









Multi-modality imaging assessment of native valvular regurgitation: an EACVI and ESC council of valvular heart disease position paper

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Valvular regurgitation represents an important cause of cardiovascular morbidity and mortality. Imaging is pivotal in the evaluation of native valve regurgitation and echocardiography is the primary imaging modality for this purpose. The imaging assessment of valvular regurgitation should integrate quantification of the regurgitation, assessment of the valve anatomy and function, and the consequences of valvular disease on cardiac chambers. In clinical practice, the management of patients with valvular regurgitation largely relies on the results of imaging. It is crucial to provide standards that aim at establishing a baseline list of measurements to be performed when assessing native valve regurgitation. The present document aims to present clinical guidance for the multi-modality imaging assessment of native valvular regurgitation.

Keywords

valvular regurgitation • echocardiography • cardiac magnetic resonance imaging • computed tomography
• expert's consensus • aortic valve • mitral valve • tricuspid valve • pulmonary valve

Introduction

Imaging and especially Doppler echocardiography is critical to initial and longitudinal assessment of patients with native valvular regurgitation. It provides detailed anatomic and functional information and clarifies the mechanisms underlying valvular regurgitation.

Non-invasive cardiac imaging not only detects the presence of regurgitation but also provides an understanding of the mechanisms of regurgitation, quantification of its severity, and haemodynamic consequences.^{1–4} In clinical practice, the management of patients with native valvular regurgitation largely integrates the results of imaging. It is thus crucial to provide standards that aim at

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establishing a baseline list of measurements to be performed when assessing regurgitation. Practically, the evaluation of valvular regurgitation requires the use of different imaging modalities, should integrate multiple parameters, should be performed under optimized medical therapy, and should be combined with clinical data. The present document, based on the thorough review and interpretation of the literature by experts in the field, aims to present clinical guidance for the multi-modality imaging assessment of native valvular regurgitation and to complement the 2021 ESC guidelines on valvular heart diseases.⁵

General imaging considerations

Echocardiography

Two-dimensional (2D) transthoracic echocardiography (TTE) is the first-line imaging in valvular regurgitation and is often sufficient for diagnosis. Two-dimensional transoesophageal echocardiography (TOE) is indicated when TTE is insufficient or when further diagnostic refinement is required. Three-dimensional (3D) echocardiography provides realistic and intuitive anatomic images of valvular apparatus, which may provide additional information, particularly in patients with complex valve lesions, and allows more accurate quantitation of haemodynamic consequences of the regurgitation on cardiac chambers.⁶

Valve assessment: key points

- (1) TTE is the first-line imaging modality in valvular regurgitation.
- (2) TOE is advocated when TTE is of non-diagnostic value or when further diagnostic refinement is required.
- (3) TOE is not indicated in patients with a good-quality TTE except before planning valvular repair or in the operating room at the time of surgery.
- (4) 3D echo provides additional information in patients with complex valve lesions and is increasingly used for assessing repair suitability.

In practice, the evaluation of valvular regurgitation starts with 2D TTE, which can orient readily to a severe regurgitation in the presence of a major valvular defect or to a minor leak when the valve anatomy and leaflet motion are normal. The aetiology (cause of the valve disease) and mechanism of the regurgitation (lesion/deformation resulting in valve dysfunction) including the dysfunction type (cusp motion abnormality) are described according to the Carpentier's classification of leaflet motion: Type I: normal leaflet motion, Type II: excessive motion, and Type III: restrictive motion.⁷

Then, a careful assessment of the *regurgitant jet* by colour Doppler, using multiple views, can rapidly diagnose minimal regurgitation, which requires a priori no further quantification (Figure 1). In all other cases, the use of a more quantitative method is advised when feasible (vena contracta, VC; proximal isovelocity surface area, PISA).

Estimation of the severity of valvular regurgitation: key points

- (1) The colour Doppler flow area of the regurgitant jet is not appropriate to quantify the severity of valvular regurgitation.
- (2) Both VC measurement and the PISA method are the preferred methods to evaluate the severity of regurgitation when feasible.
- (3) Adjunctive parameters should be used when there is discordance between the quantified degree of regurgitation and the clinical context.

In the second step, the impact of the regurgitation on the ventricles, the atria and the pulmonary artery pressures is estimated. Mode of acquisition, advantages, and limitations of the various echo Doppler parameters used for the assessment of valvular regurgitation severity are detailed in Tables 1 and 2. Finally, all the collected data are compared with the individual clinical context in order to stratify the management and the follow-up.⁵ When uncertainty persists alternative imaging modalities can be used for example TOE and cardiac magnetic resonance (CMR) and stress echocardiography. The use of stress echocardiography in valvular heart disease is the subject of a different document.⁸ Briefly for left-sided valves, a quantitative exercise echocardiography can help identify valvular lesion that have been underestimated on baseline imaging as well as the ventricular and pulmonary consequences of the regurgitation. According to the clinical context and the grade of regurgitation, appropriate monitoring will be delivered.^{5,9,10}

Cardiac magnetic resonance

CMR adds important advantages to the assessment of native valvular regurgitation (provides a view of the entire heart without limitations of body habitus or imaging windows, allows free choice of imaging planes, is free of ionizing radiation, does not require contrast administration).¹¹ This becomes particularly relevant when uncertainty exists as to the severity or aetiology of regurgitant valve lesions particularly in the presence of eccentric valve lesions, multiple regurgitant jets, right-sided valve lesions, and in patients with poor echocardiographic windows.⁵ In these situations, CMR has emerged as a useful second line investigation providing quantitative assessments of valve regurgitation, heart chamber size, and systolic function that helps in the adjudication of valve severity. The ability of CMR to accurately assess the right ventricle, pulmonary, and tricuspid valves (TVs) lends itself to the assessment of right-sided valve lesions.^{1,3,4}

The scan protocol in regurgitant valve disease evaluation is based around cine images [using balanced steady-state free precession (bSSFP) or fast spoiled gradient echo (FSPGR) sequences] to assess cardiac structure and function as well as velocity encoded phase-contrast pulse sequences that assess blood flow through the heart.¹² Long-axis cines images are acquired in two-, three-, and four-chamber views for assessments of left-sided valve lesions with equivalent views of the right ventricle to assess the tricuspid and pulmonary valves. Further modified valve views can be acquired in any plane to provide a detailed assessment of valve function and morphology. A

Table 1 Echocardiographic parameters used to quantify regurgitation severity: recordings

Parameters	Aortic regurgitation (AR)	Pulmonary regurgitation (PR)	Mitral regurgitation (MR)	Tricuspid regurgitation (TR)
Valve morphology	<ul style="list-style-type: none"> • Visual assessment • Multiple views 	<ul style="list-style-type: none"> • Visual assessment • Multiple views 	<ul style="list-style-type: none"> • Visual assessment • Multiple views 	<ul style="list-style-type: none"> • Visual assessment • Multiple views
Annulus diameter	<ul style="list-style-type: none"> • Measured on three-chamber view on echocardiography • Co-axial short-axis view on CMR or CT 			<ul style="list-style-type: none"> • Apical four-chamber view • Lateral inner edge to septal inner edge
Colour flow regurgitant jet	<ul style="list-style-type: none"> • Optimize colour gain/scale. Recommended Nyquist settings: 50–70 cm/s • Parasternal long- and short-axis views 	<ul style="list-style-type: none"> • Optimize colour gain/scale. Recommended Nyquist settings: 50–70 cm/s • Evaluate in parasternal short-axis view 	<ul style="list-style-type: none"> • Optimize colour gain/scale. Recommended Nyquist settings: 50–70 cm/s • Evaluate in two views • Measure blood pressure 	<ul style="list-style-type: none"> • Optimize colour gain/scale. Recommended Nyquist settings: 50–70 cm/s • Evaluate in two views • Measure blood pressure
VC width and area	<ul style="list-style-type: none"> • PT-LAX is preferred (apical four-chamber view if not available) • Optimize colour gain/scale. Recommended Nyquist settings: 50–70 cm/s • Identify the three components of the regurgitant jet (VC, PISA, jet into LV) • Reduce the colour sector size and imaging depth to maximize frame rate • Expand the selected zone (Zoom) • Use the cine-loop to find the best frame for measurement • Measure the smallest VC (immediately distal to the regurgitant orifice, perpendicular to the direction of the jet) • Tracing of VC cross-sectional area by 3D imaging using cropping planes to locate the VC 	<ul style="list-style-type: none"> • Parasternal short-axis view • Optimize colour gain/scale. Recommended Nyquist settings: 50–70 cm/s • Identify the three components of the regurgitant jet • Reduce the colour sector size and imaging depth to maximize frame rate • Expand the selected zone (Zoom) and find the best frame for measurement • Measure the smallest VC • Tracing of VC cross-sectional area by 3D imaging using cropping planes to locate the VC 	<ul style="list-style-type: none"> • Two orthogonal planes (PT-LAX, apical four-chamber view) • Optimize colour gain/scale. Recommended Nyquist settings: 50–70 cm/s • Identify the three components of the regurgitant jet (VC, PISA, jet into LA) • Reduce the colour sector size and imaging depth to maximize frame rate • Expand the selected zone (Zoom) • Use the cine-loop to find the best frame for measurement • Measure the smallest VC (immediately distal to the regurgitant orifice, perpendicular to the direction of the jet) 	<ul style="list-style-type: none"> • Apical four-chamber view • Optimize colour gain/scale. Recommended Nyquist settings: 50–70 cm/s • Identify the three components of the regurgitant jet (VC, PISA, jet into RA) • Reduce the colour sector size and imaging depth to maximize frame rate • Expand the selected zone (Zoom) • Use the cine-loop to find the best frame for measurement • Measure the smallest VC (immediately distal to the regurgitant orifice, perpendicular to the direction of the jet)
PISA method	<ul style="list-style-type: none"> • Apical five-chamber for central jets (PT-LAX for eccentric jets) • Optimize colour flow imaging of AR. • Zoom the image of the regurgitant aortic valve • Increase the Nyquist limit in apical views decrease or increase in PT-LAX • With the cine mode select the best PISA • Display the colour off and on to visualize the AR orifice 	<ul style="list-style-type: none"> • Parasternal short-axis view • Optimize colour flow imaging of PR. • Zoom the selected region • Increase the Nyquist limit (colour flow zero baseline). Recommended Nyquist settings: 25–40 cm/s • Measure the PISA radius at mid-systole using the first aliasing and along the direction of the ultrasound beam 	<ul style="list-style-type: none"> • Apical four-chamber • Optimize colour flow imaging of MR. • Recommended Nyquist settings: 25–40 cm/s • Zoom the image of the regurgitant mitral valve • Decrease the Nyquist limit (colour flow zero baseline) • With the cine mode select the best PISA 	<ul style="list-style-type: none"> • Apical four-chamber • Optimize colour flow imaging of TR • Zoom the image of the regurgitant tricuspid valve • Decrease the Nyquist limit (colour flow zero baseline). Recommended Nyquist settings: 25–40 cm/s • With the cine mode select the best PISA

Continued

Table 1 Continued

Parameters	Aortic regurgitation (AR)	Pulmonary regurgitation (PR)	Mitral regurgitation (MR)	Tricuspid regurgitation (TR)
	<ul style="list-style-type: none"> Measure the PISA radius at diastole using the first aliasing and along the direction of the ultrasound beam Measure AR peak velocity and TVI (CW) Calculate flow rate, EROA, R Vol 	<ul style="list-style-type: none"> Measure PR peak velocity and TVI (CW) Calculate flow rate, EROA, R Vol 	<ul style="list-style-type: none"> Display the colour off and on to visualize the MR orifice Measure the PISA radius at mid-systole using the first aliasing and along the direction of the ultrasound beam Measure MR peak velocity and TVI (CW) Calculate flow rate, EROA, R Vol 	<ul style="list-style-type: none"> Display the colour off and on to visualize the TR orifice Measure the PISA radius at mid-systole using the first aliasing and along the direction of the ultrasound beam Measure TR peak velocity and TVI (CW) Calculate flow rate, EROA, R Vol
CW regurgitant jet profile	<ul style="list-style-type: none"> Apical five-chamber CW AR jet Avoid over gaining or incomplete spectral traces 	<ul style="list-style-type: none"> Parasternal short-axis view Avoid over gaining or incomplete spectral traces 	<ul style="list-style-type: none"> Apical four-chamber Avoid over gaining or incomplete spectral traces 	<ul style="list-style-type: none"> Apical four-chamber Avoid over gaining or incomplete spectral traces
Pressure half-time	<ul style="list-style-type: none"> Apical five-chamber CW AR Doppler Avoid over gaining or incomplete spectral traces 	<ul style="list-style-type: none"> CW PR Doppler Avoid over gaining or incomplete spectral traces 	–	–
Diastolic flow reversal in descending aorta	<ul style="list-style-type: none"> PW Doppler Proximal descending aorta/abdominal aorta 	–	–	–
Pulmonary vein flow	–	–	<ul style="list-style-type: none"> Apical four-chamber Sample volume of PW placed into the right upper pulmonary vein Interrogate the different pulmonary veins when possible 	–
Hepatic vein flow	–	–	–	<ul style="list-style-type: none"> Subcostal view Sample volume of PW placed into the hepatic vein
Peak E velocity	–	–	<ul style="list-style-type: none"> Apical four-chamber Sample volume of PW placed at mitral leaflet tips 	<ul style="list-style-type: none"> Apical four-chamber Sample volume of PW placed at tricuspid leaflet tips
Ventricular size	<ul style="list-style-type: none"> Use preferably the Simpson method to assess the LV 	<ul style="list-style-type: none"> Use preferably the RV dimension from the apical four-chamber view 	<ul style="list-style-type: none"> Use preferably the Simpson method to assess the LV 	<ul style="list-style-type: none"> Use preferably the RV volume using 3D Echo or CMR

AR, aortic regurgitation; CW, continuous wave; EROA, effective regurgitant orifice area; LA, left atrium; LV, left ventricle; MR, mitral regurgitation; PR, pulmonary regurgitation; PT-LAX, parasternal long-axis view; PW, pulsed wave; RA, right atrium; RV, right ventricle; R Vol, regurgitant volume; TR, tricuspid regurgitation; TVI, time-velocity integral; VC, vena contracta.

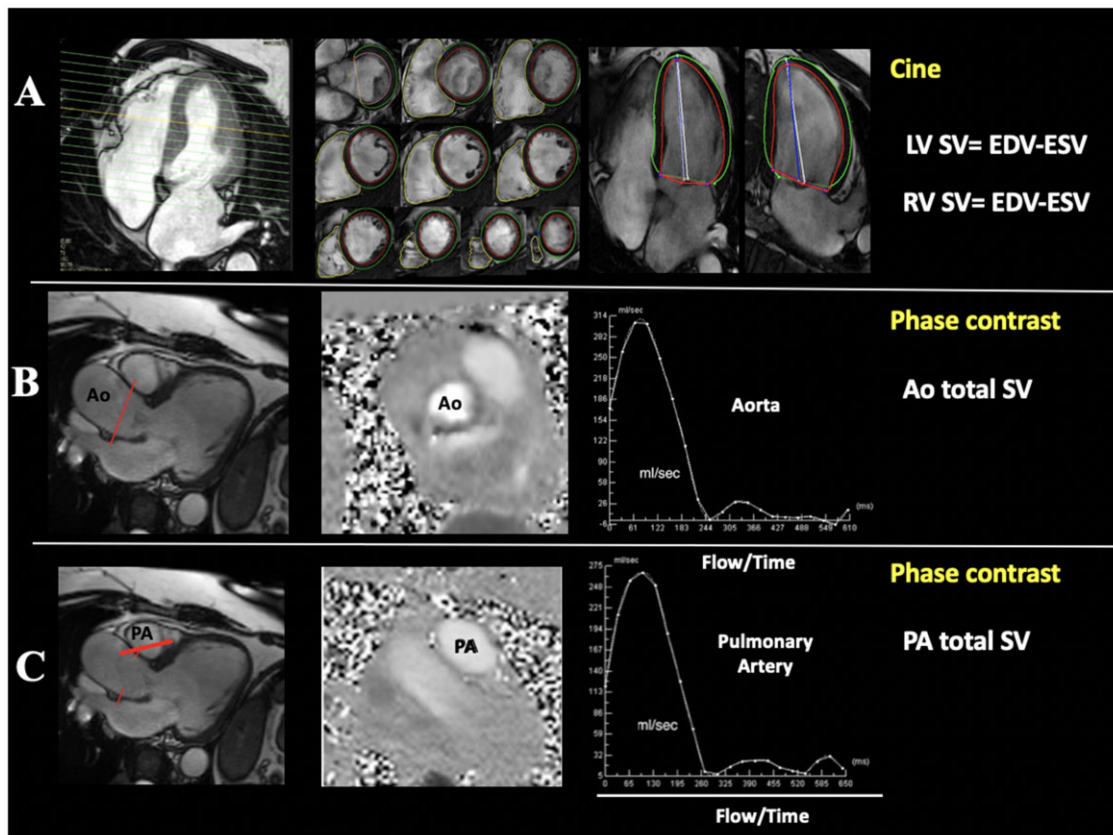


Figure 3 Methods of quantification of valvular regurgitation by cardiac magnetic resonance imaging (CMR). A: evaluation of left ventricular (LV) and right ventricular (RV) stroke volume (SV) using cine CMR acquisitions. LV and RV endocardial contours are traced in systole and diastole from a short-axis stack from base to apex; Aortic (Ao) (B) and pulmonary (PA) (C) flow assessed using phase-contrast sequence and the analysis of the flow time plot.

synchronized acquisitions. Recent technical innovations, improvement of spatial resolution down to 0.5 mm, and the introduction of wide coverage scanners have allowed the acquisition of the entire heart including all cardiac cycles in one beat with high spatial resolution and low radiation exposure.²⁵ Nevertheless, the current role of CCT in the assessment of patients with valve regurgitation remains limited. There is no current clinically validated method for measuring flow velocity or flow volume using CCT.⁵ The main indications for CCT in these patients include assessments of aortic dilatation; rapid rule out of aortic dissection; assessment of valve morphology, calcifications, and non-calcific thickening; and the rule out significant coronary artery disease in patients with an indication for surgery and low probability of coronary atherosclerosis. Finally, CCT could be used for LV and RV volumes and function evaluation or to planimeter ROAs when both echocardiography and CMR are not available or contra-indicated.²⁶

Assessment of cardiac chambers size and function

Ventricular size and function are measured using diameters and/or volumes (Figure 4) (Tables 4 and 5). By echocardiography,

Simpson's biplane method provides an estimate of both diastolic and systolic volume (with indexing to body surface area) and systolic contractile function (LV ejection fraction, LVEF) and should be performed in all cases where image quality permits. RV focused apical four-chamber view is the preferred view for RV dimension assessment.²⁷ Given its improved accuracy, 3D estimates of chamber volume and function are best for the assessment and surveillance of chamber size, function, and adverse remodelling.⁶ CMR evaluation of LV or RV function represents a valuable alternative in case of poor acoustic window or when data obtained by echocardiography are inconclusive.²⁰ When available, CMR is the preferred method to assess the right ventricle due to its high accuracy and reproducibility, particularly in patients with tricuspid and PR.⁵ Of note, ejection fraction (EF) is load dependent and often overestimates ventricular systolic performance. New parameters [myocardial velocities and global longitudinal strain (GLS)] are currently available for assessment of ventricular function and are entering routine clinical practice. Cut-off values are however yet to be validated in larger series. Atrial volumes can be reliably measured by the 2D echo biplane area-length method, 3D echocardiography, CMR, or computed tomography (CT) scan.^{11,26}

Table 3 CMR evaluation of valvular regurgitation: advantages and technical limitations

Parameters	Usefulness/advantages	Limitations
Cine imaging Assessment of valve morphology as well as cardiac chambers size and function (bSSFB is the preferred sequence)	<ul style="list-style-type: none"> • Provides assessment of valve morphology and regurgitant jet visualization in any plane • Allows assessment of the impact of regurgitant lesions on cardiac chambers • Assessment of diastolic flow reversal in the descending aorta can aid assessment of AR severity • High diagnostic accuracy • High reproducibility • Not based on geometric assumptions 	<ul style="list-style-type: none"> • Time consuming • It requires multiple breath hold • Limited accuracy and reproducibility in patients with arrhythmic disorders during acquisition
AR and PR Direct quantitative regurgitant flow measurements (phase-contrast sequence)	<ul style="list-style-type: none"> • Direct measurement of forward and reverse flow through the plane of the valve or vessel • Not based on geometric assumptions • Accurate in aortic regurgitation and pulmonary regurgitation quantification • Contribute to the calculation of MR and TR alongside ventricular stroke volumes outlined below 	<ul style="list-style-type: none"> • Time-consuming • It could require additional dedicated scan acquisition • Challenging in the identification of appropriate plane alignment and angulation outside of the setting of aortic regurgitation or pulmonary regurgitation
MR and TR Indirect quantitative regurgitant flow measurements as difference between left and right ventricle stroke volumes versus anterograde aorta and pulmonary flow, respectively (both bSSFB and PhC sequence are required)	<ul style="list-style-type: none"> • Second line test to confirm findings from direct and indirect methods described above. • High accuracy and reproducibility • It does not require additional acquisition 	<ul style="list-style-type: none"> • Limited accuracy and reproducibility in patients with arrhythmic disorders during acquisition • Background or phantom corrections could be useful with additional scan time
Confirmatory Techniques		
Indirect quantitative regurgitant flow measurements as difference between left and right ventricle stroke volumes (bSSFB is the preferred sequence)	<ul style="list-style-type: none"> • High accuracy and reproducibility for the assessment of MR and TR (not required for AR and MR) • It does not require additional acquisition 	<ul style="list-style-type: none"> • It can be applied only in patients with single valve disease
Direct visualization of regurgitant jet (FSPGR is the preferred sequence)	<ul style="list-style-type: none"> • Linear relationship between dephasing spin velocity and signal loss • Laminar flow suggests at least moderate aortic regurgitation 	<ul style="list-style-type: none"> • Time-consuming • It requires multiple breath hold • Limited spatial resolution in chambers evaluation as compared to bSSFP • They should be acquired on top of bSSFP sequences • Visual estimation of jet with limited correlation with semi-quantitative or quantitative method
Planimetry of the anatomical regurgitant orifice area (bSSFB is the preferred sequence)	<ul style="list-style-type: none"> • High in-plane spatial resolution allowing accurate detection of regurgitant orifice 	<ul style="list-style-type: none"> • Time-consuming • Challenging in the identification of appropriate plane alignment and angulation • Based on geometric assumptions

AR, aortic regurgitation; bSSFP, balanced steady-state free precession; FSPGR, fast spoiled gradient echo; MR, mitral regurgitation; PhC, velocity encoded phase-contrast; PR, pulmonary regurgitation; TR, tricuspid regurgitation.

