Multimodality Imaging for the Assessment of Mitral Valve Disease

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KEYWORDS

• Mitral valve • Echocardiography • Magnetic resonance imaging • Computed tomography

KEY POINTS

- The mitral valve complex's proper function needs the integrity of leaflets, annulus, chordae, papillary muscles, ventricle, and atrium. Functional, structural, or geometric distortion of one or more of these parts may cause valvular dysfunction. Therefore, comprehensive evaluations of these parameters with any imaging modality are crucial.
- Echocardiography is the primary imaging modality for visualizing the mitral valve. Three-dimensional (3D) imaging provides incremental value in assessing the severity of valvular heart disease and establishing its mechanism. For patients undergoing transcatheter intervention, real-time 3D images facilitate manipulating the catheter, to position and orient the device.
- Roles of computed tomography and cardiac MRI (CMR) are increasing. The utility of CMR for the evaluation of mitral regurgitation has recently been adopted as part of the guideline.

INTRODUCTION

The burden of valvular heart disease is increases with age. Mitral valve (MV) disease is the most common valvular heart disease. The prevalence in subjects older than 75 years is almost 10%.[1] Imaging is needed to assess or be evaluated for (1) valve morphology to determine the etiology (anatomic assessment), (2) valve function and the severity of valvular heart disease (hemodynamic assessment), (3) remodeling of the left ventricle (LV) and right ventricle (RV), and (4) preplanning and guidance of percutaneous intervention. Echocardiography is the primary imaging modality for visualizing the MV. Although roles of computed tomography (CT) and cardiac magnetic resonance (CMR) are increasing, echocardiography serves as the first-line imaging modality for diagnosis and serial follow-up in most cases. This review summarizes the roles of multimodality imaging currently available from research fields to daily clinical practice.

NORMAL MITRAL VALVE ANATOMY

The MV apparatus comprises an annulus, 2 leaflets, chordae tendineae, and papillary muscles (Fig. 1).[2] The MV annulus, a D-shaped ring rather than circular shape positioned in the left atrioventricular groove, extends from 2 fibrous trigones located at either end of the area of fibrous continuity between the aortic leaflet of the MV and the aortic root.[3] This straight border forms the anterior part of the annulus, which is in fibrous continuity with the aortic valve. The remaining border of the annulus forms the posterior annulus. Annular remodeling occurs predominantly in the posterior part of the annulus (asymmetric annular dilation), because the posterior part of the annulus faces pliant endocardium, not a fibrous skeleton.[4]

Anterior and posterior mitral leaflets are not equal in size.[5] The anterior leaflet attaches to one-third of the annulus but encloses a larger portion of the valve orifice than the posterior leaflet dose. The anterior leaflet is one of the parts of LV outflow tract

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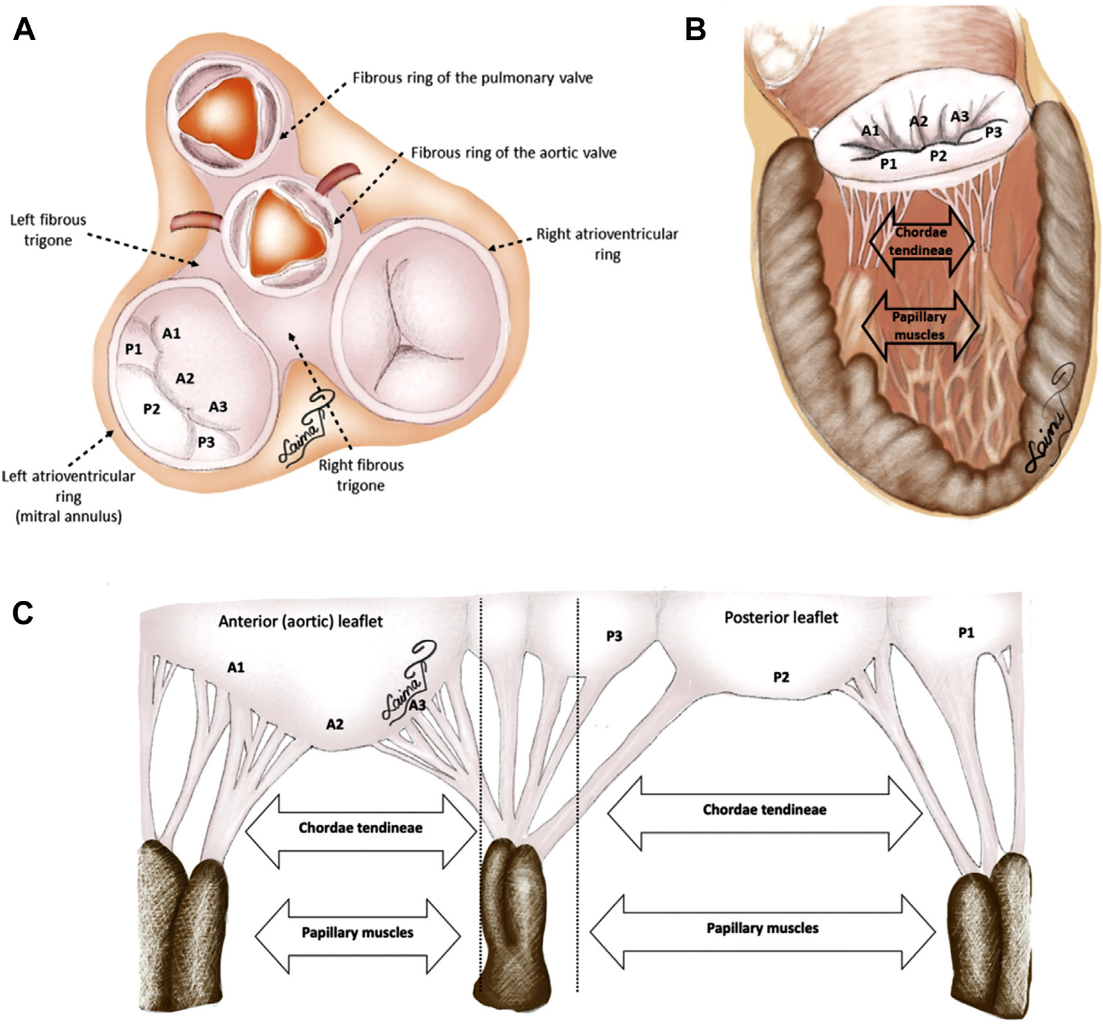

Fig. 1. Anatomy of the MV apparatus. Craniocaudal view of the heart (*A*) with components of the fibrous skeleton. Longitudinal cross-sectional view (*B*) highlighting the position of the MV, chordae tendineae and PMs. Expanded view of the MV leaflets, chordae, and proximal parts of the PMs (*C*). (*From* Tumenas A, Tamkeviciute L, Arzanauskiene R, Arzanauskaite M. Multimodality Imaging of the Mitral Valve: Morphology, Function, and Disease. *Current Problems in Diagnostic Radiology.* 2020; with permission.)

