Echocardiographic Evaluation of Successful Mitral Valve Repair or Need for a Second Pump Run in the Operating Room

Mitsuhiko Ota, MD[a,*], Takeshi Kitai, MD, PhD[b]

KEYWORDS

• Mitral regurgitation • Mitral valve repair • Intraoperative transesophageal echocardiography

KEY POINTS

- Intraoperative transesophageal echocardiography provides immediate diagnostic feedback and assessment of results during valve repair procedures and has become an essential guiding tool for decision-making among surgeons.
- Systematic echocardiographic evaluation of mitral valve repair based on a specific algorithm is mandatory.
- Three-dimensional transesophageal echocardiography plays a pivotal role in both preprocedural and postprocedural assessments in mitral valve repair.

INTRODUCTION

Mitral valve (MV) repair has become the gold standard surgical procedure for significant mitral regurgitation (MR).[1] The objectives of MV repair are to preserve or restore full leaflet motion, to create a good surface for leaflet coaptation, and to remodel and stabilize the entire annulus.

Detailed preoperative echocardiographic assessment of the MV apparatus is crucial for surgical planning.[2] Three-dimensional (3D) transesophageal echocardiography (TEE) plays a pivotal role in both preprocedural and postprocedural assessments in MV repair and has become widely adopted in echocardiographic laboratories and operating rooms worldwide.[3–6] In the operating room, intraoperative TEE evaluation requires accurate analysis of the MV anatomy and details of affected valve lesions.[7] Furthermore, as surgeons must rapidly decide whether cardiopulmonary bypass (CPB) should be continued to be weaning off or a second pump run should be selected, the echocardiographer conducting intraoperative TEE is required to be trained according to a certain algorithm. In particular, when the saline test results are difficult to judge the extent of residual regurgitation, evaluation by intraoperative TEE may be faster and more accurate under physiologic cardiac movement after weaning off the CPB.

The present review aimed to examine the current clinical role of intraoperative TEE in MV repair in the operating room.

Funding sources: None.
Declarations of interest: None.
[a] Department of Cardiovascular Center, Toranomon Hospital, 2-2-2 Toranomon, Minato-ku, Tokyo 105-8470, Japan; [b] Department of Cardiovascular Medicine, Kobe City Medical Center General Hospital, 2-1-1 Minatojima Minamimachi, Chuo-ku, Kobe 650-0047, Japan
* Corresponding author.
E-mail address: mohta5288923@gmail.com

Cardiol Clin 39 (2021) 233–242
https://doi.org/10.1016/j.ccl.2021.01.004

ROLE OF INTRAOPERATIVE TRANSESOPHAGEAL ECHOCARDIOGRAPHY IN MITRAL VALVE REPAIR: WHAT IS SUCCESSFUL MITRAL VALVE REPAIR?

Echocardiographic imaging of the MV before and immediately after repair is crucial for immediate and long-term outcomes.[8–10] Postrepair echocardiographic imaging reveals the new baseline anatomy, assesses the function, and determines whether further intervention is required.

Successful MV repair is defined as a decrease in MR severity to mild or less without mitral stenosis or left ventricular outflow tract obstruction owing to systolic anterior motion (SAM). The surgeon should achieve complete MR elimination while minimizing valve area reduction.[11] An inadequate technique may result in either residual MR or mitral stenosis, which can be shown using intraoperative TEE. Such information will improve treatment options, enhance the timing of invasive therapies, and lead to advancements in repair techniques, thereby yielding better outcomes.

Quantitatively, an ideal MV repair should restore competency (MR <1+), ensure adequate patency (mean gradient of $\leq$6 mm Hg and MV area of $\leq$1.5 cm^2), and have durability (>10 years without significant MR and/or reoperation).[12–16] Because intraoperative TEE provides immediate diagnostic feedback and assessment of results during valve repair procedures, it has become an essential guiding tool for decision-making among surgeons.[11]

In the operating room, optimizing the communication between the surgeon and the cardiologist performing echocardiography is mandatory to ensure the best possible outcomes for patients. Because postprocedural echocardiographic evaluation can be conducted immediately after aortic cross-clamp release, the cardiologist must be on standby in the operating room before the completion of left atrial suture. Furthermore, obtaining information from the surgeon on how valve repair was performed is important. An online environment in which the surgical field can be viewed from all medical record terminals in the hospital enables cardiologists to observe directly the repaired valve remotely from an echocardiographic laboratory (**Fig. 1**). The key to successful MV repair is that the final 3D images of the repaired valve can be shared simultaneously between surgeons and cardiologist when the CPB was weaned off.

Because the procedures used in MV repair differ depending on the facility and surgeon, it is necessary to share information among echocardiographers on surgical techniques that are often used in daily clinical practice.

Systematic echocardiographic evaluation of MV repair is mandatory. At the initial time when the CPB is weaned off, the most sufficient imaging view for the evaluation of the repaired MV is the midesophageal (ME) long axis (LAX) view, not the 4-chamber view or mitral commissural view. The reasons for this are as follows: (1) it is easy to observe the dynamic state of the aortic valve starting to open, because the volume is loaded to the left ventricle. (2) Both the anterior and posterior MV leaflets can be visualized simultaneously. (3) The mobility, coaptation, and regurgitation of the repaired MV, as well as the iatrogenic regurgitation of the aortic valve, can be evaluated at a glance. The following checkpoints for the assessment of MV repair are recommended (**Fig. 2**).

Checkpoint 1: Residual Mitral Regurgitation

A successfully repaired MV should not have more than mild MR immediately after separation from the CPB.[17,18] The principles for the echocardiographic assessment of residual MR are the same as those for the evaluation of the native valve.[13] Such assessment should be performed with a sufficiently loaded left ventricle and a systolic blood pressure of greater than 100 mm Hg to simulate physiologic status and avoid residual MR underestimation. Surgeons need to put up a few minutes for proper volume and afterload settings and for their echocardiographic assessments, which results in the best benefit to patients. MR jet area with color flow Doppler (CFD) is the most common method used for the rapid quantitative evaluation of residual MR.