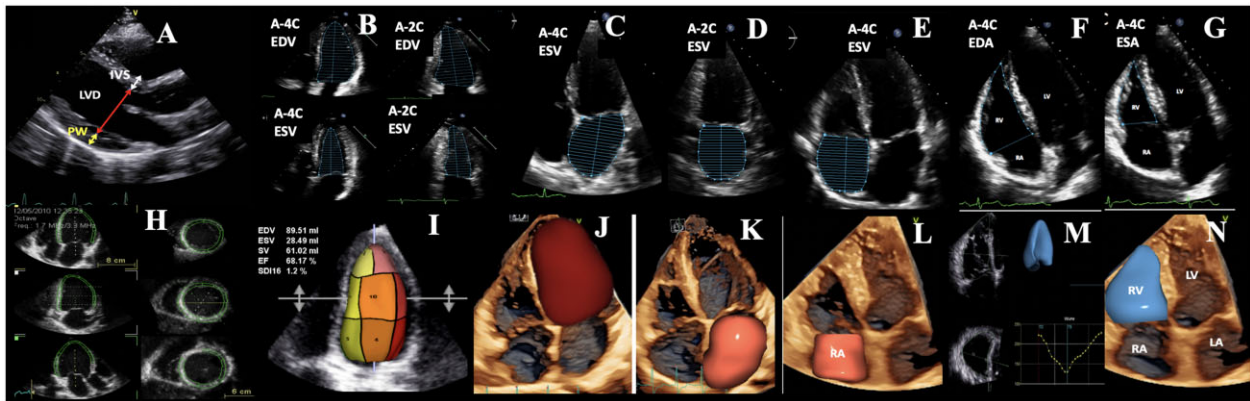


Figure 4 Assessment of cardiac chambers size and function by 2D and 3D echocardiography. (A) 2D measurement of LV diameters. (B–E) Estimation of cardiac volumes by summation method of disc (B: LV, C and D: LA, E: RA). (F and G) RV fractional area change assessment. (H–N) 3D echo assessment of cardiac chamber volumes (H–J: LV; K: LA; L: RA; M and N: RV).

Table 4 Heart chamber size and function: key points

- (1) Quantitative assessment of left ventricular (LV) diameters, volumes, and ejection fraction (EF) is mandatory
- (2) 2D measurement of LV/RV diameters is mandatory
- (3) The 2D-based biplane summation method of discs is the standard approach for the estimation of LV volumes and ejection fraction
- (4) 3D echo assessment of LV/RV function provides more accurate and reproducible data
- (5) Contrast echo is indicated in patients with poor acoustic window
- (6) CMR evaluation of LV/RV function is a valuable alternative in case of poor echogenicity or when data obtained by echo are inconclusive
- (7) CCT evaluation of LV/RV function is a valuable alternative in case of poor echogenicity/data obtained by echo are inconclusive and CMR is not available or contraindicated
- (8) Qualitative assessment of LV/RV function is not advised
- (9) Left atrial volume is the best parameter to assess its size

Aortic regurgitation

AR is a common valvular disease. Non-invasive imaging plays a key role in the assessment and management of patients with AR.^{1,2}

Anatomy and function of the aortic valve

The aortic valve consists of a composite of structures surrounding the aortic orifice along the outflow tract of the left ventricle.²⁸ Typically, the valve has three leaflets or cusps, which are semi-lunar in shape (Figure 5). The cusps are inserted into a fibrous connective tissue sleeve, which is attached to the aorta media above (the Valsalva sinuses and the sino-tubular junction). Below, the cusps are attached to the myocardium of the LV outflow tract (LVOT) and to the anterior mitral leaflet (virtual basal ring), below the anatomic ventriculo-aortic junction. Hence, the true anatomic aortic annulus is not

actually the ring projected at the most basal leaflet insertion—as usually defined and measured with various imaging techniques—but a crown-like 3D structure. Of note, the size of aortic annulus and root is influenced by inner pressure and changes dynamically during the cardiac cycle. Each cusp is attached to the aorta along its curved edge, and the cusps meet at three commissures that are equally spaced along the circumference of the sleeve at the supra-aortic ridge. In normal aortic valve, the cusps are symmetrical, mobile, and free at the commissures, with equal overlap on closure. The cusps are named left, right, and non-coronary cusps based on the location of the coronary ostia.

Aetiology and mechanisms of AR

AR results from disease of either the aortic leaflets or the aortic root that distorts the leaflets and prevents their correct apposition. Common causes of leaflet abnormalities that result in AR include senile leaflet calcifications, bicuspid aortic valve, infective endocarditis, and rheumatic fever. Aortic causes of AR include annulo-aortic ectasia (idiopathic root dilatation), Marfan's syndrome, aortic dissection, collagen vascular disease, and syphilis. The Carpentier's classification is also commonly used to describe the mechanism of AR (Figure 6; Table 6).²⁹

Key point: In patients with AR, careful assessment of the aortic valve, aortic annulus, and aortic root is mandatory. The imaging report should include information about the aetiology, the lesion process, and the type of dysfunction. The likelihood of valve repair should also be discussed in case of pure AR.

Imaging evaluation in AR

Imaging findings in AR

Information about the cusp pathology (redundancy, restriction, cusp height to indicate likely adequacy of coaptation, mobility/pliability, thickness, and integrity), commissure variations (fusion, splaying,

Table 5 Multimodality imaging for the assessment of the patients with valvular regurgitation

	Echocardiography (TTE/TOE)		CMR	CCT
	2D/colour Doppler/PW and CW Doppler	3D/colour Doppler		
Qualitative				
Valve morphology	+++	+++	++	++
Regurgitant jet	+++	+++	++	-
Flow reversal into aorta/pulmonary arteries	+++	+	+++	-
Flow reversal into veins	+++	+	++	-
Regurgitant jet morphology	++	+++	++	-
Semi-quantitative				
Vena contracta width	+++	+++	++	-
Vena contracta area	-	+++	++	-
Quantitative				
Anatomic ROA	-	+	++	+++
EROA	++ (PISA)	+(PISA)	-	-
R Vol	++ (PISA)	++ (PISA)	+++	-
RF	+	+	+++	-
Heart chamber size				
Annular dimensions	++	+++	+++	+++
Volumes	++	+++	+++	+++
Ejection fraction	++	+++	+++	+++
Vena cava diameter	+++ (proximal only)	+++	+++	+++
Vascular assessment	+	+	+++	+++
Calcification burden	++	++	+	+++

+, Somewhat useful; ++, useful; +++, very useful; -, not useful; EROA, effective regurgitant orifice area; RF, regurgitant fraction; R Vol, regurgitant volume; VC, vena contracta.

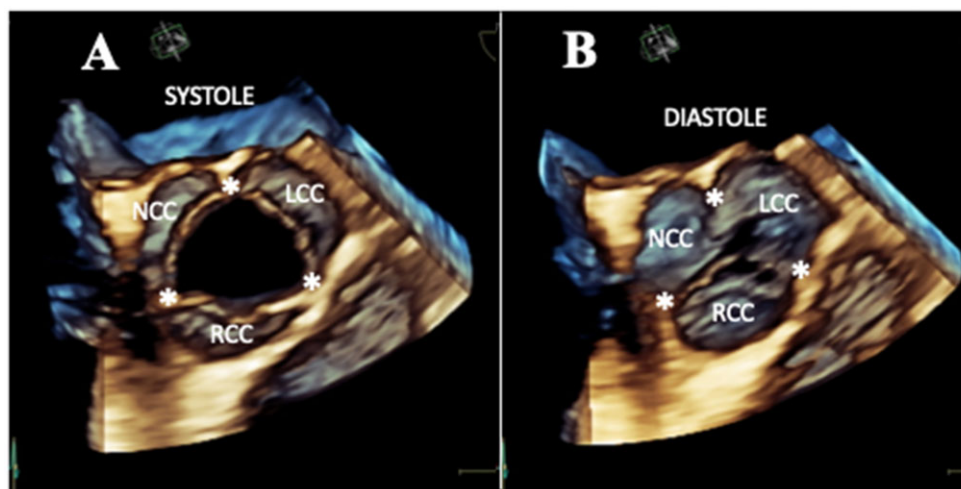


Figure 5 Transesophageal 3D images of normal aortic valves (AV) in systole (A) and diastole (B) as seen from the aorta. Each valve has three semi-lunar cusps and three commissures (asterisk)*. LCC, left coronary cusp; NCC, non-coronary cusp; RCC, right coronary cusp.

attachment site, and alignment), and root morphology (septal hypertrophy, annular size, sinus and sino-tubular junction dimension, and ascending aorta dimension) should be provided. The presence of a flail valve is specific for severe AR.

Echocardiography usually provides all this information as the first line imaging approach. The parasternal long-axis view is classically used to measure the LVOT, the aortic annulus, and the aortic sinus dimensions. Leaflet thickness and morphology can be visualized from

this window as well as from the parasternal short-axis view and the apical five and three-chamber views. However, not uncommonly, 2D TTE does not allow a complete assessment of the anatomy and causes of AR. In this situation, if the acoustic window is optimal, 3D echo could provide better delineation of the aortic valve morphology.^{6,28} Three-dimensional TOE is increasingly used for assessing the mechanisms and causes of AR, as well as the aortic root dimensions and morphology.²⁹ TOE is often used for further detailed examination of the aortic valve and root. Additionally, 2D (reverse doming of the anterior MV leaflet; basal septal hyperechogenic aspect) and M-mode (high frequency fluttering of the anterior mitral leaflet, the MV chordae or the interventricular septum; premature MV closure; premature diastolic opening of the aortic valve) echo findings that can be associated with AR should also be looked for (Figure 7).

CMR imaging in AR begins with standard three-chamber and coronal SSFP cine views, which provide a visual assessment of the aortic valve, LV, and LVOT structure and function.¹² It can provide useful information on leaflet morphology and motion. With CCT, multiplanar images can be reconstructed that are analogous to standard echocardiographic views of the aortic valve.

CMR provides limited information on aortic valve leaflets.³⁰ CCT can also accurately delineate aortic valve anatomy, and it is uniquely useful in evaluating the size of the aortic annulus and the burden of valvular, aortic, and coronary calcifications. Both CMR and CCT, also, allow comprehensive assessment of entire aorta for quantifying aortic dilation or the presence of coarctation in patients with bicuspid aortic valve.³¹

CCT is the preferred imaging modality to assess maximum diameter in patients with dilated aorta and also for sizing the aorta before surgery, while CMR can be used for serial evaluation to limit radiation.³²

Assessment of AR severity

Semi-quantitative methods

Colour flow Doppler imaging. Using colour flow Doppler, the regurgitant jet into the left ventricle during diastole can be visualized from multiple views. The colour jet area and length are weakly correlated to the degree of AR, are affected by the aortic to LV diastolic pressure gradient and LV compliance, and are often overestimated in the apical views. They are currently considered as not appropriate to quantitate AR severity. Practically, colour flow Doppler serves for detection and initial visual assessment of AR. Central jets are suggestive of rheumatic disease, while eccentric jets are often associated with aortic valve prolapse or perforation. Colour-coded M-mode is suitable for assessing the time-course of flow signals during the heart cycle (Figure 8). The diameter and the cross-sectional area of the jet at its origin are semi-quantitative colour Doppler indexes of AR severity. The maximum colour jet diameter (width) is measured in diastole immediately below the aortic valve (at the junction of the LVOT and aortic annulus) in the parasternal long-axis view. The jet width is proportional to the size of the aortic valve defect. However, since it assumes a circular regurgitant orifice, if the orifice shape is irregular, as in bicuspid valve, the colour jet width is less related to the degree of regurgitation. Its accuracy can thus be improved by normalizing the jet width for the LVOT diameter. The cross-sectional area of the jet from the parasternal short-axis view and its ratio to the LVOT

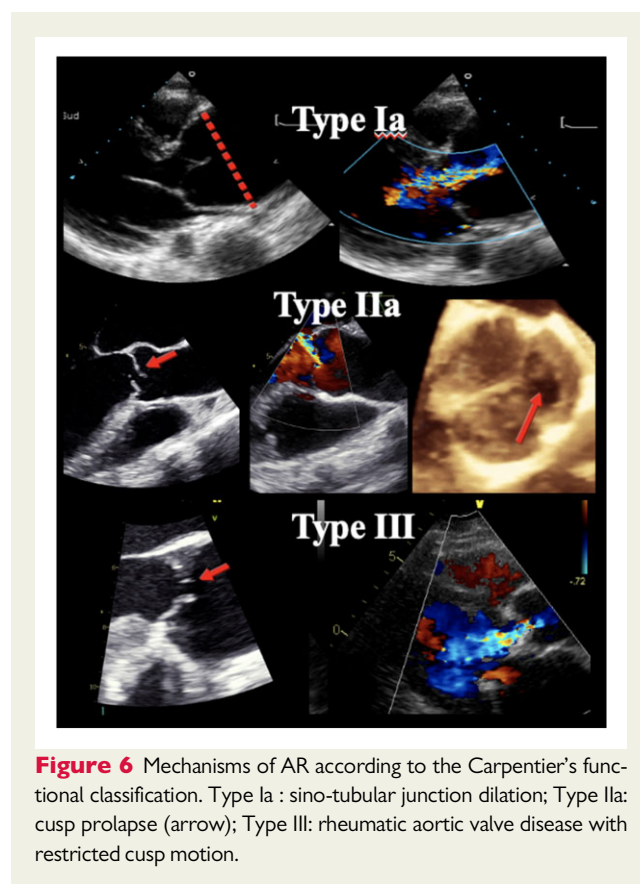


Figure 6 Mechanisms of AR according to the Carpentier's functional classification. Type Ia : sino-tubular junction dilation; Type IIa: cusp prolapse (arrow); Type III: rheumatic aortic valve disease with restricted cusp motion.

area are also semi-quantitative parameters of AR severity. Although these measurements suffer from a high inter-observer variability, a jet width ratio >65% is an argument for severe AR (Figure 9).³³

Key point: The colour flow area of the regurgitant jet, as a single parameter, is not appropriate to quantify the severity of AR. The colour jet width and its ratio to the LVOT diameter may be used to semi-quantitate AR severity. A more quantitative approach is required when more than a small central AR jet is observed.

Vena contracta width. For AR, imaging of the VC—the regurgitant jet as it traverses the aortic orifice or the effective regurgitant area—is obtained from the parasternal long-axis echocardiographic view.^{32,34,35} Practically, the VC represents the smallest flow diameter at the level of the aortic valve in the LVOT, immediately below the flow convergence region (Figure 10). It provides an estimate of the size of the effective regurgitant orifice area (EROA) and is smaller than the regurgitant jet width in the LVOT (expansion of the jet occurs immediately below the VC). With echo, using a Nyquist limit of 50–60 cm/s, a VC width of less than 3 mm correlates with mild AR, whereas a width >6 mm indicates severe AR. The measurement of the VC is affected by several factors including the presence of multiple jets. In this situation, the respective widths of the VC are not additive. Moreover, the concept of VC is indeed based on the assumption that the regurgitant orifice is almost circular. The orifice is however often elliptical or irregular, which changes the width of the

chamber view (Figure 12). However, effort should be made to obtain correct Doppler angle in order to minimize errors related to possible ultrasound beam misalignment. For eccentric jets, better signals may be obtained from the right parasternal window. While faint spectral display is compatible with trace or mild AR, significant overlap between moderate and severe AR exists in more dense jet tracings. Practically, the CW density does not provide useful information about the severity of AR. The grading by this method is qualitative. The rate of deceleration of the diastolic regurgitant jet and the derived pressure-half time reflect both the degree of regurgitation and the ventricular end-diastolic pressures. As the degree of AR increases, the aortic diastolic pressure decreases and the LV end-diastolic pressure increases.^{37,38} The late diastolic jet velocity is thus reduced and the pressure half-time shortened. A pressure half-time of <200 ms is consistent with severe AR, whereas a value >500 ms suggests mild AR. Of note, the pressure half-time is however influenced by LV and aortic compliance, the acuteness of AR (i.e. in severe acute AR, the pressure half-time is almost always short) and the aorto-ventricular pressure gradient.

Key point: The CW Doppler density of the AR jet does not provide useful information about the severity of AR. The assessment of the pressure-half time requires good Doppler beam alignment. A careful probe angulation is often needed. Because of the influences by LV and aortic chamber compliance and pressures, pressure half-time can only serve as a complementary finding for the assessment of AR severity.

Quantitative assessment

Anatomic orifice area. The anatomic ROA may be measured directly by planimetry using 2D/3D echocardiography, CCT, or CMR. Using an 'en face view' of the aortic valve, the smallest diastolic ROA in mid-diastole is traced. Cut-offs of severity are, however, less well defined than for EROA and its clinical use is still limited. With CMR, an anatomic ROA $\geq 48 \text{ mm}^2$ is consistent with severe AR.³⁹

The proximal isovelocity surface area method. With echocardiography, the assessment of the flow convergence zone has been less extensively studied in AR than in mitral regurgitation.^{40,41} Imaging of the flow convergence zone is obtained from the apical three- or five-chamber or parasternal long-axis or upper right parasternal views. The radius of the PISA is measured at diastole using the first aliasing. R Vol and EROA are obtained using the standard formulas (Figures 13 and 14). The flow convergence or PISA method has several limitations. Firstly, it is not feasible in a significant percentage of patients with AR due to interposition of valve tissue and difficulty in correctly identifying the flow convergence zone. Non-planar or confined flow convergence zones that invalidate the hemispheric assumption are potential causes of either under- or over-estimation of AR severity by the PISA method. Accordingly, caution should be exercised when using the PISA method in patients with obtuse flow convergence angles, such as those with aneurysmal dilation of the ascending aorta or those with confined flow convergence-zone such as could occur in

patients with cusp perforation or commissural leaks. The use of 3D echocardiography to improve the accuracy of the PISA method and the VC area to quantify AR is promising but requires further validation.⁶ The PISA method also allows to measure the R Vol but in addition to the limitations of the PISA method mentioned above for the measurement of the EROA, the CW Doppler signal of AR is often incomplete, especially in eccentric jets. Grading of severity of AR classifies regurgitation as mild, moderate or severe, and sub-classifies the moderate regurgitation class into 'mild-to-moderate' (EROA of 10 to 19 mm² or an R Vol of 20–44 mL) and 'moderate-to-severe' (EROA of 20–29 mm² or an R Vol of 45–59 mL). An EROA $\geq 30 \text{ mm}^2$ or an R Vol $\geq 60 \text{ mL}$ indicates severe AR. A RF [R Vol divided by the LVOT stroke volume] greater than 50% indicates severe AR. A moderate EROA or R Vol may, in fact, correspond to a large RF and thus to a severe AR in patients with depressed LV systolic function and low flow state or in patients with acute AR. In such cases, more weight should be given to the RF to grade AR severity. Hence, patient with an EROA and a R Vol that are in the moderate range but a RF $\geq 50\%$ should be considered as having severe AR.

Key point: When feasible, the PISA method is highly suggested to quantify the severity of AR. It can be used in both central and eccentric jets. In eccentric AR jets, the parasternal long-axis view must preferentially be used to evaluate the flow convergence zone. An EROA $\geq 30 \text{ mm}^2$ or a R Vol $\geq 60 \text{ mL}$ indicates severe AR. A RF greater than 50% indicates severe AR, even if EROA and R Vol are in the moderate range.

Doppler volumetric method. PW Doppler method can be used as an alternative method to quantify the AR severity.^{1–3} In the absence of significant mitral regurgitation (MR), the mitral inflow is used to calculate the systemic stroke volume (see MR section). The RV outflow tract site can be used in patients with significant MR. The total stroke volume is derived from the LVOT stroke volume. This approach is time consuming and is associated with several drawbacks.

CMR quantification. CMR is the alternative method of choice to quantify the R Vol and RF. In AR, the phase-contrast direct method is the most validated approach with the advantage of not being affected by coexisting valvular regurgitation lesions. Phase-contrast velocity mapping is used to calculate aortic forward and reverse flow per cardiac cycle (Figure 14). A through plane phase-contrast imaging slice is positioned at the level of aortic root, often just above the aortic valve and at or below the sinotubular junction. In some cases, velocity-encoded phase-contrast is unreliable as when the area of interest is obscured by artefacts, when flow is complex in a markedly dilated aortic root, or in case of arrhythmias. In these contexts, indirect methods may be used. The RF is calculated by dividing the R Vol by the LV stroke volume. RF is an independent predictor of outcome in patients with AR,⁴² and a RF >33% has been shown to predict the likelihood of requiring surgery within 9 years.⁴³ RF limits that optimize concordance of CMR and echo severity grades are: mild $\leq 15\%$, moderate 16–25%, moderate–severe 26–48%, and severe >48%.^{1,12}

Key point: Although large outcome CMR studies are lacking, CMR is the alternative method of choice for quantitative assessment of AR. The direct approach using the phase-contrast technique is the most reproducible with the advantage of not being affected by coexisting valvular regurgitation lesions. A RF $\geq 50\%$ indicates severe AR.

Consequences of AR on LV size and function

The presence of severe AR has significant haemodynamic effects, primarily on the left ventricle. AR imposes additional volume load on the left ventricle. In acute AR, the left ventricle is classically not enlarged, while in the chronic situation, the left ventricle progressively dilates and irreversible LV damage may occur. Hence, dilatation is sensitive for chronic significant (moderate to severe) AR, while normal size almost excludes severe chronic AR. However, dilatation can be observed in other conditions (non-specific) or may be absent in acute severe AR. Three-dimensional echocardiography allows more accurate measurement of LV volumes and EF than 2D echocardiography. LV volumetric data derived by echocardiography (LV end-systolic volume index ≥ 45 mL/m²)⁴³ or CMR (LV end-diastolic volume >246 mL with RF $>33\%$)⁴² may be instrumental in the

identification of patients at increased risk of clinical progression. Strain imaging (GLS $< -19\%$) may be helpful in identifying subclinical LV dysfunction in the setting of serial echocardiograms and may help for risk stratification.⁴⁴ Thresholds recommended in current ESC guidelines⁵ for intervention in asymptomatic patients with severe AR are: LVEF $\leq 50\%$, LV end-systolic diameter >50 mm or >25 mm/m². CMR may be used for the detection of myocardial fibrosis, especially in high-risk patients, where it is associated persisting symptoms post-AVR, poor LV recovery, and an adverse prognosis. Further studies are required.⁴⁵

Key point: LV diameters, volumes, and ejection fraction should always be measured and reported in patients with AR. The LV diameters and volumes must be indexed to the body surface area. Three-dimensional echocardiography and CMR imaging allows more accurate evaluation of LV volumes and EF than 2D echocardiography. However, until further data are available current cut-offs for intervention are based on 2D echo results.

