

Multi-modality imaging for pre-procedural planning of transcatheter mitral valve interventions

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KEYWORDS

Multi-modality imaging;
Transcatheter mitral valve
intervention;
Echocardiography

Transcatheter mitral valve interventions (TMVI), either repair or replacement, are established alternative options for patients with mitral regurgitation (MR) deemed not suitable for conventional open-heart surgery. Multi-modality imaging plays a pivotal role in the selection of patients, gaining insights into the anatomy of the mitral valve the mechanism and the severity of MR, which are essential to predict the success of these procedures. The aim of this review is to provide an overview on the role of multi-modality imaging in the patient selection and pre-procedural planning of TMVI.

Introduction

Mitral regurgitation (MR) is the second most frequent heart valve disease, which affects >10% of individuals over 75 years.¹ Traditional cardiac surgery is accepted as the standard of care for MR, however, large clinical registries demonstrated that up to 50% of symptomatic patients with severe MR are at high surgical risk.² In this perspective, transcatheter mitral valve interventions (TMVI), either repair or replacement, represent a valuable therapeutic option.³ Accurate patient selection is crucial for procedural success and is based on careful pre-procedural multi-modality imaging evaluation. Echocardiography, cardiac magnetic resonance (CMR), and cardiac multi-detector computed tomography (MDCT) provide complementary information to guide patient and device selection. Evaluation of mitral valve (MV) anatomy, identification of MV lesion, and quantification of MR severity should be integrated by comprehensive pre-procedural assessment of chamber size, biventricular systolic and diastolic functions, and haemodynamic impact.

Mitral valve assessment

Two-dimensional (2D) transthoracic echocardiography (TTE) is the first-line imaging technique for the

assessment of the aetiology and mechanism of MR. Primary MR is due to intrinsic involvement of MV leaflets and chordae tendinae, secondary MR is caused by left ventricle (LV) dilation and dysfunction with dislocation and dyssynchrony of the papillary muscles that are determinants in reducing the closing forces of the valve, thus causing the tethering and coaptation defect, often in association with high left atrial pressure. A further possible pathophysiological mechanism is mitral ring dilatation, atrial remodelling and atrial fibrillation, which can cause a coaptation defect similar to LV dilatation and dysfunction.⁴ The mechanisms of MR are described according to Carpentier's classification of leaflet motion, Type I: normal leaflet motion, Type II: excessive motion, and Type III: restrictive motion.⁵ Transoesophageal echocardiography (TEE) is a second level imaging modality, it is indicated when TTE is of non-diagnostic value or when further diagnostic refinement is required. Both 2D TTE and TEE allow good morphological analysis of MV and subvalvular apparatus with >85% accuracy compared with surgical inspection.⁴ The introduction of real-time 3D TEE echocardiography has significantly improved diagnostic accuracy, showing a >95% agreement with surgical findings and providing a detailed description of MV dysfunction even in complex lesions.⁶ 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. In all other cases, the use of a more quantitative method

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Table 1 Severe mitral regurgitation criteria based on 2D echocardiography

	Primary mitral valve regurgitation	Secondary mitral valve regurgitation
Qualitative		
Mitral valve morphology	Flail leaflet, ruptured papillary muscle, severe retraction, large perforation	Normal leaflets but with severe tenting, poor leaflet coaptation
Colour flow jet area	Large central jet (>50% of LA) or eccentric wall impinging jet of variable size	Large central jet (>50% of LA) or eccentric wall impinging jet of variable size
Flow convergence	Large throughout systole	Large throughout systole
Continuous wave Doppler jet	Holosystolic/dense/triangular	Holosystolic/dense/triangular
Semi-quantitative		
Vena contracta width (mm)	≥7 (≥8 mm for biplane)	≥7 (≥8 mm for biplane)
Pulmonary vein flow	Systolic flow reversal	Systolic flow reversal
Mitral inflow	E-wave dominant (>1.2 m/s)	E-wave dominant (>1.2 m/s)
TVI mitral/TVI aortic	>1.4	>1.4
Quantitative		
EROA (2D PISA, mm ²)	≥40 mm ²	≥40 mm ² (may be ≥30 mm ² if elliptical regurgitant orifice area)
Regurgitant volume (mL/beat)	≥60 mL	≥60 mL (may be ≥45 mL if low flow conditions)
Regurgitant fraction (%)	≥50%	≥50%
Structural		
Left ventricle	Dilated (ESD ≥40 mm)	Dilated
Left atrium	Dilated (diameter ≥55 mm or volume ≥60 mL/m ²)	Dilated

2D, two-dimensional; ESD, end-systolic diameter; EROA, effective regurgitant orifice area; LA, left atrium; PMR, primary mitral regurgitation; SMR, secondary mitral regurgitation; PISA, proximal isovelocity surface area; TVI, time-velocity integral.