If residual MR is more than mild or occurs in eccentric jets, a detailed assessment is required to determine the mechanism of residual MR and aid in the revision of re-repair on a second CPB pump run (second pump run) (**Fig. 3**). The need for a second pump run is considered when the MR jet area is more than 1.0 cm^2 or an eccentric MR jet is observed in the authors' institution.[18]

If the site and mechanism of regurgitation cannot be evaluated accurately, the surgeon may face a problem in deciding where and how to repair the second pump run. In particular, depicting the coaptation zone of the MV in the ME LAX view is sometimes difficult owing to the acoustic shadowing caused by the annuloplasty ring implanted into the annulus. When the acceleration flow by CFD cannot be detected on the ventricular side of the repaired MV and only the regurgitant jet spreading into the left atrium can be observed, transgastric (TG) LAX and short axis views should be attempted (**Fig. 4**). The coaptation zone of the MV and subvalvular structures can often be clearly

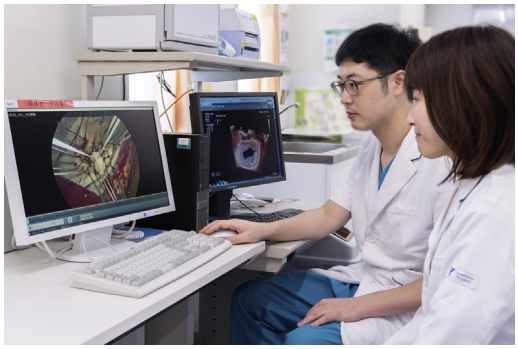

Fig. 1. Electronic medical records system that enables viewing of real-time surgical field in an echocardiographic laboratory, allowing efficient real-time information sharing between surgeons and echocardiographers.

visualized in TG views; therefore, the detection of the acceleration flow becomes easier.

Checkpoint 2: Leaflet Mobility and Alignment

It is necessary to simultaneously observe leaflet mobility and state of coaptation while searching for regurgitation using CFD. The ME LAX view and mitral commissural view by clockwise and counterclockwise probe rotation are applied for the assessment of leaflet appearance and motion. The leaflets' height should be aligned neatly next to or opposite each other with no coaptation gaps in systole. Additionally, an assessment of the degree and level of coaptation is essential; a successfully repaired MV should have a leaflet coaptation length of 5 to 8 mm at the A2 to P2 level (Fig. 5).[19]

Checkpoint 3: Systolic Anterior Motion

SAM refers to the dynamic movement of the MV toward the interventricular septum during systole, resulting in left ventricular outflow tract obstruction and/or MR. Because postrepair SAM is well-known to occur in 1% to 16% of patients undergoing MV repair,[20–23] the presence of SAM immediately after repair must therefore be excluded in the ME LAX view. Excessive anterior or posterior leaflet tissues, a small and hyperkinetic left ventricle, bulging of the basal interventricular septum, and the use of a small annuloplasty ring have been identified as risk factors for SAM.[24–26] When SAM is observed during weaning from the CPB, the initial management strategy should focus on ventricular volume loading, discontinuation of inotropes, use of beta-blockers, and increasing the afterload.[27] The effects of these treatments can be observed immediately in the same ME LAX view. If significant SAM is persistent despite these medical treatments, further surgical revision is required, including reduction of the posterior leaflet's height, shortening of the neo-chords, and the use of a larger annuloplasty ring or band (Fig. 6).

When assessing the presence of SAM, it is important to ensure that all left ventricular segments begin to contract normally. Air embolism in the right coronary artery is a common

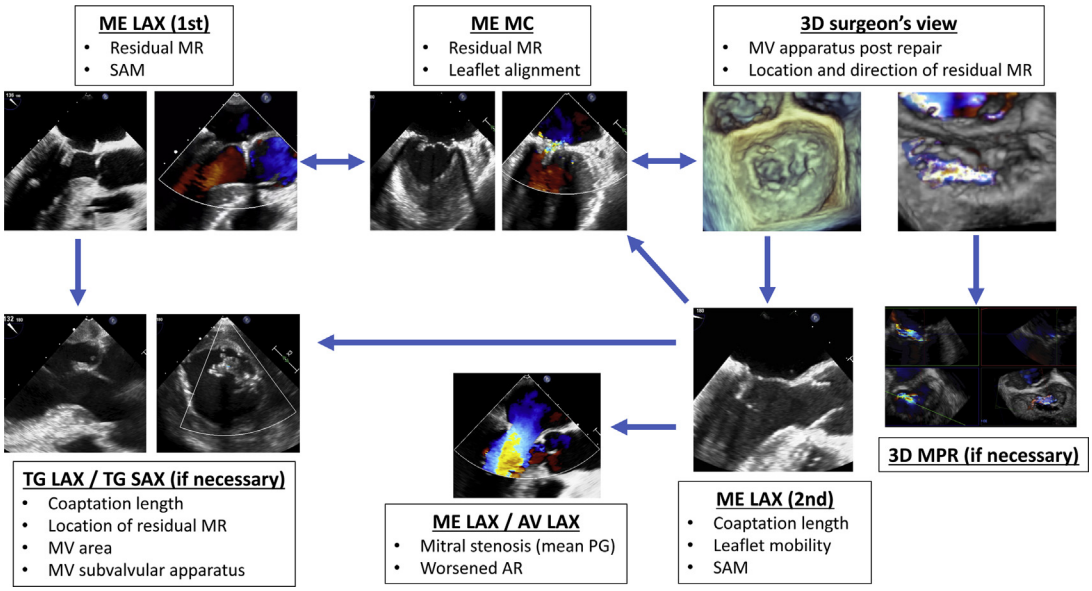

Fig. 2. Proposed TEE imaging strategy starting from the ME LAX view for MV repair. AR, aortic regurgitation; LAX, long axis; MC, mitral commissural; MPR, multiplanar reconstruction; SAX, short axis; TG, transgastric.