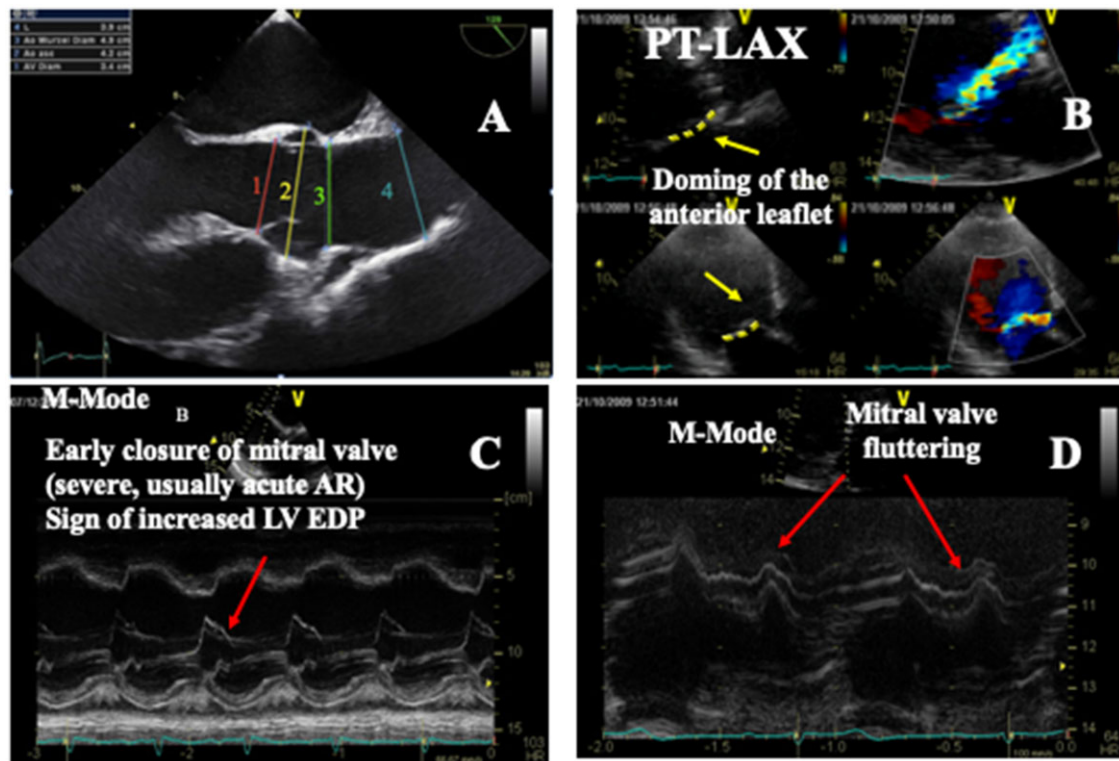


Figure 7 (A) Measurements of the aortic diameters. 1: valve annulus, 2: aortic sinuses, 3: sinotubular junction, 4: proximal ascending aorta; (B) example of AR jet impinging on the anterior mitral valve leaflet with a reverse doming of the anterior mitral valve leaflet; (C) M-mode recording showing early mitral valve closure in a patient with severe AR; (D) M-mode recording showing the fluttering motion of the anterior mitral leaflet in a patient with severe AR.

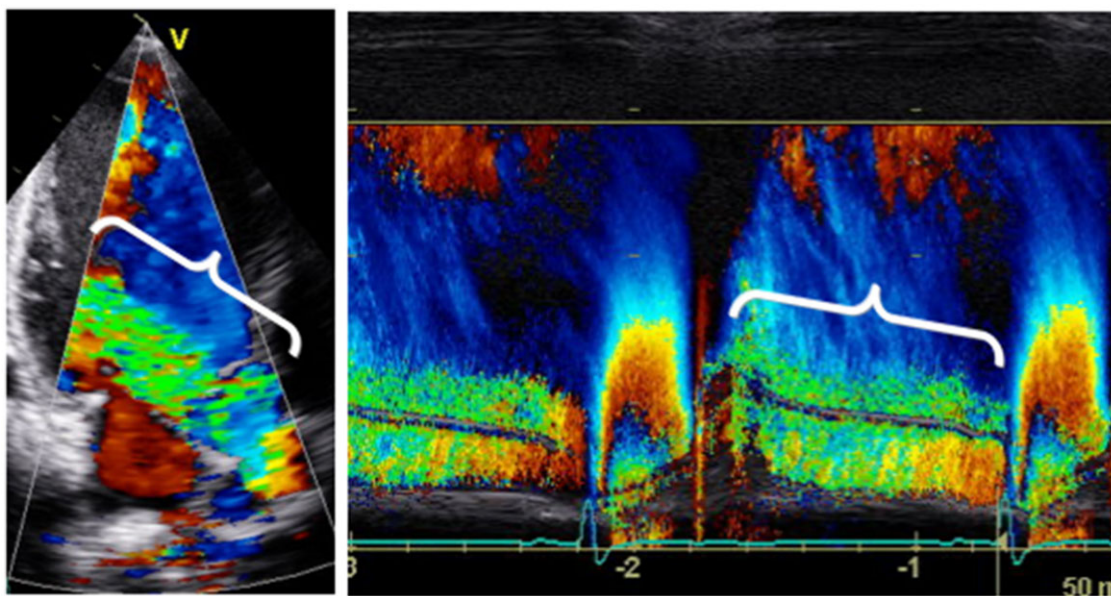


Figure 8 (A) Colour Doppler showing a severe AR. (B) Colour-coded M-mode depicting the time-dependency of flow signal during the heart cycle.

Role of exercise echocardiography

The development of symptoms during exercise testing is useful in predicting outcome in patients with severe AR who are apparently asymptomatic at rest. The observed magnitude of change in ejection fraction or stroke volume from rest to exercise is related not only to myocardial contractile function but also to severity of volume-overload and exercise-induced changes in preload and peripheral arterial resistance. However, the absence of contractile reserve—decrease in LVEF by 5% at exercise—has been associated with LV decompensation after surgery.⁸ As the incremental value of stress echocardiography in predicting outcome of patients with asymptomatic AR is limited by the small number of available studies, this specific application is currently limited to the research arena. In the symptomatic patient with moderate AR, stress echocardiography can be useful to identify factors related to AR or other concomitant conditions that may be responsible for the symptoms, such as significant rise in pulmonary pressure during exercise (>60 mmHg), inducible myocardial ischaemia, or failure to increase LVEF during exercise.⁸

Integrating indices of severity

Echocardiographic assessment of AR should follow a multi-parameter integrative approach that includes data from 2D/3D imaging of the aortic root, aortic valve, and left ventricle as well as Doppler measures of regurgitation severity (Table 7) (Figure 15). Effort should be made to quantify the degree of regurgitation, except in the presence of mild or less severe AR or when AR is considered severe using specific signs. Both the VC width and the PISA method are the preferred parameters, whenever possible. Adjunctive parameters help to consolidate about the severity of AR. CMR is the alternative method of choice and should be used when the results of echocardiography (TEE and TOE) are

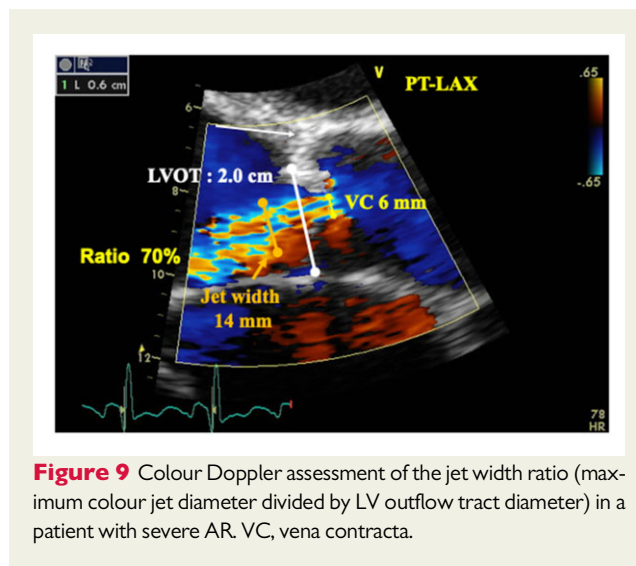


Figure 9 Colour Doppler assessment of the jet width ratio (maximum colour jet diameter divided by LV outflow tract diameter) in a patient with severe AR. VC, vena contracta.

unsatisfactory or inconclusive or when there is discrepancy between AR severity and clinical findings. These parameters should be interpreted according to the chronicity of AR and the LV remodeling. CMR may provide additional information about the mechanism of AR, the dimension of aorta, and the presence of local fibrosis. Either echocardiography or CMR is used for serial evaluation of aortic dimension, although the latter gives a more complete assessment of the thoracic aorta. CCT scanning is not routinely used but can be helpful in specific circumstances, especially in the preprocedural intervention planning (presence and extent of aortic valve and root calcifications, annular size assessment, presence of coronary artery disease, and dimension of the aorta).

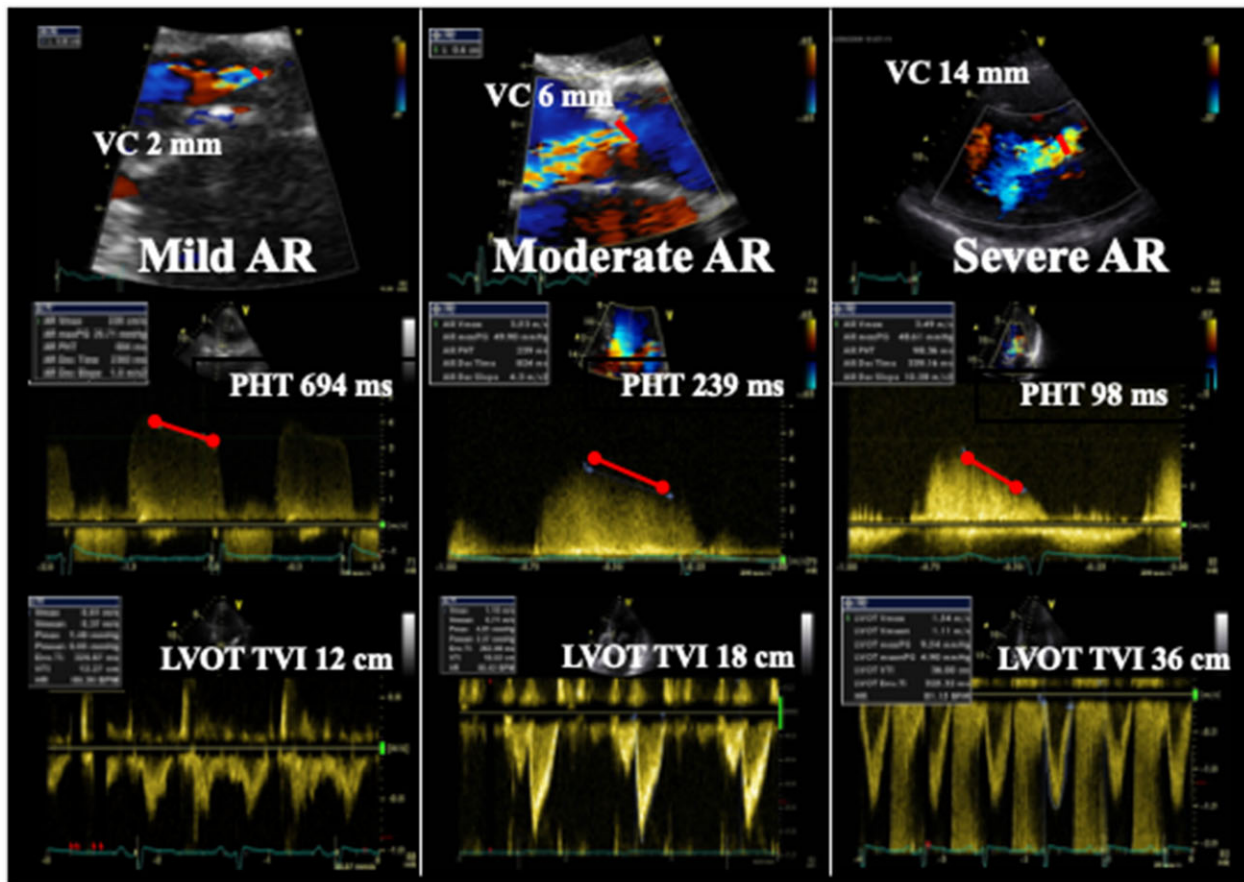


Figure 12 Three examples of AR are provided, all taken from the parasternal long-axis view using colour Doppler (top) and from the apical five-chamber view using continuous wave Doppler (mid). The vena contracta (VC) increases with the severity of AR. The pressure half-time (PHT) decreases with more severe AR whereas the left ventricular outflow time velocity (LVOT TVI) integral increases.

Intervention guidance

The incidence of valve sparing or repair decreases with the severity of dysfunction and is less than 50% in type III dysfunction. The presence and extent aortic calcifications (i.e. porcelain aorta) on CCT may limit the surgical approach by precluding clamping or cannulation. Three-dimensional TOE and CCT, using automated modelling, provide precise measurements of leaflet free edge, height, and coaptation height, which might help estimating the size of the graft during aortic valve surgery. A height <8 mm is predictive of recurrent AR after aortic valve surgery.⁴⁶

Suggested follow-up

Asymptomatic patients with mild AR, no LV dilatation and normal LVEF require echocardiographic evaluation every 2–3 years. In patients with asymptomatic severe AR and normal LV function and size, first echocardiographic monitoring should be performed 3–6 months after the initial diagnosis. After that, follow-up evaluation should be done when symptoms occur, or in asymptomatic patients every 1 year or every 3–6 months when LV size and function are close to thresholds for surgery or in cases of aortic dilatation. If the

aorta is not well imaged with echocardiography then a CMR or CCT should be performed, particularly if surgery is being considered. Either echocardiography or CMR are preferred for follow-up assessment of aortic dimension (no radiation exposure). Any increase >3 mm in aortic dimension should be validated by CMR or CCT.^{5,47}

Pulmonary regurgitation

A slight amount of PR has been reported in 40–78% of patients with normal pulmonary valves. Acquired mild to moderate PR is most often seen in patients with pulmonary hypertension with dilatation of the pulmonary artery. Severe PR is uncommon and usually observed in patients with anatomic abnormalities of the valve or after valvulotomy.⁴⁸ There are very few validated studies owing to the low prevalence rates and difficulties in imaging.

Anatomy and function of the pulmonary valve

The pulmonary valve is a three-leaflet structure, anatomically similar to the aortic valve (Figure 16). The pulmonic valve structure is

Table 7 Grading the severity of AR

AR severity classes ^a	Moderate			Severe
	Mild	Mild-to-moderate ^a (Grade 2 or 2+)	Moderate-to-severe ^a (Grade 3 or 3+)	
AR severity sub-classes^a	Mild (Grade 1 or 1+)	Mild-to-moderate^a (Grade 2 or 2+)	Moderate-to-severe^a (Grade 3 or 3+)	Severe (Grade 4 or 4+)
Qualitative parameters				
Aortic valve morphology	Normal/abnormal	Normal/abnormal	Abnormal/prolapse/moderate coaptation defect	Abnormal/ flail/large coaptation defect
Colour flow AR jet width ^b	Small in central jets	Intermediate	Large in central jet , variable in eccentric jets	Large in central jet , variable in eccentric jets
Color flow convergence	None or very small	Intermediate	Intermediate	Large
CW signal of AR jet	Incomplete/faint	Dense	Dense	Dense
Diastolic flow reversal in descending aorta ^c	Brief, proto-diastolic flow reversal	Intermediate	Holodiastolic flow reversal (end-diastolic velocity 10 to <20 cm/s)	Holodiastolic flow reversal (end-diastolic velocity ≥ 20 cm/s)
Diastolic flow reversal in abdominal aorta ^c	Absent	Absent	Present	Present
Semi-quantitative parameters				
VC width (mm)	<3	3–6	3–6	>6
Jet width/LVOT diameter (%)	<25	25–45	46–64	≥ 65
Jet CSALVOT CSA (%)	<5	5–20	21–59	≥ 60
Pressure half-time (ms) ^{c,d}	>500	Intermediate, 500 to 200	Intermediate, 500 to 200	<200
Quantitative parameters				
EROA (mm ²)	<10	10–19	20–29	≥ 30
R Vol (mL)	<30	30–44	45–59	≥ 60
RF (%)	<30	30–39	40–49	≥ 50
CMR parameters				
RF (%)	<30	30–39	40–49	≥ 50
Structural parameters				
LV size ^e	Usually normal	Normal or dilated	Usually dilated	Usually dilated

AR, aortic regurgitation; CSA, cross-sectional area; CW, cross-sectional area; LV, left atrium; EROA, effective regurgitant orifice area; LV, left ventricle; RF, regurgitant fraction; R Vol, regurgitant volume; VC, vena contracta.

In bold: specific signs for severe AR.

^aGrading of severity of AR classifies regurgitation as mild, moderate or severe, and sub-classifies the moderate regurgitation group into two subclasses: 'mild-to-moderate' (EROA of 10–19 mm² or a R Vol of 20–44 mL) and 'moderate-to-severe' (EROA of 20–29 mm² or a R Vol of 45–59 mL).

^bAt a Nyquist limit of 50–60 cm/s.

^cThese parameters are influenced by LV and aortic compliance. Hence, low transvalvular end-diastolic aorta to LV pressure gradient due to concomitant moderate/severe LV diastolic dysfunction may lead to false positive results. The high dependency of aortic flow reversal on aortic compliance considerably limits the utility of this parameter in the elderly population. These parameters are also influenced by chronotropy.

^dPressure half-time is shortened with increasing LV diastolic pressure, vasodilator therapy, and in patients with a dilated compliant aorta or lengthened in chronic AR.

^eUnless for other reasons, the LV size is usually normal in patients with mild AR. In acute severe AR, the LV size is often normal. Accepted cut-off values for non-significant LV enlargement: LV end-diastolic diameter <56 mm, LV end-diastolic volume <82 mL/m², LV end-systolic diameter <40 mm, LV end-systolic volume <30 mL/m².

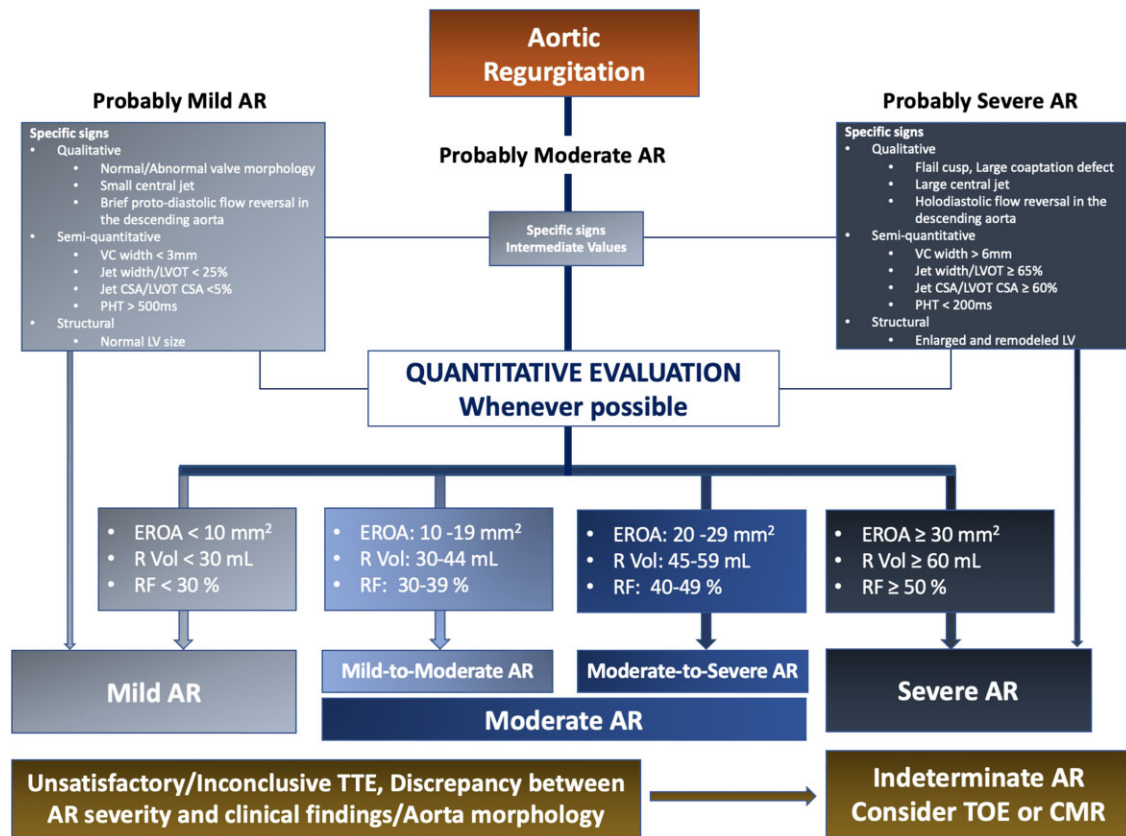


Figure 15 Algorithm for the assessment of AR severity. CSA, cross-sectional area; LVOT, left ventricular outflow tract; PHT, pressure half time; VC, vena contracta.

