

# Mitral Regurgitation with Multiple Jets: An Integrated and Hierarchical Approach

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## Abstract

Mitral regurgitation (MR) with multiple jets is a highly complex diagnostic scenario, frequently encountered in Barlow disease and functional phenotypes associated with ventricular remodeling. Conventional two-dimensional methods (e.g., vena contracta width, color jet area, and hemispheric proximal isovelocity surface area) have important limitations in the presence of multiple regurgitant orifices, eccentric jets, the Coanda effect, overlap of flow convergence zones, or noncircular annular geometry, which may lead to underestimation of volume overload. Three-dimensional echocardiography overcomes part of these limitations by enabling en face characterization of the mitral valve, planimetric measurement of the vena contracta area using multiplanar reconstruction, and the application of volumetric methods based on directly measured anatomical areas. The three-dimensional continuity equation (3D-CE), particularly in mitral valve prolapse and Barlow disease, has demonstrated promising agreement with the regurgitant volume measured using cardiac magnetic resonance (CMR); however, the available evidence should still be interpreted in the context of recent studies and patient populations. CMR remains the reference standard for volumetric assessment when echocardiographic findings discord with the clinical presentation, acoustic windows are suboptimal, or pre-interventional decision-making involves borderline parameters. This review proposes a hierarchical, multiparametric, and technically reproducible approach for assessing MR with multiple jets.

## Introduction

Mitral regurgitation (MR) with multiple jets is one of the most challenging scenarios in valvular echocardiography. This condition is frequently observed in Barlow disease and in complex forms of functional MR, and its quantification challenges the fundamental assumptions underlying conventional two-dimensional methods, which were originally developed for single regurgitant orifices and

simpler geometries, representing an important source of diagnostic error that may mask substantial volume overload.<sup>1,2</sup>

In the presence of multiple regurgitant orifices, eccentric jets, and noncircular mitral annuli, conventional parameters (e.g., vena contracta width and hemispheric proximal isovelocity surface area [PISA]) may substantially underestimate the severity of regurgitation and its volumetric consequences. In this context, three-dimensional echocardiography and advanced volumetric methods have emerged as tools capable of more directly assessing the true geometry of the regurgitant orifice and integrating complex anatomical phenotypes.<sup>3–5</sup>

This review discusses the physical and geometric principles underlying the limitations of two-dimensional methods and the role of three-dimensional techniques and cardiac magnetic resonance (CMR) in a multiparametric approach. We also propose a practical, hierarchical strategy for systematically assessing MR with multiple jets (Central Illustration). The main limitations of two-dimensional methods are summarized in Table 1.

## Fundamental Principles: Why Multiple Jets Compromise Quantification

MR quantification is primarily based on estimating the effective regurgitant orifice area (EROA) and regurgitant volume (RV). The vena contracta (i.e., region of highest flow acceleration and smallest cross-sectional flow area) represents the echocardiographic marker that most closely approximates the effective regurgitant orifice. However, in the presence of multiple regurgitant orifices, geometric assumptions underlying conventional two-dimensional methods frequently become invalid. These limitations arise primarily from three physical mechanisms:<sup>1,2</sup>

**Quadratic relationship between diameter and area:** as area increases with the square of the radius ( $A = \pi r^2$ ), the sum of the linear widths of multiple jets measured by two-dimensional Doppler does not correspond to the sum of their effective areas. Thus, two jets measuring 3 mm width correspond to a combined area of approximately 14 mm<sup>2</sup>, whereas a single 6-mm jet has an area of approximately 28 mm<sup>2</sup>. Consequently, simply summing linear measurements may substantially underestimate the global EROA and MR severity.<sup>1,3–5</sup>

**Coanda effect:** eccentric jets that adhere to the atrial wall dissipate kinetic energy along the adjacent surface; thereby, artificially reducing the apparent jet area on color Doppler imaging. This phenomenon leads to a systematic qualitative underestimation of regurgitation severity, particularly for posterior jets and those originating from the commissural regions. Figure 1 illustrates distinct patterns of regurgitant jets on three-dimensional color Doppler imaging, including separate jets.<sup>1,2,5</sup>

## Keywords

Mitral Valve Insufficiency; Three-Dimensional Echocardiography; Multimodal Imaging

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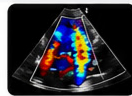
DOI: <https://doi.org/10.36660/abcimg.20260083i>

## Central Illustration: Mitral Regurgitation with Multiple Jets: An Integrated and Hierarchical Approach



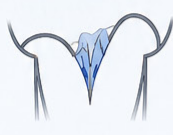
## ECHOCARDIOGRAPHIC ASSESSMENT: STEP BY STEP

## Multiple-Jet Mitral Regurgitation

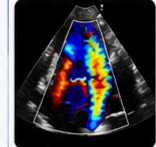
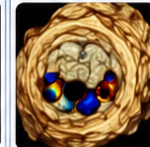


The assessment of MR with multiple jets should follow a systematic, reproducible, and mechanism-oriented sequence. The goal is to first define the anatomy and pathophysiology of regurgitation and then select the most appropriate quantitative method according to the valve phenotype.

## 1 IDENTIFY THE MECHANISM BEFORE QUANTIFYING

CARPENTIER II  
Prolapse / flail / Barlow

CARPENTIER IIb  
Tethering / functional MR


- Analyze the parasternal long-axis view and the four-chamber view (A1-A2-A3 / P1-P2-P3).
- Assess prolapse, flail, systolic retraction, papillary muscles, mitral annulus, and leaflet coaptation.
- Apical color Doppler: number, direction, eccentricity, and systolic variation of the jets.
- 3D en face view (TEE or TTE with matrix-array transducer): number and location of orifices, extent of the involved segments, and commissural jets.