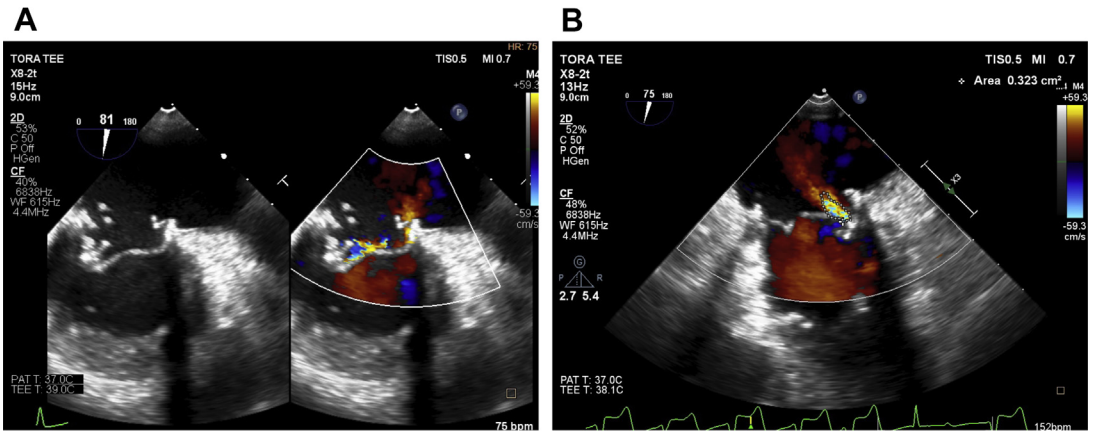

Fig. 3. Example of postrepair eccentric MR jets owing to incomplete repair. (*A*) Midesophageal (ME) commissural view showing eccentric MR toward the prosthetic ring caused by residual P3 prolapse. (*B*) ME commissural view showing eccentric MR caused by residual P1 prolapse.

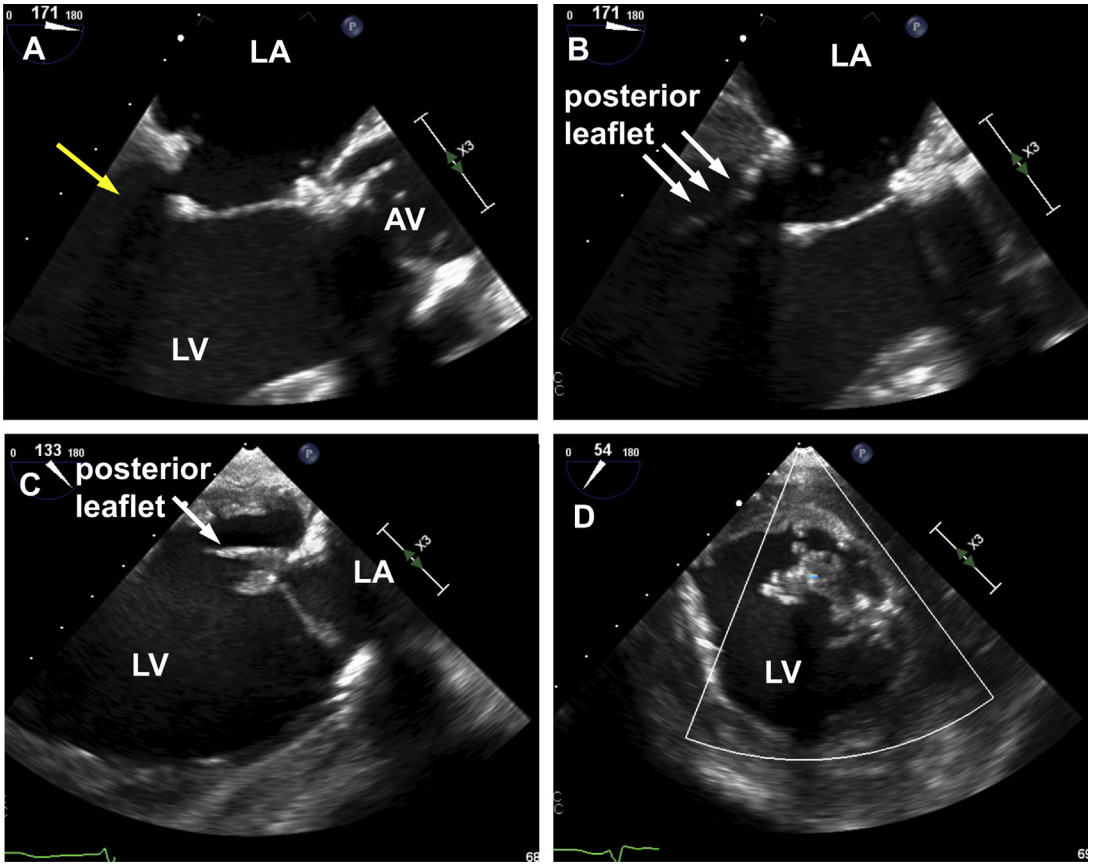

Fig. 4. Intraoperative ME TEE and TG TEE views of a case of MV repair. ME LAX views showing the repaired MV at the A2 to P2 level in peak systole (*A*) and diastole (*B*). The posterior leaflet (*arrow*) is sometimes difficult to visualize because of shadowing from the prosthetic ring (*yellow arrow*). TG LAX view of the MV at the A2 to P2 level in systole (*C*), which clearly shows the coaptation surface of the MV. The acceleration flow of residual MR can be observed with CFD in the TG short axis view of the MV at the orifice level (*D*).