(LVOT) during systole, causing outflow tract obstruction in hypertrophic obstructive cardiomyopathy.[6] Three segments form each leaflet: A1, A2, and A3 in the anterior leaflet and P1, P2, and P3 in the posterior leaflet. The clefts or indentations along the free margin of the posterior leaflet make it a scalloped appearance. Despite the absence of indentations, similar terminology is applied for the anterior leaflet scallops. Three scallops are not equal in size, and middle scallops are larger in most cases.[7] When the leaflets coapt during diastole, the view of the valve from the atrium resembles a smile. Each end of the coaptation line is named as a commissure. Normally, the valvar leaflets are thin, translucent, and soft, and each leaflet has an atrial and a ventricular surface.

The MV leaflets are braced by chordae, and attach to 2 papillary muscles (PMs). The tendinous cords are stringlike structures that connect the ventricular surface or the free edge of the leaflets to the PMs.[8] The first-order cords are inserted into the free edge of the MV. Second-order cords insert on the ventricular surface of the leaflets beyond the free edge, forming the rough zone. Third-order cords are connected only to the mural leaflet because they arise directly from the ventricular wall.[8] The Toronto group classified them into leaflets and interleaflet or commissural cords.[9] Viewed from the atrial aspect, the 2 PMs are located below the commissures, positioning in anterolateral and posteromedial directions. The anterolateral PM is a single in 70% of cases, and the posteromedial PM is 2 or 3 in number or 1 PM with 2 or 3 heads in 60%.[8]

Echocardiography

Transthoracic echocardiography (TTE) is the first-line imaging modality for screening, assessment, diagnosis, and surveillance of valvular disease. For MV disease, TTE is still the mainstream for evaluating the etiology, anatomic morphology, and grade of mitral regurgitation (MR) or stenosis (MS). The proper function of the MV complex needs the integrity of leaflets, mitral annulus, chordae, PMs, LV, and left atrium (LA). Functional, structural, or geometric distortion of 1 or more of these parts may cause valvular dysfunction.[10] The grading of severity of valvular heart disease will not be discussed herein. Comprehensive approaches with multimodality imaging are especially required for the assessment of MR.[11]

Three-dimensional (3D) imaging provides incremental value in the assessment of severity of valvular stenosis (Fig. 2A) or regurgitation (Fig. 2B) and in establishing its mechanism. Traditionally, two-dimensional (2D) imaging requires multiple view acquisitions, including modified views of the MV, to make a detailed assessment of MV morphology, adjuring longer study time and expert interpretation. Three-dimensional transesophageal echocardiography (TEE) has become widely used in operating rooms and cardiac catheterization laboratories. Three-dimensional TEE has been proven to be superior to 2D TEE in the assessment of both MV anatomy and MR.[12] One reason for this superiority is that 3D TEE allows the MV to be visualized en face in an orientation identical to the surgeon's view of the MV intraoperatively (Fig. 2B, C), and 3D TEE enables the person with relatively little training to acquire high-quality real-time 3D images even in a single beat. Three-dimensional echocardiography has multiple acquisition modes and display options (simultaneous multiplane imaging, tomographic slices, surface rendering, and volume rendering); moreover, simultaneous 2D multiplane imaging ("x-plane or biplane mode") in a modifiable angulation.[13] Accurate preoperative or preprocedural assessment of the valve anatomy and location of lesions are critical in the management of patients with severe MR.[14] This information determines whether the patient should undergo valve repair or replacement and influences the timing of surgery accordingly.

For patients undergoing transcatheter intervention for MR, adequate patient selection for these therapies requires a precise assessment of MV anatomy and function. Moreover, live 3D TEE en face views of the MV facilitate manipulation of

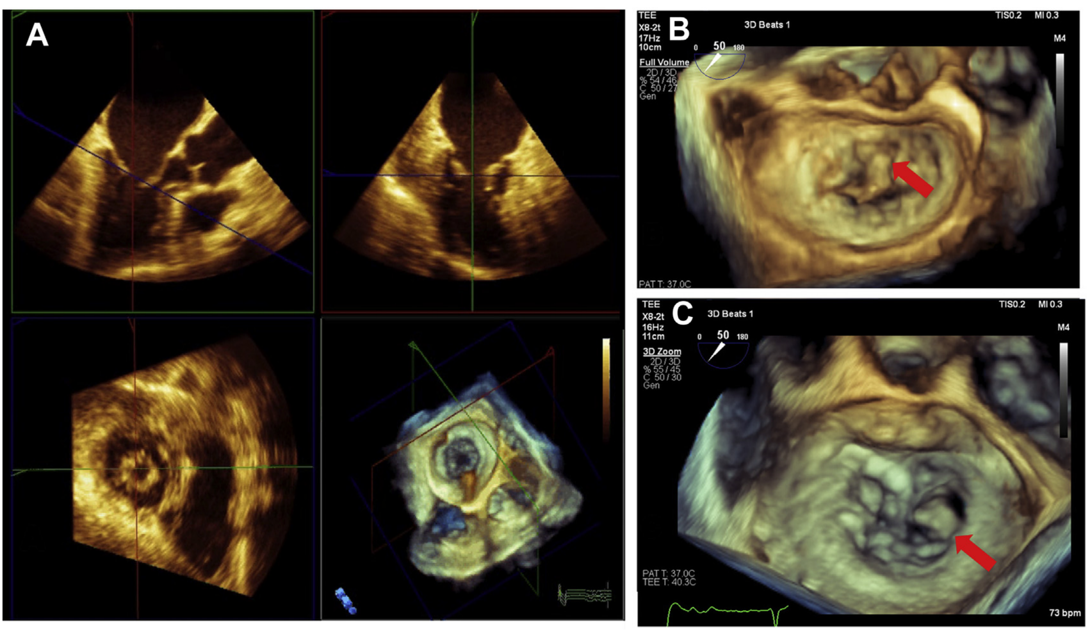

Fig. 2. Multiplanar reconstruction (MPR) mode on 3D TEE to assess the MV. Using MPR mode in patients with mitral stenosis allows a more accurate valve measurement (*A*). Three-dimensional reconstruction of the MV en face in an orientation identical to the surgeon's view shows A2 prolapse with ruptured chordae (*red arrow*, *B*). Three-dimensional en face view depicting a medical commissural prolapse (*red arrow, C*). Differentiation between commissural prolapse and A3, P3 prolapse is crucial in the era of the MV intervention.

the catheter, to position and orient the device without damaging adjacent structures (Fig. 3A, B). The biplane (x-plane) views show simultaneously the bi-commissural, and the 3-chamber long-axis planes (Fig. 3C) is most frequently used to fine-tune the orientation of the device relative to the largest regurgitant orifice area and perpendicular to the coaptation line.

