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Review

Advanced Imaging in Transcatheter Cardiac Surgery: From Patient Selection to Outcome Prediction

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Abstract

Transcatheter cardiac surgery (TCS), which primarily comprises transcatheter aortic valve replacement (TAVR) and mitral transcatheter edge-to-edge repair (M-TEER), has transformed the treatment of valvular heart disease over the past two decades. Moreover, TAVR is now supported by robust randomized trial evidence across the surgical risk spectrum, establishing this technique as a cornerstone therapy for aortic stenosis. Moreover, M-TEER is gaining clinical relevance, with expanding registry and trial data further defining the role of this technique. Meanwhile, advanced imaging has become central to both TAVR and M-TEER, extending beyond diagnosis to patient selection, procedural planning, and risk assessment of complications. Furthermore, advanced imaging enhances procedural safety and improves short- and mid-term clinical outcomes by enabling accurate anatomical characterization, precise device sizing, and early detection of complications such as paravalvular leak or leaflet thrombosis. Echocardiography and computed tomography form the backbone of the preprocedural evaluations, whereas cardiac magnetic resonance and positron emission tomography provide complementary insights into myocardial pathology and prosthetic valve dysfunction. Imaging enables structured surveillance for paravalvular leak, leaflet thrombosis, recurrent regurgitation, and structural valve degeneration, all of which directly affect outcomes. However, despite considerable progress, important challenges persist, including limited evidence on the long-term durability of TAVR, a lack of standardized grading of residual mitral regurgitation after M-TEER, and the need to integrate right heart–pulmonary circulation assessments into decision-making. Recent innovations such as quantitative three-dimensional echocardiography, fusion imaging, and artificial-intelligence-based image analysis are expected to refine procedural planning further, reduce operator variability, and enable more predictive, patient-specific management. Nonetheless, multimodality imaging is slated to remain the cornerstone for lifetime management strategies in TCS.

Keywords: transcatheter cardiac surgery; imaging; transcatheter aortic valve replacement; mitral transcatheter edge-to-edge repair

1. Introduction

Over the past two decades, transcatheter cardiac surgery (TCS) has undergone remarkable evolution, transforming the management of valvular heart disease. Among these procedures, transcatheter aortic valve replacement (TAVR) is the most extensively studied. Multiple landmark randomized controlled trials have demonstrated the noninferiority of TAVR to surgical aortic valve replacement (SAVR) in high- and intermediate-risk populations, as well as its superiority in selected low-risk cohorts [1–8]. These results have led to broad guideline endorsement of TAVR across the surgical risk spectrum, establishing it as a cornerstone therapy in managing aortic stenosis (AS). In contrast, transcatheter interventions for the mitral valve remain at an earlier stage of evidence development. For treating mitral regurgitation (MR), the EVEREST II trial compared mitral transcatheter edge-to-edge repair (M-TEER) with surgery [9], while The Cardiovascular Outcomes Assessment of the MitraClip Percutaneous Therapy (COAPT) and MITRA-FR trials produced divergent findings regarding the efficacy of M-TEER in secondary MR, underscoring the importance of patient selection [10,11]. Taken together, these differences highlight that while TAVR has achieved clinical maturity, supported by robust validation, mitral interventions are still in an early phase of clinical adoption, with ongoing trials expected to shape their future role.

In this review, we focus on TAVR and M-TEER, the two TCS interventions with the strongest clinical evidence and broadest adoption. Other emerging techniques such as transcatheter mitral valve replacement (TMVR) are discussed only briefly in the context of future perspectives. By narrowing the scope of our discussion, we provide a focused appraisal of technological advances, clinical trial data, and challenges, with emphasis on the evolving role of multimodality imaging. To ensure a comprehensive and balanced overview, we primarily cited landmark randomized controlled trials published between 2010 and 2024, major international guidelines, and review articles from high-impact journals. Beyond anatomical characterization, imaging now guides patient selection, procedural planning, and complication prediction; imaging therefore shapes both short- and long-term outcomes. Additionally, we highlight the complementary role of cardiac surgery in patient selection, complication management, and hybrid strategies, reinforcing the concept that surgical and transcatheter therapies are not competing but complementary modalities in managing valvular heart disease.

2. TAVR

2.1 Historical Background, Expansion of Indications, and Device Platforms

Balloon aortic valvuloplasty (BAV), introduced in the late 1980s, was the first catheter-based therapy for severe AS [12]. Although it provided temporary hemodynamic improvement, restenosis occurred in over 50% of patients within one year, limiting its long-term efficacy [13]. Nevertheless, BAV laid the technical foundation for TAVR, which was first performed in humans in 2002 [1].

Initial randomized controlled trials, including PARTNER 1 and CoreValve High Risk, demonstrated the noninferiority of TAVR compared with SAVR in patients with an inoperable condition and those at high risk [2,3,14]. Subsequent trials (PARTNER 2A, SURTAVI) expanded the indications to intermediate-risk populations [4,5], while PARTNER 3 and Evolut Low Risk confirmed excellent outcomes in selected low-risk cohorts, with one-year mortality and stroke rates as low as 1–2% [6,7]. These results led to guideline endorsement of TAVR across all surgical risk categories and shifted decision-making toward anatomical suitability, age, and life expectancy.

The currently available devices are broadly categorized into balloon-expandable valves (BEVs) and self-expanding valves (SEVs). BEVs are associated with lower rates of paravalvular leak (PVL) and permanent pacemaker implantation (PPI), while SEVs provide larger effective orifice areas and lower transvalvular gradients [15–17]. Device selection requires careful assessment of annular dimensions, coronary ostial height, calcium distribution, vascular access, and the feasibility of future coronary re-access, primarily using computed tomography (CT) [18].

The stepwise imaging workflow for TAVR is summarized in Fig. 1 before detailing modality-specific roles.

The roles of different imaging modalities across the TAVR continuum are summarized in Table 1.

2.2 Imaging for Procedural Planning

Multimodality imaging plays a central role in TAVR planning, guiding indications, access strategy, and device selection.

2.2.1 Assessment of Procedural Indication

Transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE) are fundamental for confirming severe AS, defined using an aortic valve area (AVA) <1.0 cm^2, mean gradient >40 mmHg, or peak velocity >4.0 m/s [19–21] (Table 2). In reduced ejection fraction, dobutamine stress echocardiography (DSE) is useful for distinguishing true AS from pseudo-severe AS through assessment of contractile reserve. An increase in stroke volume $\geq$20% with an AVA remaining ≤1.0 cm^2 and high gradients indicate true severe AS, whereas an AVA >1.0 cm^2 suggests pseudo-severe AS [22]. In patients without contractile reserve, differentiation is challenging. In such cases, CT-derived calcium scoring can provide valuable diagnostic information. However, in suspected LFLG AS, CT-AVC alone poorly discriminates between moderate and severe disease and cannot replace DSE [23,24]. While absent contractile reserve has historically been associated with poor post-SAVR outcomes, recent data suggest that it may not significantly influence prognosis following TAVR [25].

2.2.2 Access Route Evaluation

CT is the gold standard for vascular access assessment [18]. A minimum iliofemoral diameter of 5.5–6.0 mm is generally required, with attention to calcification and tortuosity [26]. In patients unsuitable for transfemoral access, CT also guides consideration of alternative routes. For subclavian (or axillary) access, vessel diameters of at least 5.5–6.0 mm are generally required, while $\geq$7.0 mm is preferred to accommodate larger delivery systems, with additional attention to circumferential calcification and clavicular proximity [27,28]. For transcarotid access, CT allows measurement of carotid diameters and evaluation of calcification and tortuosity, often complemented by duplex ultrasound to assess cerebral circulation. A minimal lumen diameter of $\geq$5.5–6.0 mm is typically required, with $\geq$6–7 mm offering greater safety margins [29]. In contrast, transapical and transaortic approaches are now considered primarily obsolete options because of their higher invasiveness and complication rates [30]. Nevertheless, CT remains important to identify a safe puncture site, ensuring sufficient myocardial thickness and evaluating ascending aortic dimensions and calcification. While no fixed threshold exists, cross-sectional imaging helps avoid apical regions with thinning or scarring. Cardiac magnetic resonance (CMR) data suggest that left ventricular (LV) wall thickness <11 mm is normal, whereas values >11 mm indicate hypertrophy, though these are general cardiology norms rather than TAVI-specific cutoffs [31].