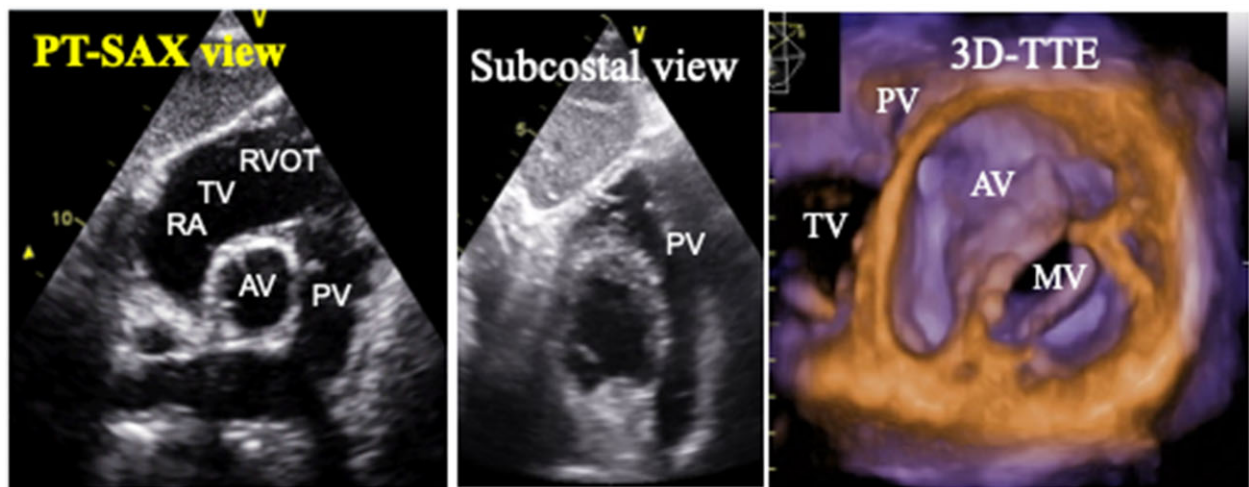


Figure 16 2D and 3D echo recordings of the pulmonic valve. PT-SAX, parasternal short-axis view.

for other regurgitations, the same limitations are applicable. A VC/pulmonary valve annulus ratio $\geq 50\%$ is an indicator of greater than mild PR. A ratio ≥ 0.7 is a marker of severe PR. The shape of the VC is complex in most cases. Though, the value of 3D echo has not yet been clearly defined,⁵⁶ a 3D VC area $> 0.45 \text{ cm}^2$ is in keeping with severe PR.

Pulsed Doppler. Theoretically, PW Doppler assessment of the forward and reverse flows at the pulmonary annulus and in the pulmonary artery can be used to calculate R Vol and RF. The pulmonary annulus should be measured carefully during early ejection (2–3 frames after the R wave on the ECG), just below the valve. This technique is subject to errors in measurement and is not well validated.⁵⁷

Continuous wave Doppler of the PR jet. The density of the CW signal provides a qualitative measure of regurgitation.⁵⁸ In mild PR, there is a slow deceleration of the jet velocity. A rapid deceleration rate with termination of flow in mid to late diastole (deceleration time $< 260 \text{ ms}$) is not specific but compatible with severe PR. In patients with congenital disease, a pressure half time $< 100 \text{ ms}$ yields good sensitivity and specificity for severe PR.⁵⁹ The pressure half time is dependent not only on PR severity but also on diastolic intrapulmonary pressures and on diastolic properties of the right ventricle, with shorter pressure half time when RV physiology is restrictive. A PR index < 0.77 (ratio of PR duration by CW Doppler to total diastolic time) is consistent with severe PR, although not specific.⁶⁰

Quantitative assessment

Anatomic orifice area

There is no clinically validated data on direct measurement of the anatomic orifice area.

The proximal isovelocity surface area method. In some patients, the flow convergence zone can be assessed (Figure 20). However, no studies have examined the clinical accuracy of this method in quantifying the severity of PR.

Doppler volumetric method. There is no clinically accepted method of quantifying PR using CW Doppler.

CMR quantification. CMR is currently the best method to quantitate PR and serially assess RV remodelling and function in patients with significant PR and congenital heart disease.⁶¹ It should be considered in most patients with suspected substantial PR unless echocardiographic findings are conclusive. Visual assessment of the degree of signal loss due to spin dephasing from the regurgitation can also be used but are less validated and provide only a qualitative assessment of PR severity. Both direct (phase-contrast technique) (Figure 20) and indirect methods of quantification can be used to calculate R Vol and RF. The direct method is however the preferred approach, with a co-axial through plane phase-contrast sequence planned just above the pulmonary valve. Quantification of the R Vol by comparing LV and RV stroke volumes is also possible but only valid in the absence of any other concomitant valvular regurgitation. The R Vol can also be calculated from the difference between RV total (using planimetry of short-axis cine images) and forward stroke volume across the aortic

valve (using phase-contrast velocity mapping) in the absence of significant TR. Considered RF threshold for assessing PR severity on CMR are: mild $< 20\%$, moderate 20–40%, and severe $> 40\%$.⁶¹ When available, CMR is the preferred method to assess the right ventricle due to its high accuracy and reproducibility.

Key point: CMR is an accurate tool for quantitative assessment of PR. The direct approach using the phase-contrast technique is the most reproducible with the advantage of not being affected by coexisting valvular regurgitation lesions. A RF $> 40\%$ indicates severe PR. When available, CMR is the preferred method for assessing RV size.

Consequences of PR

Evaluation of the size and function of the right ventricle in the absence of pulmonary hypertension provides indirect clues to the severity of PR. Evidence of RV dilatation is however not specific for severe PR, especially if observed in the context of pulmonary hypertension. Nevertheless, its absence suggests milder degree of PR or acute PR. Of note, dilatation can be observed in other conditions (non-specific) or may be absent in acute severe PR. As for TR, the RV function is classically evaluated on echocardiography by the RV volumes and the RV fractional area change. Three-dimensional echocardiography allows more accurate evaluation of RV ejection fraction (RVEF) than 2D. The utility of the other indices deriving from tissue Doppler or strain imaging has not been extensively examined in the context of PR unrelated to congenital heart disease. When available, CMR is the preferred method to assess the right atrium and right ventricle due to its high accuracy and reproducibility. CMR provides larger right atrial (RA)/RV volumes than echocardiography, due to different handling of trabeculations, which are excluded on echocardiography. Conversely, RVEF by 3D echocardiography is comparable to CMR.⁶ Indexed RV end-diastolic volume $> 160 \text{ mL/m}^2$ on CMR has been associated with a low likelihood of RV functional recovery after reintervention for severe residual PR in the context of corrected tetralogy of Fallot.⁶²

Role of exercise echocardiography

Latent RV dysfunction and impaired functional response to stress can be unmasked by exercise echocardiography. Except in the setting of congenital heart disease, the value of exercise testing in patients with PR has not been specifically examined.⁸

Integrating indices of severity

Echocardiographic assessment of PR includes integration of data from 2D/3D imaging of the pulmonary valve and right ventricle as well as Doppler measures of regurgitation severity (Table 8) (Figure 21). In the absence of extensive data on quantitation of PR, the experts strongly suggest to assess the PR severity by integrating information from all different approaches available and to corroborate each other. The simplest and most robust method is PR jet width and VC. CMR is the alternative method of choice and should be used in most cases when there is concern about clinically significant PR (i.e.

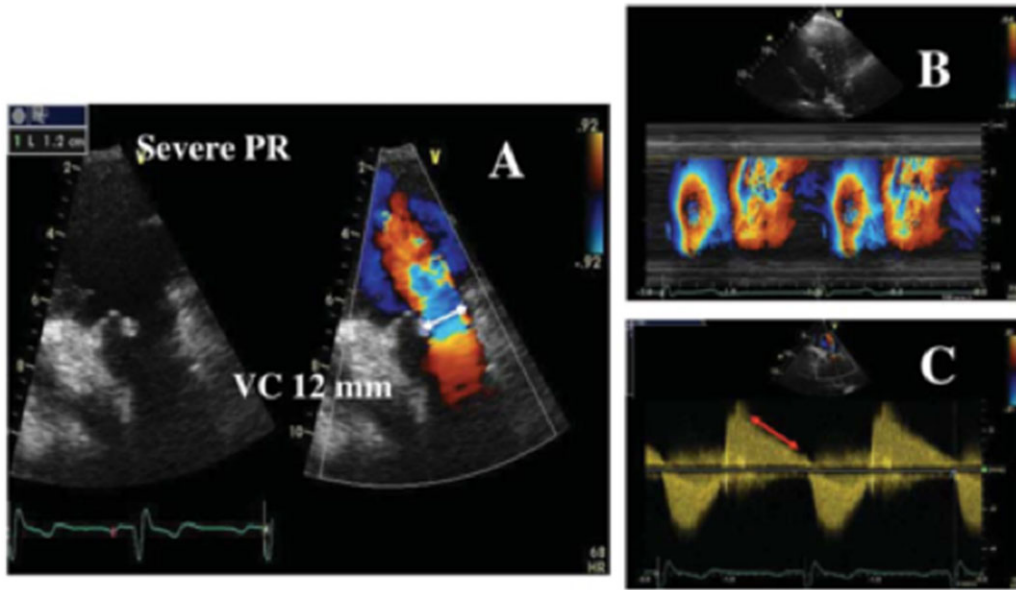


Figure 19 Example of a patient with a severe PR. (A) Left, complete lack of valve coaptation and right, measurement of the vena contracta width (VC); (B) colour-coded M-mode depicting the time-dependency of flow signal during the heart cycle; and (C) Continuous Doppler recording of PR showing a rapid flow deceleration during the diastole (red arrow) and increased systolic flow velocity (not related to concomitant pulmonary stenosis).

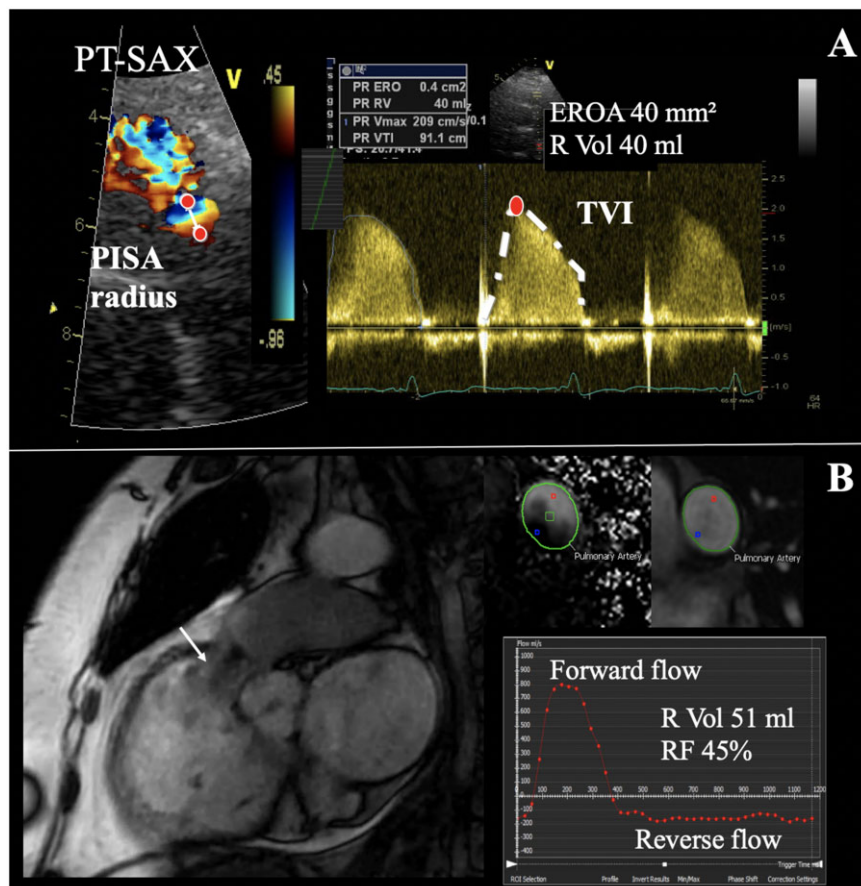


Figure 20 Assessment of PR severity by the PISA method (A) and the CMR phase-contrast method (direct method) (B). White arrow: extent of the signal loss on cine CMR. Phase-contrast velocity mapping and flow-time curves computing forward and reverse or backward flows. The reverse flow represents the directly measured volume of PR.

Table 8 Grading the severity of PR

PR severity classes	Mild	Moderate	Severe
Qualitative parameters			
Pulmonic valve morphology	Normal	Normal/Abnormal	Abnormal
Colour flow PR jet width ^a	Small, usually <10 mm in length with a narrow origin	Intermediate	Large, with a wide origin; may be brief in duration
Reversal flow in pulmonary artery branches	Absent	Absent	Present
CW signal of PR jet ^b	Faint/Slow deceleration	Dense/variable	Dense/steep deceleration, early termination of diastolic flow
Pulmonic vs. aortic flow by PW	Normal or slightly increased	Intermediate	Greatly increased
Semi-quantitative parameters			
VC width (mm)	Not defined	Not defined	Not defined
Deceleration time of the PR	Not defined	Not defined	<260 ms
Pressure half-time ^c	Not defined	Not defined	<100 ms
Jet width/annulus ratio	Not defined	Not defined	>65%
PR index ^d	Not defined	Not defined	<0.77
Quantitative parameters			
EROA (mm ²)	Not defined	Not defined	Not defined
R Vol (mL)	Not defined	Not defined	Not defined
RF (%)	<20	20–40	>40
CMR parameters, RF (%)	<20	20–40	>40
Structural parameters, RV size ^e	Usually normal	Normal or dilated	Usually dilated

CW, continuous-wave; EROA, effective regurgitant orifice area; PR, pulmonic regurgitation; PW, pulse wave; R Vol, regurgitant volume; RV, right ventricle; VC: vena contracta. In bold: specific signs for severe PR.

^aAt a Nyquist limit of 50–60 cm/s.

^bSteep deceleration is not specific for severe PR.

^cPressure half time is shortened with increasing RV diastolic pressure.

^dPR index: ratio of PR duration by CW Doppler to total diastolic time.

^eUnless for other reasons, the RV size is usually normal in patients with mild PR. In acute severe PR, the RV size is often normal. Accepted cut-off values for non-significant RV enlargement (measurements obtained from the apical 4-chamber view): Mid RV dimension ≤ 33 mm, RV end-diastolic area ≤ 28 cm², RV end-systolic area ≤ 16 cm², RV fractional area change $>32\%$, maximal.

only moderate PR with dilating RV) unless the echocardiographic findings are conclusive. CCT scan can be helpful in specific circumstances to complement echocardiography, especially in the preprocedural intervention planning.

Intervention guidance

Intervention guidance mainly refer to pulmonary valve replacement either surgically or percutaneously.⁶³ It should be considered in patients with severe PR and symptoms of evidence of RV decompensation.

Suggested follow-up

As for other valvular regurgitation, the follow-up of patients with PR depends on the aetiology and severity of PR, the size and function of the right ventricle, and the associated diseases. Although information is limited, careful follow-up should be organized in patients with moderate to severe PR.⁵

Mitral regurgitation

MR is increasingly prevalent in Europe despite the reduced incidence of rheumatic disease. Non-invasive imaging plays a key role in the assessment and management of patients with MR.⁵

Anatomy and function of the mitral valve

Normal MV function depends on optimal function of the complex interaction between the mitral leaflets, the subvalvular apparatus (chordae tendineae and papillary muscles), the mitral annulus, the left atrium and the left ventricle. An abnormality in any one of these components can cause the valve to leak.⁶⁴ The normal MV has two leaflets; the posterior attached to the two-thirds of the annular plane and the anterior, to the remaining one-third. They are each divided into three scallops: A1, A2, A3 and P1, P2, P3. A1 and P1 correspond to the external, anterolateral portion of their respective leaflet, close to the antero-lateral commissure and the left atrial appendage. On the opposite side, A3 and P3 are internal, close the postero-medial commissure and the tricuspid annulus (Figure 22). Normal leaflet

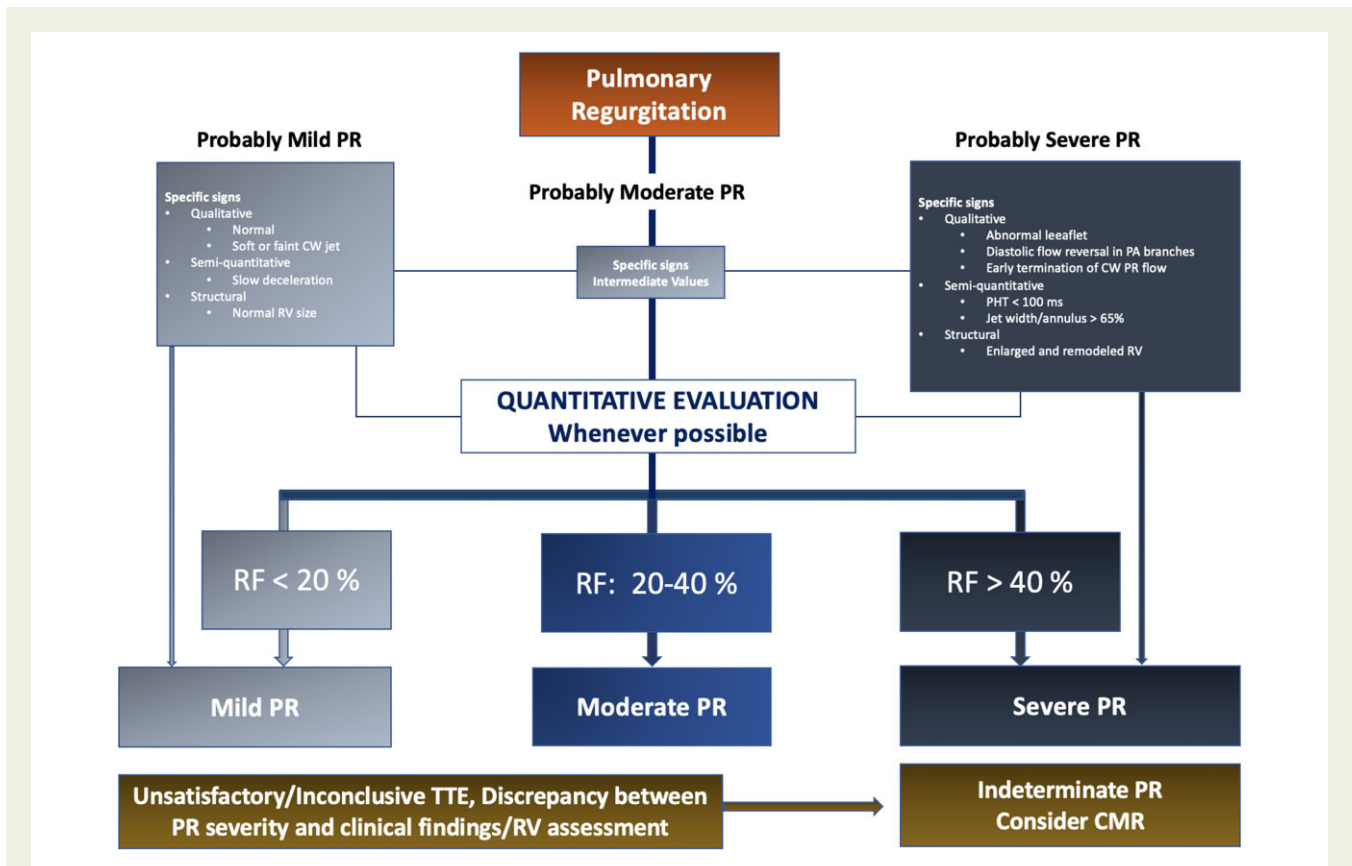
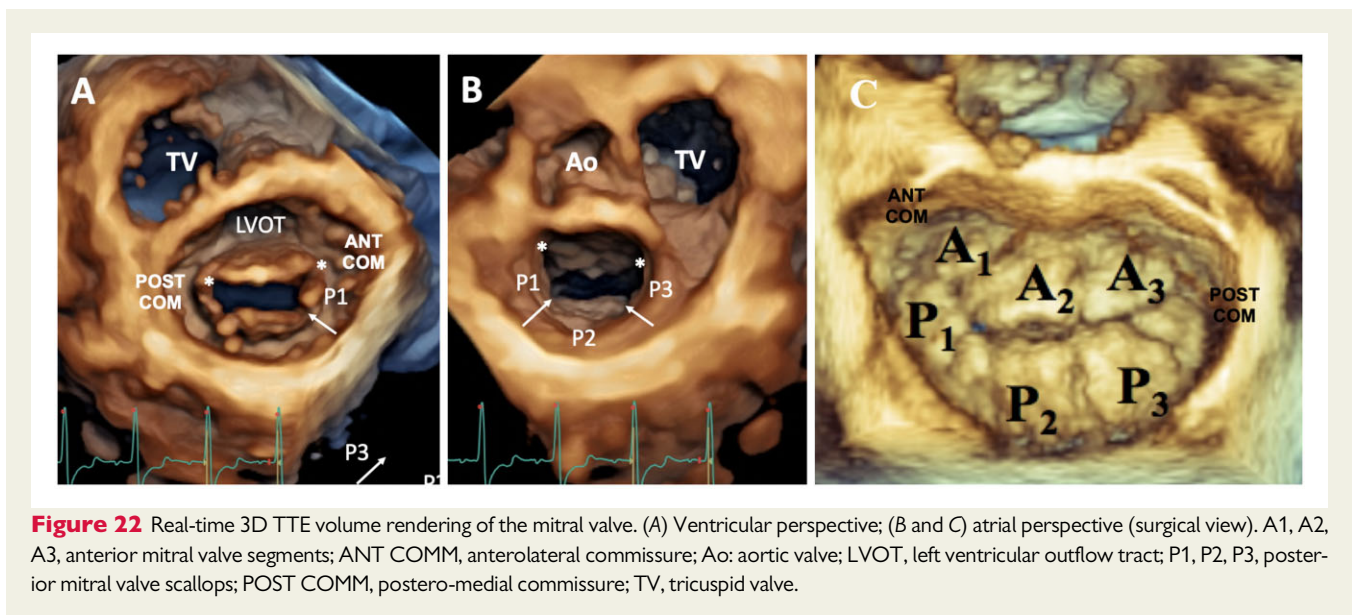


Figure 21 Algorithm for the assessment of PR severity. CW, continuous wave; pressure half time.



