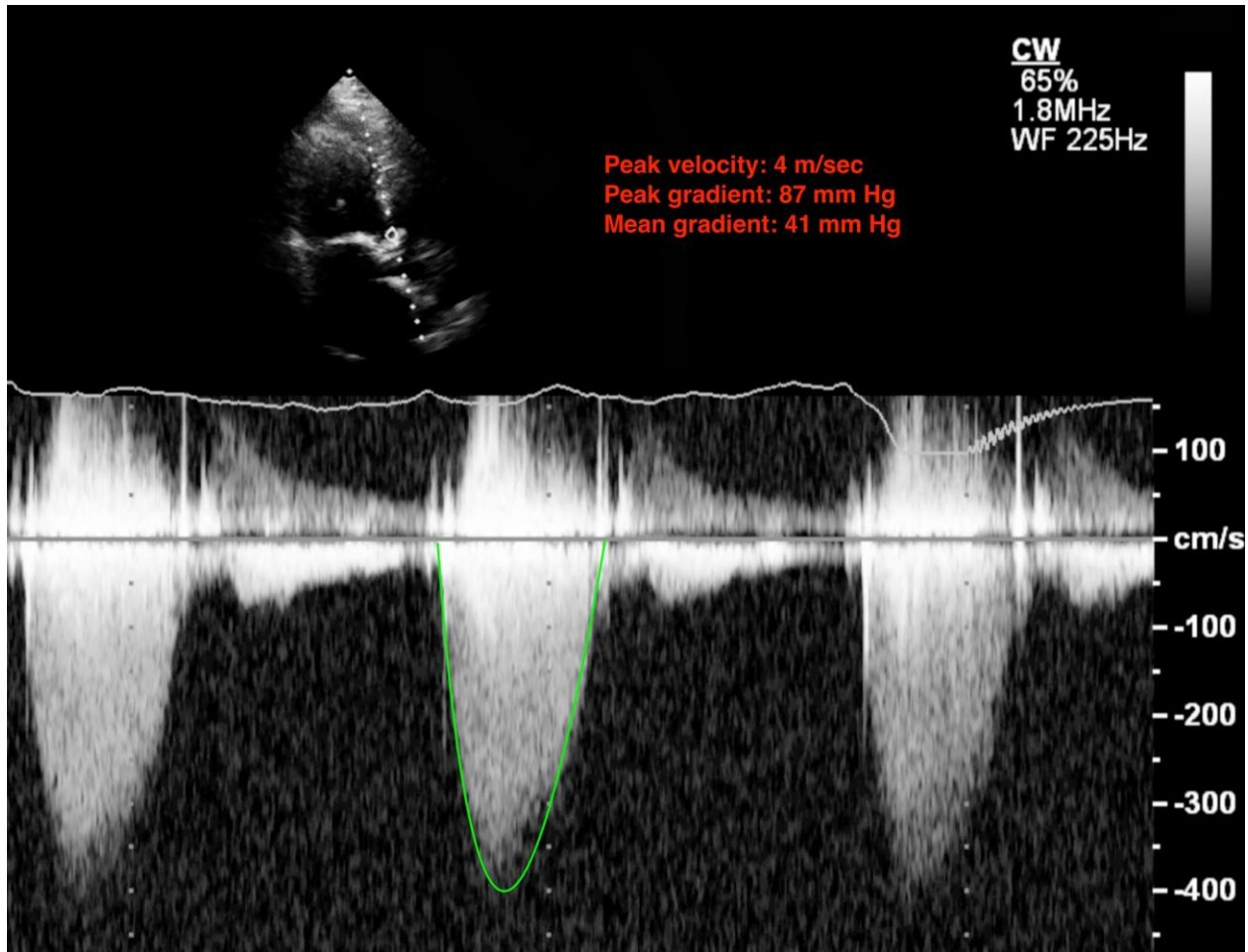


Figure 4: AS – TTE three chamber view, continuous wave Doppler (CW).

In contrast to PW, CW measures the highest velocity of the aortic jet, irrespective of its location. This view, along with the five chamber view, can be used to measure the maximum velocity of the aortic jet. AV TVI is then manually traced in order to obtain mean and peak gradients.

Using the data collected as illustrated above, AVA can be calculated by the following formula:

$$AVA = [\pi \times (LVOT/2)^2 \times LVOT TVI] / AV TVI$$

Please note that an error of only 1 mm in measuring LVOT diameter can result in a major change of AVA, as this parameter is squared in the AVA calculation formula.

In addition, the incomplete continuous wave (CW) examination of the aortic valve from all available views (Figure 5), or confusing mitral regurgitation (MR) signal, or a large intracavitary gradient as AS during CW examination, can also lead to erroneous AS severity grading.



Figure 5: AS – right parasternal border, non imaging Pedoff transducer, CW.

A complete examination of an aortic jet includes velocity recordings from this window, as well as the supraclavicular fossa, suprasternal notch and left ventricular apex. The non imaging CW probe frequently yields high quality Doppler recordings, and contributes to an accurate assessment of the AS severity.

In the presence of *classic* low flow, low gradient (LF-LG) AS (decreased LV ejection fraction; LVEF) or *paradoxical* LF-LG AS (preserved LVEF, marked LV hypertrophy, reduced LV filling and longitudinal strain), low dose dobutamine stress TTE, and multidetector computed tomography (MDCT) help to separate patients with true severe AS from those with pseudo-severe AS.(2) Aortic cusp morphology, and the degree and distribution of valve and root calcification are best evaluated by MDCT.

TTE parasternal long-axis and TEE LVOT views are used to obtain accurate mid-systolic diameters of the aortic annulus, sino-tubular junction, and ascending aorta (Figure 1). TTE measurements tend to slightly underestimate dimensions of aortic annulus and valve area, compared to MDCT.(3) Echocardiography readily identifies contraindications for TAVR: severe aortic or mitral regurgitation (MR), or significant hypertrophy of the basal interventricular septum.(1)

The potential benefit of 3D TTE or TEE over two dimensional (2D) echocardiography remains operator dependent, as either modality can lead to over- or underestimation of anatomical measurements.(4) In most centers, standard TTE complemented by MDCT angiography are the only imaging studies required for a complete evaluation of AS.

Percutaneous Edge-to-Edge Mitral Valve Repair (MitraClip® Procedure)

TTE is the gold standard for the diagnosis of MR, as it identifies the etiology and mechanism of regurgitation, and allows quantification of its severity. Furthermore, TTE provides valuable information about the impact of MR on LV size and function, the presence of pulmonary hypertension, and of any associated valvular lesions.