Further anatomic or geometric qualifications with echocardiography

In patients with hypertrophic cardiomyopathy, LV outflow tract obstruction (LVOTO) is produced by systolic anterior motion of the MV. Clinical implications of MV size in hypertrophic cardiomyopathy have been elucidated with 2D and 3D echocardiography, which recently allowed mitral leaflet size and area in the beating heart (Fig. 4).[15,16] In vivo measurement of mitral leaflet area makes it possible to understand more on the mechanisms of ischemic/function MR in detail using 3D echocardiography.[4,17,18] Recently, commercialized software supports the measurement.[19,20]

The visualization of mitral annulus shape using 3D echocardiography has contributed to the development of nonplanar mitral annuloplasty rings.[21] Comprehensive analysis of annulus geometry, including area, perimeter, nonplanar angle, diameters, intertrigone distance, and height can provide valuable information to reveal the mechanism of valvular heart disease (Fig. 5).[22,23] Minimal mitral annulus dimensions are present in early systole, and annulus dimensions increase toward late systole. Changes in all parameters acquired from annulus geometry can be calculated during the cardiac cycle; annular dynamics differ between healthy subjects and patients with MV disease.[24]

Computed Tomography Scan

Cardiac CT scan acquires the images with the injection of contrast agents, and protocol is structured to allow assessment of the coronary arteries as well. The pathologic imaging findings of the MV including prolapse, vegetation, and coaptation gap, can be well demonstrated in the systolic phase of the cardiac cycle. Cine reconstruction methods using volume-rendered images are useful for visualizing MV structure. At our institution, cardiac CT for evaluation of both the coronary artery and MV is performed with a second-generation dual-source CT scanner (Definition Flash; Siemens, Erlangen, Germany). The images acquired in the mid-systolic phase are used to evaluate the MV. Images are reconstructed with the 5% R-R interval (20 images per 1 cardiac cycle) for retrospective electrocardiogram (ECG)-gated scanning and at 10-ms intervals for prospective ECG-triggered scanning.[25]

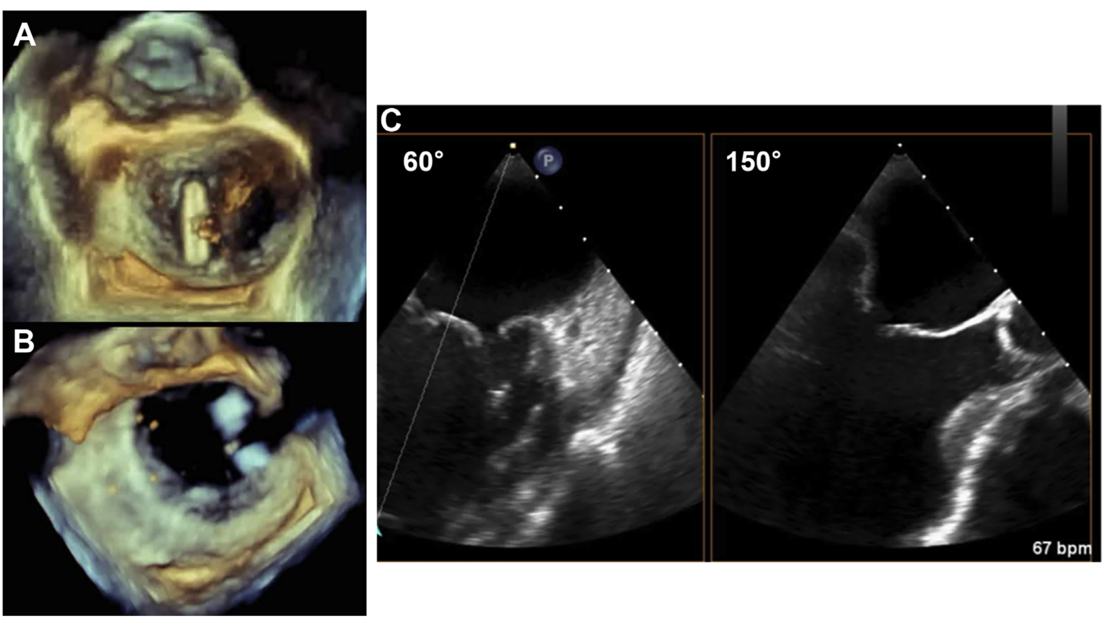

Fig. 3. Real-time 3D images make it possible to check a clip orientation during the percutaneous MV edge to edge repair (*A*, *B*). The clip is recommended to be placed perpendicular to the coaptation line. Reducing 3D gain can visualize the clip in the LV (*B*). X-plane imaging is advantageous to guide the percutaneous mitral intervention. The bi-commissural (*left*) and LVOT view (*right*) images are crucial for the MitraClip intervention (*C*).

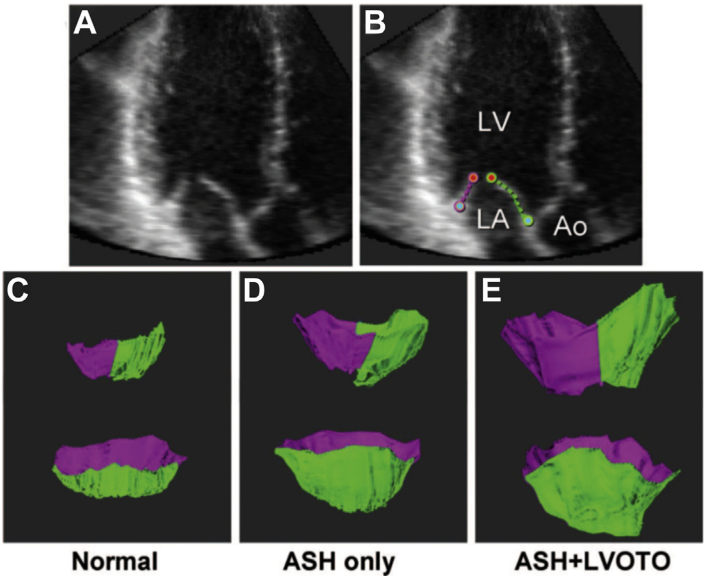

Fig. 4. Component view with mitral leaflet traces for 3D reconstruction (*A*, *B*). Representative open mitral leaflet area measurements in green and purple for anterior and posterior leaflets viewed from the side (*C* through *E*, top row, lateral commissure in foreground) and LVOT aspect below, largest in asymmetric septal hypertrophy (ASH) and ASH with LVOTO. Ao, aorta. (*From* Kim DH, Handschumacher MD, Levine RA, et al. In vivo measurement of mitral leaflet surface area and subvalvular geometry in patients with asymmetrical septal hypertrophy: insights into the mechanism of outflow tract obstruction. Circulation. 2010;122(13):1298-1307; with permission.)