COLOR DOPPLER  
APICAL 4-CHAMBER VIEW

3D EN FACE  
(TEE/TTE)


## 2 CONFIGURE COLOR DOPPLER FOR 3D ACQUISITION



**Nyquist**  
50-70 cm/s

Avoid very low values (blooming) or very high values (reduced sensitivity).



**Color gain**

Reduce until pixels disappear within structures without flow.



**3D sector**

Restrict to the minimum necessary to include all jets.



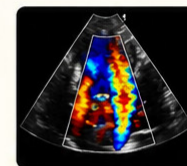
**Volume rate**

Aim for a volume rate  $\geq 20$  Hz.

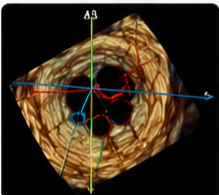


**Acquisition**

Prefer multibeam acquisition with stable sinus rhythm (attention to stitching artifacts).



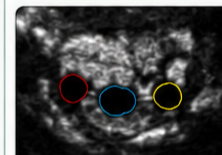
## 3 PLANIMETRY OF VCA BY MPR: TECHNIQUE AND CAUTIONS



Measure at the smallest cross-sectional area of the jet, immediately distal to the regurgitant orifice.

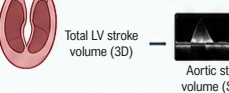
- Position the plane at the smallest cross-sectional area of the jet, before expansion into the left atrium.
- Measure each orifice separately.
- Distinguish true orifices from areas of flow convergence in the left atrium.
- $\Sigma VCA = \text{sum of VCAs} \rightarrow \text{estimated global EROA}$
- Measure  $\geq 3$  beats and use the average.
- High variability: technically unstable acquisition, low volume rate, arrhythmia, or beat-to-beat variation.
- In Barlow disease, integrate with 3D volumetry, preferably.

## VCAS SEPARADAS



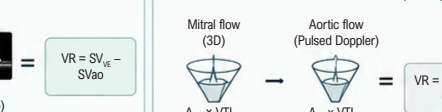
$\Sigma VCA = VCA_1 + VCA_2 + VCA_3$   
= estimated global EROA

## 4 VOLUMETRIC METHODS: QUANTIFICATION INDEPENDENT OF JET GEOMETRY

VOLUMETRIA 3D  
(CONservation of Mass)


Less dependent on the number, direction, or geometry of the jets. Limitation: may underestimate LV volumes in relation to CMR.

## 3D CONTINUITY EQUATION (3D-CE)



Useful in Barlow disease: uses 3D areas, independent of jet geometry.

## INDICATIONS

- VCA not visible or difficult to measure
- Eccentric multiple jets
- Discordance between qualitative parameters and remodeling

## 5 INTEGRATE SUPPORTING PARAMETERS



**Pulmonary venous flow**  
Systolic reversal = strong sign of significant MR (absence does not exclude severity)



**Continuous-wave Doppler of MR**  
Dense, triangular spectrum with early peak suggests significant regurgitation



**Remodeling**  
LA and LV dilation, elevated PASP, and LVEF  $< 60\%$  reinforce significant regurgitation



**Global longitudinal strain**  
May help detect subclinical ventricular dysfunction, especially in Barlow disease.

Assessment should always be multiparametric and performed in the clinical context.

## 6 DECIDE WHEN TO REFER FOR CMR



- Discordance between echocardiographic findings and clinical status/remodeling
- Limited acoustic window
- Borderline parameters in the pre-intervention decision



**CMR ADDS VALUE**

- Quantification of regurgitant volume independent of jet geometry
- Tissue characterization with LGE, T1 mapping, and ECV (fibrosis and arrhythmic risk)



In prolapse with voluminous leaflets, incorporate the volume of prolapsed tissue into the calculation of regurgitant volume to avoid underestimation.

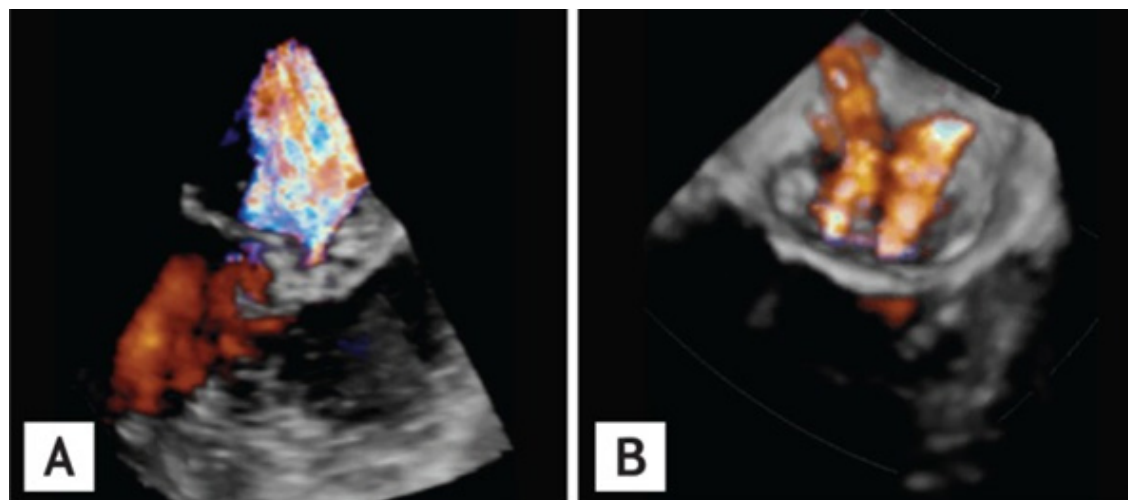


**Figure 1** – Clinical examples of two patterns of functional mitral regurgitation evaluated by three-dimensional transesophageal color Doppler echocardiography: continuous jet (A) and two separate jets (B).