TTE classifies the etiology and mechanism of MR as:

- (1) Primary (*degenerative*): This is a disease of the valve itself, which results from leaflet myxomatous degeneration, with leaflet prolapse, where the body of the leaflet is seen above mitral annulus) (Figures 6, 7, 8, 9). In extreme cases, chordal rupture leads to a flail leaflet, where the edge of the leaflet is seen above the mitral annulus plane. The most commonly affected leaflet segment is the mid posterior scallop (P2), which has the least anatomical chordal support.(7) The regurgitant jet is typically highly eccentric, directed away from the diseased leaflet, and more pronounced toward the end of systole. Therefore, the jet severity is overestimated by traditional Doppler methods, which assume constant regurgitant flow throughout the entire systole.(8) TTE allows measurement of the flail gap and flail width as the main criteria to establish eligibility for MitraClip® procedure (Figure 12).(9)

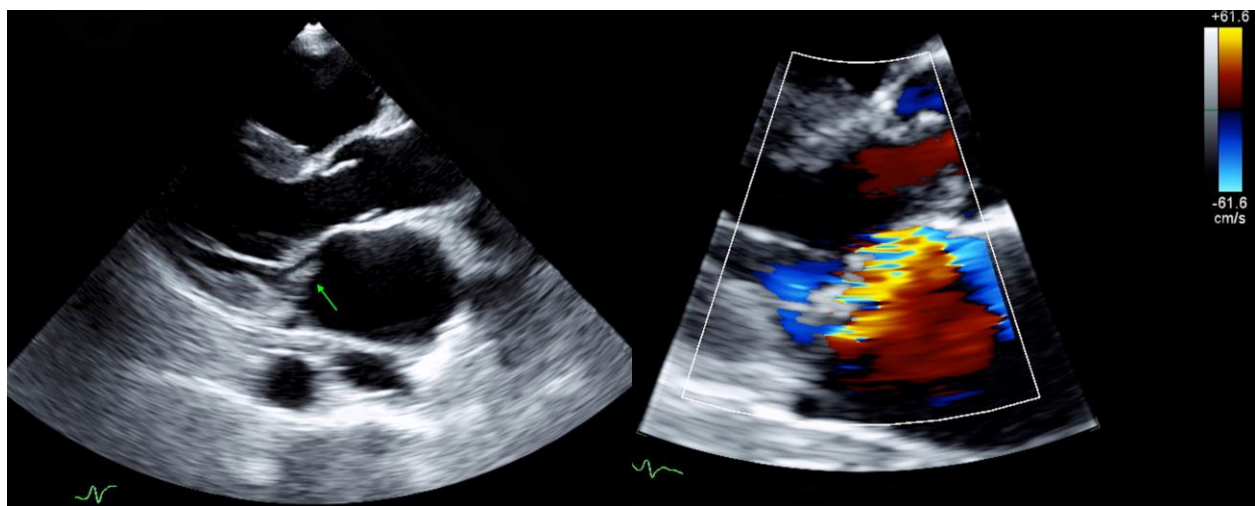


Figure 6: MR – degenerative, TTE parasternal long axis view

Notice peak systolic, incomplete coaptation, resulting from severe prolapse and flail of the posterior leaflet, with a highly eccentric jet, oriented anteriorly, **away** from the prolapsing posterior leaflet.

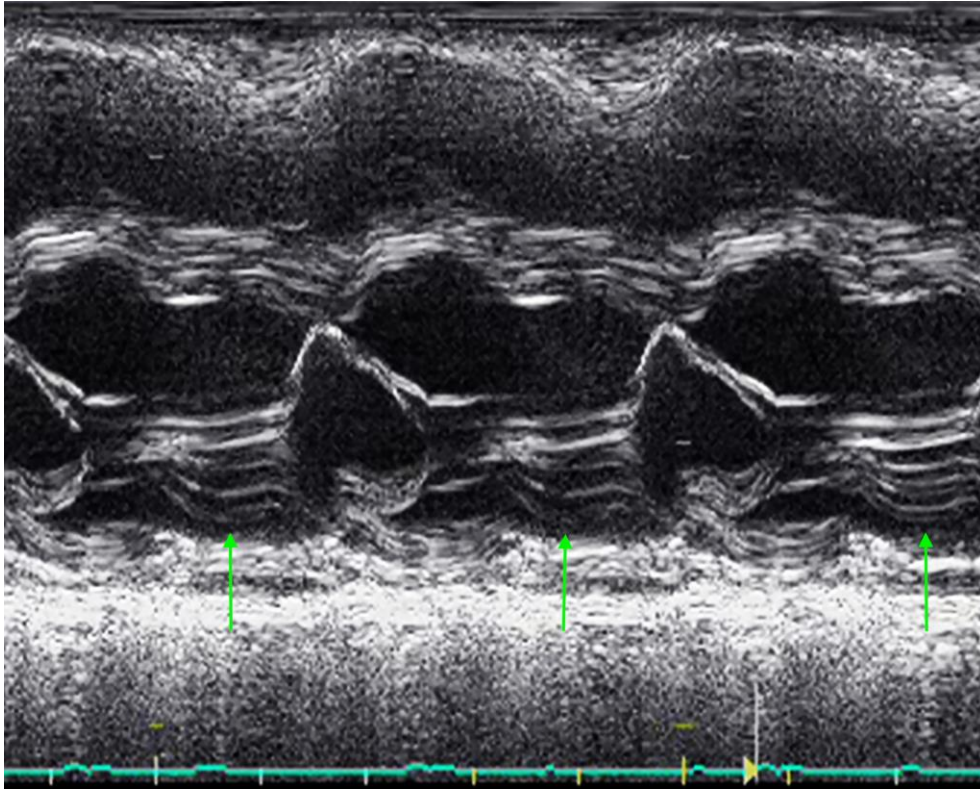


Figure 7: MR – degenerative, TTE M Mode.

M mode has the highest temporal resolution of all imaging modalities, allowing precise timing of cardiac events. Note the characteristic “hammock sign” (arrows), due to the prolapse of the posterior mitral leaflet, limited to mid- and end-systole.