Thus, multimodality imaging not only determines the feasibility of transfemoral access but also provides route-specific information essential to the safe performance of alternative access strategies. Intravascular lithotripsy (IVL) has recently emerged as a valuable adjunct in heavily calcified iliofemoral disease. IVL can expand the feasibility of transfemoral TAVR by modifying severely calcified access vessels. Although patients undergoing IVL-assisted TAVR generally present with higher baseline risk, registry and nationwide data demonstrate high procedural success and acceptable short-term outcomes [32].

2.2.3 Device Selection

Device selection relies on CT measurements of annular dimensions, the sinus of Valsalva, and coronary ostial height to determine the appropriate device type and size [18]. Predictable complication risks, such as PVL, conduction disturbances requiring PPI, and coronary obstruction, should be considered when selecting the device, as is dis-

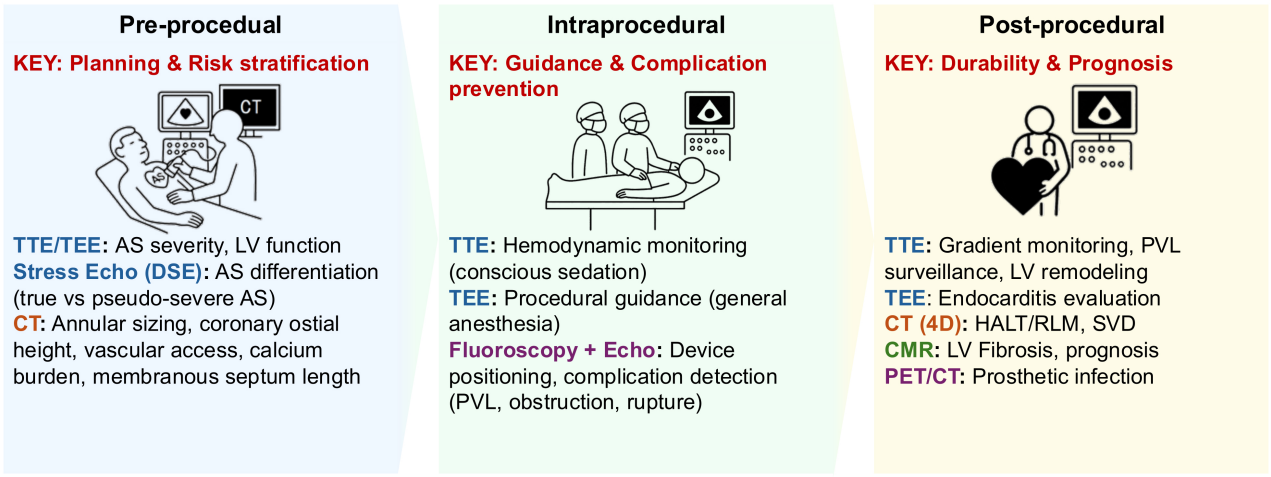

Fig. 1. Imaging workflow for transcatheter aortic valve replacement (TAVR). Multimodality imaging guides every procedural phase, from preprocedural CT-based annular sizing and vascular access assessment, to intraprocedural TEE (under general anesthesia) or TTE (under conscious sedation) guidance, as well as postprocedural surveillance for paravalvular leak (PVL) or leaflet thrombosis. Abbreviations: TTE, transthoracic echocardiography; TEE, transesophageal echocardiography; DSE, dobutamine stress echocardiography; CT, computed tomography; PVL, paravalvular leak; CMR, cardiac magnetic resonance; PET, positron emission tomography. Key takeaway: Accurate preprocedural CT planning and real-time echocardiographic guidance are critical for procedural safety and optimal valve function.

cussed in subsequent sections. This section focuses on common imaging-based criteria, including CT-derived annular dimensions and anatomical risk factors; therefore, device-specific comparisons are not included.

2.3 Imaging in Complication-Risk Assessment

Despite technological advances, TAVR remains associated with specific complications. Imaging plays a central role in risk stratification, early detection, and prevention of these events. During TAVR performed under general anesthesia, intraoperative TEE is indispensable for confirming prosthesis positioning, assessing immediate valve function, and detecting early complications such as PVL, pericardial effusion, or annular injury. In contrast, in procedures performed under conscious sedation, TTE is typically used for rapid hemodynamic assessment, although its diagnostic resolution for subtle complications is limited compared with TEE (Table 3).

2.3.1 Coronary Obstruction Risk

Although rare (0.5–1%), coronary obstruction is associated with a high risk of early mortality (>40%) [33]. Risk is determined based on not only coronary height but also anatomical features, including cusp height relative to the ostium, a virtual valve-to-coronary distance (VTC) $\leq$4 mm, and leaflet calcium volume >600 mm^3 [34,35]. Effaced sinuses markedly increase risk, while adequate sinus size may mitigate the impact of low coronary height [35,36]. Cusp length exceeding coronary height and reduced residual sinus width are additional predictors, with models combining these factors (cusp length > coronary height plus VTC $\leq$4 mm or leaflet calcium volume >600 mm^3) achieving high sensitivity, though reduced on external validation [37].

In TAV-in-TAV, the incidence of coronary obstruction has been lower than initially anticipated, likely because of rigorous screening and careful patient selection. A distinctive concern is the formation of a neo-skirt, created by the displaced host transcatheter heart valve (THV) leaflets against the new frame; if this skirt extends above the sinotubular junction (STJ), it may cause sinus sequestration. The height of the neo-skirt depends on host leaflet length, the type of the index THV, and the implantation depth of the new valve. In addition to VTC, CT-based measurement of the virtual THV-to-STJ distance has been proposed for risk stratification, with <3.5 mm suggested as a high-risk threshold. However, the supporting evidence for the virtual THV-to-STJ distance remains less robust than for VTC, and further validation is required [38].

2.3.2 PVL

Although the incidence of moderate or severe PVL has markedly declined with newer-generation valves, it remains strongly associated with increased mortality and heart failure hospitalization [6,39,40]. Preprocedural CT plays a preventive role by identifying anatomic risk factors such as annular ellipticity, high annular or LV outflow tract (LVOT) calcium burden (>300 mm^3), and asymmetric calcium distribution, which predispose to malapposition and PVL [41]. These risks are particularly influenced by annular size and geometry, with both very small and very large annuli posing specific challenges [42–44]. Intraprocedurally, echocardiography is the primary tool for real-time detection and grad-

Table 1. Comparative imaging roles in TAVR and M-TEER workflows.

Imaging modality	Preprocedural planning	Intraprocedural guidance	Postprocedural follow-up
TTE		TAVR	
	Screening for AS severity; assessment of LV function and remodeling	Used during conscious sedation or monitored anesthesia care TAVR for immediate hemodynamic and valve function evaluation; however comprehensive PVL grading and complication screening are more accurate with TEE under general anesthesia	First-line modality for PVL surveillance, LV remodeling, prosthetic valve gradients, prosthetic valve thrombosis suspicion
		M-TEER	
	Screening for MR severity; LV function and remodeling assessment	Not primary	Evaluation of MR recurrence, LV remodeling, and prosthetic valve gradients
STE (DSE/Exercise)		TAVR (DSE)	
	To differentiate between true and pseudo-severe AS (assessment of contractile reserve)	Not routinely used	Not routinely used
		M-TEER (Exercise)	
	Assessing MR dynamic (exercise-induced PH), optimal timing for intervention	Not routinely used	Not routinely used
TEE		TAVR	
	Optional for TAVR under general anesthesia	Primarily used during TAVR under general anesthesia; enables real-time valve deployment guidance, PVL assessment, and detection of procedural complications	Evaluation of prosthetic valve endocarditis
		M-TEER	
	Mechanistic assessment of MR (primary vs. secondary); evaluation of anatomical suitability for M-TEER	Essential for M-TEER — device navigation, leaflet grasping, and residual MR	Quantification of residual MR; evaluation of prosthetic valve endocarditis
ICE		TAVR and M-TEER	
	Not routinely used; alternative to TEE if it is contraindicated (e.g., esophageal disease)	Emerging role as an alternative to TEE for intraprocedural guidance	Limited postprocedural use
CT, 3D/4D		TAVR	
	Gold standard for annular sizing, coronary ostial height, vascular access route, and calcium quantification; quantification of aortic valve calcium score for differentiation of true vs. pseudo-severe AS	Adjunct to fluoroscopy (fusion imaging, experimental use)	HALT/RLM detection; prosthetic degeneration; evaluation of IE complications and coronary access planning for redo-TAVR
		M-TEER	
	Comprehensive assessment of mitral annular dimensions and nonplanarity, subvalvular anatomy including chordae and papillary muscles, and neo-LVOT area prediction through 3D reconstruction	Adjunct to fluoroscopy (fusion imaging, experimental use)	Not routinely used

Table 1. Continued.