**Limitations of the geometric assumptions underlying two-dimensional PISA:** the PISA method assumes a single, central, hemispheric flow convergence zone, which is frequently absent when multiple regurgitant orifices are present. Adjacent, asymmetric, or partially overlapping flow convergence zones impair the estimation of total regurgitant flow and reduce the accuracy of the method. In Barlow disease, the presence of a large, noncircular mitral annulus amplifies these geometric distortions.<sup>1–5</sup>

### Three-dimensional Echocardiography: Tools and Role in the Multiparametric Approach

Three-dimensional echocardiography primarily provides a more direct and anatomical assessment of regurgitant orifice geometry; thus, reducing dependence on geometric assumptions inherent to conventional two-dimensional techniques. Despite these advantages, the method has several limitations, including lower spatial and temporal resolution, difficulty in defining color Doppler boundaries, the influence of regurgitant orifice nonplanarity, and dependence on acoustic window quality. Figure 2 demonstrates an example of a complex degenerative anatomy with a P2 flail leaflet evaluated using two-dimensional and three-dimensional imaging.<sup>3–6</sup>

Table 2 summarizes the main three-dimensional tools currently available, their potential roles, and respective limitations in assessing MR with multiple jets. In this context, incorporating the true three-dimensional mitral annular area into the three-dimensional continuity equation deserves particular attention. By avoiding the geometric assumption of annular circularity, which is inappropriate in Barlow disease because the mitral annulus is frequently dilated and noncircular, this approach has demonstrated excellent agreement with CMR and outperformed conventional two-dimensional methods. The application of multiplanar reconstruction for individual area measurements is illustrated in Figure 3.<sup>1,6–8,17</sup>

### CMR and Integrated Severity Criteria

CMR quantifies RV as the difference between total left ventricular stroke volume and antegrade aortic flow measured by phase-contrast imaging, an approach largely independent of the geometry or number of regurgitant jets. For this reason, CMR assumes a particularly important role in scenarios of greater anatomical complexity or when echocardiographic findings are discordant. Figure 4 illustrates this volumetric strategy using 3D echocardiography, while Figure 5 presents the indirect volumetric method using CMR, currently considered the reference standard when there is discordance between echocardiographic methods.

New 3D echocardiography software enables automated acquisition of ventricular volumes and left ventricular stroke volume, allowing regurgitant volume to be calculated as the difference between the ventricular stroke volume and the effective systolic volume ejected into the aorta. As with CMR, this is a volumetric method based on the principle of mass conservation, making it less influenced by the geometry of the regurgitant orifice, the presence of multiple jets, or the Coanda effect. Although it still depends on the quality of the three-dimensional acquisition and requires further clinical validation, this technology represents an important advance in the integrated assessment of complex MR.

CMR remains the reference volumetric method for quantifying MR. RVol is calculated as the difference between the left ventricular stroke volume obtained by cine-MRI and the antegrade aortic flow measured by phase-contrast imaging. Because it is practically independent of the number, direction, and geometry of the regurgitant jets, this approach maintains high accuracy in complex anatomies, making it an important complementary method when there is discordance between echocardiographic findings and the clinical context, or when therapeutic decision-making depends on more precise quantification.<sup>9–12</sup>