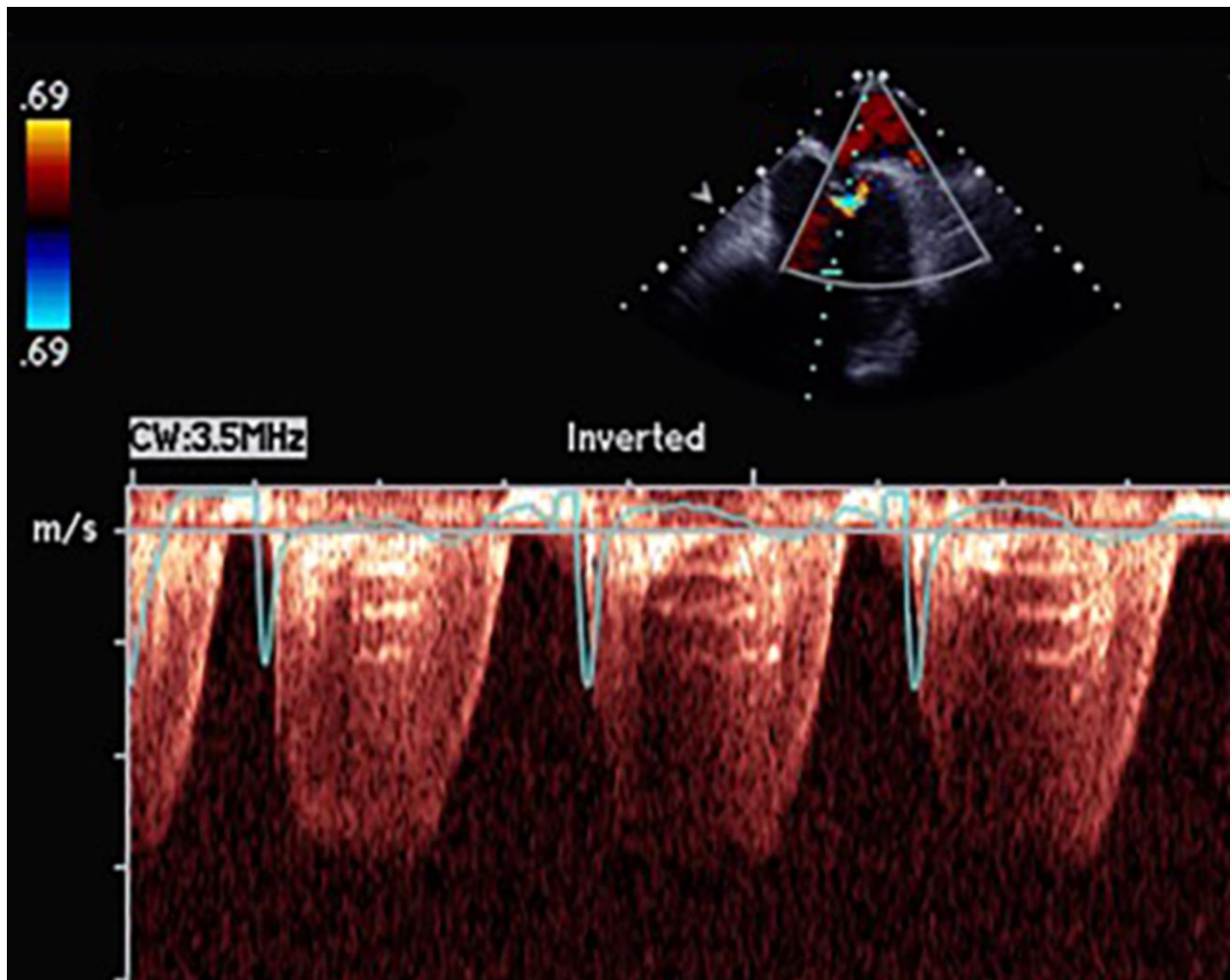


Figure 8: MR – degenerative, TEE two chamber view, CW.

The presence of “tiger stripes” on CW spectral Doppler potentially indicates chordal rupture and a flail scallop, generally associated with severe MR.

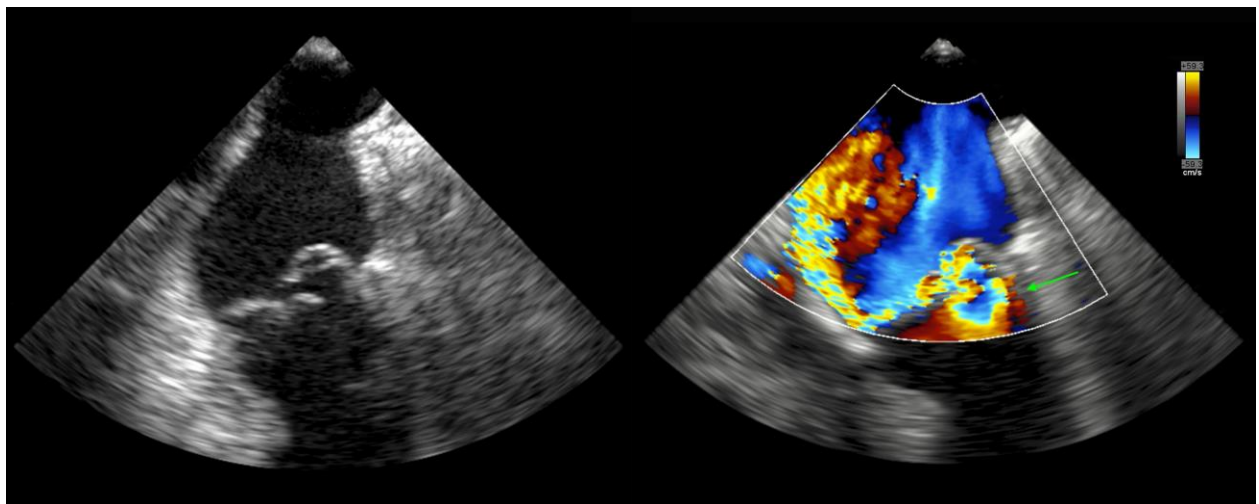


Figure 9: MR – degenerative, TEE two chamber view.

Notice chordal rupture and flail posterior leaflet, resulting in a wide open regurgitant orifice. The jet is highly eccentric, with typical Coanda effect: jet impinges on the interatrial septum, loses energy and appears small, out of proportion for the size of the regurgitant orifice. Both color Doppler and PISA calculation would underestimate MR severity in this case. Also, note the large flow convergence zone (arrow), at a Nyquist limit of 59 cm/sec, suggestive of severe regurgitation. To maintain consistency through recurrent examinations, color Doppler Nyquist limit must be within 55-65 cm/sec.

- (2) Secondary (*functional*) MR is a disease of the LV, affecting the function of an otherwise normal valve (Figures 10,11). The regurgitation is caused by: (i) annular dilatation with reduced leaflet tenting, and/or by (ii) papillary dysfunction with leaflet longitudinal tethering, typically of the posterior leaflet, which results in reduced coaptation depth and coaptation length. These parameters can be easily measured by TTE as criteria for procedural eligibility (Figure 12). The regurgitant jet is oriented toward the tethered leaflet, or remains central, and is more pronounced at the beginning of systole, which may lead to overestimation of its severity by PISA method.

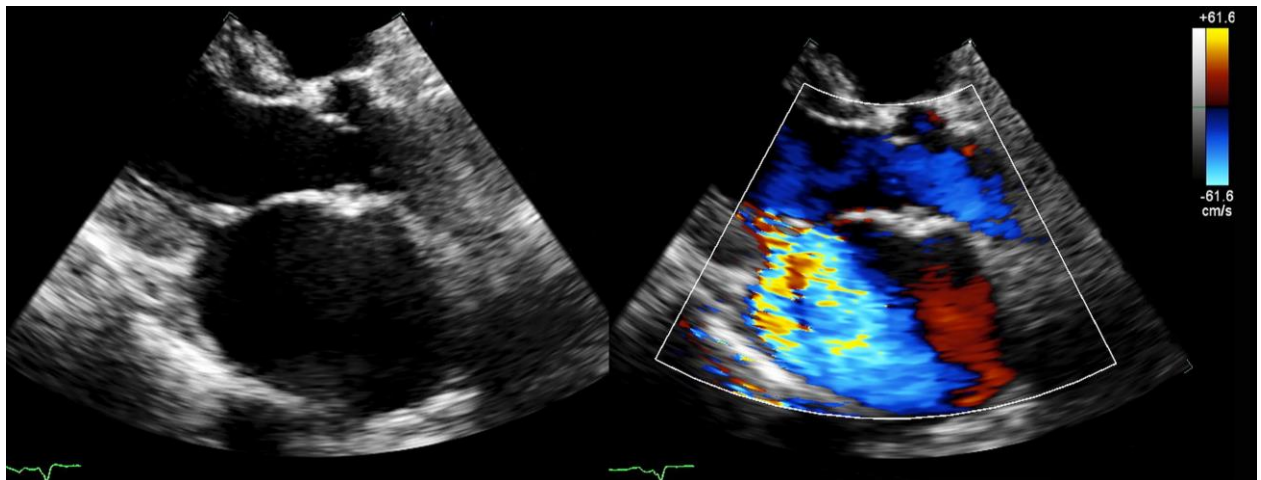


Figure 10: MR – functional, TTE long axis parasternal view.