Imaging modality	Preprocedural planning	Intraprocedural guidance	Postprocedural follow-up
CMR	TAVR and M-TEER		
	Assessment of LV/RV function and myocardial fibrosis (LGE, ECV)	Not used intraprocedurally	Prognostic evaluation of fibrosis burden and ventricular remodeling
	M-TEER		
	MR quantification		
PET/CT	TAVR and M-TEER		
	Not routinely used	Not used intraprocedurally	High sensitivity for detection of prosthetic valve endocarditis and perivalvular infection

Abbreviations: TAVR, transcatheter aortic valve replacement; M-TEER, mitral transcatheter edge-to-edge repair; TTE, transthoracic echocardiography; STE, stress echocardiography; DSE, dobutamine stress echocardiography; TEE, transesophageal echocardiography; ICE, intracardiac echocardiography; CT computed tomography; 3D, three-dimensional; 4D, four-dimensional; CMR, cardiac magnetic resonance; PET, positron emission tomography; AS, aortic stenosis; LV, left ventricular; PVL, paravalvular leak; MR, mitral regurgitation; PH, pulmonary hypertension; HALT, hypo-attenuated leaflet thickening; RLM, reduced leaflet motion; IE, infective endocarditis; LVOT, left ventricular outflow tract; RV, right ventricular; LGE, late gadolinium enhancement; ECV, extracellular volume.

Table 2. Key echocardiographic and CT parameters for TAVR.

Parameter	Thresholds/Criteria	Context	Reference imaging modality
AS	AVA <1.0 cm^2, mean PG >40 mmHg, peak velocity >4.0 m/s	Definition of severe AS	TTE/TEE
Low-flow, low-gradient AS	DSE $\rightarrow$ ΔSV $\geq$20% with AVA ≤1.0 cm^2 and mean PG >40 mmHg indicates true severe AS	Differentiation between true and pseudo-severe AS	Stress Echo (DSE)
CT calcium scoring	Agatston score: >2000 (men), >1200 (women)	Supportive criterion for diagnosing true severe AS in low-flow states	CT

Abbreviations: AS, aortic stenosis; CT, computed tomography; AVA, aortic valve area; PG, pressure gradient; TTE, transthoracic echocardiography; TEE, transesophageal echocardiography; DSE, dobutamine stress echocardiography; SV, stroke volume.

Table 3. Imaging markers for risk stratification in TAVR.

Complication	Imaging marker(s)	Modality	Clinical implication
PVL	Annular ellipticity, asymmetric LVOT/annular calcium (>300 mm^3), small annulus	CT, TTE/TEE	Predictor of malapposition; associated with increased HF hospitalization and mortality
Coronary obstruction	Low coronary ostial height ($<$10–12 mm), cusp height $>$ ostial height, valve-to-coronary distance ≤4 mm, bulky leaflet calcium (>600 mm^3)	CT	High early mortality ($>$40%); prevention with BASILICA or coronary-protection strategies
Annular rupture	Localized annular calcium, ellipticity, prosthesis oversizing	CT	Rare but catastrophic; influences device type (BEV vs SEV) and sizing
Conduction disturbances/PPI	Short membranous-septum length (<4 mm), deep implantation depth	CT	Higher PPI rate with SEV; preprocedural CT can guide implantation depth
Stroke	Aortic-arch atheroma, bulky valve calcium, embolic debris	CT, TEE, MRI (DWI)	Occurs in 1–2% of cases; related to atheroma or debris; selective cerebral protection may reduce lesion burden

Abbreviations: PVL, paravalvular leak; PPI, permanent pacemaker implantation; LVOT, left ventricular outflow tract; CT, computed tomography; TTE, transthoracic echocardiography; TEE, transesophageal echocardiography; HF, heart failure; BEV, balloon-expandable valve; SEV, self-expandable valve; MRI, magnetic resonance imaging; DWI, diffusion-weighted imaging.

ing of PVL [45], guiding corrective measures such as additional balloon post-dilatation or, in selected cases, vascular plug implantation [46–48]. Accordingly, a combined strategy of CT-based preprocedural risk stratification and intraprocedural echocardiographic monitoring is essential to minimize the incidence and clinical impact of PVL. Given

its prognostic weight, standardized postprocedural surveillance is required.

2.3.3 Annular Rupture

Eccentric calcification and annular ellipticity increase the likelihood of annular rupture, especially in the setting of TAVR with BEVs, where excessive prosthesis oversizing, heavy and asymmetric calcium burden, and elliptical root geometry are major contributors [49–52]. Preprocedural multidetector CT should evaluate not only global calcium burden but also the regional distribution and protrusion of subannular/LVOT nodules—especially beneath the noncoronary cusp—which, together with excessive BEV oversizing, markedly increases the risk of annular injury [18,53]. Emerging regional calcium metrics and patient-specific simulations may further refine rupture-risk estimation and inform strategies such as cautious balloon underfilling or device downsizing [54].

2.3.4 Conduction Disturbances and PPI

The need for PPI remains higher with SEVs (10–15%) than with BEVs (5–8%) [55,56]. A short membranous septum length (<4 mm) increases the risk of PPI [57,58]. CT-based assessment of implantation depth helps minimize conduction abnormalities. Recent CT-based studies emphasize that the difference between membranous septum length and implantation depth is a key predictor of post-TAVR conduction disturbances [59].

2.3.5 Stroke

Stroke occurs in 1–2% of cases [60]. Predictors include heavy valve calcification and aortic-arch atheroma [61]. Diffusion-weighted magnetic resonance imaging frequently detects silent embolic lesions [62], and the use of cerebral embolic-protection devices can reduce total lesion burden. However, consistent improvements in clinical outcomes have not yet been demonstrated [63].

Summary of imaging-based strategies to minimize procedural complications:

- Coronary obstruction: Perform detailed CT analysis of coronary height, sinus width, cusp length, and leaflet calcium volume. Calculate both virtual VTC and virtual THV-to-STJ distances, and use virtual-valve simulation to visualize potential obstruction.
- PVL: Evaluate annular ellipticity and LVOT/annular calcium distribution using CT. During implantation, confirm valve expansion and sealing with real-time TEE/TTE, and grade residual PVL to guide post-dilatation or plug placement.
- Annular rupture: Assess both global and regional calcium burden and subannular protrusions on CT, particularly beneath the noncoronary cusp. Avoid >20% oversizing in heavily calcified or asymmetric roots, and consider CT-based virtual simulation before deployment.
- Conduction disturbances: Measure membranous septum length and implantation depth on CT to predict conduction risk. For short septum (<4 mm), consider higher implantation or BEV use; verify final depth with fluoroscopy and echo correlation.
- Stroke: Evaluate aortic-arch atheroma and bulky valve calcium on CT or TEE and employ cerebral protection selectively in high-risk anatomy.

2.4 Imaging in Postprocedural Follow-up

Structured imaging follow-up is essential for early detection of complications and monitoring long-term outcomes after TAVR. Each imaging modality has specific strengths, and a multimodality approach provides the most comprehensive assessment of prosthetic valve function and cardiac remodeling.

2.4.1 PVL

Follow-up focuses on using structured TTE to quantify PVL severity and its hemodynamic impact; cardiac CT is reserved for delineating mechanisms (e.g., malapposition, calcification bridging) when echocardiography is inconclusive.

2.4.2 Patient–prosthesis Mismatch (PPM)

PPM is defined as an indexed effective orifice area (EOA) that is too small relative to the patient's body surface area, resulting in higher-than-expected transvalvular gradients despite normally functioning prosthetic leaflets. According to established criteria, PPM is classified as moderate when the indexed EOA is <0.85 cm^2/m^2 and severe when it is <0.65 cm^2/m^2 [64]. PPM causes persistent LV pressure overload, limits reverse remodeling, and has consistently been associated with reduced survival after valve replacement [65]. It occurs more frequently in patients with small annuli and in valve-in-valve procedures [66–68]. Compared with SAVR, TAVR generally achieves larger EOA and lower PPM incidence, as shown in multiple meta-analyses [69]. Conversely, SAVR offers the possibility of annular or root enlargement, which can mitigate PPM risk in selected patients [70]. Imaging follow-up with echocardiography allows serial quantification of gradients and EOA, supplemented by CT when anatomical clarification is required.