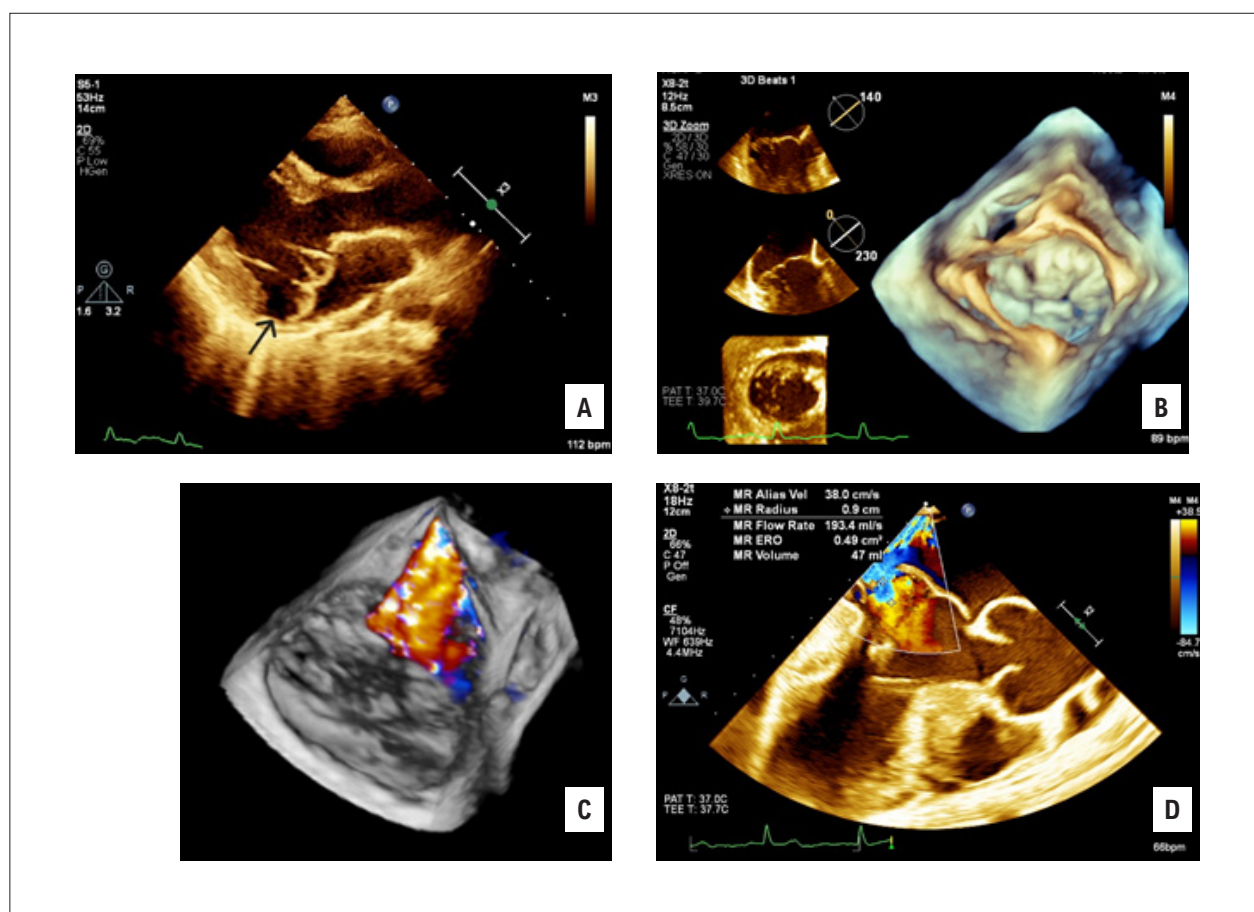


**Figure 2** – Clinical example of degenerative mitral regurgitation with complex anatomy. A — Parasternal long-axis view, showing Barlow's disease, with prolapse of both leaflets and mitral annular disjunction (arrow). B — Three-dimensional zoomed image of the mitral valve, viewed from the left atrium (LA), with prolapse of multiple segments, characterizing Barlow's disease. C — Three-dimensional zoomed image with color Doppler. D — 110° cross-sectional view, showing jet eccentricity and hindering accurate measurement of PISA, EROA, and RVol, resulting in underestimation of MR severity. EROA of 0.49 cm<sup>2</sup>, yet with an RVol of 47 mL: discordant parameters.

**Table 1** – Limitations of two-dimensional methods for assessing mitral regurgitation with multiple jets

| Method                                                               | Primary limitation                                                                                                                                     | Clinical consequence                                                                                                                                             |
|----------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Two-dimensional vena contracta width                                 | The sum of linear widths does not correspond to the sum of effective areas (quadratic relationship: $A = \pi r^2$ ).                                   | Underestimation of global EROA; severe MR may be misclassified as moderate.                                                                                      |
| Two-dimensional hemispheric PISA                                     | Assumes a single, central, hemispheric flow convergence zone; this assumption is frequently violated in the presence of multiple regurgitant orifices. | Reduced accuracy in multiple and eccentric jets; imprecise estimation of total EROA.                                                                             |
| Color Doppler jet area                                               | The Coanda effect artificially reduces the visible jet area.                                                                                           | Qualitative underestimation of severity; inadequate for quantitative assessment.                                                                                 |
| Volumetric method using two-dimensional measurements ( $\Delta SV$ ) | Propagation of geometric errors resulting from two-dimensional estimation of valvular areas and the left ventricular outflow tract.                    | Imprecise RV estimation using two-dimensional measurements; methods based on three-dimensional anatomical areas provide more reliable volumetric quantification. |

PISA: proximal isovelocity surface area; EROA: effective regurgitant orifice area; RV: regurgitant volume;  $\Delta SV$ : difference between stroke volumes.

**Table 2 – Three-dimensional tools and their role in the assessment of mitral regurgitation with multiple jets**

| 3D parameter                                                                 | Role and limitations in mitral regurgitation with multiple jets                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Three-dimensional VCA by multiplanar reconstruction (direct planimetry)      | Enables more direct estimation of the area of each regurgitant orifice; the sum of individual VCAs provides an approximation of the global EROA. Demonstrates good correlation with CMR-derived RV. Limitations include temporal and spatial resolution, definition of color Doppler boundaries, and regurgitant orifice nonplanarity.                                                                                                                                                                                                                                                                                                                 |
| Three-dimensional PISA                                                       | Assesses the true flow-convergence surface, reducing the geometric assumptions of two-dimensional PISA. Limitations include reduced frame rate and overlap of flow convergence zones in adjacent jets. It has a complementary rather than primary role.                                                                                                                                                                                                                                                                                                                                                                                                |
| Three-dimensional volumetry: total LVSV – aortic SV (Simpson method)         | RV is calculated as the difference between total LVSV, obtained by direct three-dimensional volumetry, and antegrade aortic SV. The method is less dependent on mitral annular geometry and largely independent of the number and eccentricity of regurgitant jets. The main limitation compared with CMR is the systematic underestimation of ventricular volumes.                                                                                                                                                                                                                                                                                    |
| Three-dimensional en face anatomy                                            | Enables detailed anatomical assessment of the mitral valve apparatus, including the number and location of coaptation orifices, the extent of prolapse, flail, tethering, and annular dilatation. It is an indispensable tool for surgical and transcatheter procedural planning.                                                                                                                                                                                                                                                                                                                                                                      |
| Three-dimensional continuity equation: annular area × velocity-time integral | RV is calculated using the true three-dimensional areas of the mitral annulus and the left ventricular outflow tract, reducing errors arising from the circularity assumption in the two-dimensional method. It is particularly useful in Barlow disease, in which the mitral annulus is frequently enlarged and noncircular, and largely independent of the number, eccentricity, and systolic duration of regurgitant jets. It has also demonstrated excellent agreement with CMR compared with conventional two-dimensional methods. The main limitation is the reduced applicability in the presence of other significant valvular heart diseases. |

MR: mitral regurgitation; EROA, effective regurgitant orifice area; CMR, cardiac magnetic resonance; MAD, mitral annular disjunction.