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is advised when feasible, according to current guidelines for native valve regurgitation^{7,8} (Table 1). Different methods are available such as qualitative (visualization of color-Doppler regurgitant jet area and evaluation of

continuous wave Doppler signal), semi-quantitative (vena contracta width, mitral inflow velocity, and pulmonary vein flow pattern), or quantitative [effective regurgitant orifice area (EROA), regurgitant volume (RVol), and regurgitant fraction (RF) by PISA or volumetric method]. As a true gold standard for accurate MR grading is not available, a multi-parametric approach is the cornerstone for a reliable quantification of MR.^{8,9}

Specific parameters, derived from echocardiography, needed for each procedure planning are described more in detail below in the relative sections.

Left ventricle assessment

In both primary and secondary MR, accurate measurement of LV ejection fraction and dimensions are essential in the decision-making process for treatment of patients with severe MR.⁷ The size, shape, and function of the LV are typically assessed using 2D TTE. However, 2D echocardiography may be inaccurate in some patients, and interobserver variability remains debated. These limitations for LV assessment may be overcome by 3D assessment, including 3D echocardiography, CMR, or MDCT. Nevertheless, it has been suggested that LV ejection fraction may not be an accurate marker of LV systolic function in severe MR because the calculated differences between LV end-diastolic and end-systolic volumes do not reflect the true 'forward stroke volume.' Due to significant backward flow into the LA, LV systolic function may be overestimated when derived from LV volumes. In contrast, LV strain analysis may be a more accurate method to assess LV systolic function. It has been demonstrated that global LV longitudinal strain may be impaired in MR.¹⁰

Cardiac magnetic resonance

CMR is the gold standard to assess cardiac dimension, function, and tissue characterization. It has acquired an emerging role in the context of MV as a quantitative method to assess MR in discordant cases or when echocardiography is of suboptimal quality, also in the context of multi-valvular disease, without limitations of imaging window or body habitus.⁹ RVol and RF are calculated as the difference between LV total stroke volume and forward flow. In the upcoming years, the potential advancement of the 4D-flow CMR retrospective valve tracking method, quantifying flow directly at MV, could further improve CMR assessment.⁹ Moreover, CMR allows to characterize the extent of scarring and myocardial viability in secondary mitral regurgitation¹¹ and the presence and the extent of myocardial fibrosis in primary mitral regurgitation that has been associated with sudden cardiac death and ventricular arrhythmias.¹²

Cardiac multi-detector computed tomography

Cardiac MDCT is becoming an important imaging modality for characterizing the anatomy of the MV and its spatial relationships. Electrocardiographically gated MDCT permits retrospective acquisition of data throughout the entire cardiac cycle, which can be subsequently reconstructed

at each 5% or 10% of the RR interval and in multiple planes. The short axis of the MV can be reconstructed, thus identifying the mechanism of MV dysfunction (MR or mitral stenosis). In addition, the grade of mitral stenosis or MR can be estimated by measuring the anatomic MV area and the anatomic regurgitant orifice area, respectively. MV parameters that need to be assessed with MDCT for successful TMVI are being actively investigated and empirically include mitral annular dimensions (perimeter and inter-trigonal, inter-commissural and septolateral distances), mitral annular calcification (MAC), leaflet length, distance between papillary muscles, LV outflow tract (LVOT) area and the course of the coronary sinus (CS) and circumflex coronary artery (LCX) relative to the annular plane.⁴ All of these parameters are pivotal for anuloplasty devices and TMVR and are described more in detail in the respective sections.

Transcatheter mitral valve interventions and choice of approach

TMVI can be divided according to the target structure or mechanism by which MR will be reduced: MV leaflets, MitraClip (Abbott Vascular), Pascal (Edwards Lifesciences, Irvine, California), NeoChord DS 1000 (NeoChord, Inc, St Louis Park, Minnesota), Harpoon mitral valve repair system (Edwards Lifesciences); MV annulus, Cardioband (Edwards Lifesciences), Mitralign (Mitralign, Tewksbury, Massachusetts), Carillon (Cardiac Dimensions, Kirkland, Washington); MV replacement, CardiAQ (Edwards Lifesciences), Tiara (Neovasc Tiara, Inc., Vancouver, British Columbia, Canada), Tendyne (Abbott Vascular), Intrepid TMVR System (Medtronic, Inc., Redwood City, California), SAPIEN 3 (Edwards Lifesciences, Irvine, CA), CardioValve (Cardiovalve, Or-Yehuda, Israel).