Notice the incomplete MV leaflet coaptation at peak systole (AV cusps fully open), and the enlarged left atrium. This results from tethering of the posterior leaflet, after a myocardial infarction involving the posterior LV wall. The regurgitant jet is oriented posteriorly, **toward** the tethered leaflet.

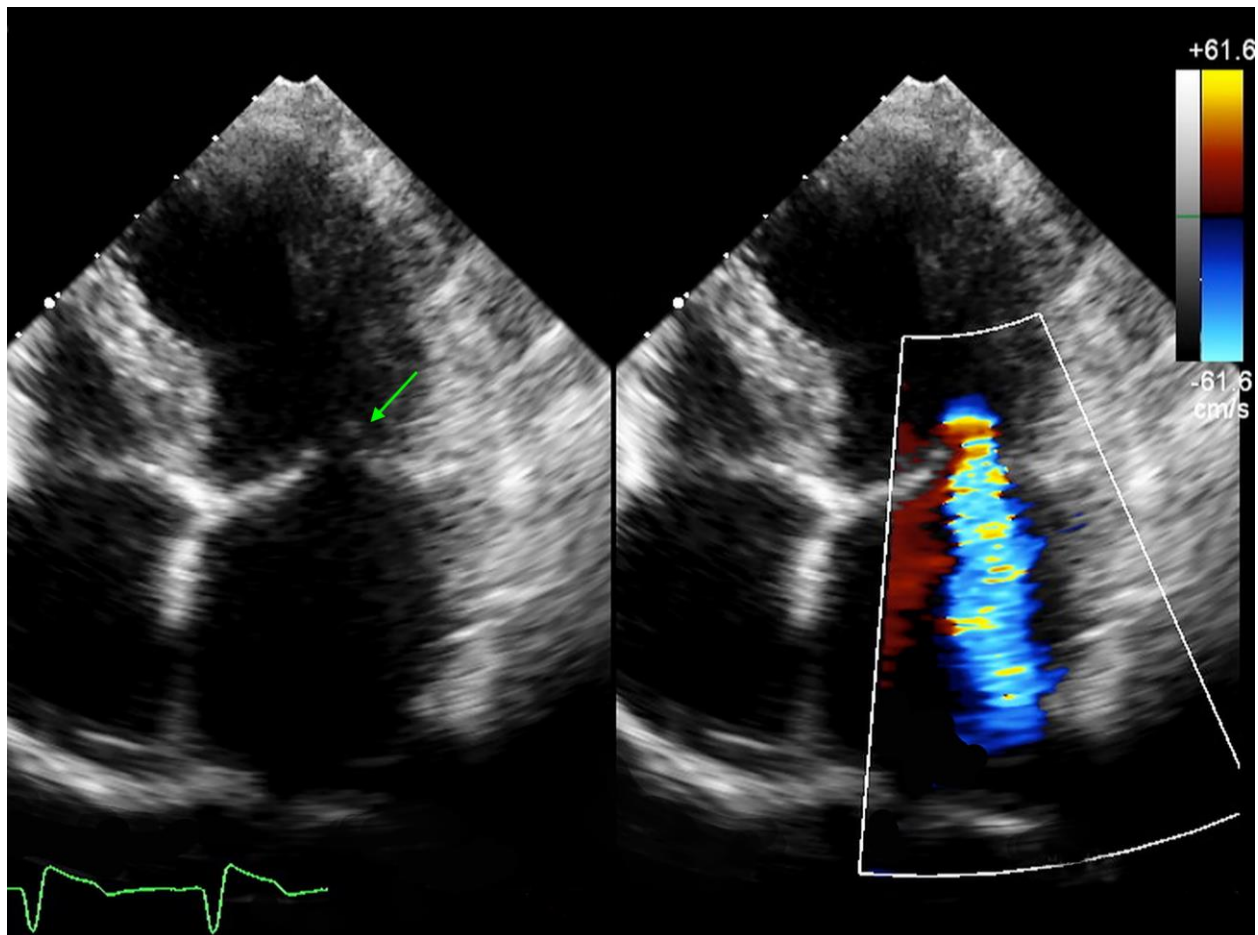


Figure 11: MR – functional, TTE four chamber view

A complete color Doppler examination of the regurgitant jet must include all views. Notice the persistence of jet turbulence almost through the entire length of the dilated left atrium, and the limited excursion of the tethered posterior leaflet (green arrow).