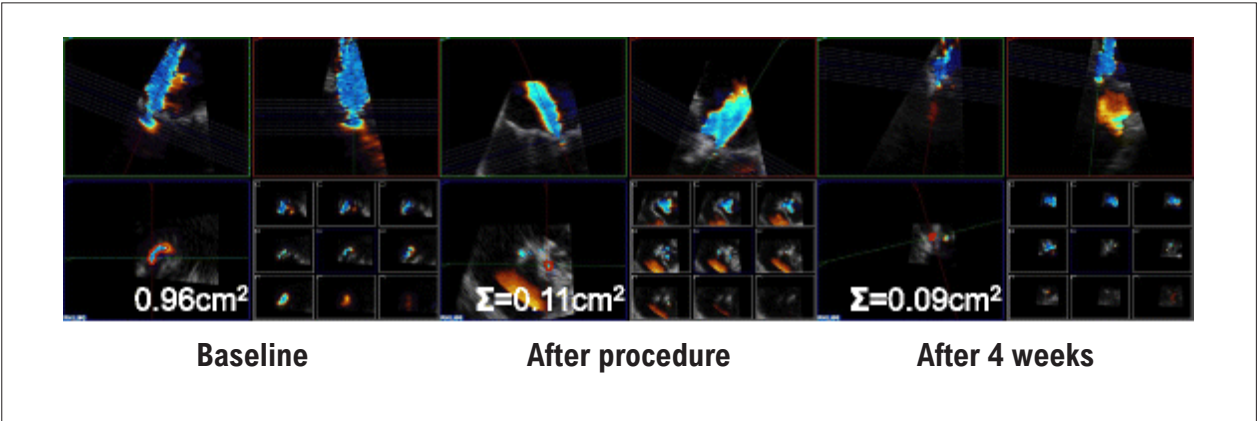


**Figure 3 – Clinical example of vena contracta area measurement using three-dimensional transesophageal echocardiography and multiplanar reconstruction. Following transcatheter mitral valve repair, residual regurgitant jets are measured individually, and their areas are summed. Temporary reference image to be replaced with an anonymized exam. Source: Dietl et al. Cardiovascular Ultrasound. 2018;16:1. CC BY 4.0 license.**

In patients with bileaflet mitral valve prolapse and bulky leaflets, the volume of prolapsed tissue must be incorporated into the RVol calculation to avoid underestimating the regurgitation.<sup>14,15</sup> 4D Flow CMR further expands this capability by enabling three-dimensional assessment of regurgitant flow patterns. However, despite promising results, its routine clinical application remains limited.<sup>11</sup>

No single parameter, including the summed three-dimensional vena contracta area, should be used as the sole determinant of MR severity. Contemporary guidelines consistently recommend a multiparametric approach integrating anatomical, quantitative, and hemodynamic data. In this context, the threshold values presented in Table 3 should be interpreted according to the underlying

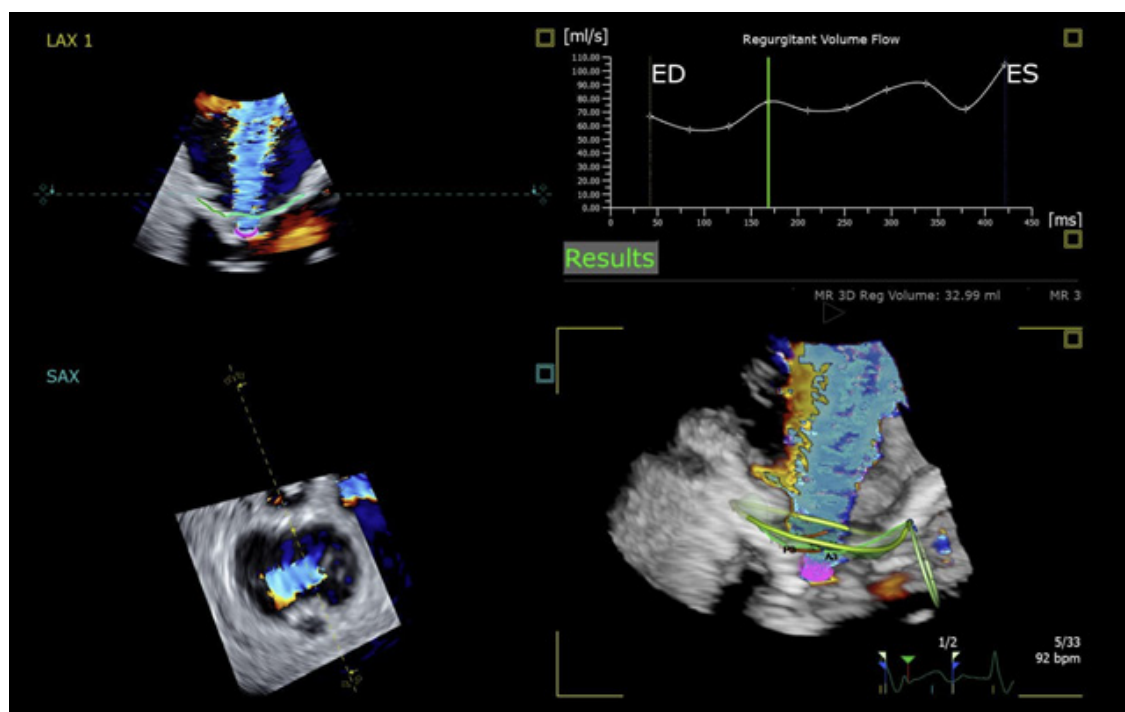


**Figure 4** – Automated 3D color flow quantification using artificial intelligence to measure mitral regurgitant volume.

etiology, technical quality of the examination, and clinical context, particularly in complex phenotypes of MR with multiple jets.<sup>12,16,17</sup>

#### Echocardiographic Assessment: A Stepwise Approach

The assessment of MR with multiple jets should follow a systematic, reproducible, and mechanism-oriented sequence. The primary objective is to define the anatomy and pathophysiology of regurgitation before selecting the quantitative method most appropriate for the specific valvular phenotype.<sup>1,–5,20</sup>

The algorithm is summarized in the Central Illustration.