2.4.3 Subclinical Leaflet Thrombosis [Hypo-Attenuated Leaflet Thickening (HALT)/Reduced Leaflet Motion (RLM)]

Subclinical leaflet thrombosis after bioprosthetic valve implantation is most often detected using 4D-CT as HALT; it histologically corresponds to fibrin or thrombus deposition on valve leaflets. This structural change may result in RLM, a functional correlation that can lead to increased transvalvular gradients or, less frequently, thromboembolic complications [71]. HALT is observed in 10–40% of patients after TAVR and is often reversible with anticoagulation, although its management remains controver-

sial because of bleeding risks [72]. Similar findings have been described after SAVR, but at lower frequencies and with a less well-defined clinical impact than that seen after TAVR [73].

2.4.4 Infective Endocarditis (IE)

IE after TAVR occurs at an annual incidence of 0.3–1.2%, similar to that observed after SAVR [74]. However, differences exist in pathogen distribution, therapeutic options, and prognosis [75]. TAVR-associated IE is particularly difficult to treat surgically and is associated with higher mortality [76]. Therefore, early and accurate imaging is essential. Although TTE has limited sensitivity, TEE, contrast-enhanced CT, and PET/CT provide complementary value for detecting prosthetic complications, highlighting the importance of multimodality imaging in this setting.

2.4.5 Structural Valve Degeneration (SVD)

Long-term durability remains a central concern. SVD manifests as leaflet thickening, calcification, or stent-frame deformation. CT enables early recognition of these changes, facilitating timely decision-making regarding reintervention, including repeat TAVR or surgery. Compared with SAVR, long-term data beyond 10 years for TAVR remain limited. Some studies suggest higher rates of subclinical degeneration in transcatheter valves, whereas surgical bioprostheses benefit from longer follow-up experience [77]. Therefore, ongoing multimodality imaging surveillance is critical to clarify durability differences and guide optimal reintervention strategies.

2.4.6 LV Function

The reduction in afterload achieved with TAVR directly leads to improvements in LV function [78]. During follow-up, assessing sensitive parameters such as global longitudinal strain (GLS) and LV mass index (LVMI) is important, in addition to assessing conventional LV ejection fraction (LVEF). Echocardiography, owing to its simplicity, noninvasiveness, and feasibility for repeated assessments, is the most practical modality for monitoring longitudinal changes in GLS and LVMI. Patients who demonstrate improvement in these parameters after TAVR generally have better long-term outcomes, whereas those with limited improvement often have residual fibrosis or diastolic dysfunction, which are associated with an increased risk of heart failure and mortality [79,80]. Moreover, reduced preprocedural GLS and the presence of myocardial fibrosis on CMR, assessed using late gadolinium enhancement (LGE) or elevated extracellular volume, are independent predictors of adverse outcomes. These parameters provide valuable information for risk stratification and the likelihood of functional recovery [81,82]. In addition, positron emission tomography (PET) has emerged as a complementary modality for assessing myocardial viability and metabolic activity, particularly in patients with coexisting coronary artery disease. These applications may enhance prognostic risk stratification and inform postprocedural management, although evidence in TAVR-specific populations remains limited [83]. Therefore, comprehensive follow-up of LV function is essential for prognostication and risk assessment.

2.5 Current Challenges and Future Perspectives

2.5.1 Durability and Long-term Management

With the expansion of TAVR indications to younger and lower-risk populations, long-term durability has emerged as the foremost challenge. Evidence beyond 10 years remains limited, and surgical explantation after TAVR carries substantial perioperative risk, with reported mortality rates of 10–15% [84–86]. Beyond durability concerns and subclinical leaflet thrombosis (HALT/RLM), discussed in Sections 2.4.3 and 2.4.5, long-term management requires systematic imaging surveillance and individualized antithrombotic strategies tailored to each patient's risk profile. Standardized definitions of SVD and consensus on imaging-based follow-up intervals will be essential to ensure consistent assessment of valve durability in the coming decade.

2.5.2 Lifetime Management and Reintervention Strategy

Beyond these durability-related issues, lifetime management has emerged as a central concept, particularly for younger patients with a longer life expectancy [87,88]. Imaging-guided procedural planning is therefore critical not only for selecting the optimal device and access route but also for anticipating the feasibility of future reinterventions, such as valve-in-valve TAVR or surgical explantation. Furthermore, bicuspid aortic valves remain a distinct challenge because of their heterogeneous anatomy, underscoring the importance of careful patient selection and tailored procedural strategies [89,90]. Comprehensive lifetime planning, supported by CT-based modeling and risk stratification, will help preserve reintervention options and optimize outcomes throughout the patient's treatment continuum.

2.5.3 Emerging Imaging Technologies

Recent advances in quantitative 3D echocardiography, fusion imaging, and artificial intelligence (AI) are reshaping procedural planning and surveillance in TAVR. AI-based segmentation and automated annular measurements achieve >95% agreement with expert analyses, markedly reducing interobserver variability [91]. Fusion platforms integrating CT or 3D ultrasound with fluoroscopy reach achieve registration errors of <5 mm, improving spatial orientation and potentially reducing contrast use [92]. Patient-specific 3D printing and virtual simulation demonstrate approximately 80–90% concordance with *in vivo* device sizing in TAVR while achieving higher (>90%) agreement in other structural applications; however, prospective multicenter validation in TAVR remains warranted [93].

2.5.4 Future Outlook

In the coming years, integrating multimodality imaging into standardized lifetime management algorithms encompassing procedural planning, risk stratification, structured follow-up, and neuro-protection strategies will be essential to ensure long-term valve durability and optimize outcomes across decades of patient life expectancy. Nevertheless, major uncertainties persist regarding valve durability beyond 10 years, the optimal antithrombotic strategy for subclinical leaflet thrombosis (HALT/RLM), and the role of cerebral embolic protection during transcatheter valve implantation. Ongoing clinical trials in these domains are anticipated to clarify their clinical impact such as the PROTECTED TAVR study for stroke prevention [83]. Future advancement will depend on integrating emerging imaging tools, clinical data, and multidisciplinary collaboration to achieve truly personalized and durable transcatheter valve therapy.

While TAVR has established the paradigm for transcatheter valve replacement, its success has also accelerated the development of repair-based interventions for the mitral valve. Many of the imaging concepts refined in TAVR—such as CT-based annular sizing and echocardiographic guidance—have been adapted to M-TEER. The following section highlights the distinct imaging challenges and evolving role of multimodality imaging in transcatheter mitral repair.

3. M-TEER

3.1 Historical Background, Expansion of Indications, and Device Platforms

The mitral valve poses unique anatomical and functional challenges for transcatheter intervention because of its saddle-shaped annulus and subvalvular apparatus. The M-TEER technique, inspired by the surgical Alfieri stitch [94], was first performed in humans in 2003 and commercially introduced in 2008 with the MitraClip system [95,96]. Initially reserved for patients at high risk or those with an inoperable condition with severe MR, M-TEER rapidly gained acceptance; this progress is supported by registry data demonstrating symptomatic improvement and reduced heart failure hospitalizations [97].

Randomized evidence has further influenced the role of M-TEER. The EVEREST II trial compared M-TEER with surgery in patients with primary MR, showing superior safety, but higher rates of residual MR [9]. More recently, the COAPT and MITRA-FR trials assessed M-TEER in secondary MR, yielding divergent outcomes that underscored the importance of careful patient selection and optimization of medical therapy [10,11]. Current guidelines now recommend M-TEER for symptomatic patients with severe primary MR at prohibitive surgical risk and for selected patients with secondary MR who remain symptomatic despite guideline-directed medical therapy [19–21].

Device technology has also evolved. The MitraClip platform has expanded to include multiple clip sizes and configurations, enabling treatment of complex anatomies and multijet regurgitation [98,99]. In addition, the PASCAL system, incorporating features such as a central spacer and independent leaflet grasping, has emerged as an alternative; early studies have demonstrated comparable safety and efficacy [98,100]. These advances in device platforms, together with growing clinical evidence, continue to broaden the applicability of M-TEER across diverse populations with MR.

To provide an overview of the imaging workflow in M-TEER, we have summarized the stepwise process in Fig. 2 before detailing modality-specific roles.

The imaging markers for risk stratification in M-TEER–related complications are summarized in Table 4.

3.2 Imaging for Procedural Planning

Multimodality imaging is central to procedural planning for M-TEER, guiding patient selection, anatomical suitability, and device strategy (Table 5).

3.2.1 Baseline Severity and Mechanism of MR

TTE and TEE are essential for confirming severe MR and differentiating between primary and secondary etiologies. Quantitative parameters include effective regurgitant orifice area (EROA $\geq$0.40 cm^2), regurgitant volume ($\geq$60 mL), and vena contracta width [19–21]. Three-dimensional (3D) TEE provides detailed leaflet morphology and facilitates assessment of prolapse, flail, or tethering mechanisms. However, the proximal isovelocity surface area (PISA) method has important limitations, particularly in secondary MR, where elliptical or crescentic orifices and low-flow states can lead to substantial underestimation of regurgitant severity. Therefore, values of EROA and regurgitant volume derived from PISA, as well as single-plane vena contracta width, should always be interpreted within the context of an integrative multiparametric assessment [19–21].