Assessment of prolapse segment with computed tomography scan

In our clinical practice, we review the quality of images with 4-dimensional multiphase CT data including the 3-chamber view. We found that the best-quality images were obtained during the 25% to 35% cardiac phases in approximately 80% of patients with MV prolapse.[25] A step-by-step method for the image reconstruction of MV can be summarized as follows: (1) determine the best cardiac phase; (2) identify the location and extent of disease on sagittal and coronal views of the MV by using a multiplanar reformatted technique (anterior vs posterior leaflet in the sagittal view; medial, middle, or lateral scallops in the coronal view); and (3) recheck the extent and location of the disease on the 3D volume-rendered image (Fig. 6).[25]

The localization of the MV prolapse segment is feasible on a per-scallop basis, but it may underestimate the extent of prolapsed scallop compared with TEE, particularly in patients with multiple-scallop lesions. The per-scallop sensitivity of cardiac CT was slightly lower than that of echocardiography (80% vs 87%, P = .004), with similar specificity (both 95%).[26]

Detection of paravalvular leakage in patients with prosthetic heart valve

Paravalvular leakage (PVL) is defined as an abnormal communication between the sewing ring and valve annulus and the prevalence of

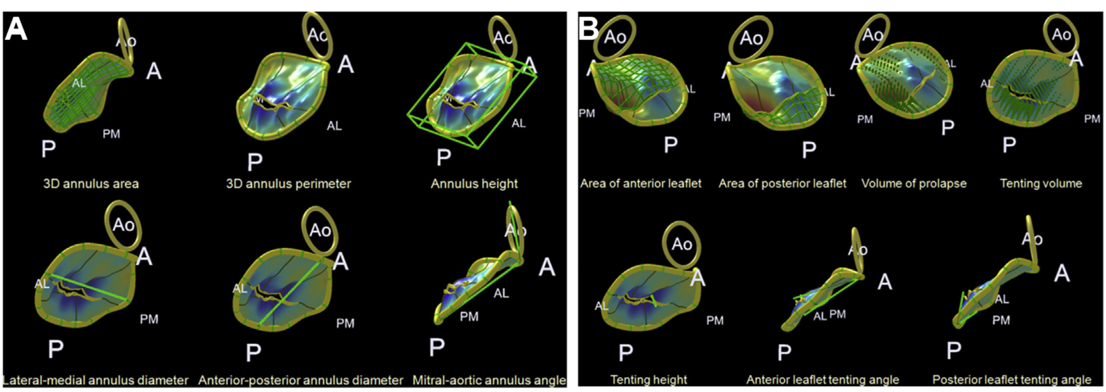

Fig. 5. Parameters for MV annulus geometry (*A*). Parameters for MV leaflet geometry (*B*). A, anterior; AL, anterolateral; Ao, aortic annulus; P, posterior, PM, posteromedial. (*From* Song JM, Jung YJ, Jung YJ, et al. Three-dimensional remodeling of mitral valve in patients with significant regurgitation secondary to rheumatic versus prolapse etiology. Am J Cardiol. 2013;111(11):1631-1637; with permission.)

PVL after MV replacement ranges from 3% to 15%.[27] For severe symptomatic PVL, surgical corrections perform either repair of the leak or re-replacement have been recommended. However, the recurrence rates range from 12% to 35%, and therefore percutaneous device closure has been introduced as an alternative option to treat PVL.[28] For decision making in PVL treatment, anatomic information, including the size, shape, and the 3D relationship with adjacent structures should be considered as parts of pre-procedural planning. Echocardiography is the primary modality of choice that provides excellent temporal resolution and real-time imaging capabilities with color Doppler information, but sometimes image quality can be compromised. In contrast, cardiac CT can give more precise anatomic details, including the exact location and morphology of the PVLs. Pretreatment planning could be better tailored and individualized with cardiac CT scan (**Fig. 7**).[29]

Detection and diagnosis of infective endocarditis

Echocardiography is the imaging method of choice for the diagnosis of infective endocarditis (IE), but the operator dependency and poor sonic window caused by calcifications or detection on vegetation on mechanical prosthetic valves are still limitations. A recent meta-analysis showed that CT might provide incremental value to TEE for diagnosing prosthetic valve IE.[30] Kim and colleagues[31] reported the overall detection rate of vegetation was inferior in CT compared with TEE (97.3% vs 72.0%), but cardiac CT shows comparable diagnostic performance with TEE for large vegetation ($\geq$10 mm). TEE was better for detecting small vegetation, valve perforation, and intracardiac fistula, whereas CT was more useful for detecting perivalvular abscess and coronary artery disease.[31] In contrast, another report showed similar sensitivities between CT and TEE to detect IE, and excellent interobserver agreement.[32]

Leaflet size, annulus geometry, and relationship with papillary muscles

Mitral leaflet area and annulus area measured by CT were comparable with 3D echocardiography, and there was no difference in agreement with 3D TEE for patients scanned with single-source versus dual-source CT.[33] Song and colleagues[34] explored geometric predictors of LVOTO in patients with hypertrophic cardiomyopathy by using cardiac CT and found that anterior mitral leaflet length and the distance between lateral PM base and LV apex were independent predictors of LVOTO. Cardiac CT has an advantage of more accurate evaluation of the 3D geometry of myocardial hypertrophy pattern and PMs than CMR and echocardiography.[29,32,34]