Volumetric datasets acquired during 3D imaging provide visualization of the valve from any angle or in any plane (Figures 22, 27, and 28). The TTE MV datasets can be acquired in either the

parasternal or apical views. The 'en face' view of the valve from the atrial perspective is identical to the surgical view in the operating room.^{2,3,6} In this view, by displaying the aortic valve at the

Table 9 Pathophysiological classification of MR

	Leaflet structure	Pathophysiology	Aetiology	Imaging	Transcatheter treatment
Primary	<ul style="list-style-type: none"> Abnormal 	<ul style="list-style-type: none"> Lack of leaflet coaptation due to intrinsic changes, excessive mobility, or perforation 	<ul style="list-style-type: none"> Myxomatous disease Rheumatic Endocarditis Congenital Toxic Ischaemic papillary muscle fibrosis/elongation 	<ul style="list-style-type: none"> According to the aetiology Description of the aetiology, lesions and dysfunction 	<ul style="list-style-type: none"> Leaflet devices Percutaneous TV replacement
Secondary					
A. Atrial	<ul style="list-style-type: none"> Normal 	<p>LA enlargement and dysfunction leading to significant isolated annulus dilation; LV often normal</p> <p>Global LV enlargement/dysfunction leading to significant leaflet tethering and annulus dilation</p>	<ul style="list-style-type: none"> Atrial fibrillation/flutter 	<ul style="list-style-type: none"> Severe LA dilatation/remodelling LV basal diameter may appear abnormal, despite normal LV volume Leaflet tethering is absent or minimal 	
B. Ventricular	<ul style="list-style-type: none"> Considered normal 	<p>Regional LV enlargement/dysfunction leading to significant leaflet tethering and annulus dilation</p> <p>Conduction disorders (left bundle branch block/pacemaker-induced dyssynchrony)</p>	<ul style="list-style-type: none"> Previous large anterior myocardial scar or multiple infarction Non-ischaemic dilated cardiomyopathy Previous infero-posterior myocardial infarction <p>Papillary muscles dyssynchrony</p>	<ul style="list-style-type: none"> Mostly symmetric tethering, LV global remodelling/dysfunction, annular dilation/dysfunction Mostly asymmetric tethering, annular dilation/dysfunction Asymmetric tethering due to local/regional LV remodelling, and some degree of annular dilation/dysfunction 	<ul style="list-style-type: none"> Leaflet devices Percutaneous TV replacement
				<ul style="list-style-type: none"> Dyssynchrony between papillary muscles and wall motion 	<ul style="list-style-type: none"> Cardiac resynchronisation therapy

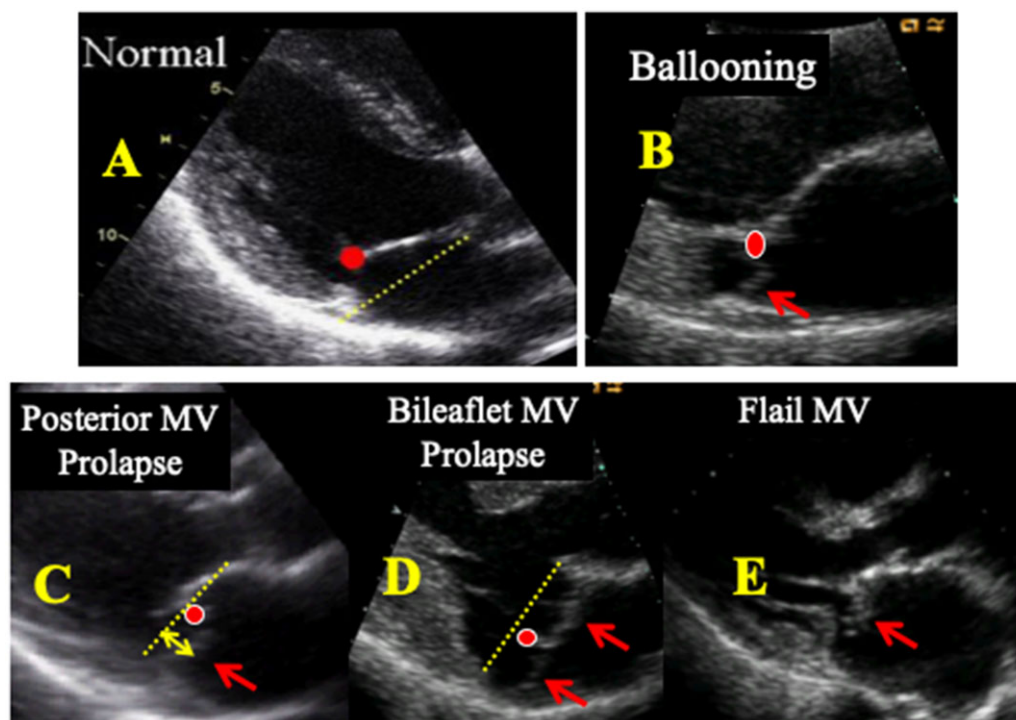


Figure 24 (A) In normal mitral valve, the coaptation (red point) occurs beyond the mitral annular plane (line). (B) Billowing mitral valve is observed when a part of the mitral valve body protrudes into the left atrium (arrow). (C and D) Mitral valve prolapse is defined as abnormal systolic displacement of 1 (C: posterior prolapse) or both leaflets into the left atrium below the annular (D: bileaflet prolapse). (E) Flail of the anterior leaflet (arrow).

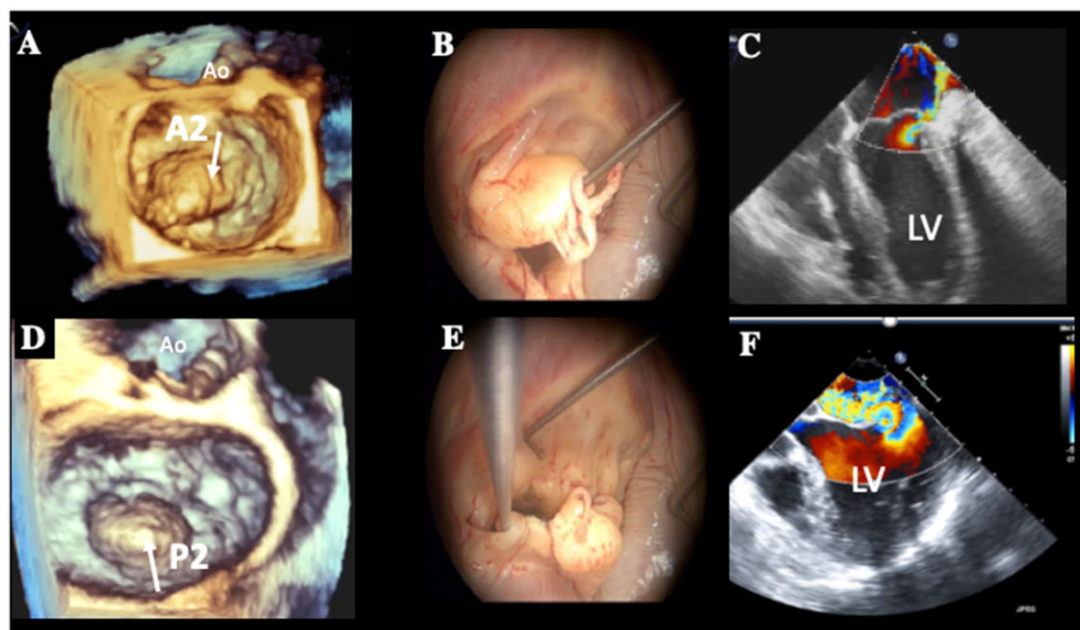


Figure 25 Examples of anterior (top panels) and posterior prolapses (bottom panels). (A) Flail of A2 (arrow) with (B) the corresponding intraoperative image and (C) the colour Doppler showing the direction of the jet towards the lateral wall of the left atrium. (D) Flail of P2 (arrow) with (E) the corresponding intraoperative image and (F) the colour Doppler showing the direction of the jet towards the interatrial septum.

intensity (jet density) of the CW envelope of the MR jet can be a qualitative guide to MR severity. A dense MR signal with a full envelope indicates more severe MR than a faint signal (Figure 33). The CW Doppler envelope may be truncated (notched) with a triangular contour and an early peak velocity (blunt). This indicates elevated LA pressure or a prominent regurgitant pressure wave in the LA due to severe MR. In eccentric MR, it may be difficult to record the full CW envelope of the jet because of its eccentricity, while the signal intensity shows dense features.^{1–3}

Key point: The CW Doppler density of the MR jet is a qualitative parameter of MR severity.

Quantitative assessment

Anatomic regurgitant orifice area. The AROA may be measured directly by planimetry using 2D/3D echocardiography, CT or CMR. Cut-offs of severity are, however, less well defined than for EROA and its clinical use remains limited.

The proximal isovelocity surface area method. The flow convergence method is the most valuable quantitative approach whenever feasible⁸¹ (Figure 34). The apical four-chamber view is classically used for optimal visualization of the PISA. However, the parasternal long- or short-axis view is often useful for visualization of the PISA in case of anterior MV prolapse. The area of interest is optimized by lowering imaging depth and reducing the Nyquist limit to approximately 15–40 cm/s. The radius of the PISA is measured at mid-systole using the first aliasing from a single-frame image. R Vol and EROA are obtained using the standard formulas (Figure 35). Qualitatively, the presence of flow convergence at a Nyquist limit of 50–60 cm/s should alert to the presence of severe MR.^{1–3}

The PISA method faces several advantages and limitations (Figures 36–39).^{1–3,81} Colour M-mode is important to assess the variation of MR flow and the related PISA during systole (Figure 36). The PISA radius is most frequently constant in patients with rheumatic MR. It frequently increases progressively with a maximum during the second half of systole in patients with MV prolapse. In the presence of secondary MR, there is a dynamic variation of ROA with early and late systolic peaks and a mid-systolic decrease. These changes reflect the phasic variation in transmitral pressure that acts to close the mitral leaflets more effectively when pressure reaches its peak in mid-systole.⁸² The PISA method assumes hemispheric symmetry of the velocity distribution proximal to the circular regurgitant lesion, which may not hold for eccentric jets, multiple jets, or complex or elliptical regurgitant orifices. Practically, the geometry of the PISA varies, depending on the shape of the orifice and MV leaflets surrounding the orifice. In secondary MR, the PISA might look like an ellipsoidal shape and two separate MR jets originating from the medial and lateral sides of the coaptation line can be observed on 2D echo. When the shape of the flow convergence zone is not a hemisphere, the PISA method may underestimate the degree of secondary MR, particularly when the ratio of long-axis length to short-axis length of the 3D regurgitant orifice is >1.5 .⁸³ When the EROA is calculated with the hemispheric assumption (using the vertical PISA), the horizontal length of PISA is ignored. In primary MR, the shape of the PISA is rounder, which

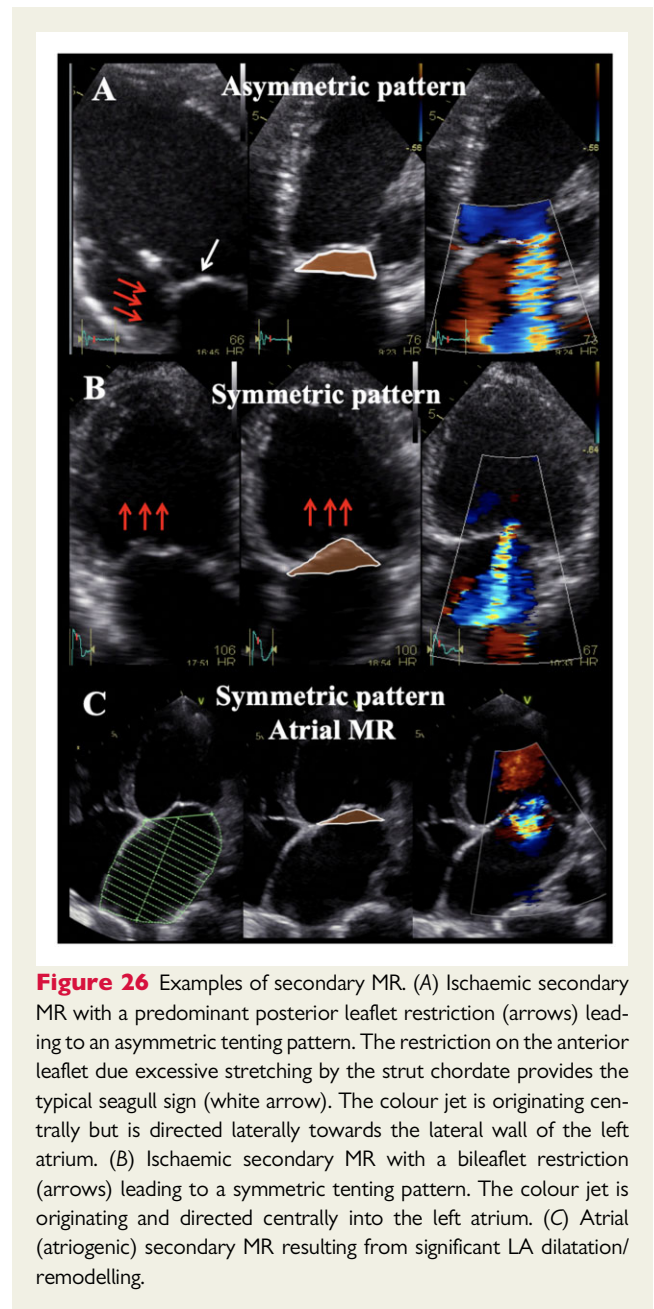


Figure 26 Examples of secondary MR. (A) Ischaemic secondary MR with a predominant posterior leaflet restriction (arrows) leading to an asymmetric tenting pattern. The restriction on the anterior leaflet due to excessive stretching by the strut chordate provides the typical seagull sign (white arrow). The colour jet is originating centrally but is directed laterally towards the lateral wall of the left atrium. (B) Ischaemic secondary MR with a bileaflet restriction (arrows) leading to a symmetric tenting pattern. The colour jet is originating and directed centrally into the left atrium. (C) Atrial (atriogenic) secondary MR resulting from significant LA dilatation/remodelling.

minimizes the risk of EROA underestimation (Figure 39A). These findings could, in part, explain why the threshold used to define a severe secondary MR is inferior to that used for primary MR. EROA is the most robust parameter as it represents a marker of lesion severity. A large EROA can lead to a large regurgitant kinetic energy (large RVol) but also to more potential energy with low RVol in case of high LA pressure. The R Vol may also be lower in low flow states, which is often present in patients with secondary MR. In such conditions, a moderate R Vol may correspond to a severe RF.

In secondary MR, the EROA is expected to increase in proportion to increasing LV size as a result of leaflet tethering and annular dilatation. In proportionate MR, the estimated degree of MR is proportionate to the size of the left ventricle. In disproportionate MR, the degree of MR is unexpectedly large compared with the LV size, and

so the symptoms are driven by MR and the outcome is improved after transcatheter MV repair.^{84–86} Grading the severity of secondary MR should be performed under optimal medical therapy.

Grading of severity of MR using semi-quantitative and quantitative parameters classifies regurgitation in three main classes: mild, moderate, or severe, and sub-classifies the moderate regurgitation class into 'mild-to-moderate' (EROA of 20–29 mm² or a R Vol of 30–44 mL) and 'moderate-to-severe' (EROA of 30–39 mm² or a R Vol of 45–59 mL). The mild-to-moderate sub-class is also labelled as 'Moderate' or 'Grade 2' or '2+' and the moderate-to-severe sub-class also labelled as 'moderately severe' or 'Grade 3' or '3+' in grading schemes of other medical societies or group of experts.^{1–3,5} Quantitatively, MR is considered severe if EROA is ≥ 40 mm² and/or R Vol ≥ 60 mL. The cut-off values of EROA and R Vol at which MR has a significant impact on outcomes may be lower in secondary MR, especially in case of an elliptical regurgitant orifice or in low flow conditions (EROA ≥ 30 mm² and/or R Vol ≥ 45 mL). In secondary MR, even lower thresholds may be associated with poor prognosis (EROA ≥ 20 mm² and/or R Vol ≥ 30 mL)^{87,88} but these criteria are not sufficient to refer patients for MV intervention.^{84–86} In such conditions it is preferable to put more weight on the RF than of EROA or R Vol to grade MR severity. The RF is calculated by dividing the R Vol by the total LV stroke volume. The total stroke volume can be calculated as the difference between LV end-diastolic volume minus LV end-systolic volume measured by 2D echocardiography or preferably by 3D echocardiography. The total LV stroke volume can also be calculated as the sum of R Vol and systemic stroke volume [obtained by multiplying the LVOT area $-\pi d^2/4 = 0.785 d^2$, where d is the LVOT diameter—by LVOT time-velocity integral (TVI)]. A RF $\geq 50\%$ indicates severe MR, regardless of the EROA or R Vol.

Key point: When feasible, the PISA method is highly valuable to quantitate the severity of MR. It can be used in both central and eccentric jets. An EROA ≥ 40 mm² and/or a R Vol ≥ 60 mL indicates severe MR. In secondary MR, the cut-offs of EROA and R Vol, beyond which MR portends a significant impact on outcomes and thus requires intervention, may be lower (EROA ≥ 30 mm² and/or R Vol ≥ 45 mL; i.e. consistent with moderate-to-severe MR but with generally RF $\geq 50\%$, consistent with severe MR), especially in case of an elliptical regurgitant orifice and/or in low flow conditions.

Doppler volumetric method. Quantitative PW Doppler method can be used as an additive or alternative method, especially when the PISA and the VC are not accurate or not applicable (Figure 40). This approach is time consuming and is associated with several drawbacks.^{1–4} Briefly, mitral R Vol is obtained by calculating the difference between the total stroke volume (product of mitral annulus area $-\pi d^2/4 = 0.785 d^2$, where d is the mitral annulus diameter—and mitral inflow TVI) and systemic stroke volume (obtained by multiplying the LVOT area $-\pi d^2/4 = 0.785 d^2$, where d is the LVOT diameter—by LVOT TVI). This calculation is inaccurate and so should not be applied in the presence of significant AR.

Key point: The Doppler volumetric method is a time-consuming approach and should not be considered as a first line method to quantify MR severity. This method can however be used when PISA is not feasible or uncertain.

CMR quantification. CMR is the alternative method of choice to quantify the R Vol and RF. The preferred approach relies on the indirect calculation of the R Vol from the difference between LV total (using planimetry of short-axis cine images) and forward stroke volume across the aortic valve (using phase-contrast velocity mapping) (Figure 34). The RF is calculated by dividing the R Vol by the LV stroke volume. This method is highly reproducible and considered robust as it is not affected by the direction or eccentricity of the regurgitant jet, is not affected by the presence of AR and makes no haemodynamic or LV geometry assumptions. As a second choice, quantification of the R Vol can be obtained by comparing LV and RV stroke volumes. The phase-contrast technique with direct assessment of flow at the level of the MV is less accurate and rarely used for this purpose due to the significant motion of the MV plane during systole.^{1,89} The RF is calculated by dividing the R Vol by the LV stroke volume for the two first methods and by the mitral inflow stroke volume for the direct approach. Reference ranges for MR quantification are yet to be as firmly established as those for echocardiography. A threshold of R Vol >55 mL or RF $>40\%$ was found to be associated with progression to symptoms and need for MV surgery in patients with primary MR.⁹⁰ There are few comparative studies between echocardiography and CMR. The majority of them showed modest agreement in assessing the severity of MR, particularly in secondary MR.⁹¹ Compared to CMR, echocardiographic grading of MR severity tends to be higher and 2D-PISA-derived R Vol larger.⁹² This is because CMR calculates mitral regurgitation across systole whereas echo considers a single time point. A significant discrepancy is seen in 10–20% of patients, which requires further assessment by TOE or invasive means.⁹² We propose that a CMR RF of $\geq 50\%$ is considered as severe MR, with further work required to validate severity thresholds.⁹⁰

Key point: Although there is only modest agreement between MR severity by CMR versus quantitative echocardiography and that large studies on prognostic value of CMR-quantitated MR are lacking, CMR is the alternative or corroborating method of choice for quantitative assessment of MR. The indirect approach by comparing ventricular stroke volume to aortic forward flow is the most reproducible with the advantage of not being affected by coexisting AR, and the direction or eccentricity of the regurgitant jet. A RF $\geq 50\%$ indicates severe MR.

Consequences of MR

The presence of severe primary MR has significant haemodynamic effects, primarily on the left ventricle and LA.⁵ In acute primary MR, the left ventricle is classically not enlarged while the LVEF usually increases in response to the increased preload. In the chronic compensated phase (the patient could be asymptomatic), the forward

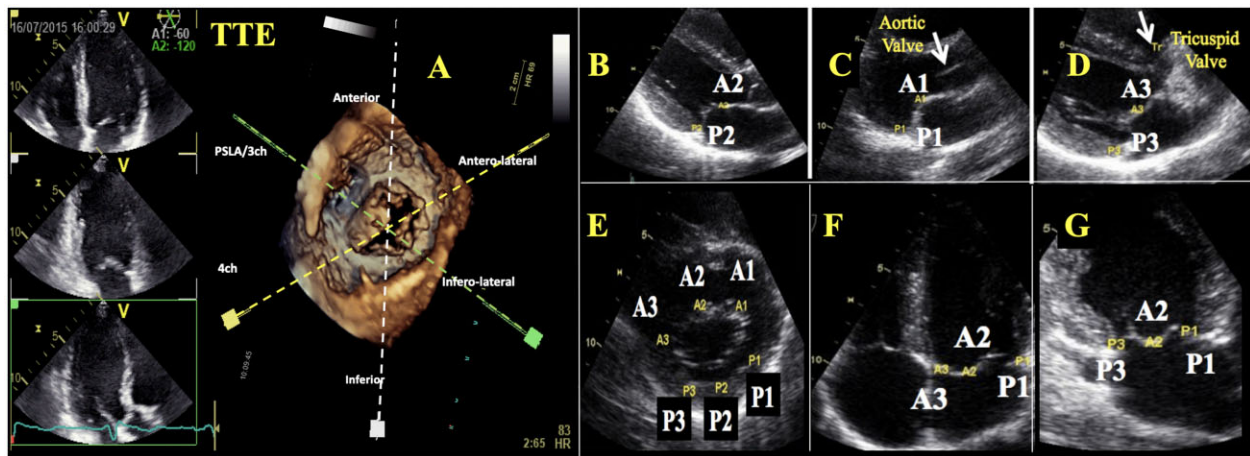


Figure 27 Mitral valvular segmentation analysis with 2D TTE. (A) 3D TTE cut planes across the mitral valve. (B) 2D TTE parasternal long-axis view depicting A2 and P2; (C) A1 and P1 (tilting of the probe towards the aortic valve); (D) A3 and P3 [tilting of the probe towards the tricuspid (Tr) valve]; (E) 2D TTE parasternal short-axis view depicting each scallop; (F) four-chamber view depicting A3, A2, and P1; (G) bicommissural view.