Patients with significant MR may present comorbidities or technical challenges that increase surgical risk or contraindicate surgery. These patients, if symptomatic or requiring recurrent hospital admission for heart failure despite optimal guideline-directed medical therapy, represent candidates for percutaneous interventions. In absence of specific contraindications, according to Carpentier's Classification, a leaflet repair approach is suitable for treating Types II and IIIb and suboptimal for Type I; annular approach is most appropriate for Types I and IIIb if limited leaflet tethering is present.⁹ When successful and durable repair is not achievable, MV replacement should be preferred over repair. In the field of redo surgery (failing bioprosthesis/rings), the convincing results for the valve-in-valve (ViV) technique suggest that it should be considered as a first-line option. For this reason, accurate assessment of MV anatomy and lesion is of utmost importance.

Leaflet repair: percutaneous edge-to-edge

Mimicking Alfieri's edge-to-edge surgical technique (*Figure 1*), MitraClip system and PASCAL device are conceived to grasp together the anterior and posterior mitral valve leaflets by advancing, through trans-septal puncture, a sophisticated delivery system at the level of regurgitant target zone of the mitral valve under echocardiographic/fluoroscopic guidance.

The safety and the feasibility of transcatheter MV leaflet repair has been tested in several randomized clinical trials and registries¹³, demonstrating its effectiveness in selected patients with either primitive or secondary MR. Moreover, thanks to dramatic improvement in procedural technique and intra-procedural imaging, especially in

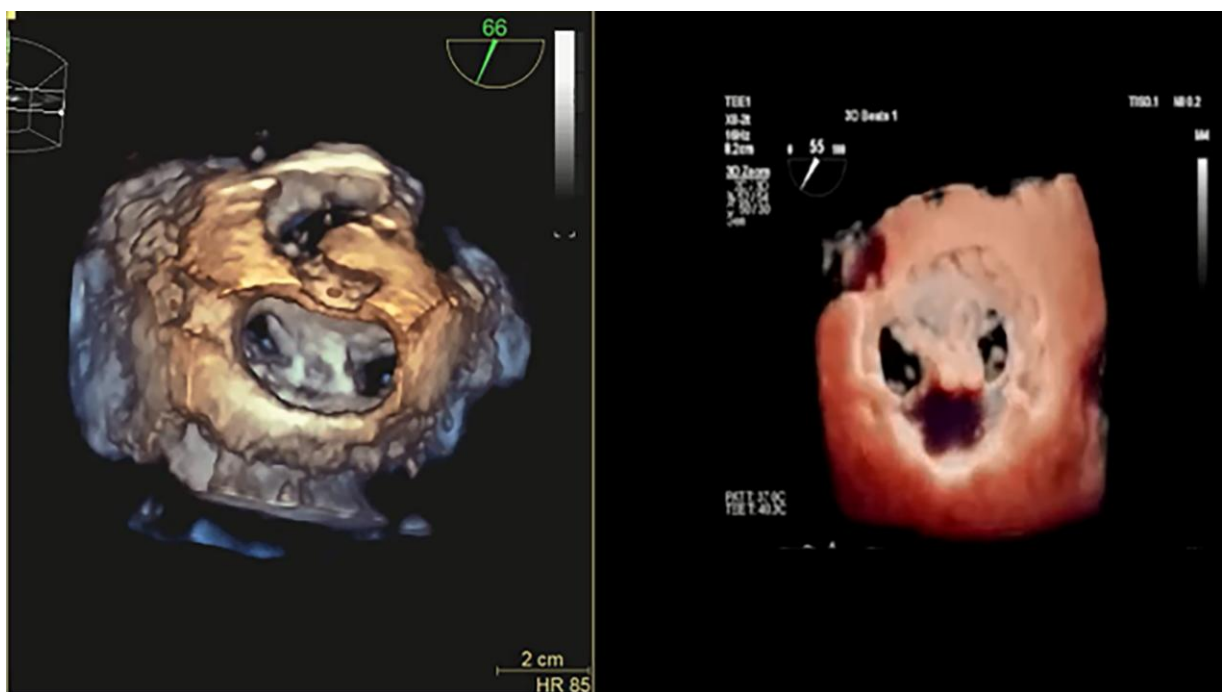


Figure 1 Transesophageal echocardiography 3D en-face view showing two clips.