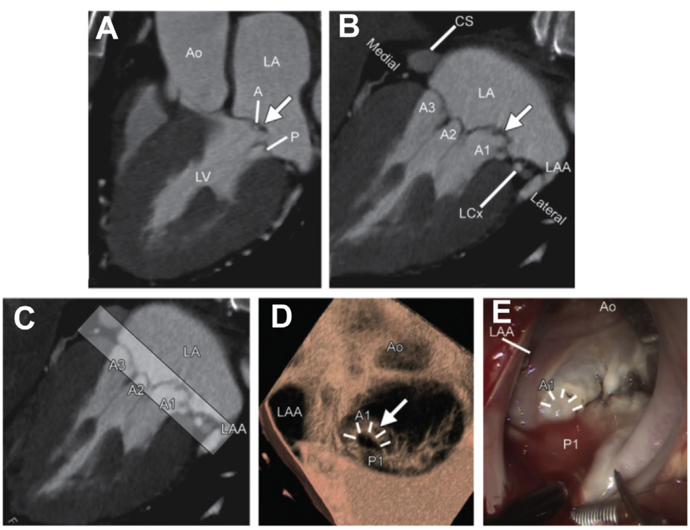

Fig. 6. Reconstruction of CT images of the MV to evaluate the extent and location of MV prolapse. A1, A2, and A3 = lateral, middle, and medial scallops of the anterior leaflet, respectively; P1, P2, and P3 = lateral, middle, and medial scallops of the posterior leaflet, respectively. Parasagittal reconstructed CT image shows MV prolapse in the A1 portion (*A*). A coronal reconstructed CT image shows a prolapsed scallop of the MV (*arrow*) near the left atrial appendage, which is a landmark of a lateral direction in the MV annulus. The proximal left circumflex artery (LCX) is also located in the lateral direction, and the coronary sinus (CS) and interatrial septum are located in the medial direction (*B*). Coronal thin-section maximum intensity projection reconstructed CT image obtained at the level of the valve shows the section thickness used to generate the surgeon's view (*C*). Surgeon's view of the MV obtained with thin-section (15-mm) volume rendering shows that the A1 scallop is prolapsed (*D*). Intraoperative photograph obtained with a robot-assisted surgery system shows that the locations of the prolapsed scallop and left atrial appendage (LAA) correspond with the CT findings (*E*). Ao, ascending aorta. (*From* Koo HJ, Yang DH, Oh SY, et al. Demonstration of mitral valve prolapse with CT for planning of mitral valve repair. Radiographics. 2014;34(6):1537-1552; with permission.)

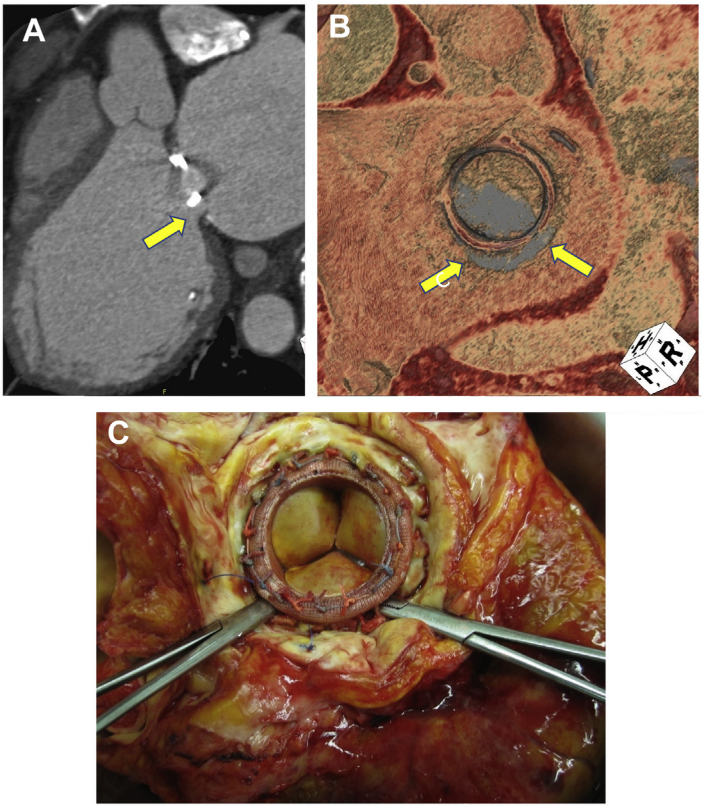

Fig. 7. Large crescent-shaped dehiscence (*yellow arrows*) that involved posterior part of the mitral annulus on CT images (*A*, *B*). A single large PVL in surgical inspection was confirmed. Surgical instruments indicate the medial and lateral ends of the paravalvular dehiscence (*C*).

In the ear of transcatheter MV replacement (TMVR), CT is becoming a critical imaging modality for identifying the MV anatomy and its spatial relationships with other structures. The parameters measuring the MV annulus geometry are essential to select the size of transcatheter MV annuloplasty devices and TMVR. The assessment of MV annulus calcification is essential to check the feasibility of various transcatheter therapies.[10] For TMVR planning, truncation of the saddle-shaped annular contour at a virtual line connecting both trigones (trigone-to-trigone [TT] distance), has been used.[24] Three-dimensional segmentation and post-processing yield annular area and perimeter, TT distance, septal-to-lateral distance (A2-to-P2 distance, minor diameter), and the intercommissural (IC) distance (major diameter).[24] Similar post-processing using 3D echocardiography full-volume set can be performed off-line (**Fig. 8**).

CARDIAC MAGNETIC RESONANCE IMAGING

CMR provides a comprehensive evaluation of cardiac anatomy, function, and myocardial tissue characterization, and the usefulness to assess valvular heart disease, especially regurgitation, is increasingly recognized. The utility of CMR for the evaluation of valvular regurgitation has recently been adopted as part of the joint American Society of Echocardiography and the Society of Cardiovascular Magnetic Resonance recommendations for the noninvasive evaluation of native valvular regurgitation.[11] For assessment of the severity of MR, CMR has become an established noninvasive imaging modality to assess the severity of MR (**Fig. 9**).[35]

Valve Structure and Ventricular Function Assessment

To visualize the morphology and motion of the MV from any desired image orientation, balanced steady-state free precession (SSFP) sequence cine imaging techniques have been widely used for the evaluation of valvular structures in motion, because it can provide a high signal-to-noise ratio (excellent contrast) between the blood pool and myocardium. Older sequences such as “black blood” turbo-spin-echo (TSE) techniques (T1-weighted and T2-weighted TSE imaging techniques) can be used for the evaluation of valvular masses such as vegetations or tumors..[36]