##### Step 1 — Identify the Mechanism Before Quantification

The first step is to define the mechanism of MR according to the Carpentier classification. In phenotypes with multiple jets, the most common findings are Type II, resulting from prolapse or flail in Barlow disease or multisegment fibroelastic degeneration, and Type IIIb, resulting from systolic leaflet restriction secondary to subvalvular tethering in ischemic or dilated functional MR.<sup>1,2,16,17</sup>

The analysis should begin with the parasternal long-axis view, including frame-by-frame assessment of the A1-A2-A3 and P1-P2-P3 scallops, identification of prolapse, flail, systolic restriction, apical displacement of the papillary muscles, mitral annular dilatation and morphology, and presence of mitral annular disjunction. In the apical views, color Doppler imaging enables mapping of the number, direction, eccentricity, and systolic variation of regurgitant jets.<sup>1,2,6</sup>

The three-dimensional en face view, obtained by transesophageal echocardiography or transthoracic echocardiography using a matrix-array transducer, complements the assessment by demonstrating the number and location of coaptation orifices, the extent of the involved scallops, and the presence of commissural jets, which are frequently difficult to characterize using two-dimensional imaging alone. This step establishes the hierarchy of the subsequent quantitative methods.<sup>6</sup>

##### Step 2 — Optimize Color Doppler Settings for Three-Dimensional Acquisition

Three-dimensional planimetry of the vena contracta area requires a carefully optimized color Doppler acquisition. Nyquist velocity should generally be maintained between 50 and 70 cm/s. Excessively low settings promote blooming artifacts and overestimate the color jet area, whereas excessively high settings reduce color Doppler sensitivity and may underestimate the vena contracta area.<sup>3–5</sup>

Color gain should be progressively reduced until color pixels disappear from structures without flow while preserving the true regurgitant jet signal. Excessive gain artificially enlarges jet boundaries and represents the most common technical error in clinical practice. The three-dimensional sector should be restricted to the minimum volume required to include all regurgitant jets; thus, increasing the volume rate. Ideally, a volume rate of at least 20 Hz should be achieved. In patients with stable sinus rhythm, multibeam acquisitions may improve spatial resolution, although they increase the risk of stitching artifacts.<sup>1,3–6</sup>

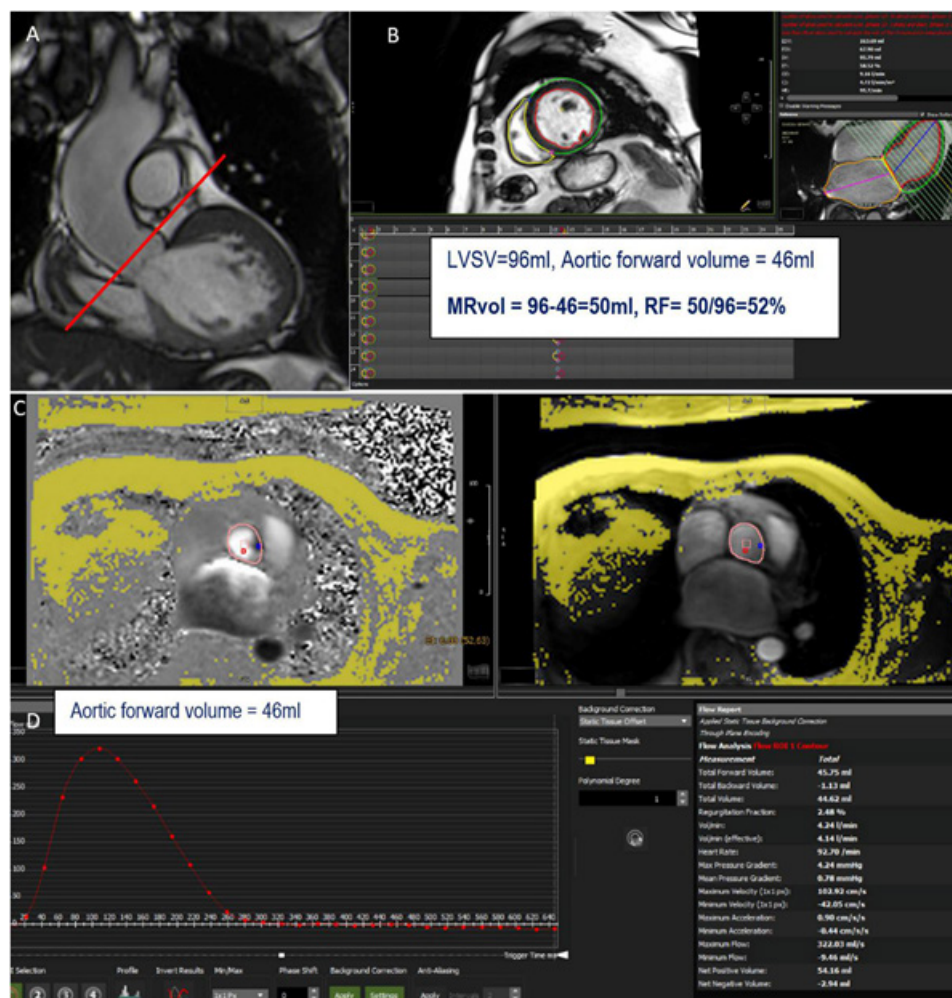


**Figure 5** – Clinical example of mitral regurgitation assessment by cardiac magnetic resonance using the indirect method. The phase-contrast imaging plane is positioned above the aortic valve, and mitral regurgitant volume (MRvol) is calculated as the difference between left ventricular stroke volume (LVSV) and the antegrade aortic flow. LVSV: left ventricular stroke volume; MRvol: mitral regurgitant volume; RF: regurgitant fraction. Source: Vermes et al.<sup>13</sup>