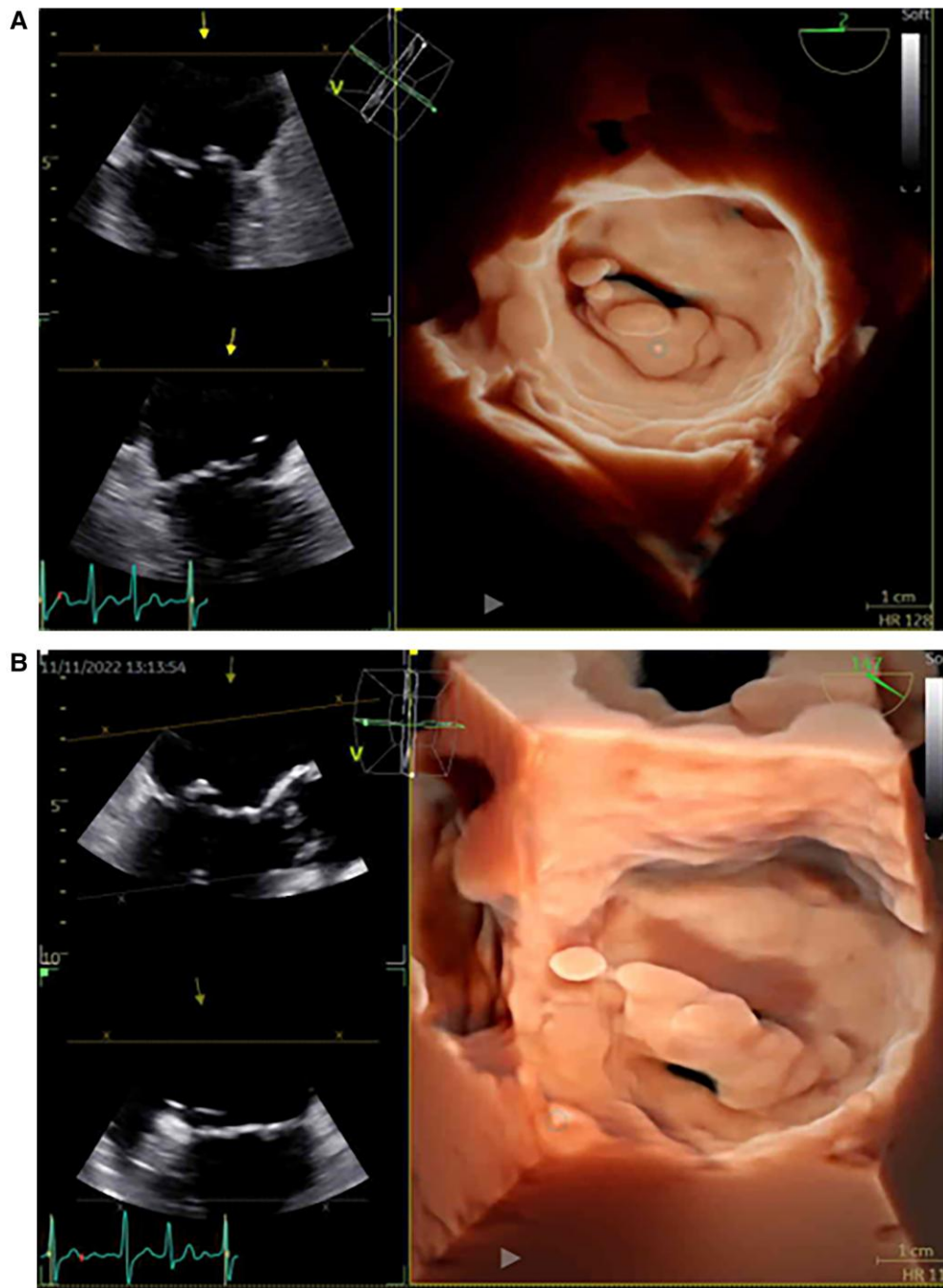


Figure 2 (A) Mitral valve 3D TEE 'en-face view' showing a large posterior flail. (B) Zoom of the lesion.

high-volume centres, nowadays it is possible to treat a great variety of challenging anatomies, overcoming the strict morphological inclusion criteria proposed in the EVEREST¹⁴ study, with only few contraindications, such as active endocarditis, the presence of severe calcification in the grasping area, the length of grasping zone <7 mm, Carpentier IIIa, multiple prolapsing segments in Barlow disease and haemodynamically relevant mitral stenosis.⁹