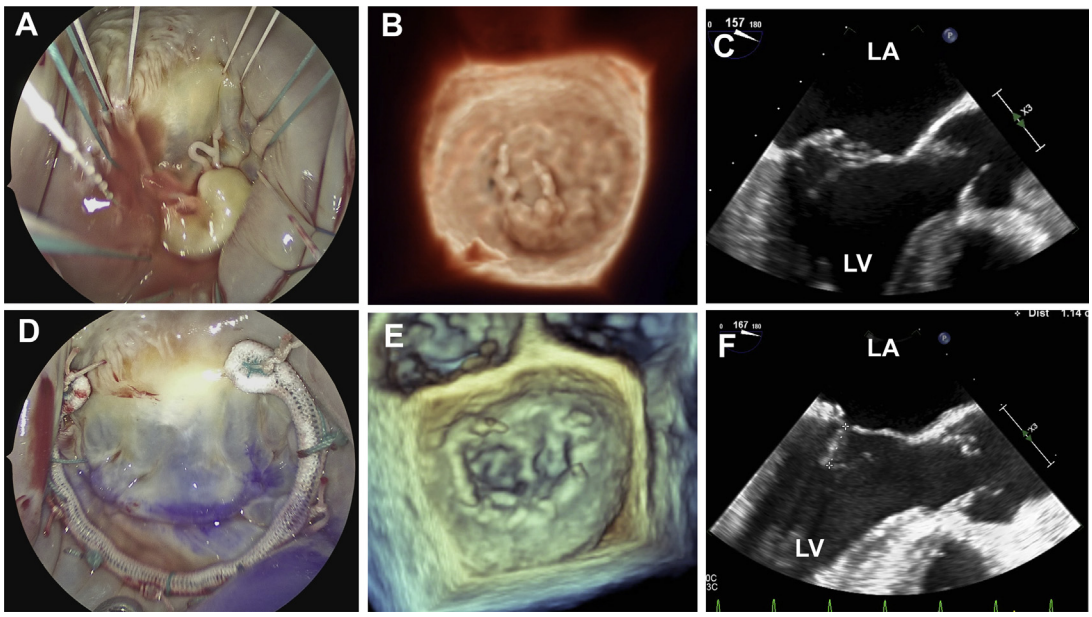

Fig. 5. A successful case of MV repair for P2 prolapse. Representative images of the MV before (*upper row*; *A–C*) and after (*lower row*; *D–F*) repair for severe MR owing to P2 prolapse. (*A*) Endoscopic view of the MV with P2 prolapse and torn chordae after placing sutures within the annulus. (*B*) A 3D photorealistic TEE surgeon's view ("TrueVue") showing a frail P2 segment and ruptured chordae tendineae. (*C*) Preoperative 2D ME LAX view showing a P2 prolapse with torn chordae. (*D*) Endoscopic view of the MV after repair during the saline test. (*E*) Intraoperative 3D TEE surgeon's view of the MV after repair at the time when the CPB was weaned off. (*F*) Postoperative 2D ME LAX view showing the coaptation surface at the A2 to P2 level.

complication immediately after CPB, which can lead to left ventricular inferior and posterior wall hypokinesis with ST-segment elevation in inferior the electrocardiographic leads (II, III, and aVF). Transient abnormalities in inferior or posterior wall motion decrease the function of papillary muscles and the mobility of the mitral posterior leaflet, thereby masking the presence of SAM. Left ventricular dyssynchrony is another component that may mask postrepair SAM. Temporary epicardial pacing is routinely used to facilitate weaning from the CPB. In several cases, TEE under pacing (often around 80–90 ppm) is forced to be continued owing to the difficulty in achieving adequate sinus rhythm and sudden atrioventricular block immediately after termination from the CPB. Nonetheless, cardiac contraction often shows a nonphysiologic pattern during ventricular

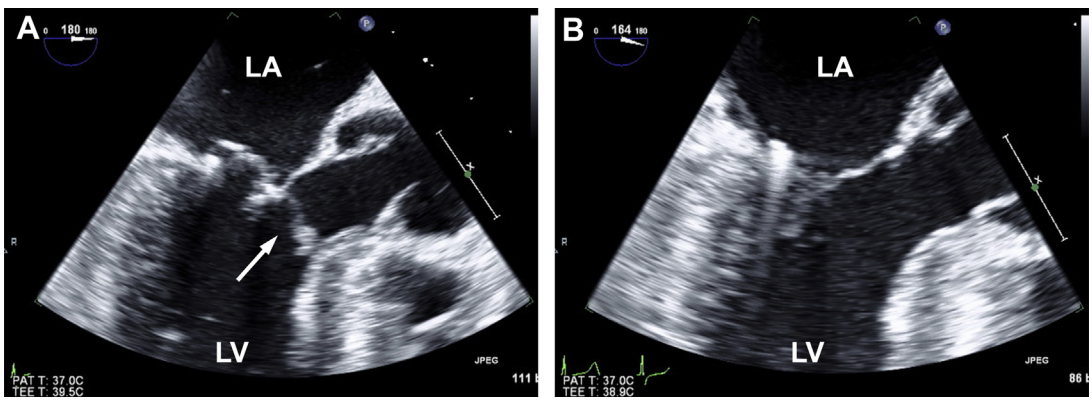

Fig. 6. An example case of SAM after MV repair requiring a second pump run and re-repair. Zoomed ME LAX views of the MV showing postrepair SAM (*arrow*) owing to excessive posterior leaflet tissue (*left, A*) and post-re-repair with shortening of the neochords after the second pump run (*right, B*).

pacing. Furthermore, there are cases in which delayed posterolateral wall contraction is generated and the posterior leaflet does not sufficiently move during systole owing to left ventricular dyssynchrony. In such cases, a significant SAM may occur as soon as an effective sinus rhythm is established. Hence, careful assessment with TEE is required because SAM may be masked when temporary cardiac pacing is indicated or the left ventricular wall motion is abnormal.