**Table 3** – Quantitative severity criteria and supportive parameters for primary mitral regurgitation

| Parameter                                 | Moderate MR                 | Severe MR                                                             |
|-------------------------------------------|-----------------------------|-----------------------------------------------------------------------|
| EROA (ΣVCA 3D)                            | 0.20 – 0.39 cm <sup>2</sup> | ≥ 0.40 cm <sup>2</sup> *                                              |
| Regurgitant volume                        | 30 – 59 mL                  | ≥ 60 mL                                                               |
| Regurgitant fraction                      | 30 – 49%                    | ≥ 50%                                                                 |
| Pulmonary vein systolic flow reversal     | Absent or blunted           | Present (supportive finding)                                          |
| Left atrial / left ventricular dilatation | Mild to moderate            | Significant dilatation; possible subclinical ventricular consequences |

EROA: effective regurgitant orifice area; MR: mitral regurgitation. \*Threshold values are derived from literature predominantly on primary MR, but have not been specifically validated for all phenotypes of MR with multiple jets. These parameters should be interpreted within a multiparametric framework, considering the underlying etiology, technical quality of the examination, and clinical context. In secondary MR, the severity threshold for EROA is generally lower (≥ 0.20 cm<sup>2</sup>). Source: Zoghbi WA et al.; Vahanian A et al.<sup>1,2,16,17</sup>

### Step 3 — Planimetry of the Vena Contracta Area Using Multiplanar Reconstruction: Technique and Practical Considerations

Following acquisition of the three-dimensional color Doppler, the dataset should be analyzed using multiplanar reconstruction. The measurement plane should be positioned at the smallest cross-sectional area of the jet, immediately distal to the regurgitant orifice and before flow expansion into the left atrium.<sup>3-6</sup>

The most common technical error is measuring the area distally within the expanding jet, which results in overestimation of the vena contracta area. Each regurgitant orifice should be planimeted individually. In adjacent jets, true regurgitant orifices should be distinguished from zones of jet confluence within the left atrium. The sum of individual vena contracta areas provides a functional estimate of the global EROA.<sup>3-6</sup>

Measuring at least three cardiac cycles and using the mean value for analysis is recommended. A high variability suggests technical instability, low volume rate, arrhythmia, or significant respiratory variation. In Barlow disease, the vena contracta area should preferably be assessed using three-dimensional volumetric methods because of the complex and noncircular geometry of the mitral annulus.<sup>3-6</sup>

### Step 4 — Volumetric Methods: Quantification Independent of Jet Geometry

Volumetric methods are useful when planimetry of the vena contracta area is not feasible, when multiple eccentric jets are present, or when qualitative parameters are discordant with the degree of cardiac remodeling.<sup>9-12</sup>

Three-dimensional volumetry based on the conservation of mass calculates RV as the difference between total left ventricular stroke volume (obtained by direct three-dimensional volumetry) and the antegrade aortic stroke volume. This approach is largely independent of the number, direction, or geometry of regurgitant jets, although it is subject to systematic underestimation of ventricular volumes compared with CMR.<sup>9-12</sup>

The three-dimensional continuity equation calculates RV as the difference between mitral and aortic stroke volumes using true three-dimensional anatomical areas. It is particularly useful in phenotypes, such as Barlow disease, in which the mitral annulus is enlarged, noncircular, and inadequately represented by two-dimensional linear measurements. In both methods, measurements should be obtained over multiple cardiac cycles, with particular attention to the correct positioning of pulsed-wave Doppler at the mitral annular plane.<sup>7</sup>

### Step 5 — Integrate Supportive Parameters

Quantitative measurements should be interpreted together with markers of hemodynamic consequences and cardiac remodeling. Systolic flow reversal in the pulmonary veins is a strong supportive finding for severe MR, although its absence does not exclude severe regurgitation in the presence of eccentric jets or the Coanda effect.<sup>1,2,16,17</sup>

Continuous-wave Doppler of the MR jet provides additional qualitative information about the density and

morphology of the spectral envelope. A dense and triangular envelope with early systolic peak suggests a hemodynamically relevant regurgitation. Progressive left atrial and left ventricular dilatation, elevated pulmonary artery systolic pressure, and a left ventricular ejection fraction below 60% further support significant hemodynamic consequences. In Barlow disease, a global longitudinal strain may help identify subclinical left ventricular dysfunction.<sup>1,2,16,17</sup>

### Step 6 — Determine When Cardiac Magnetic Resonance Should Be Performed

CMR should be considered when echocardiographic estimates of MR severity are discordant with clinical symptoms or cardiac remodeling, when acoustic windows are limited, or when echocardiographic parameters are borderline in the context of pre-interventional decision-making.<sup>9-12</sup>

In Barlow disease, CMR provides additional value by quantifying RV in a manner that is less dependent on regurgitant jet geometry and by enabling tissue characterization with late gadolinium enhancement, T1 mapping, and extracellular volume fraction, all of which are relevant for detecting myocardial fibrosis and stratifying arrhythmic risk. In prolapse with redundant leaflets, the volume of the prolapsed tissue should be incorporated into RV calculation to avoid underestimating the regurgitation severity.<sup>14,15,18</sup>

### Differential Diagnosis: Primary versus Secondary MR

The etiology of MR (i.e., primary [degenerative] or secondary [functional]) directly influences the interpretation of quantitative parameters, severity thresholds, and therapeutic strategy. In secondary MR, the EROA threshold associated with severe regurgitation is lower because of the reduced functional reserve of the remodeled left ventricle. Table 4 summarizes the main differences between these phenotypes relevant to multimodal imaging assessment.<sup>2,16,17</sup>

### Technical Pitfalls and How to Avoid Them

Technical expertise in three-dimensional image acquisition and analysis is fundamental to ensure an accurate quantification of MR with multiple jets. The most common sources of error include the following:<sup>1,3-6</sup>