For patients with primary MR, the localization and the extension of the prolapse/flail should be accurately

assessed by measuring the flail gap and width, leaflet tissue quality and length, the presence of clefts or cleft-like indentations which are responsible for residual MR after device implantation, commissural involvement, presence of severe calcification in grasping area, concomitant haemodynamically relevant mitral stenosis.⁴ In this regard, in addition to traditional 2D echocardiographic evaluation of MV anatomy, 3D TEE provides a comprehensive 'en-face' view of MV from left atrium (LA) and LV perspectives, resembling the surgical inspection of the valve and thus promoting heart team discussion

among surgeons, interventional cardiologists, and imager specialists. Furthermore, new transillumination volume-rendering tools (Figure 2) improve accuracy of anatomic analysis of MV either in pre-procedural planning and intra-procedural guidance by solving the concerns regarding the cavity-structure contrast.¹⁵ Finally, offline multi-plane reconstruction of 3D data sets renders a more precise quantification of MV regurgitation, showing better agreement with CMR in evaluating regurgitant volume than 2DE in eccentric, multiple and late-systolic regurgitant jets.⁴ For patients with secondary MR the presence of sufficient leaflet tissue for mechanical coaptation is mandatory and therefore the measurements of the coaptation depth, the coaptation length and posterior and anterior leaflets dimensions are essential.⁴

Additionally, taking into consideration that secondary MR typically develops as a consequence of LV remodelling and dysfunction, it has been shown that the assessment of proportionality or not of MR relative to LVEDV is critical to differentiate between patients in whom medical therapy should be optimised and those who may be considered for transcatheter therapy. For this purpose, an EROA:LVEDV ratio of 0.14 could provide useful information about the contribution of MR to LV dilatation.¹⁶

Annuloplasty devices

Percutaneous annuloplasty techniques are targeted to patients with secondary MR in which annular dilatation/deformation is the predominant mechanism of MV regurgitation, with the aim to reshape mitral annulus (MA) in order to reverse mitral leaflet coaptation abnormalities. Devices include indirect types, which are positioned in the coronary sinus (The Carillon, Cardiac Dimensions, Kirkland, Washington, USA), and direct types, which are implanted in the annulus, similar to surgical annuloplasty (Mitralign device-Mitralign, Tewksbury, Massachusetts, USA and The Cardioband System-Edwards Lifesciences, Irvine, CA, USA). The echocardiographic analysis of the MR mechanism, according to Carpentier's classification, is pivotal for patients' selection. As we stated, Type I (incomplete coaptation due to annular dilation/deformation), or Type IIIb (symmetrical leaflet tethering due to LV remodelling) mechanisms might be corrected by percutaneous annuloplasty approach; instead mitral valve structural abnormalities (Type II, Type IIIa), severe mitral annular calcification (MAC) or recognized tethering shapes that are predictive of unsuccessful surgical annuloplasty (i.e., LVED diameter >65 mm, coaptation depth >1 cm, asymmetric extreme tethering of posterior leaflet with angle >45° or distal leaflet anterior tenting with angle >25°, systolic tenting area >2.5 cm², end-systolic interpapillary muscle distance >20 mm and systolic sphericity index >0.7), should be excluded. Therefore, MA anatomy as well as its relationship with circumflex artery, coronary sinus and the non coronary and left coronary aortic cusps, should be carefully evaluated to assess procedural feasibility and post-procedural complications. In this perspective, the pre-procedural planning for direct annuloplasty includes the measurements of antero-posterior and inter-commissural diameters of mitral annulus (MA), circumferences of the posterior MA (from the left to the right trigones), sphericity index (antero-posterior/mediolateral diameters ratio), as well as MA area at tele-

diastolic frame.⁹ These informations are easily obtained by MPR of MDCT, together with annular thickening, the presence, degree, and localization of calcium in the annulus and its extension to the myocardium or leaflet. The pre-procedural planning of indirect mitral annuloplasty via the coronary sinus requires additional anatomical considerations: patency, diameter, tortuosity of the coronary venous system, location and extent of the Thebesian and Vieussens valves, and the spatial relationship of the coronary sinus with the MA and LCX, to avoid the coronary impingement during device position and the chincing effect on left atrial wall in case of no co-planar position of MVA and CS.⁴

Chordal implantation

A minimally invasive strategy for mitral valve repair today is the implantation of chordae tendineae with device such as NeoChord DS1000 system (NeoChord, Inc., Minnesota, USA) or Harpoon (Edwards Lifescience, California, USA) using a transapical approach. The procedure involves the insertion of the cords, which are then attached to the valve leaflets and subsequently fixed at the level of the ventricular wall at the apical site with intraoperative echocardiographic guidance. To use this technique, a number of parameters must be met pre-operatively. In particular, the MDCT study is necessary to assess the relationship between the ventricular apex and chest wall to optimize the choice of access site for device delivery. 2D TTE, in addition to assisting the MDCT study to quantify the calcification of MA and to assess the intercostal space useful for transapical access, is necessary above all to define the mitral valvular defect and a series of measurements necessary to define the feasibility of the operation. In particular, the ideal candidate is a patient with flail or prolapse of the P2 scallop with a central jet, with a distance between the prolapsing leaflet and the other of at least 9 mm, that predisposes to an adequate coaptation leaflet reserve, a ratio of posterior leaflet to mitral annulus diameter >21%, the absence of excessive calcification or dilatation of the mitral annulus. If the above criteria are met, chordal implantation is a viable alternative in a well-selected patient. Indeed, in the TACT Trial¹⁷ of the selected 30 patients, 75% of them showed a clear reduction in mitral regurgitation even at 1-year follow-up.