The mechanism of MR provides critical insights for both prognosis and therapeutic decision-making [101–103].

Primary (degenerative/organic) MR arises from structural abnormalities of the mitral valve apparatus, such as prolapse, flail, chordal rupture, or leaflet thickening/calcification.

Secondary (functional) MR results from adverse ventricular or atrial remodeling, including papillary muscle displacement, leaflet tethering, annular dilatation, or atrial enlargement, typically in the setting of LV dysfunction or atrial fibrillation.

Mixed MR refers to cases in which organic or structural valve abnormalities (e.g., degenerative changes or prolapse) coexist with functional mechanisms related to ventricular or atrial remodeling. This phenotype is increasingly recognized in clinical practice and may present unique ther-

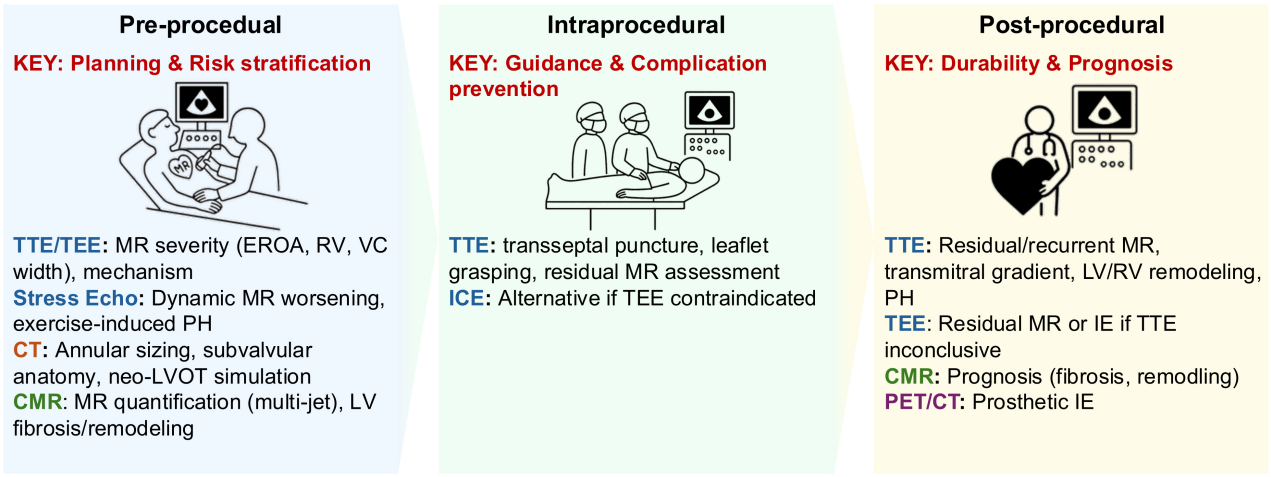

Fig. 2. Imaging workflow for M-TEER. Echocardiographic and CT integration enables patient selection, device orientation, and assessment of leaflet grasping and residual mitral regurgitation. Intraprocedural TEE provides real-time spatial guidance. Abbreviations: TTE, transthoracic echocardiography; TEE, transesophageal echocardiography; MR, mitral regurgitation; CT, computed tomography; CMR, cardiac magnetic resonance; ICE, intracardiac echocardiography; PET, positron emission tomography; LV, left ventricle; RV, right ventricle; IE, infective endocarditis. Key takeaway: Comprehensive multimodality imaging, particularly TEE, enhances clip positioning accuracy and ensures durable MR reduction.

Table 4. Imaging markers for risk stratification in M-TEER.

Complication	Imaging marker(s)	Modality	Clinical implication
Residual MR	Multiple eccentric or wall-impinging jets, high transmitral gradient, pulmonary vein flow reversal	TTE/TEE, CMR (if echo inconclusive)	Prediction of adverse outcomes (mortality, HF hospitalization)
LAE (SLDA, tear, embolization)	Incomplete leaflet grasp (<5 mm insertion), asymmetric capture, calcified leaflet, excessive traction	CT (preprocedural), TTE/TEE	Major cause of recurrent MR and reintervention; early detection enables re-grasping or surgical retrieval
Iatrogenic mitral stenosis	Mean gradient >5 mmHg, small baseline MVA (<4.0 cm^2)	CT (preprocedural), TTE/TEE	Association with persistent symptoms and HF rehospitalization
iASD	Persistent color Doppler shunt; bubble study	TTE/TEE	Worsening of symptoms in PH/RV dysfunction; indication for closure if clinically significant
LVOT obstruction	Small LV cavity, basal septal hypertrophy, aortomitral angulation	CT (preprocedural), TTE/TEE	Rare complication (<1%); requirement for prompt Doppler recognition and correction
Cardiac tamponade/hemopericardium	Pericardial effusion during transseptal puncture or catheter manipulation	TTE/TEE	Life-threatening event (0.5–1%); requires immediate pericardiocentesis
Stroke/systemic embolism	Pre-existing LA and LAA thrombus, aortic arch atheroma, air, or device debris	TEE (pre/intraprocedural); CT (preprocedural), MRI (DWI, postprocedural)	Embolic event (1–2%); prevention through screening for LA and LAA thrombus and adequate anticoagulation (ACT >250–300 s)

Abbreviations: MR, mitral regurgitation; LAE, leaflet adverse events; SLDA, single-leaflet device attachment; iASD, iatrogenic atrial septal defect; LVOT, left ventricular outflow tract; TTE, transthoracic echocardiography; TEE, transesophageal echocardiography; CMR, cardiac magnetic resonance; HF, heart failure; CT, computed tomography; PH, pulmonary hypertension; RV, right ventricular; LV, left ventricular; LA, left atrial; LAA, left atrial appendage; MRI, magnetic resonance imaging; DWI, diffusion-weighted imaging; ACT, activated clotting time; MVA, mitral valve area.

Table 5. Key echocardiographic and CT parameters for M-TEER.

Parameter	Thresholds/Criteria	Context	Reference imaging modality
MR severity	EROA $\geq$0.40 cm^2, regurgitant volume $\geq$60 mL (standard criteria for severe MR; may underestimate severity in secondary MR)	Definition of severe MR	TTE/TEE
Vena contracta width	$\geq$7 mm (primary MR), $\geq$6 mm (secondary MR)	Supportive severity parameter	TTE/TEE
Pulmonary vein flow	Systolic flow reversal	Surrogate marker of severe MR	TEE
Exercise-induced MR (STE)	Exercise-induced MR severity (ΔEROA $\geq$0.13 cm^2) or PASP $>$55–60 mmHg	Prognostic marker and timing of intervention	STE
Anatomical suitability – EVEREST	Coaptation length $\geq$2 mm, coaptation depth $<$11 mm, flail gap $<$10 mm	Classic feasibility criteria for M-TEER	TEE
Anatomical suitability – posterior leaflet	$\geq$7 mm	Additional criterion for M-TEER feasibility	TEE
Annular assessment	Annular dimensions/neo-LVOT simulation	Suitability for M-TEER and future TMVR planning	CT

Abbreviations: MR, mitral regurgitation; STE, stress echocardiography; EROA, effective regurgitant orifice area; TTE, transthoracic echocardiography; TEE, transesophageal echocardiography; PASP, pulmonary artery systolic pressure; M-TEER, mitral transcatheter edge-to-edge repair; 3D, three-dimensional; LVOT, left ventricular outflow tract; TMVR, transcatheter mitral valve replacement; CT, computed tomography.

apeutic challenges, as both components contribute to severity and may respond differently to surgical or transcatheter interventions.

Recognition of these categories is essential for guiding patient selection, anatomical suitability assessment, and device strategy in M-TEER.

3.2.2 Indications for M-TEER

Current guideline-based indications for M-TEER are derived from the accumulated trial evidence and registry experience summarized above (Table 4).

For primary (degenerative) MR, surgical repair remains the standard of care. M-TEER is considered appropriate in patients with severe symptomatic MR who are at prohibitive or high surgical risk, provided that their anatomy is suitable. The 2021 ESC/EACTS and 2020 ACC/AHA guidelines assign this a Class IIa recommendation (Level of Evidence B) [19,20].