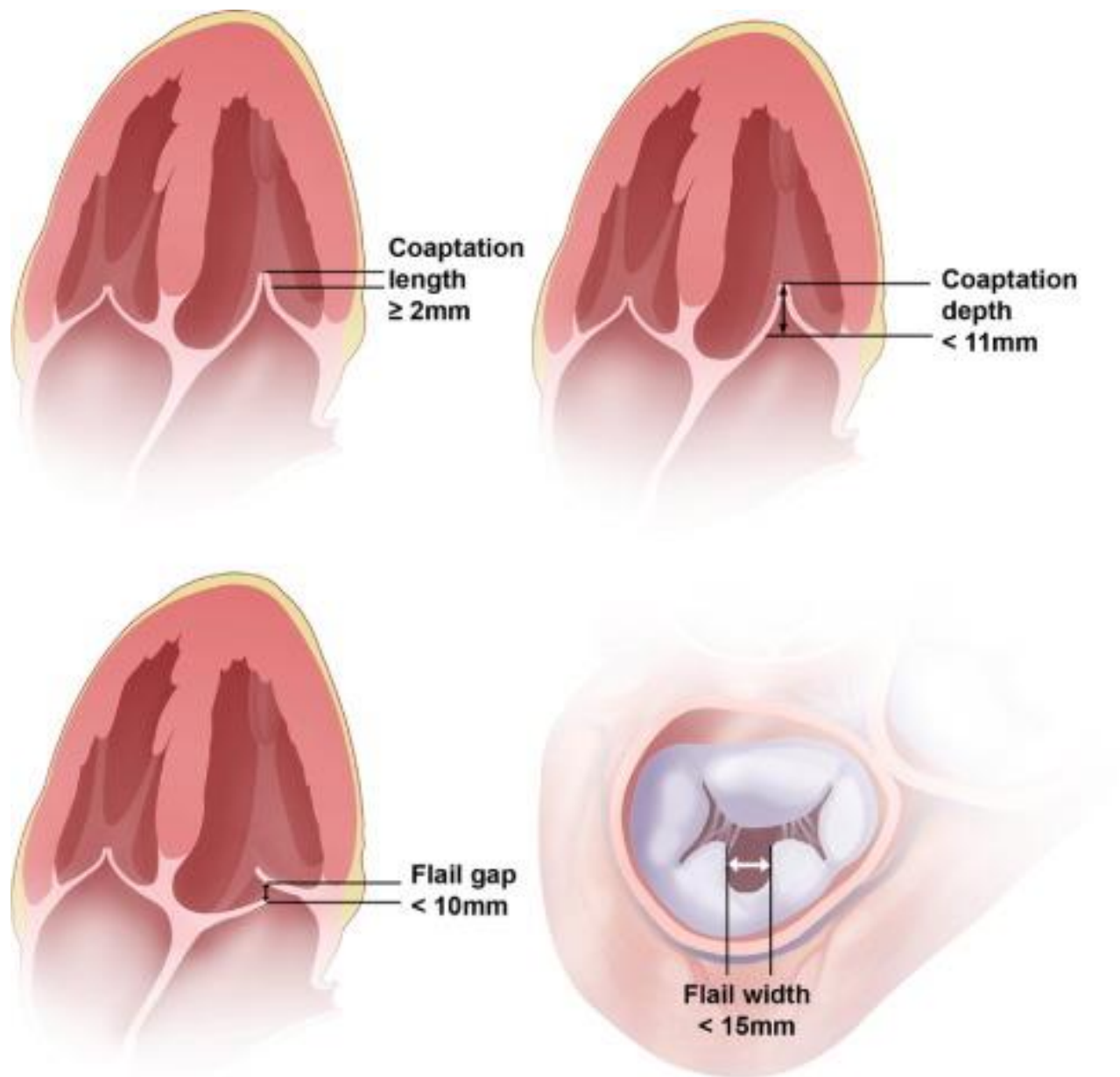


Figure 12. Eligibility criteria for MitraClip procedure according to EVEREST trial.(9)

MitraClip® patient selection is based on the inclusion and exclusion criteria outlined in the EVEREST trial:(9)

Inclusion criteria:

- Moderate-severe or severe chronic MR and:
 - Symptomatic with LVEF $>25\%$ and LV internal end-systolic diameter (LVIDs) ≤ 55 mm, or
 - Asymptomatic with one or more of the following:
 - LVEF $>25\text{-}60\%$

- LVIDs ≥ 40 -55 mm
- New onset atrial fibrillation
- Pulmonary hypertension defined as: pulmonary artery systolic pressure >50 mm Hg at rest, or >60 mm Hg during exercise.

Exclusion criteria:

- MV orifice area <4 cm²
- Endocarditis
- Rheumatic heart disease

Of particular importance is the correct grading of MR severity, using criteria as summarized in Table 1.

Table 1. Echocardiographic Severity Grading of Primary Mitral Regurgitation. (modified from Stone GW, et al; [6]).			
	Mild	Moderate	Severe
<i>Qualitative</i>			
MV morphology	Normal or Mildly abnormal	Moderately abnormal	Severe lesions: flail leaflet, ruptured papillary muscle, severe retraction/tethering, large perforation, etc.
Color flow MR jet	Small LA penetration, or not holosystolic	Moderate LA penetration, or large penetration and only late or only early systolic	Deep LA penetration and holosystolic jet
CW signal MR jet	Faint/partial/parabolic	Dense but partial or parabolic and light density	Holosystolic, and dense or triangular
<i>Semiquantitative</i>			
Vena contracta width (mm)	<3	Intermediate	≥ 7 (≥ 8 for biplane)
Pulmonary vein flow	Systolic dominance	Systolic blunting	May be normal with low LA pressure Systolic flow reversal
<i>Quantitative</i>			
EROA (mm ²)	<20	20-29*, 30-39†	≥ 40
Regurgitant volume (ml)	<30	30-44*, 45-59†	≥ 60
*Mild-moderate; †Moderate-severe MV = Mitral valve; MR = Mitral regurgitation; LA = Left atrium; CW = Continuous wave; TVI = Time velocity integral; EROA = Effective regurgitant orifice area; PA = Pulmonary artery			

The quantitative assessment of the effective regurgitant orifice area (EROA), and regurgitant volume (RV) relies on the correct use of the proximal isovelocity surface area (PISA) method (Figure 13). The following formulas are used for PISA calculations:

$$\text{ERO} = [2 \pi (\text{PISA radius})^2 \times \text{aliasing velocity}^*] / \text{MR peak velocity}$$

$$\text{Regurgitant volume} = \text{ERO} \times \text{MR TVI}$$

*baseline color Nyquist limit is shifted in the direction of the regurgitant jet, to values of 30-40 cm/sec, to obtain a larger, easier to measure, hemispherical flow convergence area.