Transcatheter mitral valve replacement

The need to perform transcatheter mitral valve replacement (TMVR, Figure 3) has developed, on the one hand because of certain limitations in performing percutaneous techniques such as edge-to-edge repair and, on the other hand, because of the need to reduce redo-surgical procedures and to seek a percutaneous alternative to traditional surgery. TMVR was initially performed in settings such as valve-in-valve (ViV), valve-in-ring (ViR), valve-in-mitral annular calcification (ViMAC). In failing bioprosthesis or ring in patients with intermediate or high risk surgery, ViV demonstrated good results and it may potentially become a viable alternative to redo surgery,³ which is associated with significant early mortality, ranging from 5% to 12%.¹⁸ With the development of new

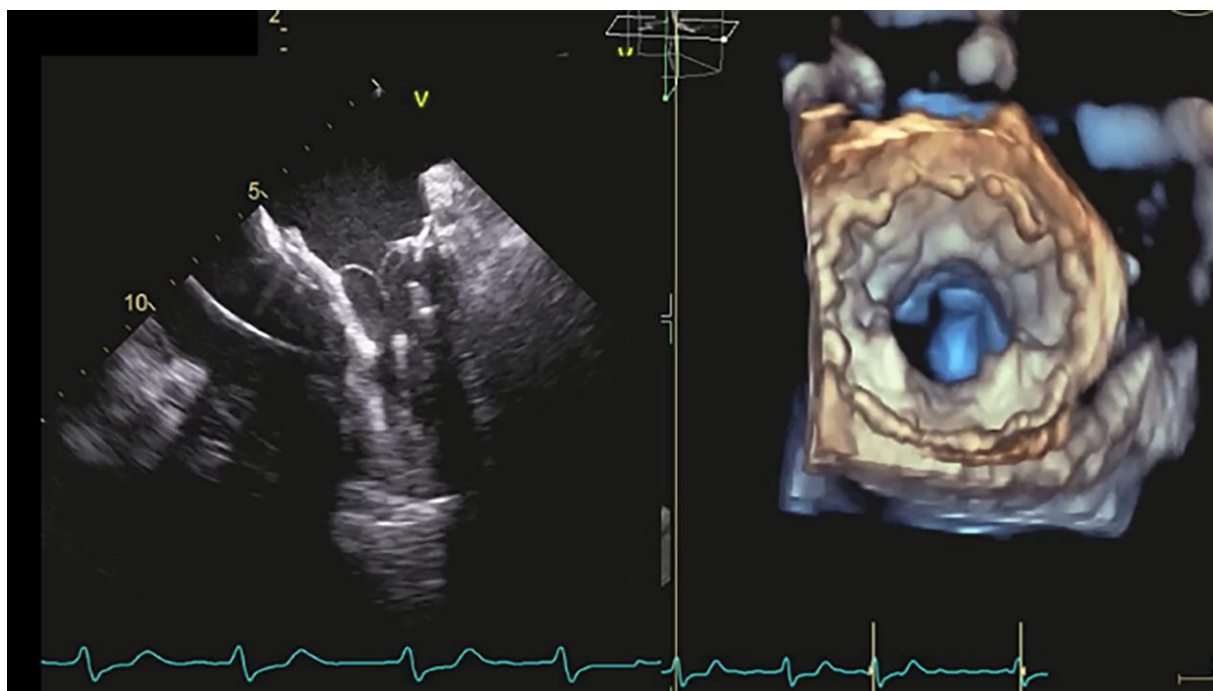


Figure 3 Three-dimensional TEE en-face view showing transcatheter mitral valve replacement (TMVR).