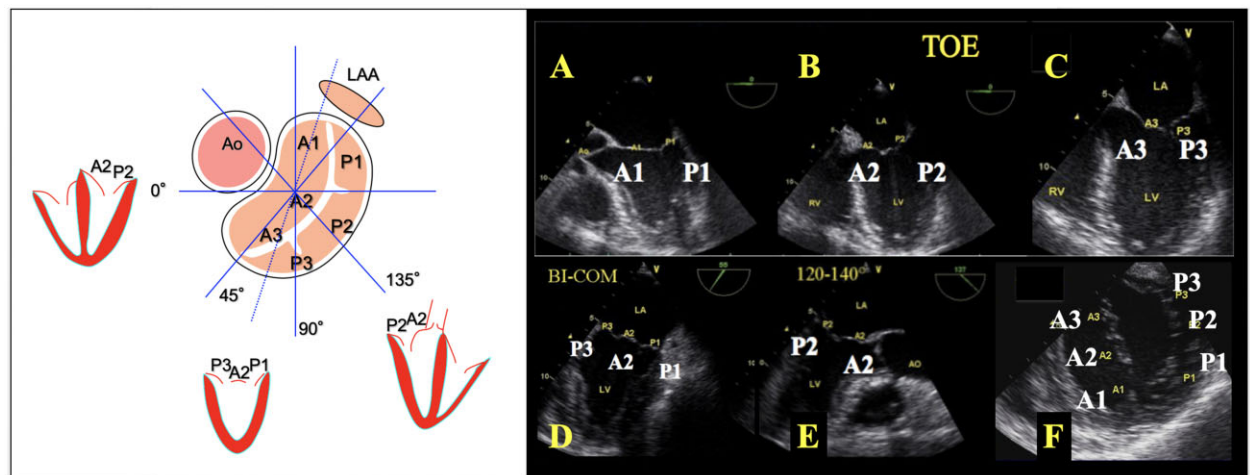


Figure 28 Mitral valvular segmentation analysis with 2D TOE. (A–C) Views obtained at 0°: (A) five-chamber view depicting A1 and P1, four-chamber view depicting A2 and P2; downward four-chamber view depicting A3 and P3; (D) bicommissural view; (E) view at 120° visualizing A2 and P2; and (F) transgastric view at 0° depicting each scallop.

stroke volume is maintained through an increase in LVEF. Such patients typically have LVEF >65%. In this phase, the LA remodels and dilates but the LA pressure is often normal. In the chronic decompensated phase (the patients could still be asymptomatic or may fail to recognize deterioration in their clinical status), the forward stroke volume decreases and the LA pressure increases significantly. The LV contractility can thus decrease silently and irreversibly. However, the LVEF may still be in the low normal range despite the presence of significant myocardial dysfunction. Hence, dilatation is sensitive for chronic significant MR, while normal size almost excludes severe chronic MR. However, dilatation can be observed in other conditions or may be absent in acute severe MR and is,

therefore, a non-specific finding. Three-dimensional echocardiography and CMR allows more accurate evaluation of LV volumes and EF than 2D. Strain imaging (GLS < -18%) may be helpful in identifying subclinical LV dysfunction in the setting of serial echocardiograms and may help determine appropriate follow-up intervals or timing for intervention.⁹³ The excess regurgitant blood entering the LA may induce a progressive LA remodelling, a rise in pulmonary arterial pressure and a significant tricuspid annular dilatation. Secondary MR has a different physiology, as it is the consequence of an initial ventricular/annular disease. The LV and LA dilatation are in excess to the degree of MR. The LA pressure is often elevated despite lower R Vol than in primary MR. Therefore, the assessment of LV size and systolic

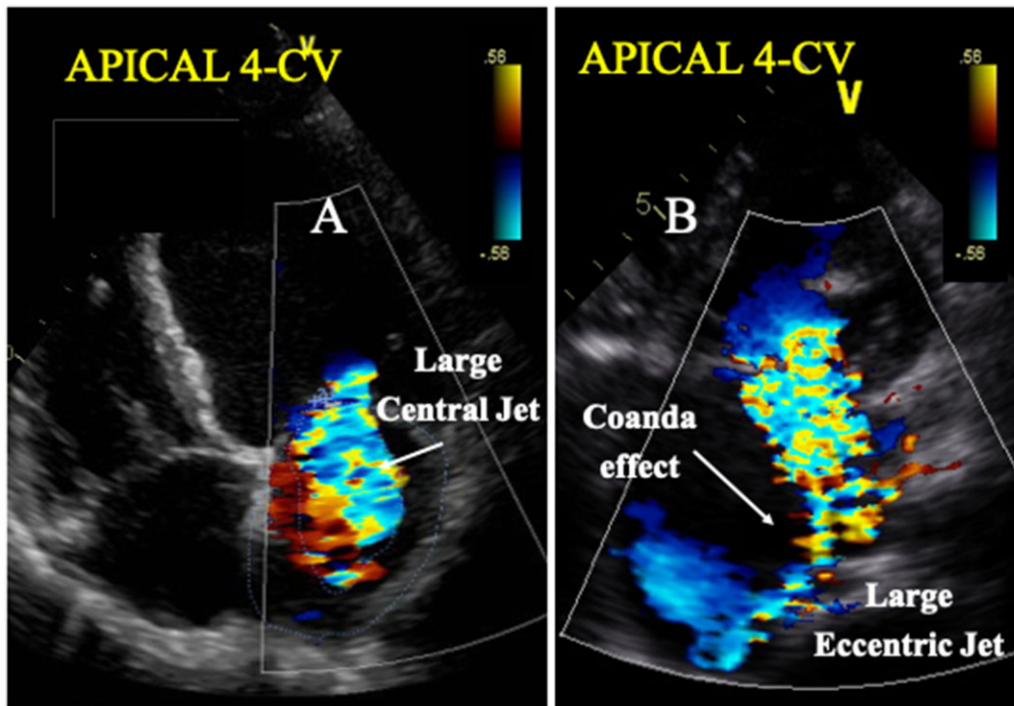


Figure 30 Visual assessment of mitral regurgitant jet using colour-flow imaging. Examples of two patients with severe mitral regurgitation (A) large central jet and (B) large eccentric jet with a clear Coanda effect. CV, four-chamber view.

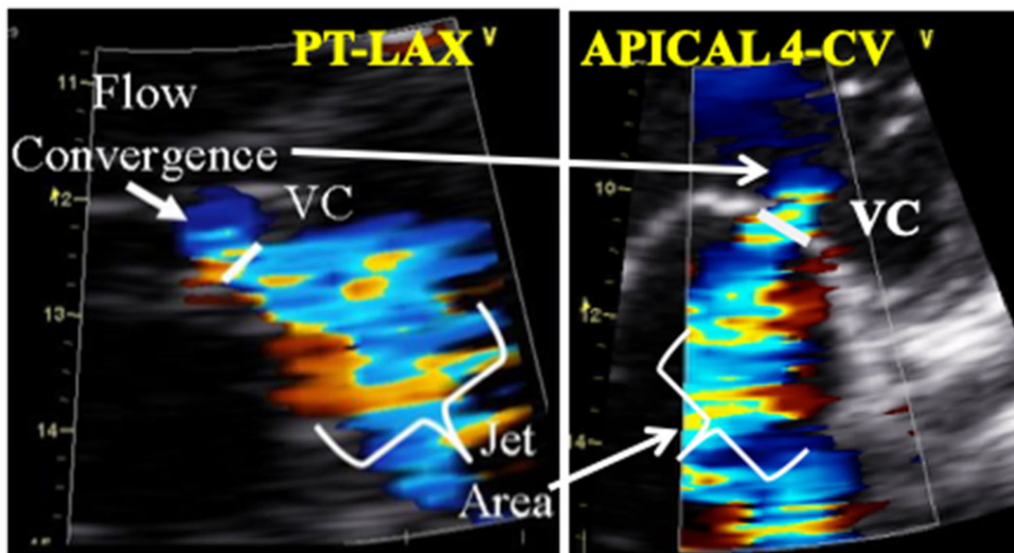


Figure 31 Semi-quantitative assessment of MR severity using the vena contracta width (VC). The three components of the regurgitant jet (flow convergence zone, vena contracta, jet turbulence) are obtained. CV, chamber view; PT-LAX, parasternal long-axis view.

Integrating indices of severity

Echocardiographic assessment of MR includes integration of data from 2D/3D imaging of the valve and ventricle as well as Doppler

measures of regurgitation severity (Table 10; Figure 41). Effort should be made to quantify the degree of regurgitation, except in the presence of mild or obviously severe MR using specific signs. Both the VC

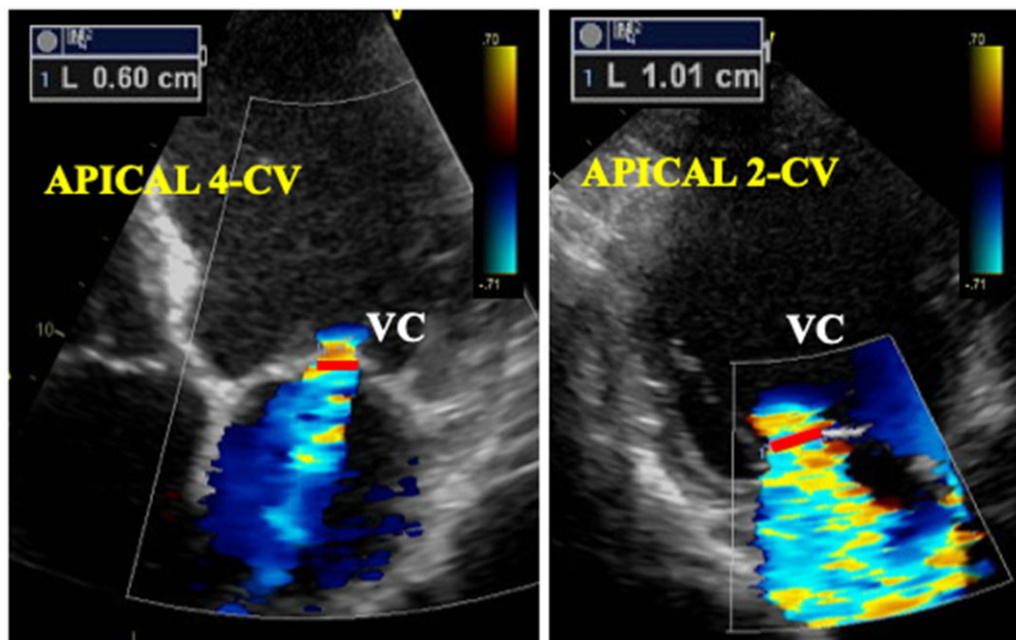


Figure 32 Semi-quantitative assessment of MR severity using the vena contracta width (VC) obtained from the apical four-chamber and two-chamber views (CV) in a patient with ischaemic functional MR. The mean vena contracta is calculated ($6 + 10/2 = 8$ mm).

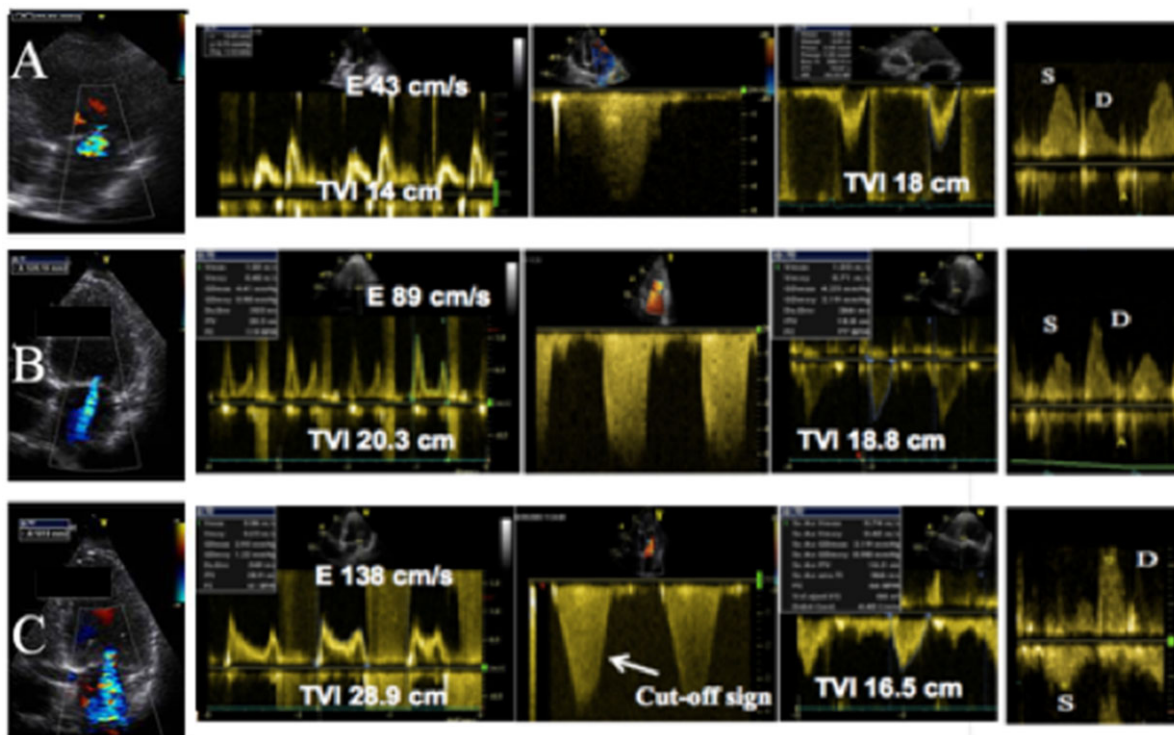


Figure 33 Three examples of various degrees of MR, mild (A), moderate (B), and severe (C) are provided. The regurgitant jet area (RJA) as well as the mitral E wave velocity increase with the severity of MR. In severe MR, the continuous wave Doppler signal of the regurgitant jet is truncated, triangular and intense. Notching of the continuous wave envelope (cut-off sign) can occur in severe MR. D, diastolic wave; Mild MR, normal pulmonary vein flow pattern; Moderate MR, blunt forward systolic pulmonary vein flow in a patient with moderate MR; S, systolic wave; Severe MR, reversed systolic pulmonary flow in a patient with severe MR; TVI, time-velocity integral.

extent of calcification of the TV and subvalvular apparatus to aid pre-procedural planning.²⁶

In secondary TR, a tenting area, measured in mid-systole from the apical four-chamber view, $>1 \text{ cm}^2$ has been shown to be associated with severe TR.¹¹² The tricuspid annulus forms a non-planar structure with an elliptical saddle-shaped pattern, having two high points (oriented superiorly towards the right atrium) and two low points (oriented inferiorly towards the right ventricle that is best seen in mid-systole).¹¹³ Normal TV annulus diameter in adults is $28 \pm 5 \text{ mm}$ in the four-chamber view. Significant tricuspid annular dilatation is defined by a diastolic diameter of $\geq 21 \text{ mm/m}^2$ ($\geq 40 \text{ mm}$). The normal contraction (decrease in annular area in systole) of the tricuspid annulus is 25%. These cut-offs are still derived from 2D echocardiography.

Assessment of TR severity

Semi-quantitative methods

Colour flow Doppler imaging. Grading the severity of TR is in principle similar to MR. However, because standards for determining the TR severity are less robust than for MR, the algorithms for relating colour flow-derived parameters to TR severity are less well developed. Colour-flow imaging is useful to recognize small jets, but the assessment of larger TR jets has important limitations.¹¹⁴ Indeed, flow jets that are directed centrally into the right atrium generally appear larger than eccentric wall-impinging jets with similar or worse severity. Basically, multiple windows (apical four-chamber, parasternal long and short-axis views, and sub-costal view) are required to assess TR severity by colour-flow analysis. The general assumption is that larger colour jets that extend deep into the RA represent more TR than smaller thin jets that are seen just beyond the tricuspid leaflets. As for MR, this method is a source of many errors and is limited by several technical and haemodynamic factors^{1-4,115} and on that basis colour flow imaging is not appropriate for assessing TR severity (Figure 46). Nevertheless, the detection of a large eccentric jet adhering, swirling and reaching the posterior wall of the right atrium is in favour of severe TR. Conversely, small thin central jets usually indicate mild TR.

Key point: The colour flow area of the regurgitant jet is not appropriate to quantify the severity of TR. Colour flow imaging should only be used for diagnosing TR. A more quantitative approach is required when more than a small central TR jet is observed.

Vena contracta width. The VC width of the TR is typically imaged in the apical four-chamber view using the same settings as for MR (Figure 47). Averaging measurements over at least two–three beats needs to be performed. A VC width $>7 \text{ mm}$ is in favour of severe while a width $<6 \text{ mm}$ may be either mild or moderate TR.⁵⁷ The geometry of the regurgitant orifice of secondary TR is usually more complex than for MR and rarely circular or ovale, given its trileaflet anatomy.¹¹⁶ If available, use of 3D echo formats such as biplane imaging to assess the VC in simultaneous orthogonal views or 3D zoom colour flow Doppler can aid in better identifying the regurgitant orifice morphology. The VC area can then be measured by manual

planimetry. A poor correlation exists between the 2D VC width and the 3D VC area, the latter being well correlated with EROA. The maximal VC diameter by 3D echocardiography is usually greater than the 2D measurement. This could underline the poor accuracy of the 2D VC width in eccentric jets. Although prognostic data is still lacking, 3D VC area is increasingly used with a suggested threshold for severe TR of $>40 \text{ mm}^2$.¹¹⁷

Key point: When feasible, the measurement of the VC is the best method to quantify TR. A VC width $>7 \text{ mm}$ defines severe TR. Lower values are difficult to interpret. In case of multiple jets, the respective values of the VC width are not additive. The assessment of the VC by 3D echo can be helpful to better delineate the regurgitant orifice morphology and grade the TR severity.

Anterograde velocity of tricuspid inflow. Similar to MR, the severity of TR will affect the early tricuspid diastolic filling (E velocity). In the absence of tricuspid stenosis, the peak E velocity increases in proportion to the degree of TR. Tricuspid inflow Doppler tracings are obtained at the tricuspid leaflet tips. A peak E velocity $>1 \text{ m/s}$ suggests severe TR (Figure 48).^{1,2,4}

Hepatic vein flow. Pulsed Doppler evaluation of hepatic venous flow pattern is another aid for grading TR. In normal individuals, the pattern of flow velocity consists of anterograde systolic, transient flow reversal as the TV annulus recoils at the end of systole, anterograde diastolic and a retrograde A wave caused by atrial contraction. Such hepatic flow patterns are affected by respiration. With increasing severity of TR, there is a decrease in hepatic vein systolic velocity. In severe TR, systolic flow reversal occurs (Figure 49). The sensitivity of flow reversal for severe TR is 80%.¹¹⁴ Thus, the absence of systolic flow reversal does not rule out severe TR. Blunted systolic hepatic vein flow can be observed in case of abnormal right atrial and RV compliance, atrial fibrillation and elevated right atrial pressure from any cause.¹¹⁸ Blunting of hepatic flow may thus lack of specificity. Retrograde systolic flow can also be seen with colour flow Doppler. It can be associated with phasic spontaneous appearance of some contrast in the hepatic vein.

Key point: The systolic hepatic flow reversal is specific for severe TR. It represents the strongest additional parameter for evaluating the severity of TR.

Continuous wave Doppler of the TR jet. As for MR, the CW envelope of the TR jet can be a guide to TR severity. A dense TR signal with a full envelope indicates more severe TR than a faint signal. The CW Doppler envelope may be truncated (notched) with a triangular contour and an early peak velocity (blunt), which is indicative of elevated right atrial pressure or a prominent regurgitant pressure wave in the right atrium due to severe TR.^{1,2,4} Marked respiratory variation (decreased TR velocity with inspiration) suggests an elevated RA pressure (Kussmaul's sign on physical examination). The TR jet can be used to determine RV or pulmonary artery systolic pressure. This

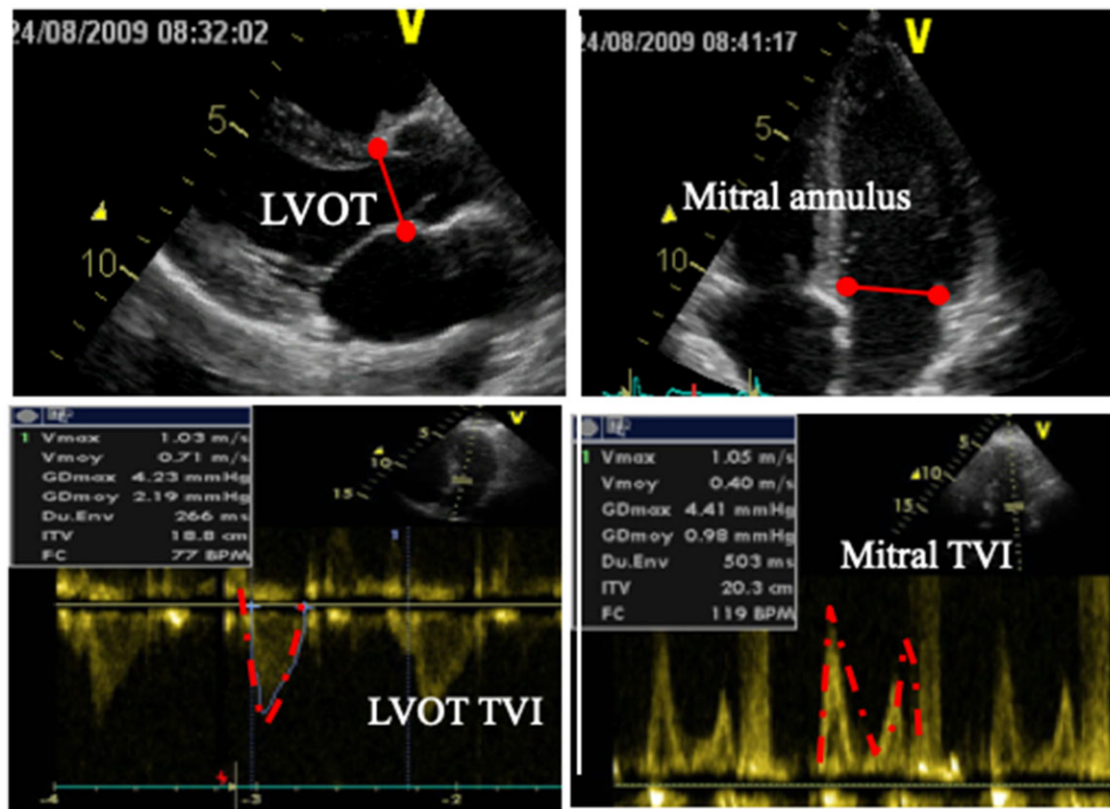


Figure 40 The quantitative assessment of MR severity by the Doppler volumetric method requires the measurement of the left ventricular outflow tract diameter (LVOT), the mitral annulus diameter and of two pulse wave velocity profiles (outflow tract and mitral inflow velocities). TVI, time-velocity integral.

of severe TR (sensitivity of 79%).¹¹² Three-dimensional echocardiography allows more accurate evaluation of RV volumes and EF than 2D and should be used as much as possible.^{6,110} Although evidence of right heart dilatation is not specific for TR and can be noted in other conditions (pulmonary valve regurgitation, left-to-right atrial shunt, and anomalous venous return), its absence suggests milder degree of TR. As for the left ventricle, the RVEF is a crude estimate of RV function. It is dependent on loading conditions, ventricular interaction as well as myocardial structure. Other parameters such as TAPSE, systolic myocardial velocities, and GLS are currently available for a better assessment of RV function.¹²⁹ Imaging the vena cava and its respiratory variation also provides an evaluation of RA pressure. Thresholds for RV dysfunction are: RV fractional area change <35%, TAPSE <17 mm, systolic myocardial velocity <9.5 cm/s, and Free-wall longitudinal strain <20%.²⁷ A tricuspid annulus dimension ≥ 40 mm or ≥ 21 mm/m² represents the threshold used for intervention in patients with mild or moderate TR undergoing left-sided valvular intervention.⁵

When available, CMR is the preferred method to assess the right atrium and right ventricle due to its high accuracy and reproducibility. CMR provides larger RA/RV volumes than echocardiography, due to different handling of trabeculations, which are excluded on echocardiography. Conversely, RVEF by 3D echocardiography is comparable to CMR.^{130,131} Indexed RV end-diastolic volume >164 mL/m² on

CMR has been associated with a low likelihood of RV functional recovery after re-intervention for severe residual TR in the context of previous left-sided valve surgery.¹²⁸

Key point: When TR is more than mild, the evaluation of RV dimensions and function, RA volume, inferior vena cava diameter and the pulmonary arterial systolic pressure is mandatory.¹ Three-dimensional echocardiography allows more accurate evaluation of RV volumes and EF than 2D. The assessment of RV systolic function using TAPSE, systolic myocardial velocities, or GLS is useful to look for RV dysfunction. When available, CMR is the preferred method for assessing RA and RV size. CMR values are not interchangeable with echo derived-data.