For secondary MR, guideline-directed medical therapy (GDMT) and device-based heart-failure management remain first-line treatment options. In patients with severe MR who remain symptomatic despite GDMT, M-TEER may be considered if anatomy is favorable. Current guidelines endorse M-TEER for selected patients as Class IIa, Level of Evidence B [19,20].

The Japanese Circulation Society (JCS 2020) guidelines similarly acknowledge M-TEER as an option for symptomatic patients at high risk with severe primary MR and for patients with secondary MR whose symptoms persist despite GDMT [21].

3.2.3 Timing of Intervention: Prognostic Role of Stress Echocardiography

Stress echocardiography (STE) refines the timing of intervention in MR by unmasking latent severity and providing prognostic information beyond resting evaluation [104].

Exercise STE increases the venous return, heart rate, and afterload. In primary MR, this augments regurgitant volume across a fixed orifice, whereas in secondary MR, LV dilatation and rising systolic pressures exacerbate leaflet tethering, dynamically enlarging the EROA and regurgitant volume [105,106]. Exercise-induced pulmonary hypertension is a strong prognostic marker: in asymptomatic degenerative MR, a pulmonary artery systolic pressure (PASP) $>$56–60 mmHg predicted symptom onset (hazard ratio 3.4), with a two-year symptom-free survival of 35%, compared with 75% in patients without pulmonary hypertension [107,108].

DSE predominantly enhances inotropy and heart rate while reducing LV end-systolic volume. In secondary MR, regurgitation may decrease if contractile reserve improves leaflet coaptation, whereas in advanced disease with poor reserve, MR may worsen because of rising systolic pressures against a tethered apparatus [105,109,110]. A dynamic increase in MR severity during stress, particularly a ΔEROA $\geq$0.13 cm^2, independently predicts cardiac death, while a decrease in MR under stress is generally associated with favorable outcomes [110,111].

Other approaches, such as passive leg raise, lower-limb compression, or handgrip exercise, have been explored in selected cases but remain less standardized in clinical practice [112–114].

Long-term studies consistently demonstrate that dynamic worsening of MR during stress is associated with increased risks of heart failure-related hospitalization and mortality. Current guidelines recommend STE when the symptoms and resting severity are discordant. The 2021 ESC/EACTS guidelines note that a resting PASP $>$50 mmHg, if confirmed invasively when it is the sole finding, supports earlier intervention in asymptomatic severe primary MR [20]. When STE reveals significant MR worsening, exercise-induced pulmonary hypertension, or disproportionate symptoms, earlier referral for intervention should be considered within a Heart Team framework that integrates LV and atrial remodeling, rhythm status, and reparability.

3.2.4 Anatomical Suitability

TEE remains the gold standard for assessing anatomical suitability for M-TEER. The classic "German/EVEREST" thresholds—coaptation length $\geq$2 mm, coaptation depth $<$11 mm, and flail gap $<$10 mm—still provide a practical framework. Contemporary experience shows that complex anatomies can be successfully treated with modern devices and experienced operators [97,115]. Short posterior leaflet length ($<$7 mm) and severe leaflet or annular calcification remain markers of procedural complexity [116], whereas broader clip portfolios and spacer-equipped systems have expanded feasibility for broad prolapse segments and multi-jet regurgitation [98,100].

Device platforms also differ in their adaptation to anatomy. Both current systems (MitraClip G4 and PASCAL) allow independent leaflet grasping; PASCAL additionally incorporates a central spacer that can bridge large coaptation gaps [117], while MitraClip offers multiple arm lengths and widths (e.g., NTR/XTR; NTW/XTW) that help address thick leaflets and wide jets. Selection should therefore be tailored to jet geometry, leaflet quality and length, and the need for single- versus multi-device strategies [96,98,100,116].

Beyond TEE, multimodality imaging refines feasibility assessment and long-term planning. Cardiac CT provides accurate quantification of annular size and shape, as well as its spatial relationship to the LVOT. While echocardiography remains the primary tool for assessing leaflet motion abnormalities such as systolic anterior motion, CT is indispensable for downstream strategy, particularly for simulating the neo-LVOT in the context of TMVR [118]. Importantly, prior M-TEER can complicate subsequent TMVR: clips may immobilize the anterior leaflet, increase the risk of LVOT obstruction, and sometimes preclude leaflet-laceration bailout techniques [119]. Therefore, in contexts where TMVR may be anticipated, the Heart Team should consider "exit-strategy–aware" clip positioning to preserve replacement options.

CMR remains useful when echocardiographic quantification is inconclusive—particularly in multi-jet MR—and for characterizing LV remodeling, complementing echo and CT in an integrative anatomical assessment [120,121].

3.2.5 Procedural Guidance

Intraprocedural TEE is indispensable for device navigation, leaflet grasping, and residual MR assessment. Real-time 3D imaging allows precise orientation of the device relative to the regurgitant jet, and color Doppler aids in immediate evaluation of procedural success.

In selected cases where TEE is contraindicated or technically limited (e.g., severe esophageal disease, prior surgery, or esophageal stenosis), intracardiac echocardiography (ICE) may serve as an alternative imaging modality. ICE can provide adequate visualization of leaflet grasping and device orientation, while potentially avoiding general anesthesia and complications related to esophageal intubation. Although not yet standard, accumulating clinical experience suggests the feasibility and safety of ICE in challenging scenarios [122–125].

In rare situations where esophageal anatomy prevents optimal TEE imaging, collaboration with gastroenterologists may be required. Contrast-enhanced TEE has also been reported in a case with severe esophageal achalasia [126].

3.3 Imaging in Complication-Risk Assessment

3.3.1 Leaflet Adverse Events (LAE)

LAE comprise a spectrum of complications related to leaflet–clip interaction, including single-leaflet device attachment (SLDA), leaflet tear or perforation, leaflet detachment, complete device embolization, and other leaflet injuries [127]. Although the overall incidence is only a few percent, LAE represents a major cause of recurrent MR and the need for reintervention. Careful preprocedural anatomical assessment using CT and TEE, meticulous intraprocedural 3D TEE monitoring of leaflet grasping, and verification before clip release are essential strategies for preventing LAE.

SLDA: SLDA occurs in approximately 1–2% of procedures in contemporary registries (EVEREST II, COAPT, EXPAND) [127,128]. Risk factors identifiable using TEE and CT include inadequate leaflet insertion depth ($<$5 mm), asymmetric leaflet grasping, and extensive calcification of the grasping zone. Intraprocedural 3D TEE allows direct visualization of leaflet capture, enabling early recognition of incomplete grasp and guiding repositioning before clip release [129,130].

Leaflet tear or perforation: This issue is observed in $<$1% of cases, typically in the setting of fragile or calcified tissue. 3D TEE can detect acute leaflet injury by identifying new eccentric MR jets [129]. Risk factors include multiple re-grasping attempts and excessive traction on the leaflets.

Severe cases may result in acute hemodynamic deterioration and occasionally require surgical intervention.

Leaflet detachment: This represents progression of SLDA, where the leaflet slips out of the clip after initial securement. The device remains attached to the opposite leaflet but becomes functionally ineffective, leading to recurrent MR [131].

Device embolization: This is an extremely rare event (<0.5% in large registries); however, it is catastrophic when it occurs. The clip completely detaches from both leaflets and embolizes into the left atrium, left ventricle, or systemic circulation. Preprocedural CT may reveal unfavorable leaflet or annular calcification that compromises stable anchoring, and continuous TEE or fluoroscopy is crucial for early detection of device instability. Surgical retrieval is often required [132–134].

Other leaflet injury: This category includes perforation, distortion, or laceration of the leaflet not meeting the above definitions. Such injuries are usually related to challenging anatomy, aggressive clip manipulation, or multiple grasping attempts. Although rare, they may lead to recurrent MR or acute procedural failure and highlight the importance of minimizing unnecessary re-grasping and ensuring optimal device–leaflet alignment [135].

3.3.2 Iatrogenic Mitral Stenosis

Elevated mean transmitral gradients (>5 mmHg) are reported in approximately 3–5% of patients who underwent M-TEER [136]. The risk increases with implantation of multiple clips or narrow baseline mitral valve area (MVA) (<4.0 cm^2) [137]. Continuous-wave Doppler during the procedure allows immediate assessment, while CT-derived MVA and annular dimensions can help anticipate the risk before the procedure.