devices, the therapeutic indications have also expanded, particularly in patients with a native valve.³ For the candidacy of patients to TMVR, it is essential that the pre-procedural MDCT examination takes into account several strict parameters such as an average annulus diameter ≤ 38.3 mm, an antero-posterior diameter > 41.6 mm, and a mitral annulus area < 8.6 cm². Also the relationship of the MV to the LV is to be considered in the quantitative parameters for evaluating the performance of a TMVR; in fact, with the insertion of the prosthesis, there is a displacement of the native anterior leaflet towards the interventricular septum, which creates a kind of neo-left ventricular outflow tract (neo-LVOT), and this is the reason why the most frequent complication of the procedure is precisely obstruction of the outflow tract (LVOTO). To minimise the likelihood of this complication and to better study the left ventricle anatomy suitable for a safe TMVR, it is therefore necessary to perform an accurate pre-operative MDCT study, making sure of the presence of certain ventricular parameters such as an aorto-mitral angle $> 130^\circ$, an annulus-apex distance ≥ 100 mm as well as the assessment of an expected neo-LVOT area with a variable cut-off from < 1.7 cm² or < 1.9 cm²¹⁹ (the area has an inverse relationship to LVOT gradient), the presence of severe MAC. The calcium quantification of pre-procedural MDCT is also related to the possibility of the development of paravalvular leaks. Moreover, grading MAC in terms of: average calcium thickness (mm), degrees of annulus circumference involved, calcification at one or both fibrous trigones, and one or both leaflets, may assist to predict valve embolization/migration during trans-septal or transapical ViMAC procedures.²⁰

Instead, the parameters to be determined on the transoesophageal echocardiogram, for a good intervention result, are an inter-commissural distance that should be

< 39 mm and a telesystolic diameter < 32 mm, the absence of a high relative wall thickness, and the absence of an evident septal bulge. Obviously, associated with the quantitative parameters there is the need for a clinical evaluation and in general, the presence or absence of certain features such as pulmonary hypertension with severe tricuspid valve regurgitation, left ventricular systolic dysfunction, baseline systolic anterior leaflet motion, unfavourable mitral valve anatomy either because it could be too large or too small. There are now numerous types of percutaneously implantable valves (Tendyne, Tiara, Interpid, Sapien 3, CardioValve, Evoque, Highlife), each with its own peculiarities in terms of shape, potential adverse effects and delivery method, mainly transfemoral or transapical. Overall, the devices used have shown in approval studies a low complication rate and a low mortality rate.²¹ The indication for TMVR of a native MV or as a re-intervention on a prosthetic valve is usually the patient's high surgical risk for all valve types regardless of which is used. When choosing the device, one must also consider its applicability with respect to the patient, taking into account, thanks to the multimodality imaging study, the parameters that may predict the development of LVOTO or not, as already mentioned, the type of device to be implanted, and the anchoring mechanism. At the procedural level, the depth at which implantation takes place must be considered, balancing on the one hand the increase in thrombogenicity if the position is excessively on the atrial side, and on the other the risk of LVOTO if it is excessively on the ventricular side, thus attempting to use the best device available for a given patient. Due to the high complexity of mitral apparatus anatomy it is clear that in the pre-procedural planning, the shape and size of the device that can better fit with each single case, must be considered.

Conclusion

Transcatheter mitral valve interventions represent the treatment of choice for all patients with mitral valve disease deemed unsuitable for cardiac surgery. Multi-modality imaging has a pivotal role in the decision-making of a patient-tailored approach, which includes accurate patient selection and choice of the treatment strategy.

Funding

None declared.

Conflict of interest: None declared.

Data availability

No new data were generated or analysed in support of this research.