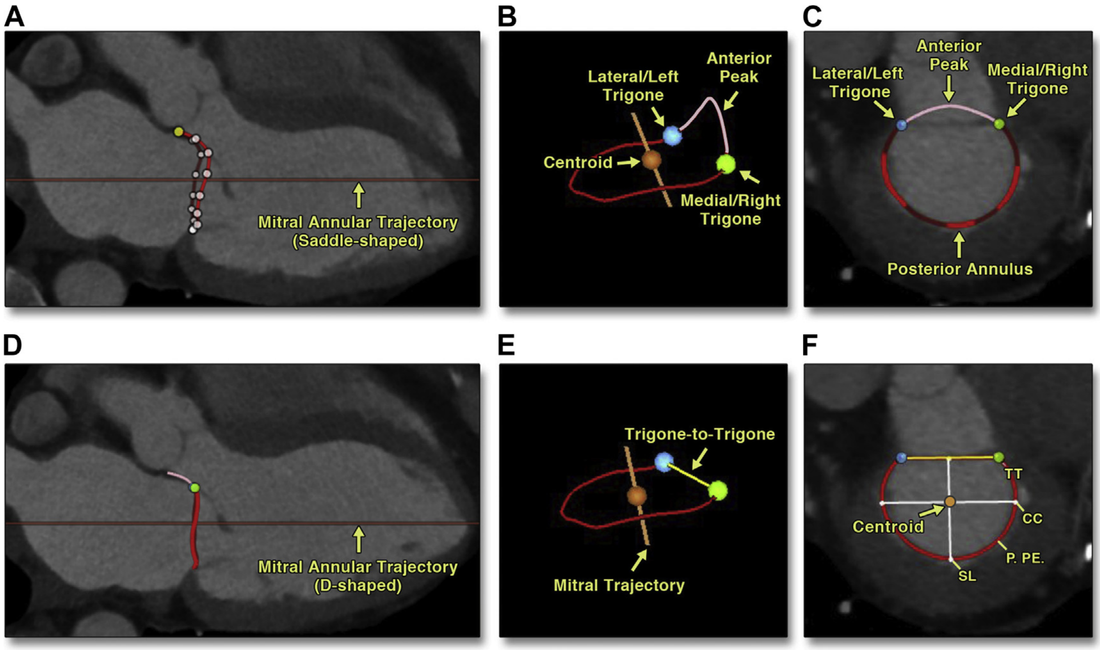

Fig. 8. Saddle-shaped annulus segmentation as a cubic spline interpolation (*A*). Pink line = anterior peak; red line = posterior peak (posterior mitral leaflet insertion, P. PE.); green and blue dots = fibrous trigones (*B*). Importantly, the anterior peak projects into the LVOT (short-axis view [*C*] and long-axis view [*D*]). The more planar D-shaped annular contour is created by truncating the saddle-shaped contour at the TT distance (*yellow lines* [*E*, *F*]). Important measurements are the projected area setal-to-lateral (SL) and intercommissural (CC) distances; the latter is oriented perpendicularly to SL while transecting through the centroid (*F*). (*From* Blanke P, Naoum C, Webb J, et al. Multimodality Imaging in the Context of Transcatheter Mitral Valve Replacement: Establishing Consensus Among Modalities and Disciplines. JACC Cardiovasc Imaging. 2015;8(10):1191-1208; with permission.)

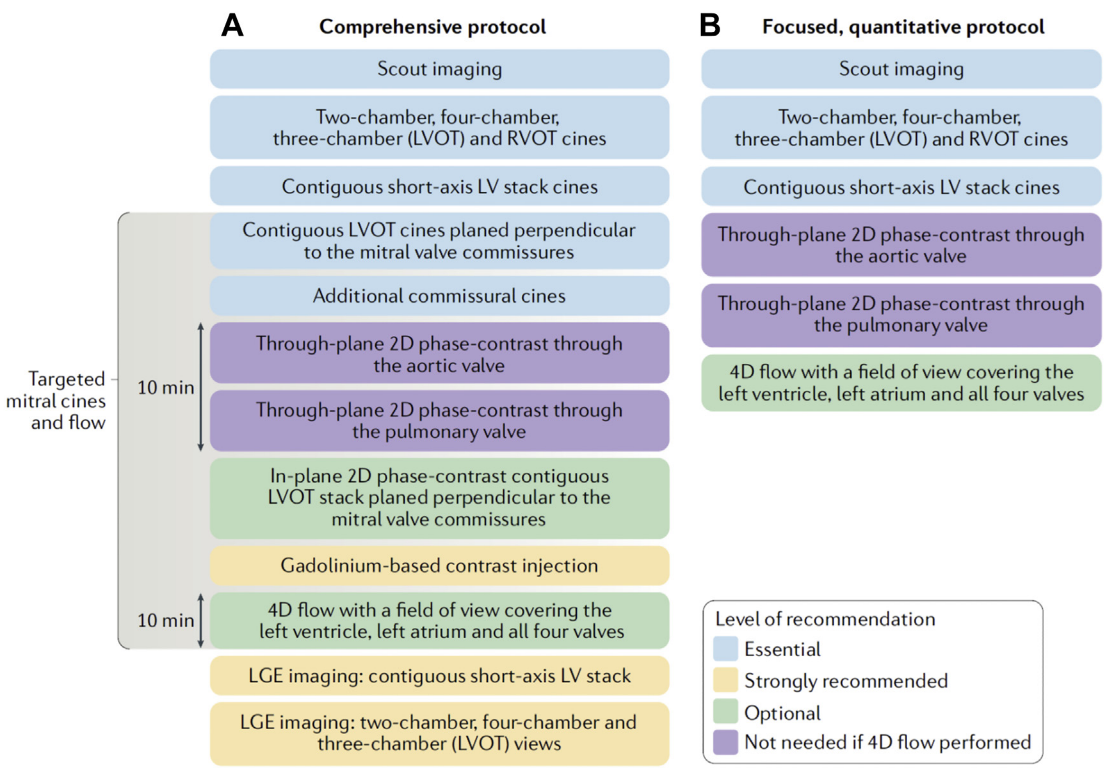

Fig. 9. Recommended cardiovascular MRI protocols for the assessment of MR. Comprehensive cardiovascular MRI protocol for the assessment of MR (*A*). Focused, quantitative protocol (*B*). LGE, late gadolinium enhancement; RVOT, right ventricular outflow tract. (*From* Garg P, Swift AJ, Zhong L, et al. Assessment of mitral valve regurgitation by cardiovascular magnetic resonance imaging. Nat Rev Cardiol. 2020;17(5):298-312; with permission.)