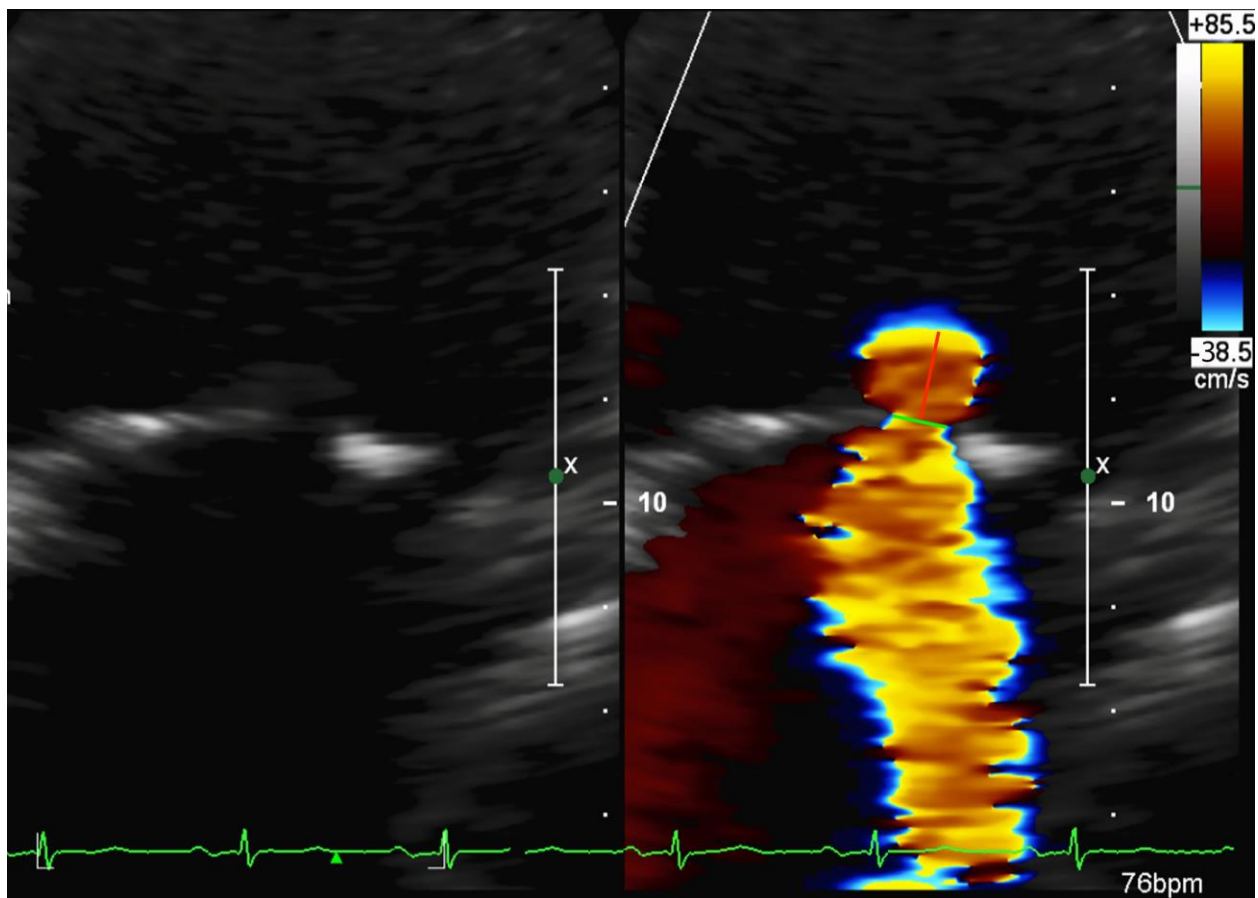


Figure 13: MR – functional, three chamber, PISA calculation.

PISA radius is measured along the direction of the jet (red). Vena contracta is defined as the narrowest portion of the jet, and is measured on the ventricular surface of the mitral leaflets (green). A PISA radius of >10 mm is typically associated with severe MR.

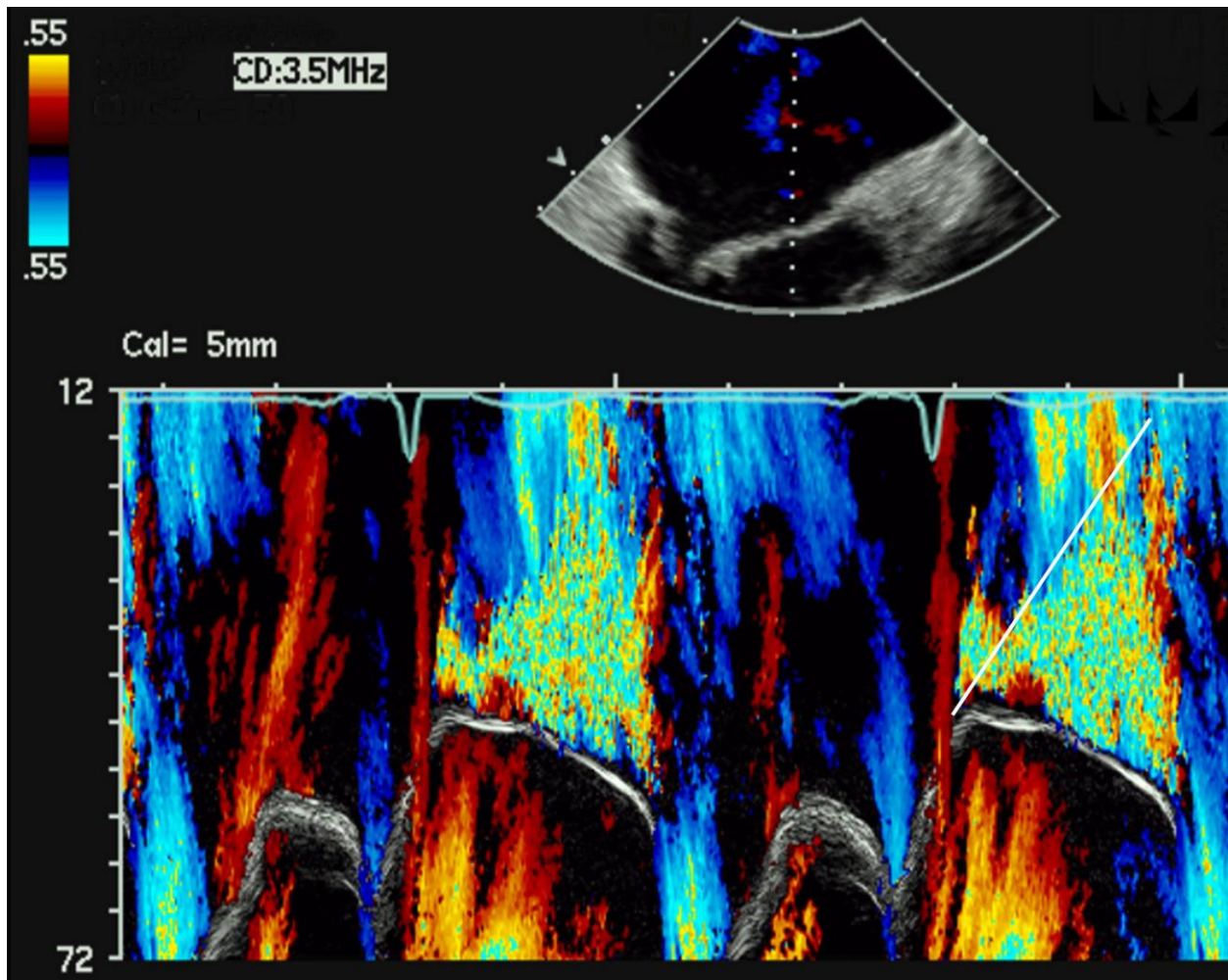


Figure 15: MR – degenerative, TEE two chamber view, color M-Mode.

Note how the regurgitant jet intensity increases progressively through systole (white line), violating one of the fundamental assumptions used in PISA calculation.

It is critical to understand the dynamic nature of MR, with highly variable severity from one examination to another. MR severity is inversely proportional to the afterload (systolic blood pressure) and directly dependent on the intravascular volume at the time of the study.

In contrast to AS evaluation, a dedicated and comprehensive 3D TEE is required for a complete study of each patient with at least moderate MR. 3D TEE “en face view” or “surgeon’s view” complements the information obtained from the TTE, by providing detailed anatomical data to establish final eligibility for the procedure. In addition, 3D TEE helps delineate the mechanism of the regurgitation, and assists in planning the type of procedure that will be performed. Given the rapid development of a large variety of transcatheter mitral devices, 3D TEE is an essential tool to help choose the appropriate device, based on the specific anatomy and regurgitation mechanism of each individual patient.

Transcatheter Closure of Perivalvular Regurgitation

Preprocedure

TTE is typically the first imaging modality to identify the presence of perivalvular regurgitation (PVL), and can quantify the severity of a single or major regurgitant jet (Figures 16, 18). In addition, TTE provides initial data needed to plan a transcatheter procedure i.e. risk of obstruction of the LVOT, mechanical interference with prosthetic tilting discs, presence of multiple jets, etc. TTE data is often complemented by additional anatomic information provided by TEE (Figure 17) and MDCT.