Checkpoint 4: Mitral Stenosis

The evaluation of the transvalvular flow across the MV immediately after surgery is important. Iatrogenic mitral stenosis is a recognized complication after MV repair.[28,29] Irrespective of technique, prosthetic ring or band annuloplasty is the mainstay of all repair procedures.[30] Rings or bands are used to improve the durability of repair and prevent further annular dilatation by decreasing the anatomic MV area; therefore, some degree of mitral stenosis will occur after MV repair with annuloplasty.[12,31] However, there exist no specific echocardiographic criteria for the intraoperative diagnosis of iatrogenic mitral stenosis after MV repair. Functional mitral stenosis is currently defined as an MV area of 1.5 cm^2 or less or a mean transmitral pressure gradient of 5 mm Hg or greater, irrespective of etiology. Although measurement of the anatomic MV area using 2-dimensional (2D) planimetry in the TG short axis view is useful for experienced echocardiologists, it is rarely conducted owing to technical challenges, especially in the intraoperative setting. Moreover, it is difficult to determine whether the TG short axis view is obtained at the tip level of the repaired MV and represents the smallest MV orifice area.[32] Consequently, most cardiologists and surgeons tend to rely on the mean transmitral pressure gradient to assess functional mitral stenosis after repair; nevertheless, hemodynamic changes immediately after the CPB affect this parameter.

The incidence of acute iatrogenic mitral stenosis during surgery remains unclear because the available parameters for MV area quantification in the setting immediately after repair have a different physiology, as compared with native valves. Postrepair acute mitral stenosis is rare, unless a ring that is, too small or an edge-to-edge procedure is used in multiple locations of the degenerative MV.

Checkpoint 5: Worsened Aortic Regurgitation

Postrepair TEE examination may show the emergence of a new aortic regurgitation or deterioration in preexisting aortic insufficiency if the aortic valve is injured or distorted during MV and/or tricuspid valve repair or replacement.[33–35] This iatrogenic injury to the aortic valve results from its anatomic proximity to the mitral annulus and annuloplasty ring stitches. The anterior mitral annulus is closely related to the aortic valve, specifically to the left and noncoronary aortic cusps. Normally, the distance between the nadir of these cusps and the anterior MV annulus is 5 to 10 mm; however, anatomic variations in the position of the nadir of the aortic valve and unintentional stitches may occur, resulting in suture needle perforation of the aortic cusp. Furthermore, tension caused by the MV annuloplasty ring or tricuspid valve replacement may lead to distortion of the aortic annulus owing to its adjacent position.[36] Thus, close attention should be paid to the emergence of a new aortic regurgitation after MV repair.

THE ROLE OF 3-DIMENSIONAL TRANSESOPHAGEAL ECHOCARDIOGRAPHY IN THE ASSESSMENT OF MITRAL VALVE REPAIR

Multiplane imaging with 2D TEE provides detailed assessment of cross-sectional valve anatomy and function. Although multiple thin 2D images can be mentally reconstructed into a 3D valve model, this process requires physicians to be skilled in acquiring 2D valve images with correct alignment of imaging planes according to a systematic imaging algorithm.[37] Real-time 3D TEE has improved and provided incremental value to the assessment of anatomic features, location, and extent of MV pathology.[38–41] Additionally, 3D TEE with CFD aids in identifying the location of the regurgitant orifice and direction of the regurgitant flow (**Fig. 7**). Real-time, single-beat 3D imaging is less operator dependent and enables the visualization of the entire MV in a single view as well as an assessment of the MV apparatus from either the left atrial or left ventricular perspective.[42,43] Furthermore, 3D TEE is superior to 2D TEE with respect to the identification of dominant lesions in patients with complex prolapse involving Barlow's disease and/or commissural lesions (**Fig. 8**).[44] The amount of commissural tissues varies greatly, and commissures sometimes exist as distinct leaflet scallops. In addition, 3D TEE is useful for recognizing the indentations that separate the posterior leaflet into 3 individual scallops.[45,46] The location of these indentations considerably varies among individuals, and there is also a bulky P3 scallop that is large enough to occupy the position of the original P2 segment (**Fig. 9**). This recognition is essential when planning

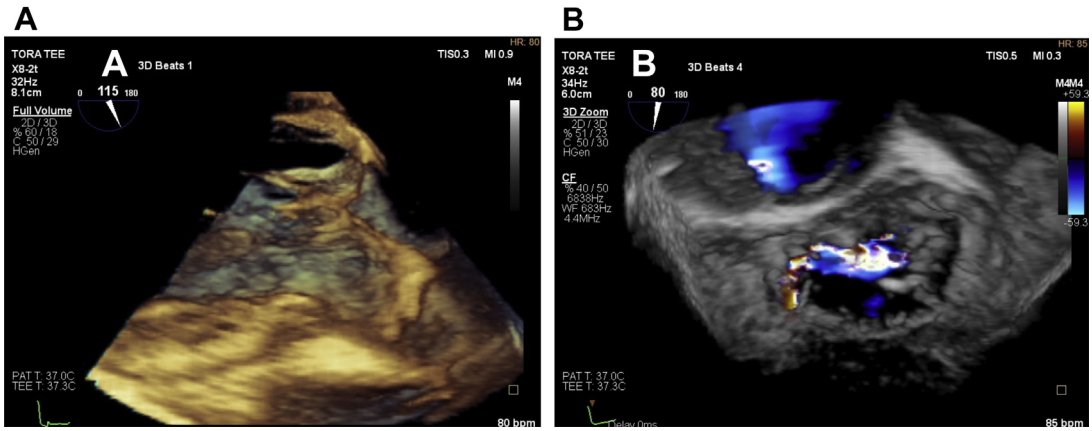

Fig. 7. Real-time 3D TG LAX view can easily shows the coaptation zone of the MV with only a single-beat acquisition (*A*). 3D multi-beat CFD of repaired MV can demonstrates an eccentric jet from P3 segment (*B*).

procedures such as indentation closure in MV repair.