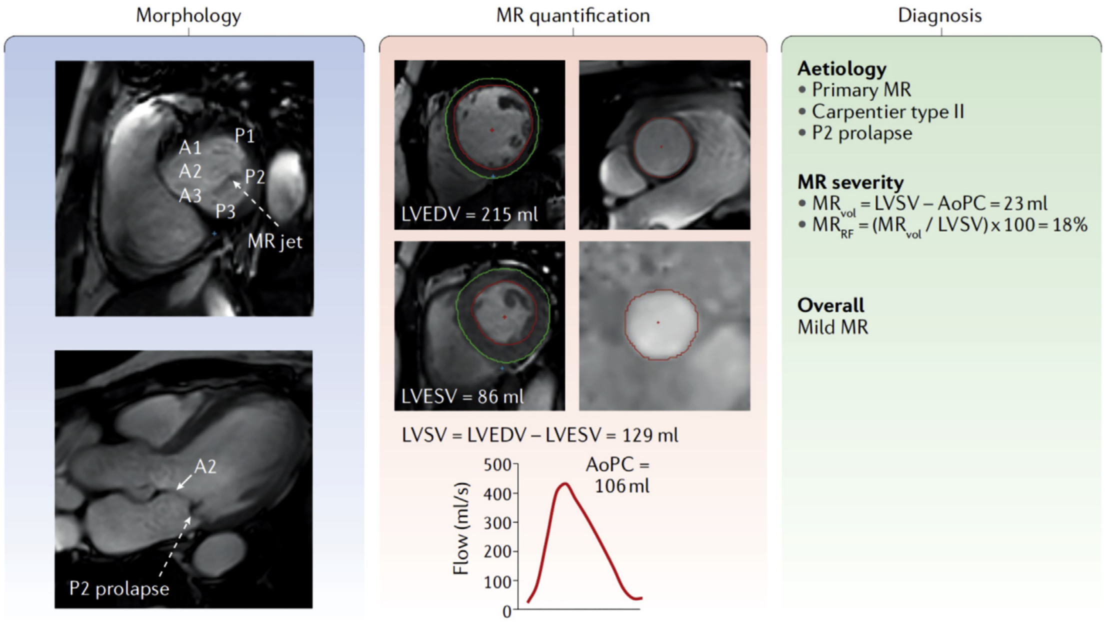

Fig. 10. MR assessment in a patient with ischemic cardiomyopathy. Incomplete coaptation owing to ventricular dilatation is seen on the short-axis cines (morphology panel, *top images*). A through-plane phase-contrast acquisition shows the central MR jet (morphology panel, *right-hand middle image*). LGE imaging reveals extensive ischemic myocardial scaring (morphology panel, *right-hand bottom image*). The MR volume (MRvol) is quantified using the standard method: LV stroke volume (LVSV) minus aortic phase-contrast forward volume (AoPC). LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; MRRF, mitral regurgitation fraction. (*From* Garg P, Swift AJ, Zhong L, et al. Assessment of mitral valve regurgitation by cardiovascular magnetic resonance imaging. Nat Rev Cardiol. 2020;17(5):298-312; with permission.)

Quantification of LV size and volumes by SSFP technique of CMR can be an integral part of a comprehensive assessment as a reference method and are needed for the decision making of a treatment plan (timing of surgery). Ventricular volumes are determined from a short-axis stack of 6-mm-thick to 8-mm-thick slices. They can be analyzed with off-line software, allowing endocardial and epicardial border tracing of both ventricles automatically or manually. Likewise, the Simpson method can be used to calculate ventricular volumes, ejection fractions, and myocardial mass.[36]

Flow Visualization and Quantification

Phase-contrast velocity encoding is a technique that uses velocity-encoding (VENC) gradients to generate a phase shift in the MRI signal, which is proportional to the velocity of the moving protons.[36] Four-dimensional-flow CMR allows for visualization of 2D velocity vectors in a designated plane, enabling a comprehensive assessment of the blood flow dynamics in the LA. Velocity vector visualization of LA flow coupled with cine CMR can help to understand the cause of the MR, similar to Doppler imaging acquired from echocardiography.[36] The MR jet cane be visualized using both cine and 2D phase-contrast CMR. Quantification of mitral regurgitant volume and fraction is the recommended technique, and the MR volume can be calculated by 4 different methods: (1) Standard method and widely used: the difference between the LV stroke volume calculated using planimetry of cine SSFP images and the aortic forward volume obtained by phase-contrast images (Fig. 10); (2) the difference between the LV and RV stroke volumes calculated using planimetry of cine SSFP images; (3) the difference between the mitral inflow stroke volume and the aortic forward volume; and (4) direct quantification of MR flow by 4D-flow CMR with retrospective MV tracking.[35]

For the evaluation of patients with MR, late gadolinium enhancement (LGE) imaging to test viability should be performed in accordance with published guidelines.[37] Contiguous, short-axis, LV stack LGE imaging is needed, in addition to LGE in the 3 standard long-axis planes.

SUMMARY

The MV complex's proper function needs the integrity of leaflets, annulus, chordae, PMs, ventricle, and atrium. Functional, structural, or geometric distortion of 1 or more of these parts may cause valvular dysfunction. Therefore, a comprehensive evaluation with multimodality imaging is crucial. Echocardiography is the primary imaging modality for assessing the MV. Although roles of CT and CMR are increasing, echocardiography will serve as the first-line imaging modality for the diagnosis and serial follow-up in most cases. Cardiac CT scan acquires the images with the injection of contrast agents. Cine reconstruction methods using volume-rendered images are useful for visualizing the MV structure, including prolapse segments, vegetation, and dehiscence of the prosthetic valve. CMR provides a comprehensive evaluation of cardiac anatomy, function, and myocardial tissue characterization, and the usefulness to assess valvular heart disease, especially regurgitation. The utility of CMR evaluating valvular regurgitation has recently been adopted as part of the guideline. Finally, improved accuracy in the noninvasive assessment of MV and its related structures with multimodality imaging will ultimately translate to better management to improve outcomes for patients with MV disease.

CLINICS CARE POINTS

- Echocardiography is the primary imaging modality for visualizing the mitral valve. 3D imaging provides incremental value in assessing the severity of valvular heart disease and establishing its mechanism and is crucial for the guidance of percutaneous interventions.
- Roles of computed tomography and magnetic resonance imaging (CMR) are increasing. For the assessment of mitral regurgitation severity, CMR has recently been adopted as part of the guideline and become an established noninvasive imaging modality.

DISCLOSURE

The author has nothing to disclose.