References

- Nkomo VT, Gardin JM, Skelton TN, Gottdiener JS, Scott CG, Enriquez-Sarano M. Burden of valvular heart diseases: a population-based study. *Lancet* 2006;**368**:1005-1011.
- Mirabel M, lung B, Baron G, Messika-Zeitoun D, D etaint D, Vanoverschelde JL *et al.* What are the characteristics of patients with severe, symptomatic, mitral regurgitation who are denied surgery? *Eur Heart J* 2007;**28**:1358-1365.
- Russo G, Gennari M, Gavazzoni M, Pedicino D, Pozzoli A, Taramasso M *et al.* Transcatheter mitral valve implantation: current Status and future perspectives. *Circ Cardiovasc Interv* 2021;**14**:e010628.
- Bax JJ, Debonnaire P, Lancellotti P, Ajmone Marsan N, Tops LF, Min JK *et al.* Transcatheter interventions for mitral regurgitation: multimodality imaging for patient selection and procedural guidance. *JACC Cardiovasc Imaging* 2019;**12**:2029-2048.
- Carpentier A, Chauvaud S, Fabiani JN, Deloche A, Relland J, Lessana A *et al.* Reconstructive surgery of mitral valve incompetence: ten-year appraisal. *J Thorac Cardiovasc Surg* 1980;**79**:338-348.
- Pepi M, Tamborini G, Maltagliati A, Galli CA, Sisillo E, Salvi L *et al.* Head-to-head comparison of two- and three-dimensional transthoracic and transesophageal echocardiography in the localization of mitral valve prolapse. *J Am Coll Cardiol* 2006;**48**:2524-2530.
- Vahanian A, Beyersdorf F, Praz F, Milojevic M, Baldus S, Bauersachs J *et al.* ESC/EACTS Scientific Document Group, ESC national cardiac societies, 2021 ESC/EACTS guidelines for the management of valvular heart disease: developed by the task force for the management of valvular heart disease of the European Society of Cardiology (ESC) and the European Association for Cardio-Thoracic Surgery (EACTS). *Eur Heart J* 2022;**43**:561-632.
- Lancellotti P, Pibarot P, Chambers J, La Canna G, Pepi M, Dulgheru R *et al.* Scientific document committee of the European association of cardiovascular imaging. Multi-modality imaging assessment of native valvular regurgitation: an EACVI and ESC council of valvular heart disease position paper. *Eur Heart J Cardiovasc Imaging* 2022;**23**:e171-e232.
- Melillo F, Boccellino A, Ingallina G, Ancona F, Capogrosso C, Napolano A *et al.* Multimodality imaging for preprocedural planning of percutaneous mitral valve repair: a comprehensive review. *Mini-invasive Surg* 2020;**4**:81.
- Kamperidis V, Marsan NA, Delgado V, Bax JJ. Left ventricular systolic function assessment in secondary mitral regurgitation: left ventricular ejection fraction vs. speckle tracking global longitudinal strain. *Eur Heart J* 2016;**37**:811-816.
- Cavalcante JL, Kusunose K, Obuchowski NA, Jellis C, Griffin BP, Flamm SD *et al.* Prognostic impact of ischemic mitral regurgitation severity and myocardial infarct quantification by cardiovascular magnetic resonance. *JACC Cardiovasc Imaging* 2020;**13**:1489-1501.
- Sabbag A, Essayagh B, Ramirez Barrera JD, Basso C, Berni A, Cosyns B *et al.* EHRA Expert consensus statement on arrhythmic mitral valve prolapse and mitral annular disjunction complex in collaboration with the ESC council on valvular heart disease and the European association of cardiovascular imaging endorsed cby the heart rhythm society, by the Asia pacific heart rhythm society, and by the Latin American heart rhythm society. *Europace* 2022;**24**:1981-2003.
- Maisano F, Taramasso F. INTERVENTIONS FOR VALVULAR DISEASE AND HEART FAILURE. Percutaneous mitral valve leaflet repair: ongoing directions and future perspectives. *EuroIntervention* 2020;**16**:803-807.
- Feldman T, Foster E, Glower DD, Kar S, Rinaldi MJ, Fail PS *et al.* Percutaneous repair or surgery for mitral regurgitation. *N Engl J Med* 2011;**364**:1395-1406.
- Gavazzoni M, Maisano F, Tagliari AP, Taramasso M, Pozzoli A, Zuber M. Truevue transillumination volume rendering for three-dimensional transoesophageal echocardiography in interventional imaging. *J Cardiovasc Med (Hagerstown)* 2021;**22**:780-787.
- Grayburn PA, Sannino A, Packer M. Proportionate and disproportionate functional mitral regurgitation: A new conceptual framework that reconciles the results of the MITRA-FR and COAPT trials. *JACC Cardiovasc Imaging* 2019;**12**:353-362.
- Seeburger J, Rinaldi M, Nielsen SL, Salizzoni S, Lange R, Schoenburg M *et al.* Off- pump transapical implantation of artificial neo-chordae to correct mitral regurgitation: the TACT trial (Transapical artificial Chordae tendinae) proof of concept. *J Am Coll Cardiol* 2014;**63**:914-919.
- Vohra HA, Whistance RN, Roubelakis A, Burton A, Barlow CW, Tsang GM *et al.* Outcome after redo-mitral valve replacement in adult patients: a 10-year single-centre experience. *Interact Cardiovasc Thorac Surg* 2012;**14**:575-579.
- Yoon SH, Bleiziffer S, Latib A, Eschenbach L, Ancona M, Vincent F *et al.* Predictors of left ventricular outflow tract obstruction after transcatheter mitral valve replacement. *JACC Cardiovasc Interv* 2019;**12**:182-193.
- Guerrero M, Wang DD, Pursnani A, Eleid M, Khalique O, Urena M *et al.* A cardiac computed tomography-based score to categorize mitral annular calcification severity and predict valve embolization. *JACC Cardiovasc Imaging* 2020;**13**:1945-1957.
- Eleid MF, Whisenant BK, Cabalka AK, Williams MR, Nejjari M, Attias D *et al.* Early outcomes of percutaneous transvenous transseptal transcatheter valve implantation in failed bioprosthetic mitral valves, ring annuloplasty, and severe mitral annular calcification. *JACC Cardiovasc Interv* 2017;**10**:1932-1942.