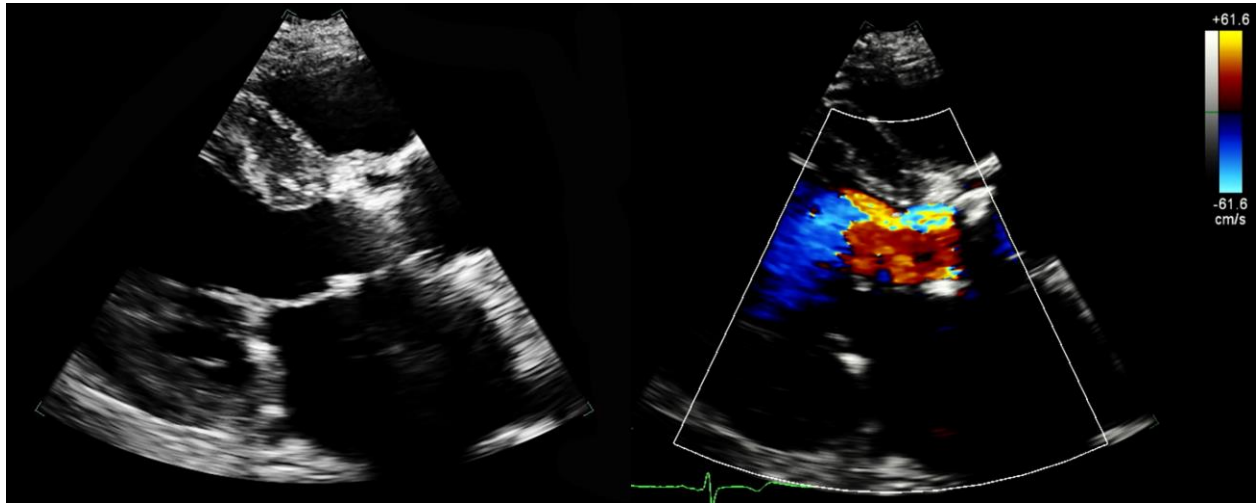


Figure 16: PVL – TTE parasternal long axis view

Biologic aortic prosthesis, with anterior perivalvular regurgitation, confirmed by TEE, subsequently closed by transcatheter occluder device.

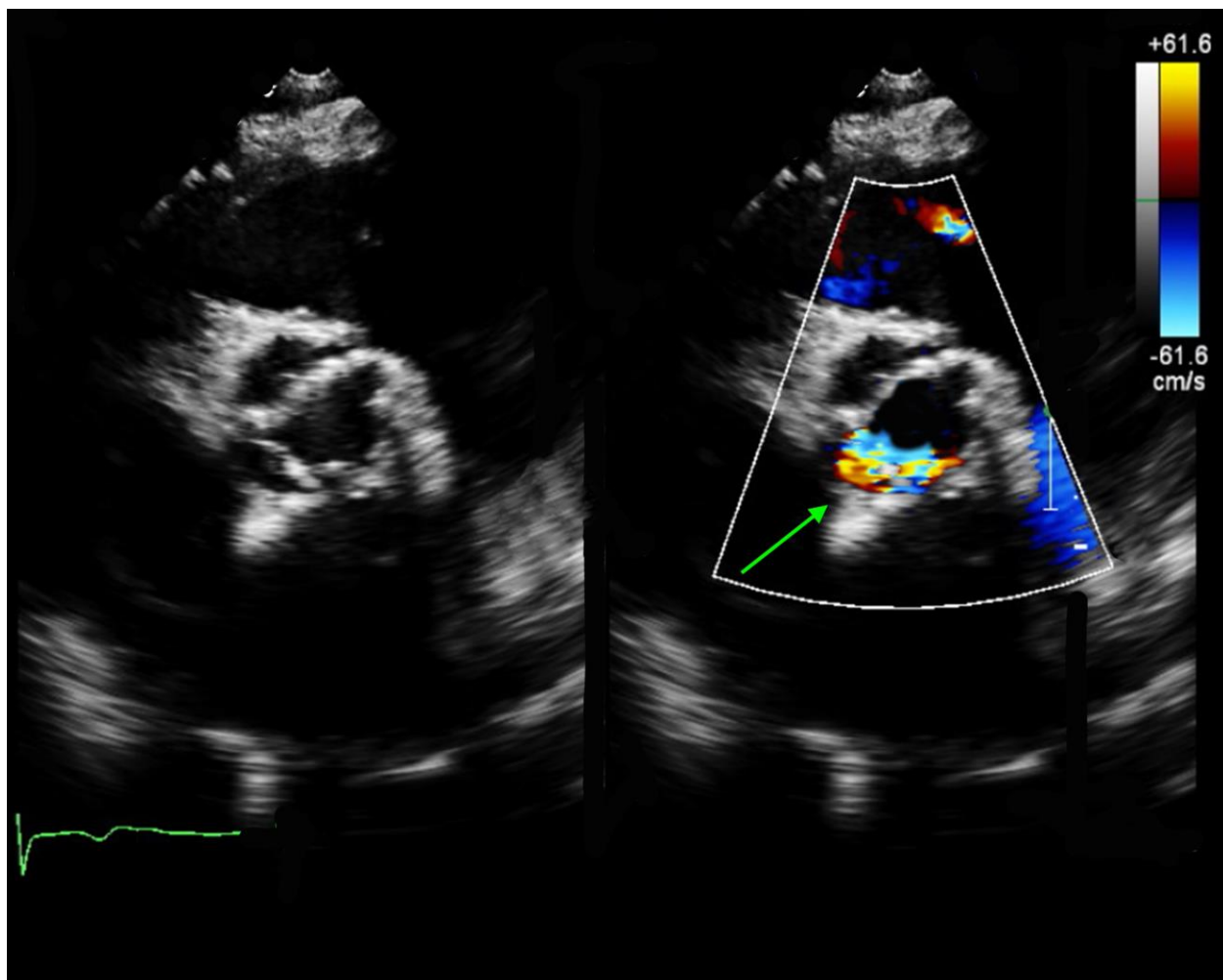


Figure 17: PVL- TEE short axis at base
Biologic aortic prosthesis, with posterior perivalvular regurgitant jet (arrow)