Role of exercise echocardiography

As for MR, the goal of exercise echocardiography is to examine the RV functional reserve and to evaluate the changes in pulmonary artery systolic pressure. No data are currently available on patients with isolated TR.⁸

Table 10 Grading the severity of MR

MR severity classes	Mild		Moderate		Severe
	Mild (Grade 1 or 1+)	Mild-to-moderate (Grade 2 or 2+)	Moderate-to-severe (Grade 3 or 3+)	Severe (Grade 4 or 4+)	
Qualitative parameters					
MV morphology	None or mild leaflet abnormality or minimal tenting	Moderate leaflet abnormality or moderate tenting	Moderate leaflet abnormality or moderate tenting	Flail leaflet/large coaptation defect/severe tenting	
Colour flow MR jet	Small, central (usually <4 cm ² or <20% of LA area)	Intermediate (usually 4–6 cm ² or 20–30% of LA area)	Intermediate (usually 6–8 cm ² or 30–40% of LA area)	Large central jet (usually >8 cm ² or >50% of LA area) or eccentric jet swirling and reaching the posterior wall of the LA	
Flow convergence zone ^a CW signal of MR jet	No or small faint/parabolic	Dense, partial or parabolic	Dense, parabolic or triangular	Large throughout systole	
Semi-quantitative parameters					
VC width (mm)	<3	3 to <5	5 to <7	≥7 (≥8 for biplane) ^b	
Pulmonary vein flow	Systolic dominance ^c	Normal or systolic blunting	Systolic blunting	Minimal to no systolic flow/ systolic flow reversal ^d	
Mitral inflow	A wave dominant ^b	Variable	E-wave dominant (Peak E > 1.2 m/s) ^f	E wave dominant (Peak E > 1.2 m/s) ^f	
VTI mitral/VTI LVOT	<1	Intermediate	>1.2 ^f	>1.4 ^f	
Quantitative parameters ^{h,i,j,k}					
EROA (mm ²)	<20	20–29	30–39	≥40	
R Vol (mL)	<30	30–44	45–59	≥60	
RF (%)	<30	30–39	40–49	≥50	
CMR parameters					
RF (%)	<30	30–39	40–49	≥50	
Structural parameters					
LV and LA size ^g	Usually normal	Normal or dilated	Usually dilated	Usually dilated	
PA pressures ^g	Usually normal	Normal or elevated	Normal or elevated	Usually elevated	

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

In bold: specific signs for severe MR.

^aAt a Nyquist limit of 50–60 cm/s.

^bFor average between apical four- and two-chamber views.

^cUnless other reasons of systolic blunting (atrial fibrillation, elevated LA pressure).

^dUsually after 50 years of age.

^eIn the absence of other causes of elevated LA pressure and/or of mitral stenosis.

^fUnless 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/m², LV end-diastolic diameter <56 mm, LV end-diastolic volume <82 mL/m², LV end-systolic diameter <40 mm, LV end-systolic volume <30 mL/m², LA diameter <39 mm, LA volume <29 mL/m².

^gThe measurement of the PISA by 2D TTE in patients with secondary MR may underestimate the true ERO because of the crescentic shape of the proximal convergence.

^hMR regurgitant volume may be lower in low flow conditions but correspond to a larger RF.

ⁱGrading of severity of MR classifies regurgitation as mild, moderate or severe, and sub-classifies the moderate regurgitation group into 'mild-to-moderate' and 'moderate-to-severe'. In secondary MR, an EROA ≥30 mm² and/or a R Vol ≥45 mL can define severe MR.

^jDiscrepancies between EROA, R Vol, and RF may be seen in case of low or high flow states.

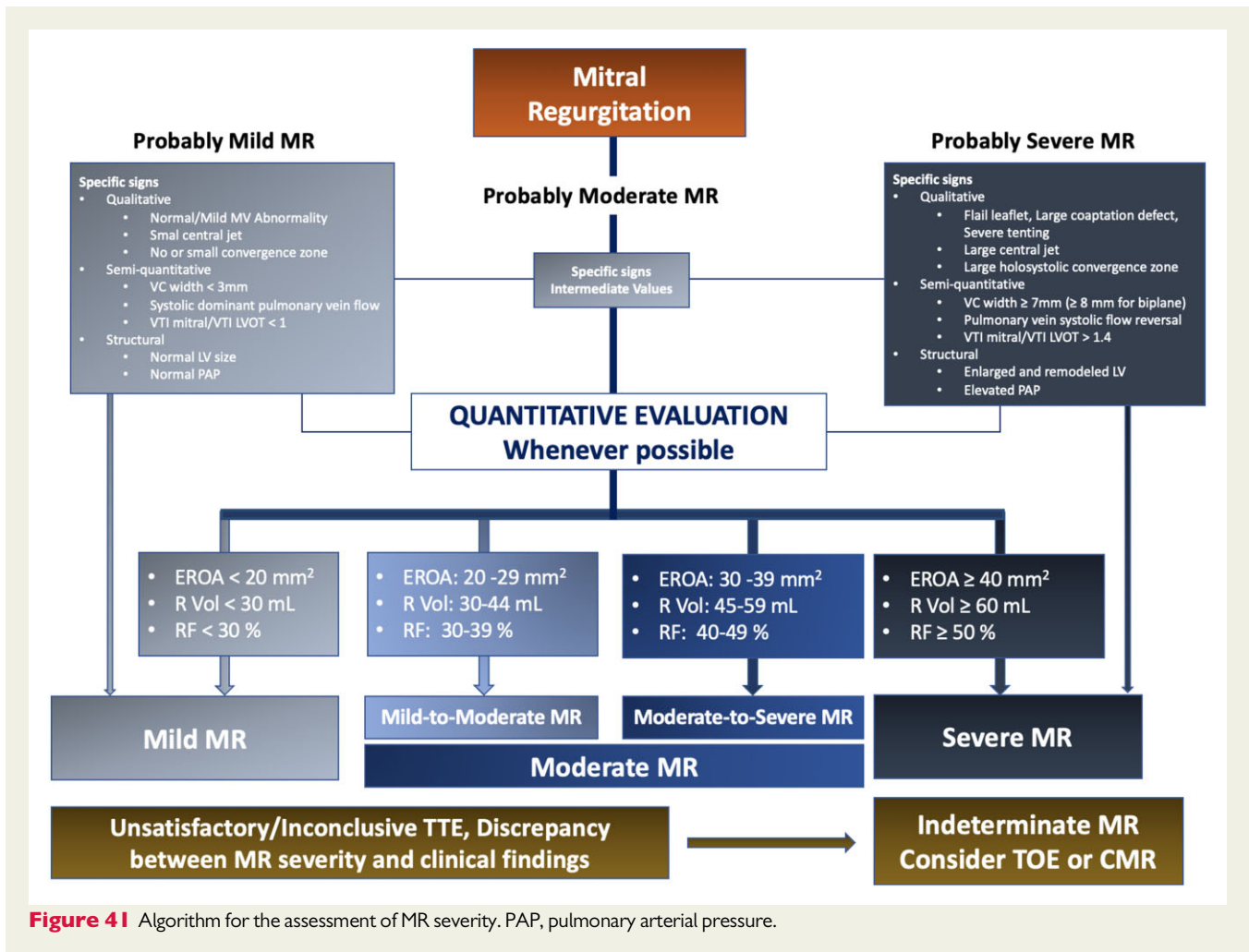


Figure 41 Algorithm for the assessment of MR severity. PAP, pulmonary arterial pressure.

Table 11 Probability of successful surgical mitral valve repair in MR based on echo findings

Aetiology	Dysfunction	Calcification	Mitral annulus dilatation	Probability of repair
Degenerative	II: Localized prolapse (P2 and/or A2)	No/localized	Mild/moderate	Feasible
Secondary	I or IIIb	No	Moderate	Feasible
Barlow	II: Extensive prolapse (≥3 scallops, posterior commissure)	Localized (annulus)	Moderate	Difficult
Rheumatic	IIIa but pliable anterior leaflet	Localized	Moderate	Difficult
Severe Barlow	II: Extensive prolapse (≥ 3 scallops, anterior commissure)	Extensive (annulus + leaflets)	Severe	Unlikely
Endocarditis	II: Prolapse but destructive lesions	No	No/mild	Unlikely
Rheumatic	IIIa but stiff anterior leaflet	Extensive (annulus + leaflets)	Moderate/severe	Unlikely
Secondary	IIIb but severe valvular deformation	No	No or severe	Unlikely

Integrating indices of severity

Echocardiographic assessment of TR includes integration of data from 2D/3D imaging of the valve, right heart chambers, septal motion and inferior vena cava as well as Doppler measures of regurgitant severity (Figures 53 and 54; Table 15). Colour-flow Doppler should be examined in multiple windows. The consensus of the expert is to advocate grading the severity of TR by using the VC width and the PISA radius, except in the presence of mild or trivial TR or when TR is considered severe using specific signs. When severe, TR can be subcategorized into severe, massive and torrential, which is of clinical

interest in patients referred for transcatheter intervention (Table 16). CMR may be useful when the results of echocardiography are unsatisfactory or inconclusive. CCT scan can be helpful in preprocedural intervention planning.

Intervention guidance

Persistent or recurrent TR has been reported in up to 20–50% of patients undergoing MV surgery.¹³² In secondary TR, this has been related to the extent of tricuspid leaflet restriction and to the severity of tricuspid annular dilatation.¹⁰⁰ Both the severity of pre-operative

Table 13 Unfavourable parameters for percutaneous mitral valve repair with MitraClip^{5,96}

Primary MR	Secondary MR
Leaflet perforation/large cleft	Severe tenting (coaptation depth > 11 mm)
Rheumatic MR	Coaptation length <2 mm, large coaptation gap
Large flail gap >10 mm	Posterior leaflet length <7 mm
Large flail width >15 mm	LVEDD >70 mm; LVEDV >200 mL or LVEDV index >96 mL/m ²
Mitral valve opening area ≤ 3 cm ²	
Leaflet calcification in the grasping area	

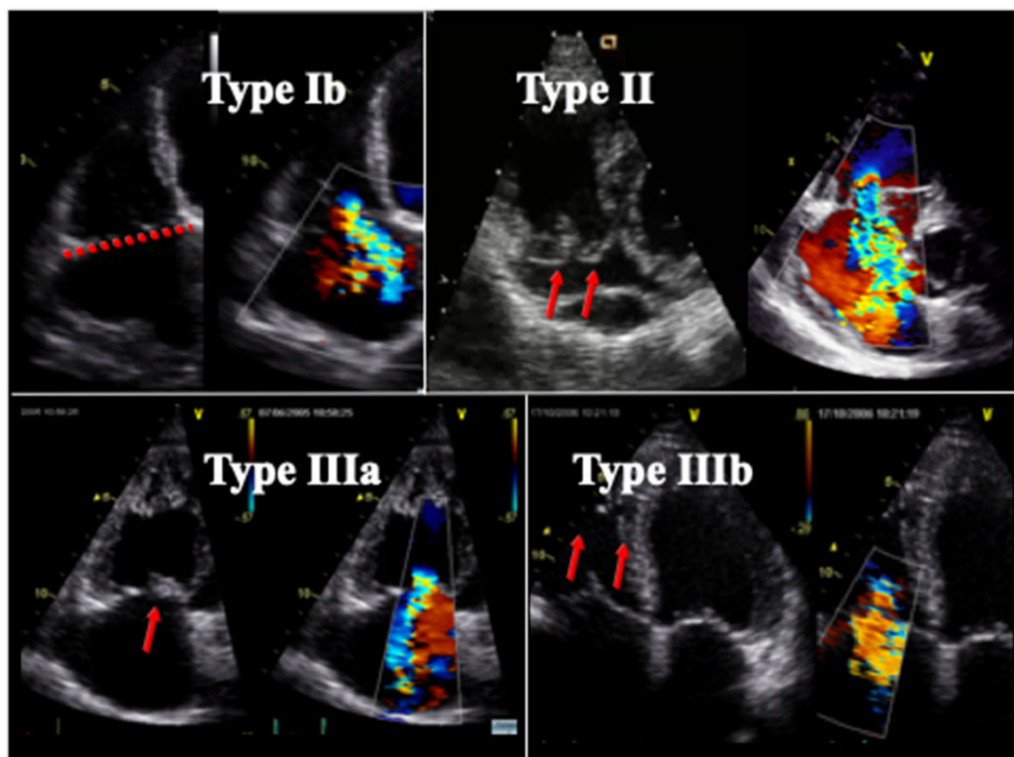
**Figure 43** Mechanisms of TR according to the Carpentier's functional classification.

Table 14 Pathophysiological classification of tricuspid regurgitation

	Leaflet morphology	Pathophysiology	Aetiology	Imaging	Treatment
Primary	Abnormal	Loss of leaflet coaptation due to intrinsic changes, excessive mobility or perforation	<ul style="list-style-type: none"> • Myxomatous disease • Endocarditis • Trauma • Carcinoid • Rheumatic • Latrogenic (biopsy) • Congenital 	<ul style="list-style-type: none"> • According to the etiology • Description of the etiology, lesions and dysfunction 	<ul style="list-style-type: none"> • Surgical annuloplasty±leaflet repair/extension • Surgical valve replacement • Transcatheter leaflet devices±annular devices • Transcatheter valve replacement
Secondary					
A. Atrial	Normal	RA enlargement and dysfunction leading to TA dilation, conical remodeling of the RV	Atrial fibrillation	<ul style="list-style-type: none"> • Severe RA remodeling • RV basale diameter may be enlarged despite usually normal RV volume • Leaflet tethering is absent or limited 	<ul style="list-style-type: none"> • Surgical annuloplasty • Surgical valve replacement • Transcatheter leaflet devices±annular devices • Transcatheter valve replacement
B. Ventricular	Considered normal	RV enlargement and/or dysfunction leading to significant leaflet tethering and TA dilation	<ul style="list-style-type: none"> • Pulmonary hypertension • RV cardiomyopathy • RV infarction 	<ul style="list-style-type: none"> • Dominant mechanism is leaflet tethering ± TA dilation 	<ul style="list-style-type: none"> • Surgical annuloplasty±leaflet repair/extension • Surgical valve replacement • Transcatheter leaflet devices • Transcatheter valve replacement
C. CIED-related					
i. Primary	Abnormal	<ul style="list-style-type: none"> • Leaflet impingement • Leaflet/chordal entanglement • Leaflet adherence • Leaflet laceration/perforation • Leaflet avulsion (post lead extraction) 	<ul style="list-style-type: none"> • Pacemaker • Implantable cardiac defibrillator • Cardiac resynchronization therapy 	<ul style="list-style-type: none"> • 3D echocardiography (±color) is mandatory for reliable diagnosis 	<ul style="list-style-type: none"> • Lead reposition/extraction • Surgical valve replacement • Transcatheter leaflet devices • Transcatheter valve replacement
ii. Secondary	Normal	RV enlargement and/or dyssynchrony/dysfunction due to pace-maker stimulation and leading to significant leaflet tethering and TA dilation	Pacemaker rhythm	Dominant mechanism is leaflet tethering ± TA dilation	<ul style="list-style-type: none"> • Surgical annuloplasty±leaflet repair/extension • Surgical valve replacement • Transcatheter leaflet devices • Transcatheter valve replacement

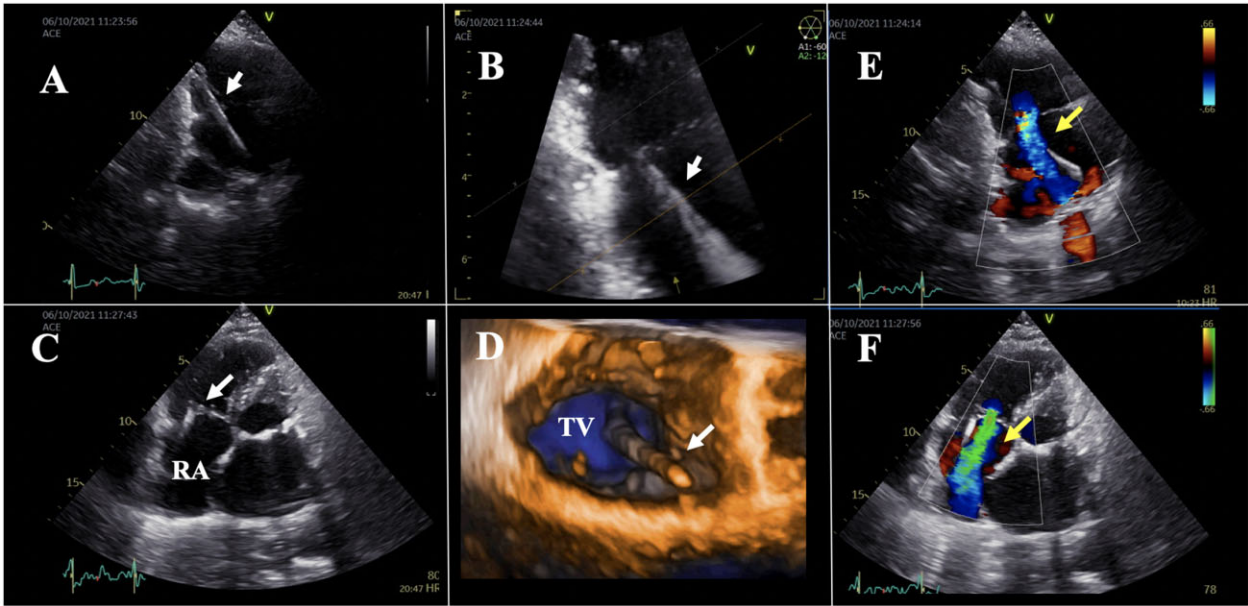


Figure 44 Pacemaker lead-associated TR. (A–D) An RV pacing lead can be seen crossing the TV (white arrow). (D) 3D TOE live zoom image of the right atrium (RA) en face view of the TV showing the position of the pacing lead close to the posterior leaflet, with resultant severe TR (E and F). TV, tricuspid valve.

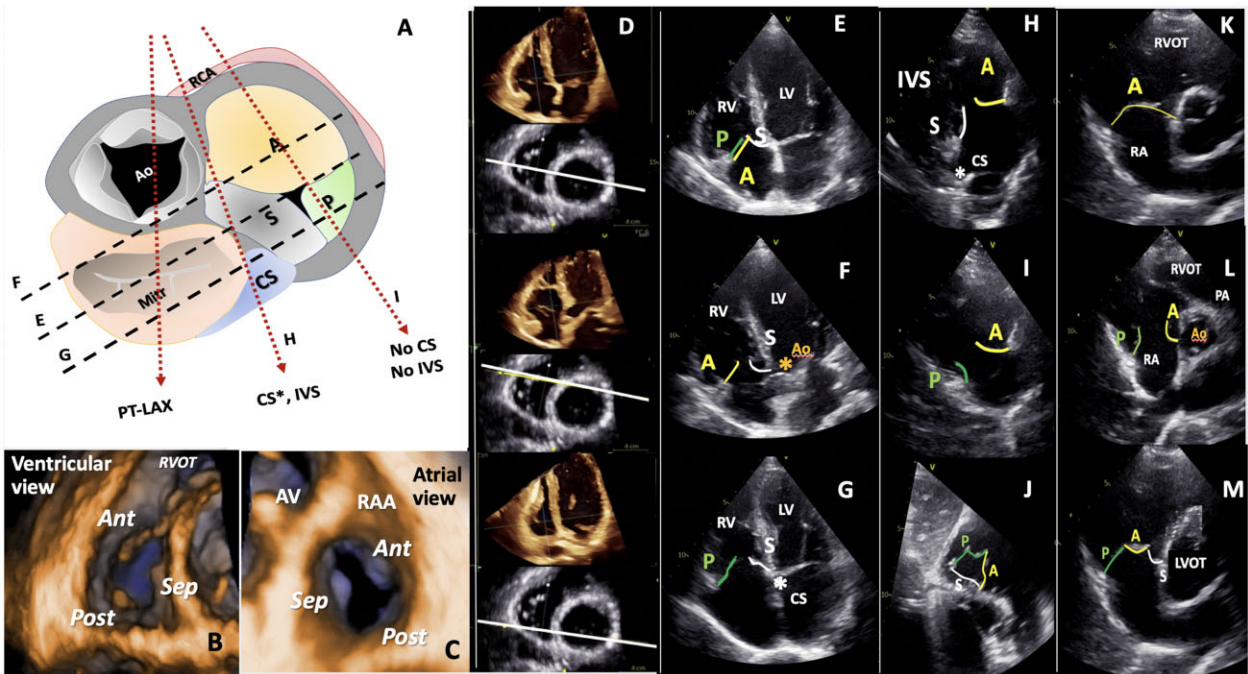


Figure 45 (A) Drawing of the TV. (B and C) 3D TTE volume rendering of the normal TV. (B) Ventricular perspective. (C) Atrial perspective (surgical view). (D) 3D cut planes through the TV. (E–M) 2D echo recordings of the TV. (E–G) Apical four-chamber views. [If the LVOT is visible, the septal and anterior TV leaflets are likely to be in view (panel F). If the coronary sinus (CS) is seen, the septal and posterior TV leaflets are likely to be imaged (panel G).] (H and I) Parasternal long-axis (PLAX) RV inflow views. If the interventricular septum (IVS) and CS can be seen, the image will most likely demonstrate the septal and anterior leaflets of the TV (panel H). If the septum and CS are not seen, it is likely to be the anterior and posterior leaflets that are imaged (panel I). (G) Sub-costal view. (K–M) Parasternal short-axis (SAX) views (see H and I). A, anterior leaflet; P, posterior leaflet; S, septal leaflet.