- **Summing two-dimensional widths instead of areas:** the sum of linear diameters does not correspond to the sum of the effective areas of multiple regurgitant orifices. Areas (cm<sup>2</sup>), rather than widths (mm), should always be summed. This error results in underestimation of the global EROA.<sup>3-5</sup>

- **Planimetry outside the true vena contracta:** measurements should be obtained at the smallest cross-sectional area of the jet, immediately distal to the regurgitant orifice. More distal measurements within the expanding jet in the left atrium overestimate the vena contracta area.<sup>3-5</sup>

- **Inappropriate Nyquist velocity:** excessively high Nyquist settings artificially reduce the color jet area, whereas excessively low settings promote blooming artifacts and artificial expansion of jet boundaries. For three-dimensional planimetry of the vena contracta area, a Nyquist velocity of 50 to 70 cm/s is recommended.<sup>3-6</sup>

**Table 4 – Differences between primary and secondary mitral regurgitation relevant to imaging assessment**

| Characteristics         | Primary MR (degenerative)                                                                                                                                                | Secondary MR (functional)                                                                                                                |
|-------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Mechanism               | Structural disease of the mitral leaflets, chordae tendineae, or mitral annulus (prolapse, flail, Barlow disease, or fibroelastic degeneration).                         | Left ventricular remodeling with tethering of the subvalvular apparatus                                                                  |
| Jet pattern             | Frequently eccentric; multiple jets are common in Barlow disease because of multisegment prolapse.                                                                       | Central or biatrial; multiple jets may occur in asymmetric tethering.                                                                    |
| EROA severity threshold | $\geq 0.40 \text{ cm}^2$ .                                                                                                                                               | $\geq 0.20 \text{ cm}^2$ (reduced myocardial reserve of the remodeled left ventricle).                                                   |
| Role of CMR             | Reference standard in cases of borderline parameters or echocardiographic-clinical discordance; useful in Barlow disease/MAD (regurgitant volume by volumetric balance). | Particularly useful when left ventricular ejection fraction is borderline or concomitant coronary revascularization is being considered. |
| Interventional strategy | Mitral valve repair or replacement; timing based on symptoms, left ventricular ejection fraction, and left ventricular dimensions or volumes.                            | Prioritary clinical optimization; surgery is reserved for patients with high regurgitant volume and favorable repair anatomy.            |

MR: mitral regurgitation; EROA, effective regurgitant orifice area; CMR, cardiac magnetic resonance; MAD, mitral annular disjunction.

- **Insufficient frame rate:** a low volume rate may capture the vena contracta outside peak systole, reducing reproducibility of the measurement. A volume rate of at least 20 to 25 Hz should be prioritized with reduction of the acquisition sector and use of valvular zoom whenever possible.<sup>3-6</sup>

- **Single-beat analysis:** planimetry should be performed over multiple cardiac cycles, and the mean value should be used for analysis. Beat-to-beat variability exceeding 20% suggests technical instability, arrhythmia, or inadequate image acquisition.<sup>3-6</sup>

- **Underrecognition of commissural jets:** commissural jets are particularly common in Barlow disease and may be numerous, small, and easily overlooked by two-dimensional imaging. Summing the individual areas of the vena contracta is important in these cases, in which the total EROA may be substantially greater than initially apparent.<sup>3-6</sup>

- **Failure to document hemodynamic conditions:** blood pressure, heart rate, and cardiac rhythm should be recorded during the exam. Acute changes in afterload may substantially alter the EROA and RV.<sup>1,2</sup>

- **Incorrect positioning of pulsed-wave Doppler at the mitral valve:** in volumetric methods, the mitral velocity-time integral should be measured at the level of the mitral annulus. Supravulvar sampling introduces systematic error into the calculation of mitral stroke volume.<sup>1,7</sup>

- **Assuming mitral annular circularity in Barlow disease:** the mitral annulus frequently exhibits a large, dynamic, and noncircular geometry. Estimating the annular area from a single diameter underestimates the true annular area and may overestimate the calculated RV. In these cases, direct measurement of the three-dimensional mitral annular area should be preferred.<sup>7,14</sup>

## Conclusion

Quantifying MR with multiple jets requires methods that accurately represent the true geometry of the regurgitant orifices and their hemodynamic consequences. In this context, three-dimensional vena contracta planimetry using multiplanar reconstruction is a central tool when technically feasible and should always be interpreted in conjunction with valvular anatomy, cardiac remodeling, and supporting parameters.<sup>1,3-5</sup>

In Barlow disease, the large, dynamic, and noncircular geometry of the mitral annulus substantially limits the accuracy of conventional two-dimensional methods. Incorporating true three-dimensional anatomical areas into the continuity equation is also an important advance for this complex anatomical phenotype.<sup>7,14</sup>

CMR should be considered the complementary reference method in cases of discordant findings, borderline parameters, or diagnostic uncertainty, particularly in more complex phenotypes with multiple jets.<sup>9,10-12</sup>

Rather than seeking a single “ideal” parameter, assessing MR with multiple jets requires a rational hierarchy of methods selected based on the valvular mechanism, regurgitant orifice geometry, hemodynamic conditions, and technical quality of image acquisition. Ultimately, understanding the physical and geometric limitations of each method is as important as mastering its technical execution.<sup>1,2,16,19</sup>

## Author Contributions

Conception and design of the research, acquisition of data, analysis and interpretation of the data, writing of the manuscript, critical revision of the manuscript for important intellectual content: Emerich TMS; Barros G; Gripp EA.

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No potential conflict of interest relevant to this article was reported.

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This article does not contain any studies with human participants or animals performed by any of the authors.

### Use of Artificial Intelligence

During the preparation of this work, the author(s) used Claude AI for spelling and bibliographic reference review. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

### Data Availability

The underlying content of the research text is contained in the manuscript.

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