3.3.3 Iatrogenic Atrial Septal Defect (iASD)

An iASD is almost universally present immediately after transseptal access. However, persistent defects are observed in approximately 10–20% of patients at 1 year after the procedure [138–140]. Most are hemodynamically insignificant and managed conservatively. However, follow-up with TEE or TTE including bubble contrast studies is useful to detect clinically relevant shunts. In patients with severe pulmonary hypertension or right ventricular (RV) dysfunction, persistent iASDs may exacerbate right-sided volume overload or, rarely, lead to right-to-left shunting with hypoxemia. In such cases, percutaneous closure with ASD occluder devices has been reported to be a safe and effective option [138]. Moreover, morphological assessment by 3D TEE has been shown to be valuable, as an eccentricity index <1.9 was strongly associated with an increased risk of persistent iASD in the MITHRAS trial substudy [141]. These findings highlight the importance of comprehensive imaging follow-up to identify patients at risk for clinically relevant shunts.

3.3.4 LVOT Obstruction

LVOT obstruction is extremely rare after M-TEER, with an incidence of <1% [142]. Although LVOT obstruction is more frequently encountered in TMVR, the risk in M-TEER should not be overlooked, particularly in patients with a small LV cavity, basal septal hypertrophy, or acute aortomitral angulation, which can be identified on preprocedural CT [118,143]. During the procedure, TEE with continuous-wave Doppler enables prompt recognition of dynamic obstruction if it develops; the obstruction is typically demonstrated by increased LVOT velocities and intraventricular gradients [144]. Hemodynamic optimization and avoidance of further clip implantation are usually sufficient; severe cases are exceptionally rare in M-TEER [142,144].

3.3.5 Cardiac Tamponade/Hemopericardium

Cardiac tamponade or hemopericardium occurs in approximately 0.5–1% of M-TEER cases and is most commonly a consequence of transseptal puncture or catheter manipulation [85,142]. Intraprocedural TEE is crucial for early detection of pericardial effusion, allowing immediate intervention with pericardiocentesis when necessary [144]. Although rare, this complication carries significant morbidity; therefore, meticulous puncture technique and real-time imaging guidance are essential preventive measures.

3.3.6 Stroke and Systemic Embolism

Periprocedural stroke occurs in approximately 1–2% of patients undergoing M-TEER procedures, according to contemporary registry data [10,142]. The underlying mechanisms include embolization of pre-existing thrombus, device- or catheter-related thrombus formation, and air or atheromatous embolism. The risk is significantly mitigated by systematic TEE screening to exclude left atrial appendage thrombus and strict intraprocedural anticoagulation, maintaining activated clotting time maintained at >250–300 seconds [97]. Despite its low incidence, stroke remains one of the most devastating complications of M-TEER procedures, underscoring the importance of meticulous preprocedural and intraprocedural management [10,97,142]. Reported stroke rates after surgical mitral valve repair or replacement are typically 2–5%, particularly in older or comorbid populations [145,146]. In comparison, M-TEER demonstrates a lower periprocedural stroke incidence of ~1–2% [10,97,142], reflecting the advantages of its less invasive, catheter-based approach.

Imaging-based strategies to minimize complications in M-TEER:

- Leaflet adverse events (SLDA, tear, embolization): Perform meticulous preprocedural CT and TEE assessment of leaflet morphology, tissue quality, and calcification. During the procedure, use 3D TEE to confirm symmetrical leaflet insertion depth (≥5 mm) and complete grasping before clip release.

- Iatrogenic mitral stenosis: Evaluate baseline MVA and transmitral gradient using CT and Doppler TEE. Avoid excessive clip number or narrow clip spacing in patients with small baseline MVA (<4.0 cm^2).
- Iatrogenic atrial septal defect (iASD): During and after the procedure, use color Doppler or bubble contrast studies to detect shunt persistence. In patients with PH or RV dysfunction, perform follow-up 3D TEE to determine the need for percutaneous closure.
- LVOT obstruction: Identify high-risk features such as small LV cavity, basal septal hypertrophy, or acute aortomitral angulation on preprocedural CT. During clip placement, monitor LVOT flow velocity with continuous-wave Doppler to detect dynamic obstruction early.
- Cardiac tamponade/hemopericardium: Use real-time TEE guidance for transseptal puncture and catheter manipulation; maintain continuous pericardial monitoring to enable immediate intervention if effusion develops.
- Stroke/systemic embolism: Exclude left atrial appendage thrombus by preprocedural TEE or CT; maintain adequate anticoagulation (activated clotting time $>$250–300 s) and minimize air entry during device exchange or flushing.

3.4 Imaging in Postprocedural Follow-up

Structured imaging surveillance after M-TEER is essential not only to confirm procedural success and detect complications but also to provide prognostic insights into long-term durability and patient outcomes.

3.4.1 Residual or Recurrent MR

TTE serves as the cornerstone of longitudinal follow-up after M-TEER [142]. Importantly, even mild residual MR does not necessarily ensure favorable outcomes. Subanalyses from the EVEREST II High-Risk Registry and the COAPT trial demonstrated that patients with $\leq$ mild residual MR had significantly better survival and lower rates of heart failure rehospitalization than those with $\geq$ moderate MR, with 2-year event-free survival of approximately 70–75% versus 45–50% [147]. Long-term COAPT results showed durable MR reduction and significantly lower 5-year all-cause mortality and heart failure hospitalizations with TEER versus GDMT; prior COAPT analyses also demonstrated that greater early MR reduction portends better outcomes, whereas recurrent MR is associated with adverse events [147,148]. Mechanisms underlying recurrent MR include SLDA (approximately 1–3%), progressive leaflet degeneration, and progression of underlying disease [149].

In clinical practice, grading residual MR after M-TEER remains particularly challenging. Unlike native MR, where a single central jet is often predominant, post-M-TEER, patients frequently exhibit multiple eccentric or wall-impinging jets that produce complex flow patterns. Conventional integrative parameters such as vena contracta width or PISA are often difficult to apply in this context [129,150]. Therefore, a multiparametric approach is recommended, including comprehensive color Doppler evaluation of all jets, assessment of pulmonary vein flow, and measurement of transmitral gradients [10]. Advanced imaging modalities, such as 3D echocardiography and quantitative Doppler methods, may provide additional insights. However, interobserver variability remains a significant limitation [86]. These technical challenges should be acknowledged when interpreting residual MR severity, as misclassification can influence both clinical decision-making and long-term outcome assessment. A major unmet need is the standardization of residual MR quantification after M-TEER, since current multiparametric echocardiographic approaches remain highly variable and lack validation against hard clinical endpoints.

3.4.2 Transmitral Gradients

Serial assessment of mean transmitral gradients using Doppler echocardiography is crucial during postprocedural follow-up, particularly in patients treated with multiple clips [142]. Unlike intraprocedural monitoring, which ensures immediate procedural feasibility, longitudinal surveillance is needed to detect progressive increases in gradients that may indicate functional mitral stenosis [151]. A mean gradient $>$5 mmHg has been associated with persistent symptoms and higher rates of rehospitalization because of heart failure [152]. Importantly, unlike surgical mitral valve replacement, where fixed prosthetic gradients are expected, the hemodynamic burden after M-TEER can evolve over time because of variable leaflet motion, clip placement, and progressive disease [153]. Recognition of elevated gradients should prompt careful clinical evaluation and may necessitate intensified medical therapy, repeat imaging, or consideration of reintervention.

3.4.3 LV Remodeling

Reverse LV remodeling is defined as a reduction in LV volumes, particularly end-diastolic and end-systolic volumes, and/or improvement in LVEF, reflecting structural and functional recovery of the ventricle [10,154]. Effective MR reduction with M-TEER promotes reverse remodeling. In the COAPT trial, LV end-diastolic volume decreased by approximately 25 mL, and LVEF improved by nearly 5%, both strongly correlated with survival benefit [10]. Recent studies have shown that patients who fail to demonstrate significant reverse remodeling despite adequate MR reduction experienced worse outcomes, underscoring the prognostic importance of LV structural response [154]. Furthermore, CMR imaging provides incremental prognostic information, the presence and extent of LGE reflecting myocardial fibrosis, and predict limited reverse remodeling and adverse clinical outcomes beyond echocardiographic parameters [155].

3.4.4 Pulmonary Hypertension and RV Function

Serial assessment of tricuspid regurgitation (TR) velocity and estimated PASP is valuable for tracking hemodynamic benefit after M-TEER [156]. Persistent pulmonary hypertension (PASP >50–60 mmHg) despite effective MR reduction has been associated with poor prognosis, whereas a significant decline in PASP predicts improved functional capacity and survival [157]. Recent imaging studies have also emphasized the prognostic role of RV function, including parameters such as RV free-wall longitudinal strain and RV GLS, as well as the impact of progressive TR during follow-up [158].