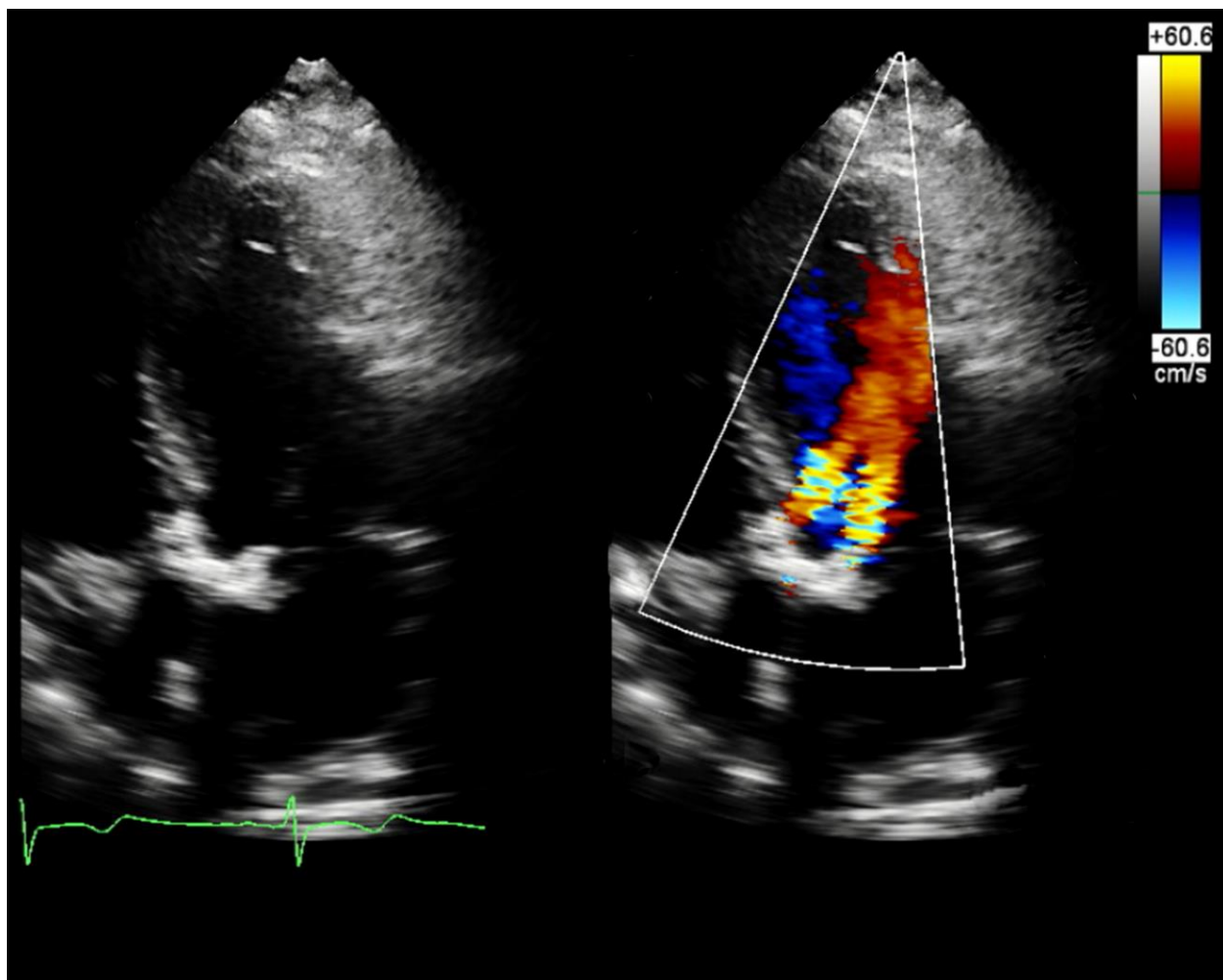


Figure 18: PVL – TTE five chamber view

Aortic biologic prosthesis, with two distinct perivalvular regurgitant jets. Confirmed by TEE and closed with two occluder devices.

Intraprocedure

3D TEE is the modality of choice for procedural guidance. A “surgeon’s view” display is primarily used throughout the procedure, with additional cropped views as dictated by the location of the defect. This view easily identifies the location and extent of annular dehiscence, regurgitant jets, presence of excessive pannus or thrombus, etc.

Postprocedure

TTE is routinely performed prior to discharge, and later as needed, to assess for pericardial effusion, residual defects, valvular function, or LVOT obstruction resulting from deployment of occluder devices or “valve in valve” procedures.

Conclusions

As transcatheter technologies grow rapidly, echocardiography evolves to provide high-quality, real-time imaging, which represents the cornerstone of patient selection, procedure planning, intraprocedure guidance, postprocedure complication assessment, and serial follow-up.

References:

1. Leon MB, Smith CR, Mack M, et al. Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery. *N Engl J Med* 2010;363(17):1597-607.
2. Blais C, Burwash IG, Mundigler G, et al. Projected valve area at normal flow rate improves the assessment of stenosis severity in patients with low-flow, low-gradient aortic stenosis: the multicenter TOPAS (Truly or Pseudo-Severe Aortic Stenosis) study. *Circulation* 2006;113(5):711-21.
3. Husser O, Holzamer A, Resch M, et al. Prosthesis sizing for transcatheter aortic valve implantation--comparison of three dimensional transesophageal echocardiography with multislice computed tomography. *Int J Cardiol* 2013;168(4):3431-8.
4. Hahn RT, Khalique O, Williams MR, et al. Predicting paravalvular regurgitation following transcatheter valve replacement: utility of a novel method for three-dimensional echocardiographic measurements of the aortic annulus. *J Am Soc Echocardiogr* 2013;26(9):1043-52.
5. Makkar RR, Fontana G, Jilaihawi H, et al. Possible Subclinical Leaflet Thrombosis in Bioprosthetic Aortic Valves. *N Engl J Med*. 2015;373(21):2015-24.
6. Stone GW, Vahanian AS, Adams DH, et al. Clinical Trial Design Principles and Endpoint Definitions for Transcatheter Mitral Valve Repair and Replacement: Part 1: Clinical Trial Design Principles: A Consensus Document From the Mitral Valve Academic Research Consortium. *J Am Coll Cardiol* 2015;66(3):278-307.
7. Orszulak TA, Schaff HV, Danielson GK, et al. Mitral regurgitation due to ruptured chordae tendineae. Early and late results of valve repair. *J Thorac Cardiovasc Surg* 1985;89(4):491-8.
8. Hamada S, Altiok E, Frick M, et al. Comparison of Accuracy of Mitral Valve Regurgitation Volume Determined by Three-Dimensional Transesophageal Echocardiography Versus Cardiac Magnetic Resonance Imaging. *Am J Cardiol* 2012;110(7):1015-20.
9. Feldman T, Kar S, Rinaldi M, et al. Percutaneous Mitral Repair With the MitraClip System: Safety and Midterm Durability in the Initial EVEREST (Endovascular Valve Edge-to-Edge REpair Study) Cohort. *J Am Coll Cardiol* 2009;54(8):686-94.
10. Faletra FF, Pedrazzini G, Pasotti E, et al. 3D TEE during catheter-based interventions. *JACC Cardiovasc Imaging*. 2014;7(3):292-308.
11. Vitarelli A, Mangieri E, Capotosto L, et al. Assessment of Biventricular Function by Three-Dimensional Speckle-Tracking Echocardiography in Secondary Mitral Regurgitation after Repair with the MitraClip System. *J Am Soc Echocardiogr* 2015;28(9):1070-82.
12. Fucci C, Sandrelli L, Pardini A, et al. Improved results with mitral valve repair using new surgical techniques. *Eur J Cardiothorac Surg*. 1995;9(11):621-6

13. Gruner C, Herzog B, Bettex D, et al. Quantification of mitral regurgitation by real time three-dimensional color Doppler flow echocardiography pre- and post-percutaneous mitral valve repair. *Echocardiography* 2015;32(7):1140-6.
14. Hamilton-Craig C, Strugnell W, Gaikwad N, et al. Quantitation of mitral regurgitation after percutaneous MitraClip repair: comparison of Doppler echocardiography and cardiac magnetic resonance imaging. *Ann Cardiothorac Surg* 2015;4(4):341-51.