REFERENCES

1. Nkomo VT, Gardin JM, Skelton TN, et al. Burden of valvular heart diseases: a population-based study. Lancet 2006;368(9540):1005–11.
2. Tumenas A, Tamkeviciute L, Arzanauskiene R, et al. Multimodality Imaging of the Mitral Valve: Morphology, Function, and Disease. Current Problems in Diagnostic Radiology. 2020. https://doi.org/10.1067/j.cpradiol.2020.09.013.
3. Berdajs D, Zund G, Camenisch C, et al. Annulus fibrosus of the mitral valve: reality or myth. J Card Surg 2007;22(5):406–9.
4. Kim DH, Heo R, Handschumacher MD, et al. Mitral valve adaptation to isolated annular dilation: insights into the mechanism of atrial functional mitral regurgitation. JACC Cardiovasc Imaging 2019;12(4):665–77.
5. Barlow JB. Perspectives on the mitral valve. Philadelphia: F.A. Davis; 1987.
6. Morris MF, Maleszewski JJ, Suri RM, et al. CT and MR imaging of the mitral valve: radiologic-pathologic correlation. Radiographics 2010;30(6):1603–20.
7. Ranganathan N, Lam JH, Wigle ED, et al. Morphology of the human mitral valve. II. The value leaflets. Circulation 1970;41(3):459–67.
8. Ho SY. Anatomy of the mitral valve. Heart 2002;88(Suppl 4):iv5–10.
9. Lam JH, Ranganathan N, Wigle ED, et al. Morphology of the human mitral valve. I. Chordae tendineae: a new classification. Circulation 1970;41(3):449–58.
10. Bax JJ, Debonnaire P, Lancellotti P, et al. Transcatheter interventions for mitral regurgitation: multimodality imaging for patient selection and procedural guidance. JACC Cardiovasc Imaging 2019;12(10):2029–48.
11. 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(4):303–71.
12. Tsang W, Lang RM. Three-dimensional echocardiography is essential for intraoperative assessment of mitral regurgitation. Circulation 2013;128(6):643–52 [discussion: 652].
13. Lang RM, Badano LP, Tsang W, et al. EAE/ASE recommendations for image acquisition and display using three-dimensional echocardiography. Eur Heart J Cardiovasc Imaging 2012;13(1):1–46.
14. 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(9):1365–74.
15. Klues HG, Proschan MA, Dollar AL, et al. Echocardiographic assessment of mitral valve size in obstructive hypertrophic cardiomyopathy. Anatomic validation from mitral valve specimen. Circulation 1993;88(2):548–55.
16. Kim DH, Handschumacher MD, Levine RA, et al. In vivo measurement of mitral leaflet surface area

and subvalvular geometry in patients with asymmetrical septal hypertrophy: insights into the mechanism of outflow tract obstruction. Circulation 2010; 122(13):1298–307.
17. Chaput M, Handschumacher MD, Tournoux F, et al. Mitral leaflet adaptation to ventricular remodeling: occurrence and adequacy in patients with functional mitral regurgitation. Circulation 2008;118(8): 845–52.
18. Dal-Bianco JP, Aikawa E, Bischoff J, et al. Active adaptation of the tethered mitral valve: insights into a compensatory mechanism for functional mitral regurgitation. Circulation 2009;120(4):334–42.
19. Cobey FC, Swaminathan M, Phillips-Bute B, et al. Quantitative assessment of mitral valve coaptation using three-dimensional transesophageal echocardiography. Ann Thorac Surg 2014;97(6):1998–2004.
20. Machino-Ohtsuka T, Seo Y, Ishizu T, et al. Novel mechanistic insights into atrial functional mitral regurgitation-3-dimensional echocardiographic study. Circ J 2016;80(10):2240–8.
21. Carpentier AF, Lessana A, Relland JY, et al. The "physio-ring": an advanced concept in mitral valve annuloplasty. Ann Thorac Surg 1995;60(5):1177–85 [discussion: 1185–6].
22. Lee AP, Hsiung MC, Salgo IS, et al. Quantitative analysis of mitral valve morphology in mitral valve prolapse with real-time 3-dimensional echocardiography: importance of annular saddle shape in the pathogenesis of mitral regurgitation. Circulation 2013;127(7):832–41.
23. Song JM, Jung YJ, Jung YJ, et al. Three-dimensional remodeling of mitral valve in patients with significant regurgitation secondary to rheumatic versus prolapse etiology. Am J Cardiol 2013;111(11):1631–7.
24. Blanke P, Naoum C, Webb J, et al. Multimodality imaging in the context of transcatheter mitral valve replacement: establishing consensus among modalities and disciplines. JACC Cardiovasc Imaging 2015;8(10):1191–208.
25. Koo HJ, Yang DH, Oh SY, et al. Demonstration of mitral valve prolapse with CT for planning of mitral valve repair. Radiographics 2014;34(6):1537–52.
26. Koo HJ, Kang JW, Oh SY, et al. Cardiac computed tomography for the localization of mitral valve prolapse: scallop-by-scallop comparisons with echocardiography and intraoperative findings. Eur Heart J Cardiovasc Imaging 2019;20(5):550–7.
27. Ionescu A, Fraser AG, Butchart EG. Prevalence and clinical significance of incidental paraprosthetic valvar regurgitation: a prospective study using transoesophageal echocardiography. Heart 2003; 89(11):1316–21.
28. Ruiz CE, Jelnin V, Kronzon I, et al. Clinical outcomes in patients undergoing percutaneous closure of periprosthetic paravalvular leaks. J Am Coll Cardiol 2011;58(21):2210–7.
29. Koo HJ, Lee JY, Kim GH, et al. Paravalvular leakage in patients with prosthetic heart valves: cardiac computed tomography findings and clinical features. Eur Heart J Cardiovasc Imaging 2018; 19(12):1419–27.
30. Habets J, Tanis W, Reitsma JB, et al. Are novel noninvasive imaging techniques needed in patients with suspected prosthetic heart valve endocarditis? A systematic review and meta-analysis. Eur Radiol 2015;25(7):2125–33.
31. Kim IC, Chang S, Hong GR, et al. Comparison of cardiac computed tomography with transesophageal echocardiography for identifying vegetation and intracardiac complications in patients with infective endocarditis in the era of 3-dimensional images. Circ Cardiovasc Imaging 2018;11(3): e006986.
32. Koo HJ, Yang DH, Kang JW, et al. Demonstration of infective endocarditis by cardiac CT and transoesophageal echocardiography: comparison with intraoperative findings. Eur Heart J Cardiovasc Imaging 2018;19(2):199–207.
33. Beaudoin J, Thai WE, Wai B, et al. Assessment of mitral valve adaptation with gated cardiac computed tomography: validation with three-dimensional echocardiography and mechanistic insight to functional mitral regurgitation. Circ Cardiovasc Imaging 2013;6(5):784–9.
34. Song Y, Yang DH, Hartaigh BÓ, et al. Geometric predictors of left ventricular outflow tract obstruction in patients with hypertrophic cardiomyopathy: a 3D computed tomography analysis. Eur Heart J Cardiovasc Imaging 2018;19(10):1149–56.
35. Garg P, Swift AJ, Zhong L, et al. Assessment of mitral valve regurgitation by cardiovascular magnetic resonance imaging. Nat Rev Cardiol 2020; 17(5):298–312.
36. Mathew RC, Loffler AI, Salerno M. Role of cardiac magnetic resonance imaging in valvular heart disease: diagnosis, assessment, and management. Curr Cardiol Rep 2018;20(11):119.
37. Kramer CM, Barkhausen J, Bucciarelli-Ducci C, et al. Standardized cardiovascular magnetic resonance imaging (CMR) protocols: 2020 update. J Cardiovasc Magn Reson 2020;22(1):17.