Acquisition of 3D datasets is mandatory, which is ideal when assessing complex structures of the MV apparatus in detail. Multibeat, wide angle, full-volume 3D imaging can provide images with greater temporal and spatial resolution.[3,45] Nonetheless, multibeat 3D imaging requires electrocardiographic-gated acquisition and breath holds to minimize stitch artifacts, and it takes considerable experience for echocardiographers to capture high-quality 3D TEE images without artifacts.

Performing TEE for detailed preoperative evaluation in the operating room is not recommended because electrocautery-induced electrical interference has a negative effect on electrocardiographic-gated images and echocardiographic image quality is likely to be poor owing to the patients' supine position instead of left lateral position.

Surgeons have ethical duties to explain planned procedures to patients and obtain valid informed consent from patients before surgery. Therefore, preoperative TEE should be completed in the echocardiographic laboratory rather than in the operating room on the day of surgery. Furthermore, 3D TEE facilitates communication with surgeons by providing images that they may see upon opening up the left atrium in the operating

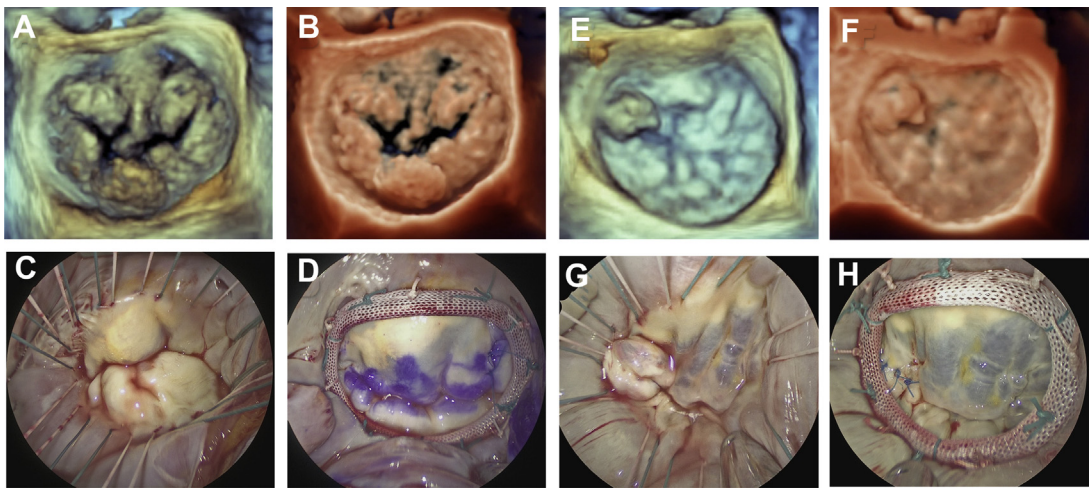

Fig. 8. Examples of Barlow's disease and commissural lesion. Representative cases of severe MR owing to Barlow's disease (*A–D*) and commissural lesion (*E–H*) are shown in 3D TEE images and endoscopic views before and after repair. Preoperative 3D surgeon's view from the left atrial perspective (*A*, *E*). Photorealistic 3D surgeon's view (*B*, *F*). Preoperative endoscopic view (*C*, *G*). Postoperative endoscopic view immediately after repair during the saline test (*D*, *H*).

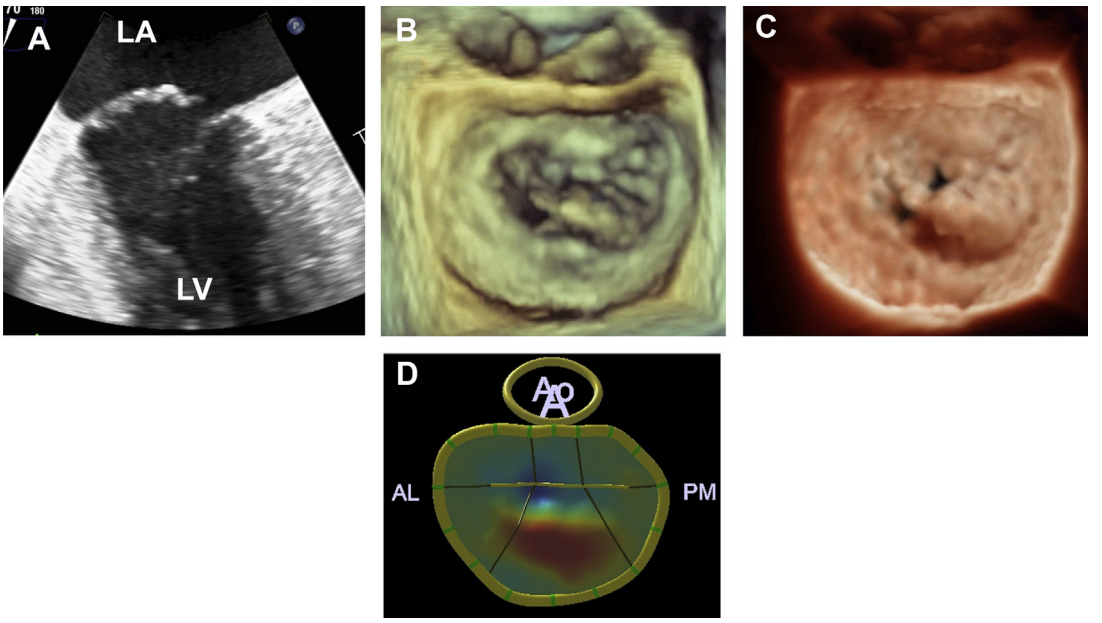

Fig. 9. A bulky P3 lesion mimicking a P2 lesion in conventional 2D images. The 2D ME commissural view shows a huge P3 lesion that is about to reach the P1 segment over the original P2 segment (*A*). These 3D surgeon's views are more intuitive for understanding the anatomic characteristics and mechanism of regurgitation (*B*). A 3D photorealistic view ("TrueVue") provides additional anatomic details (*C*). Peak systolic parametric map derived from a 3D TEE image showing prolapse of the huge P3 scallop over the P2 scallop area (*D*).

room. Further advancements in imaging will continue to improve the understanding about MV function and dysfunction both before and after repair.