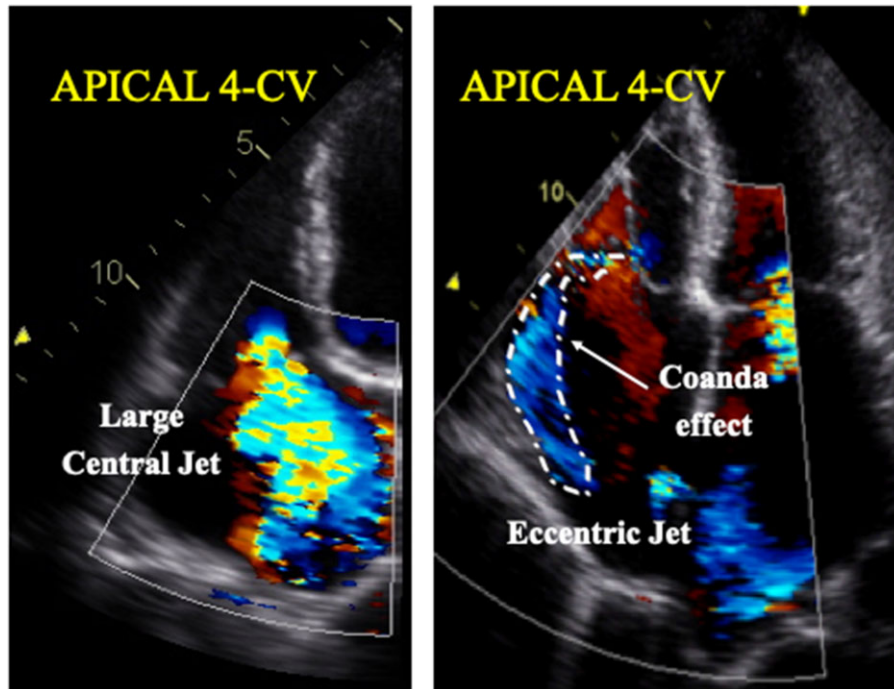


Figure 46 Visual assessment of tricuspid regurgitant jet using colour-flow imaging. (A) Large central jet. (B) Eccentric jet with a clear Coanda effect. CV, four-chamber view.

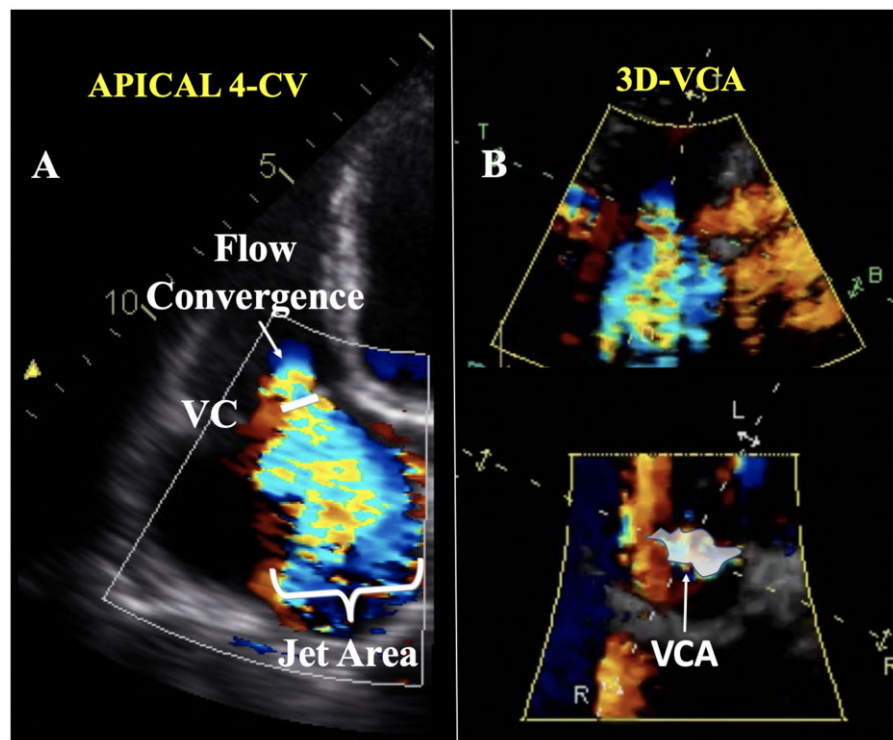


Figure 47 (A) Semi-quantitative assessment of TR severity using the vena contracta width (VC). The three components of the regurgitant jet (flow convergence zone, vena contracta, jet turbulence) are obtained. (B) 3D VC shape. CV: chamber view.

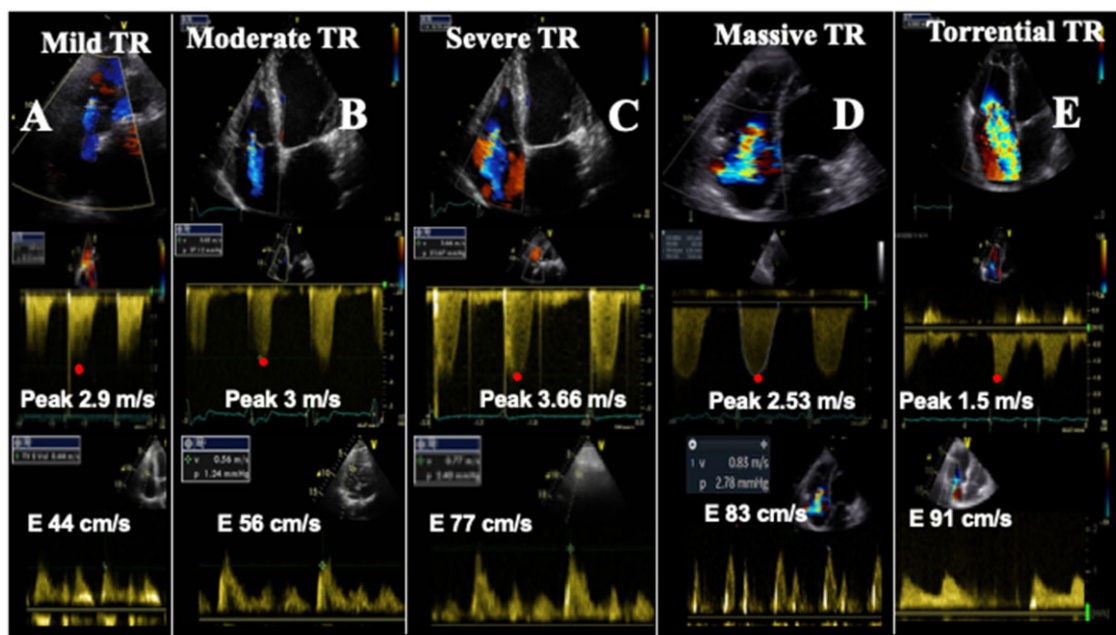


Figure 48 Five examples of various degrees of TR, mild (A), moderate (B), severe (C), massive (D), and torrential (E) are provided. The regurgitant jet area (RJA) as well as the tricuspid E wave velocity increase with the severity of TR. In severe TR, the continuous wave Doppler signal of the regurgitant jet is truncated, triangular and intense. The peak velocity of TR (continuous wave Doppler) allows the estimation of pulmonary pressure except in case of massive/torrential TR, since the Bernoulli equation is not applicable.

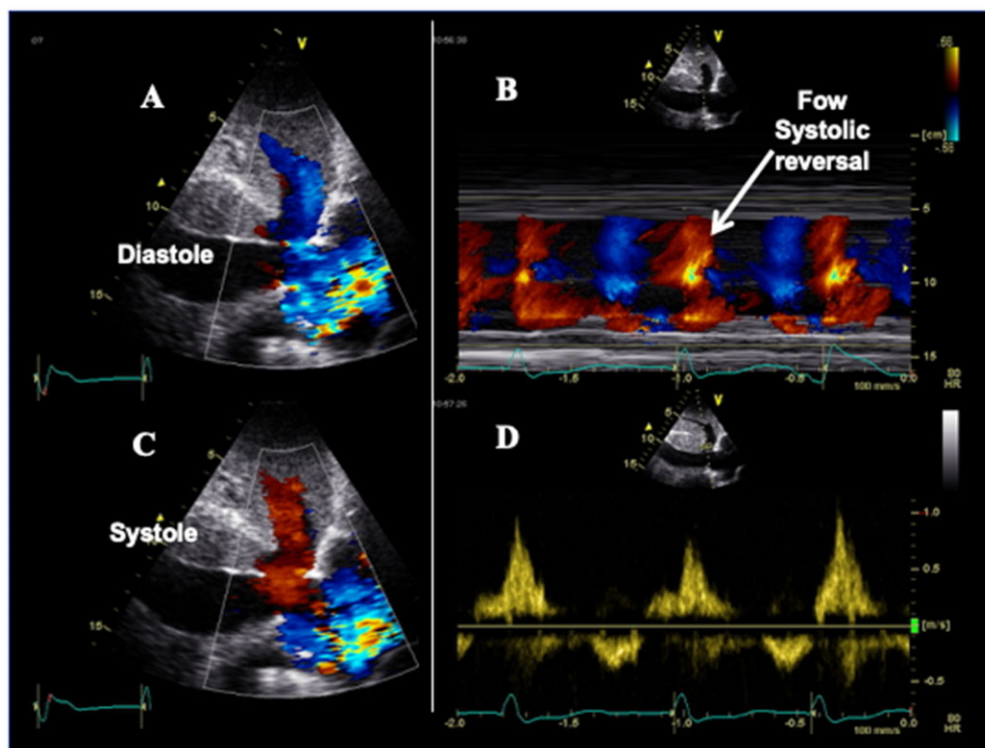


Figure 49 Subcostal echocardiogram recorded in a patient with severe TR. (A–C) The colour Doppler confirms retrograde flow into the vena cava and hepatic vein in systole consistent with TR (red). (D) A spectral Doppler recording from a hepatic vein, also confirming the systolic retrograde flow.

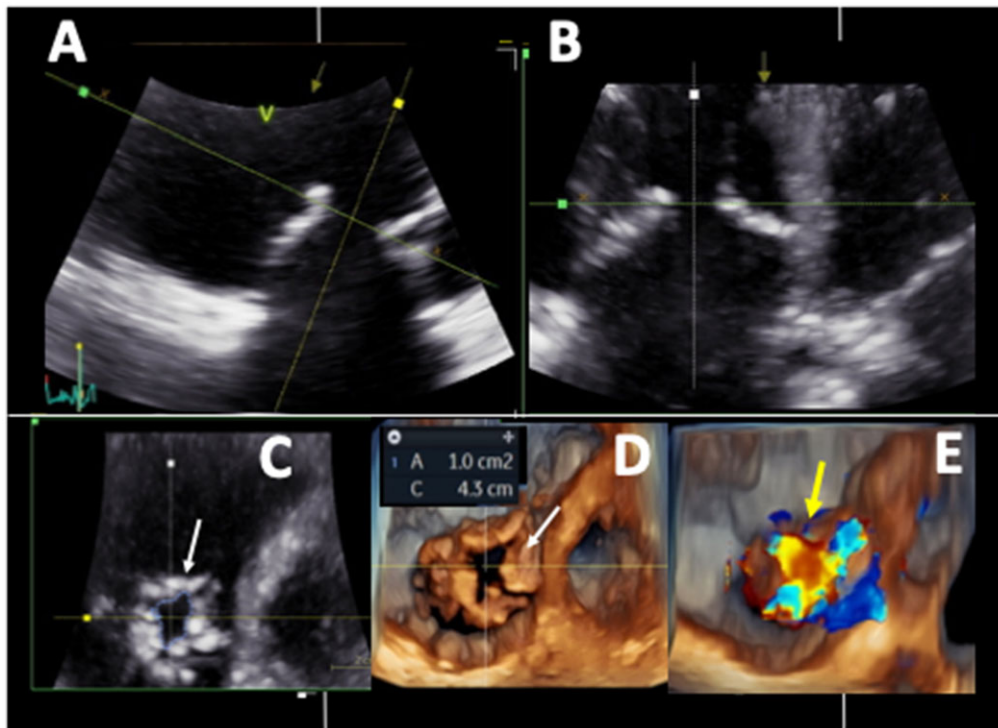


Figure 50 3D TTE acquisition in a patient with pulmonary hypertension and secondary TR. (A and B) Apical views showing the extent of leaflet tethering. (C and D) Quantitative assessment of the anatomic regurgitant orifice area using anatomically oriented cut planes to obtain and planimeter the true anatomical orifice area. (E) Size and shape of the VC obtained using 3D colour Doppler.

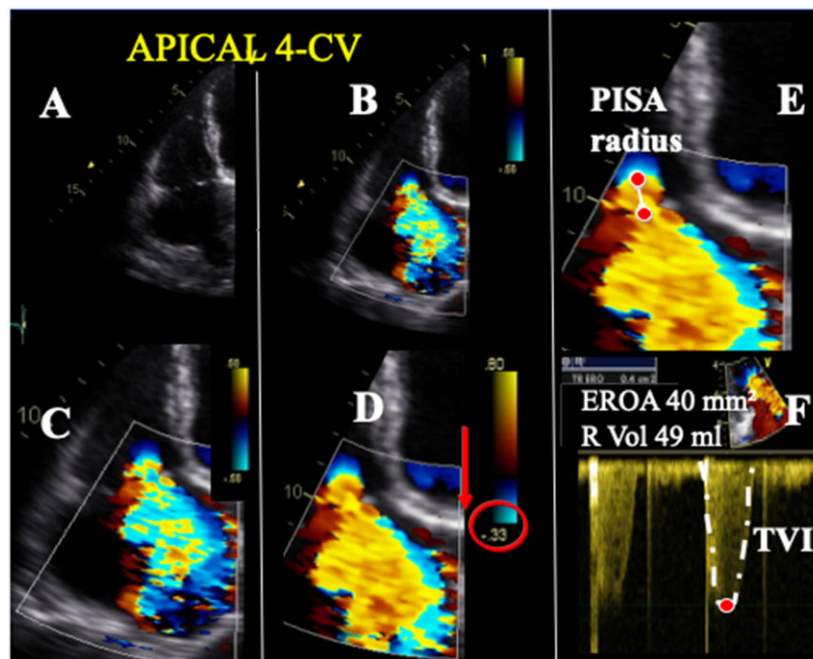


Figure 51 Quantitative assessment of TR severity using the PISA method. Stepwise analysis of TR. (A) Apical four-chamber view (CV); (B) colour-flow display; (C) zoom of the selected zone; (D) downward shift of zero baseline to obtain a hemispheric PISA; (E) measure of the PISA radius using the first aliasing; and (F) continuous wave Doppler of TR jet allowing calculation the effective regurgitant orifice area (EROA) and regurgitant volume (R Vol). TVI, time-velocity integral.

Table 15 Grading the severity of TR

TR Severity classes	Mild	Moderate	Severe
Qualitative parameters			
Tricuspid valve morphology	Normal or mildly abnormal leaflets	Moderately abnormal leaflets	Severe valve lesions/ flail/large coaptation defect/severe tenting
Colour flow TR jet ^a	Small, narrow, central	Moderate central	Large central jet or eccentric wall impinging jet of variable size
Flow convergence zone	Not visible, transient or small	Intermediate in size and duration	Large throughout systole
CW signal of TR jet	Faint/partial/parabolic	Dense/parabolic, or triangular	Dense/often triangular with early peaking (peak <2 m/s in massive TR)
Semi-quantitative parameters			
Hepatic vein flow ^b	Systolic dominance	Systolic blunting	Systolic flow reversal
Tricuspid inflow	A-wave dominant	Variable	E wave dominant (≥ 1 m/s) ^e
PISA radius (mm) ^c	≤ 5	6–9	>9
VC width (mm) ^{a,d}	<3	3–6.9	>7
3D VC area or quantitative Doppler EROA (mm ²)			75–94
Quantitative parameters			
EROA (mm ²)	<20	20–39	≥ 40
R Vol (mL)	<30	30–44	≥ 45
RF (%)	≤ 15	16–49	≥ 50
CMR parameters			
RF (%)	≤ 15	16–49	≥ 50
Structural parameters			
RV, RA, IVC size ^e	Usually normal	Normal of mild dilation	Usually dilated

CW, continuous-wave; EROA, effective regurgitant orifice area; R Vol, regurgitant volume; RA, right atrium; RF, regurgitant fraction; RV, right ventricle; TR, tricuspid regurgitation; VC, vena contracta.

In bold: specific signs for severe TR.

^aAt a Nyquist limit of 50–60 cm/s.

^bUnless other reasons of systolic blunting (atrial fibrillation, elevated RA pressure).

^cBaseline Nyquist limit shift of 28 cm/s.

^dWhen VC width is assessed as an average of measurements performed biplane the threshold value for severe TR is > 9 mm.

^eIn the absence of other causes of elevated RA pressure.

^fUnless for other reasons, the RA and RV size and IVC are usually normal in patients with mild TR. An end-systolic RV eccentricity index >2 is in favour of severe TR. In acute severe TR, the RV size is often normal. In chronic severe TR, the RV is classically dilated. Accepted cut-off values for non-significant right-sided chambers enlargement (measurements obtained from the apical four-chamber view): mid RV dimension ≤ 33 mm, RV end-diastolic area ≤ 28 cm², RV end-systolic area ≤ 16 cm², RV fractional area change >32%, maximal 2D RA volume ≤ 33 mL/m².

An IVC diameter <2.1 cm is considered normal. The IVC is dilated when the diameter is >2.5 cm.

Table 16 Grading the severity of TR in the context of transcatheter TV repair/replacement

	Severe	Massive	Torrential
Semi-quantitative parameters			
VC width (mm) ^a	7–13	14–20	≥ 21
3D VC area or quantitative Doppler EROA (mm ²)	75–94	95–114	≥ 115
Quantitative parameters			
EROA by PISA (mm ²) ^b	40–59	60–79	≥ 80
R Vol (mL)	40–59	60–74	≥ 75

EROA, effective regurgitant orifice area; RF, regurgitant fraction; R Vol, regurgitant volume.

^aAt a Nyquist limit of 50–60 cm/s.

^bBaseline Nyquist limit shift of 28 cm/s.

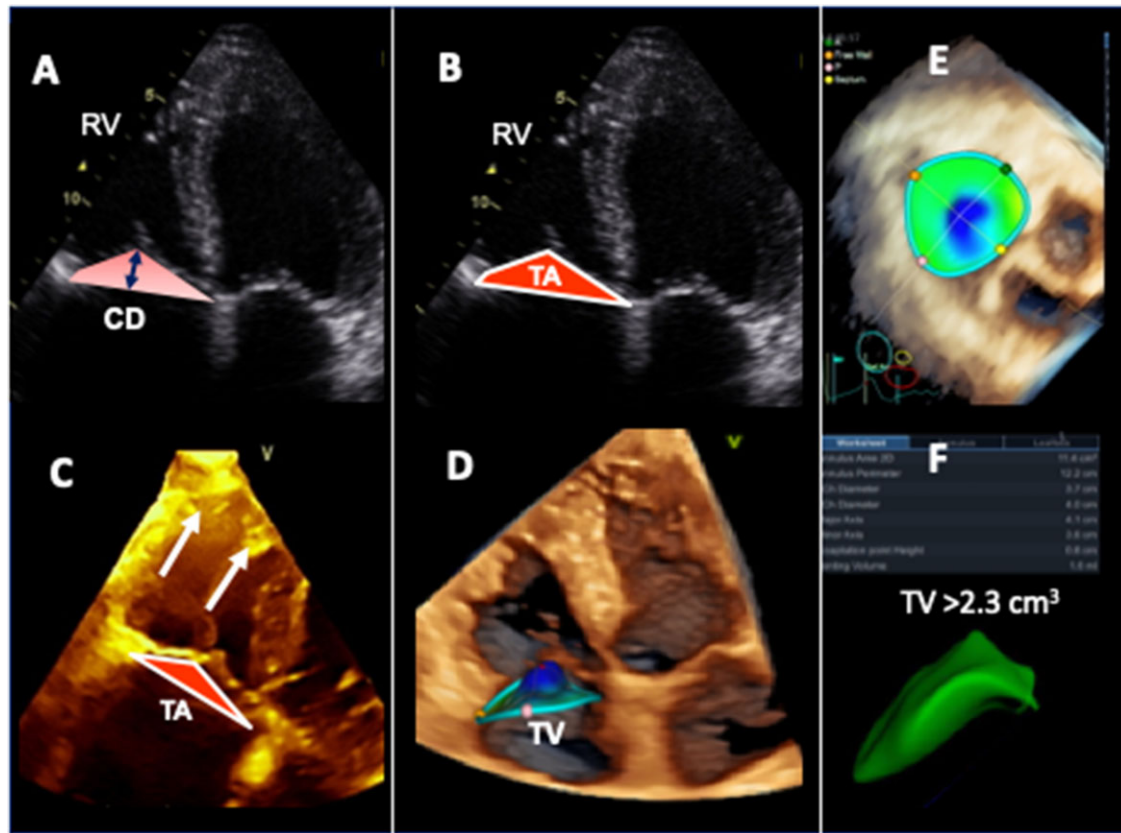


Figure 55 (A–D) 2D/3D echo morphologic parameters that are measured in secondary TR. (A–D, F) Evaluation of the tethering (coaptation) distance (CD), systolic tenting area (TA), and systolic tenting volume; (E) 3D derived tricuspid annulus.

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