Thus, multimodality imaging follow-up after M-TEER should extend beyond MR quantification to include transmitral gradients, chamber remodeling, pulmonary hemodynamics, and myocardial tissue characterization, all of which contribute to a comprehensive prognostically meaningful assessment of long-term outcomes.

3.5 Current Challenges and Future Perspectives

3.5.1 Complex Anatomies

Patients with extensive leaflet calcification, short posterior leaflets, very large regurgitant orifices, or degenerative lesions characteristic of Barlow's disease continue to pose significant technical challenges for M-TEER [116,159]. The introduction of newer clip designs, including the fourth-generation MitraClip system, and the development of the PASCAL device have expanded the range of anatomies amenable to transcatheter repair. However, a considerable proportion of patients remain unsuitable for M-TEER and may require alternative strategies such as surgical repair or TMVR [149,160].

3.5.2 Right Heart and Pulmonary Circulation

Long-term outcomes after M-TEER depend not only on LV remodeling but also on RV function and pulmonary hemodynamics [158,161]. Observational studies and COAPT subanalyses have consistently demonstrated that impaired RV function and concomitant severe TR are independently associated with increased mortality and hospitalization for heart failure [162]. Moreover, the concept of RV–pulmonary circulation uncoupling, assessed using indices such as the tricuspid annular plane systolic excursion (TAPSE)/PASP ratio, has emerged as a powerful prognostic marker [163]. These findings highlight that future patient selection and postprocedural follow-up should incorporate comprehensive evaluation of biventricular function and pulmonary hemodynamics, extending beyond MR reduction alone.

3.5.3 Atrial Functional MR

Atrial functional MR (AFMR), defined as left atrial enlargement and atrial fibrillation in the absence of significant LV remodeling, has gained increasing attention as a distinct clinical and pathophysiological entity, separate from ventricular functional MR [164,165]. Mechanistic imaging studies have clarified that AFMR is primarily driven by left atrial dilatation, mitral annular enlargement, and atriogenic leaflet tethering, underscoring its unique substrate and therapeutic implications [165]. Early registry data suggest that M-TEER may provide symptomatic and hemodynamic improvement in patients with preserved LV function [166]. However, in patients with advanced atrial remodeling or persistent atrial fibrillation, recurrence of MR remains frequent [167]. Defining the optimal timing and selection criteria for intervention in AFMR represents an important area for future investigation.

3.5.4 Integration With Other Therapies

Beyond its role as a standalone intervention, M-TEER is increasingly being positioned within a broad therapeutic continuum for MR. For patients at high surgical risk or with advanced comorbidities, M-TEER may provide interim stabilization, improving symptoms and hemodynamics while preserving candidacy for future therapies, including TMVR [168]. In others cases, it may complement transcatheter approaches targeting additional valves, such as combined treatment of MR and TR, which is frequently encountered in cases of advanced heart failure [169]. Moreover, the growing experience with multimodality imaging and device iterations supports a tailored, stepwise strategy in which M-TEER functions as a component of a long-term disease management plan rather than as an isolated procedure [170]. This integrated perspective highlights the evolution of M-TEER from a palliative tool to a central element of comprehensive transcatheter valve therapy.

3.5.5 Emerging Imaging Technologies

Recent advances in quantitative 3D echocardiography, fusion imaging, AI, and 3D printing are redefining both procedural guidance and preprocedural planning in M-TEER. Fusion imaging, which integrates 3D TEE and fluoroscopy in real time, has demonstrated high registration accuracy and can reduce fluoroscopy time by approximately 20%, facilitating clip alignment, leaflet grasping, and procedural navigation [171,172]. AI-based image analysis enables automated quantification of the regurgitant orifice area and reliable prediction of procedural success with high reproducibility. Validation studies have demonstrated strong agreement with expert manual analysis, supporting its potential integration into real-time guidance and preprocedural planning workflows [173–175]. Furthermore, 3D-printed and virtual simulation models have shown >90% concordance with intraprocedural clip selection and can shorten procedure duration by approximately 15%, providing valuable educational and procedural rehearsal opportunities, particularly in anatomically complex or redo cases [176,177]. Collectively, these emerging imaging technologies represent the next frontier in image-guided mitral interventions. Quantitative validation supports their integration

into future M-TEER workflows, enabling greater procedural precision, efficiency, and reproducibility across centers.

3.5.6 Future Perspectives

The future of M-TEER will be driven by synergistic advances in device technology, procedural algorithms, and multimodality imaging integration. Building upon recent innovations, the next stage will focus on clinical implementation and validation of advanced imaging tools—ensuring that quantitative 3D echocardiography, fusion imaging, and AI can be seamlessly incorporated into real-world workflows to enhance procedural precision and outcome consistency [172,178,179]. Integrating these imaging innovations into routine workflows may reduce operator variability and extend M-TEER applicability to patients with anatomical complexities or those who were previously ineligible. However, many of these technologies, particularly fusion imaging and AI-based tools, still require robust validation in real-world clinical practice before their widespread adoption. In parallel, continued evolution in clip systems, the emergence of alternative repair devices, and evidence-based treatment pathways will further improve procedural safety, durability, and accessibility of M-TEER across diverse populations with MR [96].

Beyond technological innovation, structured education and interprofessional collaboration within the Heart Team remain essential to optimize both medical and surgical decision-making. A shared understanding of imaging is particularly critical, as it provides a common language among cardiologists, cardiac surgeons, anesthesiologists, nurses, technicians, and other staff, thereby facilitating consistent communication and joint problem-solving. Creative approaches to education, such as the recently proposed handgrip model for visualizing tricuspid valve anatomy and leaflet relationships, exemplify how innovative teaching tools can foster deeper anatomical understanding and interdisciplinary dialogue [180]. We hope that the present review contributes to advancing such educational and collaborative initiatives, ultimately fostering a more standardized, efficient, and patient-centered practice in TCS.

4. Conclusion

Over the past two decades, TCS has evolved from being a last-resort option for patients at high risk to an established therapy across the surgical risk spectrum. Advances in device technology, imaging, and perioperative care have brought outcomes closer to conventional surgery, while the Heart Team approach—anchored using multimodality imaging as a common language—has become fundamental to success.

Despite these advances, unresolved challenges remain. Durability beyond 10 years is uncertain, residual MR grading lacks standardization, and right heart–pulmonary assessment should be incorporated into decision-making. Surgical expertise remains indispensable for patient selection, management of complex anatomies, and hybrid strategies. Future progress will depend on addressing these gaps through continued innovation and collaboration among interventionalists, surgeons, and imaging specialists. Multimodality imaging will be the key to lifetime management strategies in TCS.

Abbreviations

AFMR, atrial functional mitral regurgitation; AS, aortic stenosis; AVA, aortic valve area; BAV, balloon aortic valvuloplasty; BEV, balloon-expandable valve; CMR, cardiac magnetic resonance; CT, computed tomography; DSE, dobutamine stress echocardiography; EOA, effective orifice area; EROA, effective regurgitant orifice area; GDMT, guideline-directed medical therapy; GLS, global longitudinal strain; HALT, hypo-attenuated leaflet thickening; ICE, intracardiac echocardiography; IE, infective endocarditis; iASD, iatrogenic atrial septal defect; IVL, intravascular lithotripsy; LGE, late gadolinium enhancement; LV, left ventricle/left ventricular; LVEF, left ventricular ejection fraction; LVMI, left ventricular mass index; LVOT, left ventricular outflow tract; MR, mitral regurgitation; M-TEER, mitral transcatheter edge-to-edge repair; MVA, mitral valve area; PASP, pulmonary artery systolic pressure; PH, pulmonary hypertension; PPI, permanent pacemaker implantation; PPM, patient–prosthesis mismatch; PVL, paravalvular leak; RCT, randomized controlled trial; RLM, reduced leaflet motion; RV, right ventricle/right ventricular; SAVR, surgical aortic valve replacement; SEV, self-expanding valve; STE, stress echocardiography; STJ, sinotubular junction; SVD, structural valve degeneration; TAPSE, tricuspid annular plane systolic excursion; TAVR, transcatheter aortic valve replacement; TCS, transcatheter cardiac surgery; TEE, transesophageal echocardiography; THV, transcatheter heart valve; TMVR, transcatheter mitral valve replacement; TR, tricuspid regurgitation; TTE, transthoracic echocardiography; VTC, valve-to-coronary distance.

Author Contributions

KS conceived and designed the review, performed the literature review, wrote the manuscript, and approved the final version of the manuscript. The author read and approved the final manuscript. The author has participated sufficiently in the work and agreed to be accountable for all aspects of the work.

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