SUMMARY

TEE is an important preoperative imaging modality for successful MV repair and an essential guiding tool for intraoperative decision-making among surgeons by providing immediate diagnostic feedback and assessment of results during valve repair procedures. Systematic echocardiographic evaluation of MV repair and use of 3D TEE in combination with 2D TEE based on a specific algorithm are mandatory.

CLINICS CARE POINTS

- Successful mitral valve (MV) repair is defined as a decrease in mitral regurgitation (MR) severity to mild or less without mitral stenosis (MS) or systolic anterior motion (SAM).
- Intraoperative transesophageal echocardiography (TEE) has become an essential guiding tool for decision-making among surgeons.
- Systematic echocardiographic evaluation according to the following checkpoints, including residual MR, leaflet mobility and alignment, SAM, iatrogenic MS, and worsened aortic regurgitation should be performed immediately after MV repair.

REFERENCES

1. David TE, Armstrong S, McCrindle BW, et al. Late outcomes of mitral valve repair for mitral regurgitation due to degenerative disease. Circulation 2013; 127:1485–92.
2. Nishimura RA, Otto CM, Bonow RO, et al. Thomas JD and American College of Cardiology/American Heart Association Task Force on practice G. 2014 AHA/ACC guideline for the management of patients with valvular heart disease: executive summary: a report of the American College of Cardiology/American Heart Association Task Force on practice guidelines. J Am Coll Cardiol 2014;63: 2438–88.
3. Nicoara A, Skubas N, Ad N, et al. Guidelines for the use of transesophageal echocardiography to assist with surgical decision-making in the operating room: a surgery-based approach: from the American Society of Echocardiography in Collaboration with the Society of Cardiovascular Anesthesiologists and the Society of Thoracic Surgeons. J Am Soc Echocardiogr 2020;33:692–734.
4. La Canna G, Arendar I, Maisano F, et al. Real-time three-dimensional transesophageal echocardiography for assessment of mitral valve functional

anatomy in patients with prolapse-related regurgitation. Am J Cardiol 2011;107:1365–74.
5. Ahmed S, Nanda NC, Miller AP, et al. Usefulness of transesophageal three-dimensional echocardiography in the identification of individual segment/scallop prolapse of the mitral valve. Echocardiography 2003;20:203–9.
6. Ben Zekry S, Nagueh SF, Little SH, et al. Comparative accuracy of two- and three-dimensional transthoracic and transesophageal echocardiography in identifying mitral valve pathology in patients undergoing mitral valve repair: initial observations. J Am Soc Echocardiogr 2011;24:1079–85.
7. Mahmood F, Matyal R. A quantitative approach to the intraoperative echocardiographic assessment of the mitral valve for repair. Anesth Analg 2015; 121:34–58.
8. Shah PM, Raney AA, Duran CM, et al. Multiplane transesophageal echocardiography: a roadmap for mitral valve repair. J Heart Valve Dis 1999;8:625–9.
9. Sidebotham DA, Allen SJ, Gerber IL, et al. Intraoperative transesophageal echocardiography for surgical repair of mitral regurgitation. J Am Soc Echocardiogr 2014;27:345–66.
10. Hahn RT, Abraham T, Adams MS, et al, American Society of E and Society of Cardiovascular A. Guidelines for performing a comprehensive transesophageal echocardiographic examination: recommendations from the American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists. Anesth Analg 2014;118:21–68.
11. Adams DH, Anyanwu AC, Sugeng L, et al. Degenerative mitral valve regurgitation: surgical echocardiography. Curr Cardiol Rep 2008;10:226–32.
12. Ibrahim MF, David TE. Mitral stenosis after mitral valve repair for non-rheumatic mitral regurgitation. Ann Thorac Surg 2002;73:34–6.
13. Zoghbi WA, Adams D, Bonow RO, et al. Recommendations for noninvasive evaluation of native valvular regurgitation: a report from the American Society of echocardiography Developed in Collaboration with the Society for Cardiovascular Magnetic Resonance. J Am Soc Echocardiogr 2017;30:303–71.
14. Brinster DR, Unic D, D'Ambra MN, et al. Midterm results of the edge-to-edge technique for complex mitral valve repair. Ann Thorac Surg 2006;81:1612–7.
15. Riegel AK, Busch R, Segal S, et al. Evaluation of transmitral pressure gradients in the intraoperative echocardiographic diagnosis of mitral stenosis after mitral valve repair. PLoS One 2011;6:e26559.
16. Kasegawa H, Shimokawa T, Horai T, et al. Long-term echocardiography results of mitral valve repair for mitral valve prolapse. J Heart Valve Dis 2008;17:162–7.
17. Suri RM, Clavel MA, Schaff HV, et al. Effect of recurrent mitral regurgitation following degenerative mitral valve repair: long-term analysis of competing outcomes. J Am Coll Cardiol 2016;67:488–98.
18. Tabata M, Kasegawa H, Fukui T, et al. Long-term outcomes of artificial chordal replacement with tourniquet technique in mitral valve repair: a single-center experience of 700 cases. J Thorac Cardiovasc Surg 2014;148:2033–2038 e1.
19. Uchimuro T, Tabata M, Saito K, et al. Post-repair coaptation length and durability of mitral valve repair for posterior mitral valve prolapse. Gen Thorac Cardiovasc Surg 2014;62:221–7.
20. Ibrahim M, Rao C, Ashrafian H, et al. Modern management of systolic anterior motion of the mitral valve. Eur J Cardiothorac Surg 2012;41: 1260–70.
21. Jebara VA, Mihaileanu S, Acar C, et al. Left ventricular outflow tract obstruction after mitral valve repair. Results of the sliding leaflet technique. Circulation 1993;88:II30–4.
22. Lee KS, Stewart WJ, Lever HM, et al. Mechanism of outflow tract obstruction causing failed mitral valve repair. Anterior displacement of leaflet coaptation. Circulation 1993;88:II24–9.
23. Crescenzi G, Landoni G, Zangrillo A, et al. Management and decision-making strategy for systolic anterior motion after mitral valve repair. J Thorac Cardiovasc Surg 2009;137:320–5.
24. Maslow AD, Regan MM, Haering JM, et al. Echocardiographic predictors of left ventricular outflow tract obstruction and systolic anterior motion of the mitral valve after mitral valve reconstruction for myxomatous valve disease. J Am Coll Cardiol 1999;34: 2096–104.
25. Shah PM, Raney AA. Echocardiographic correlates of left ventricular outflow obstruction and systolic anterior motion following mitral valve repair. J Heart Valve Dis 2001;10:302–6.
26. Manabe S, Kasegawa H, Fukui T, et al. Morphological analysis of systolic anterior motion after mitral valve repair. Interact Cardiovasc Thorac Surg 2012;15:235–9.
27. Brown ML, Abel MD, Click RL, et al. Systolic anterior motion after mitral valve repair: is surgical intervention necessary? J Thorac Cardiovasc Surg 2007; 133:136–43.
28. Maslow A. Mitral valve repair: an echocardiographic review: part 2. J Cardiothorac Vasc Anesth 2015;29: 439–71.
29. Essandoh M. Intraoperative echocardiographic assessment of mitral valve area after degenerative mitral valve repair: a call for guidelines or recommendations. J Cardiothorac Vasc Anesth 2016;30: 1364–8.
30. Bothe W, Miller DC, Doenst T. Sizing for mitral annuloplasty: where does science stop and voodoo begin? Ann Thorac Surg 2013;95:1475–83.
31. Mesana TG, Lam BK, Chan V, et al. Clinical evaluation of functional mitral stenosis after mitral valve repair for degenerative disease: potential affect on

surgical strategy. J Thorac Cardiovasc Surg 2013; 146:1418–23 [discussion: 1423–5].
32. Maslow A, Mahmood F, Poppas A, et al. Three-dimensional echocardiographic assessment of the repaired mitral valve. J Cardiothorac Vasc Anesth 2014;28:11–7.
33. Hill AC, Bansal RC, Razzouk AJ, et al. Echocardiographic recognition of iatrogenic aortic valve leaflet perforation. Ann Thorac Surg 1997;64:684–9.
34. Rother A, Smith B, Adams DH, et al. Transesophageal echocardiographic diagnosis of acute aortic valve insufficiency after mitral valve repair. Anesth Analg 2000;91:499–500.
35. Lakew F, Urbanski PP. Aortic valve leaflet perforation after minimally invasive mitral valve repair. Ann Thorac Surg 2016;101:1180–2.
36. Veronesi F, Caiani EG, Sugeng L, et al. Effect of mitral valve repair on mitral-aortic coupling: a real-time three-dimensional transesophageal echocardiography study. J Am Soc Echocardiogr 2012;25: 524–31.
37. Poelaert JI, Bouchez S. Perioperative echocardiographic assessment of mitral valve regurgitation: a comprehensive review. Eur J Cardiothorac Surg 2016;50:801–12.
38. Tsang W, Weinert L, Sugeng L, et al. The value of three-dimensional echocardiography derived mitral valve parametric maps and the role of experience in the diagnosis of pathology. J Am Soc Echocardiogr 2011;24:860–7.
39. Chandra S, Salgo IS, Sugeng L, et al. Characterization of degenerative mitral valve disease using morphologic analysis of real-time three-dimensional echocardiographic images: objective insight into complexity and planning of mitral valve repair. Circ Cardiovasc Imaging 2011;4:24–32.
40. Drake DH, Zimmerman KG, Hepner AM, et al. Echo-guided mitral repair. Circ Cardiovasc Imaging 2014; 7:132–41.
41. Maffessanti F, Marsan NA, Tamborini G, et al. Quantitative analysis of mitral valve apparatus in mitral valve prolapse before and after annuloplasty: a three-dimensional intraoperative transesophageal study. J Am Soc Echocardiogr 2011;24:405–13.
42. Grewal J, Suri R, Mankad S, et al. Mitral annular dynamics in myxomatous valve disease: new insights with real-time 3-dimensional echocardiography. Circulation 2010;121:1423–31.
43. Lang RM, Badano LP, Tsang W, et al, American Society of E and European Association of E. EAE/ASE recommendations for image acquisition and display using three-dimensional echocardiography. Eur Heart J Cardiovasc Imaging 2012;13:1–46.
44. Tsang W, Lang RM. Three-dimensional echocardiography is essential for intraoperative assessment of mitral regurgitation. Circulation 2013;128:643–52 [discussion: 652].
45. Ring L, Rana BS, Ho SY, et al. The prevalence and impact of deep clefts in the mitral leaflets in mitral valve prolapse. Eur Heart J Cardiovasc Imaging 2013;14:595–602.
46. Mantovani F, Clavel MA, Vatury O, et al. Cleft-like indentations in myxomatous mitral valves by three-dimensional echocardiographic imaging. Heart 2015;101:1111–7.