REVIEW

Interventional Echocardiography: Current Role and Progress

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ABSTRACT

Advances in cardiovascular interventional techniques have enabled percutaneous treatment for a wide spectrum of non-coronary cardiovascular diseases, also known as 'structural heart diseases (SHD)'. As these therapies are performed without an open-heart surgery, the use of echocardiography is crucial for detailed visualisation of cardiac anatomy, and to provide guidance for optimal success of these catheter-based interventions. This review will describe the key role of the echocardiographic techniques and imaging protocols that are currently used in different catheter-based SHD interventions.

Keywords: Echocardiography, Catheter-based intervention, Structural heart disease, Valvular heart disease, Peri-interventional imaging

INTRODUCTION

Over the past 1–2 decades, advances in technology and procedural skills have enabled new percutaneous therapies for the treatment of a wide spectrum of non-coronary cardiovascular diseases, also known as 'structural heart diseases (SHD)'. The hallmark of this rapidly progressing field of treatment for valvular and congenital heart diseases is that these therapies are becoming very minimally invasive, which are mostly catheter-based interventions, using wire manipulation and device implantation, without an open-heart surgery. As direct vision is no longer possible, comprehensive imaging is thus mandatory for visualisation of cardiac anatomy for optimal success of the current catheter-based interventions. In this regard, echocardiography plays a pivotal role, that allows for a detailed pre-procedural assessment of the anatomic defect, appropriate sizing and selection of device and procedural planning. During the procedure, it is capable of real-time imaging and hence, used for guiding and evaluating the procedural outcomes, and detection of any procedure-related complication. After the intervention, echocardiography remains the primary imaging modality for serial evaluation and follow-up of the patients.

It is well recognised that echocardiographic assessment of patients undergoing catheter-based structural heart intervention differs from that of the routine evaluation of patients with native or prosthetic valvular disease[1]. In fact, 'interventional echocardiography' requires special training that includes constant acquisition of new imaging modalities, as well as the knowledge of a wide spectrum of SHD and the necessary details on the available transcatheter techniques and devices. This review will describe the role of echocardiography, and its current imaging techniques and protocols that are used in catheter-based interventions for SHD, using examples in percutaneous valvular interventions and closure of left atrial appendage (LAA) for illustration.

ECHOCARDIOGRAPHY

Although there are other imaging modalities available, echocardiography remains the key imaging modality in structural heart interventions. There are several reasons why echocardiography is the preferred modality. Firstly, echocardiography has a major advantage over other imaging modalities, as it is portable and can be performed bedside, in the cardiac catheterisation laboratory, in the intensive care unit and essentially

anywhere that can accommodate a wheel cart[2]. Secondly, it permits real-time imaging. Unlike fluoroscopy, which requires contrast and emits radiation and yet lacks soft tissue delineation, echocardiography provides detailed anatomic and physiologic information that is both contrast- and radiation-free. Moreover, three-dimensional (3D) echocardiography has the unique ability to depict cardiac structures, as they appear in real-time[3]. Hence, it is the most ideal imaging modality to guide complex structural heart interventions.

The currently used echocardiographic imaging techniques include transthoracic (TTE), trans-oesophageal (TEE) and intracardiac echo-cardiography (ICE). Transthoracic echocardiography is the primary modality of choice in the pre-procedural evaluation of patients with SHD. Using conventional two-dimensional (2D) TTE, colour and spectral Doppler, comprehensive assessment of the defect, severity of valvular lesion, chamber sizes, ventricular functions and detection of contraindications to catheter-based interventions, such as intracardiac thrombus, can be obtained[4]. In addition, volumetric evaluation of valvular regurgitation and shunt quantification using 3D TTE, has recently been shown to be more accurate than 2D TTE[5]. The main advantage of TTE is that it is non-invasive and can be performed repeatedly. Hence, it is also the most commonly used imaging modality for post-procedural evaluation and follow-up of patients following SHD interventions.

Due to its superior spatial resolution and anatomic definition with TEE, it is the primary imaging modality used intra-procedurally for most SHD interventions[1]. Moreover, the advent of 3D TEE allows continuous visualisation of cardiac anatomy and its spatial relationship during the procedures[3], providing real-time guidance (such as the site of trans-septal puncture, safe manipulation of catheters and correct placement of devices), followed by evaluation of procedural outcomes and any related complications. The main disadvantage of TEE is that it requires the use of general anaesthesia with prolonged oesophageal intubation. However, the extra information and superior quality images provided by TEE is far more important, especially in complex structural heart intervention (by themselves are relatively long procedures that necessitate general anaesthesia anyway). In fact, the use of intra-procedural TEE has been reported to reduce fluoroscopy time and radiation exposure[6].

Intracardiac echocardiography, placed through a central venous access into the right atrium, is increasingly used, and has demonstrated great potential for monitoring and guiding interventions[7,8]. Experimental and clinical studies have observed that ICE, with 2D, colour and spectral Doppler imaging, is comparable to TEE. It has been shown to be beneficial during radiofrequency ablation of atrial fibrillation and transcatheter atrial septal closure procedures. Its main advantage over TEE is that it provides better patient comfort, and is compatible with local anaesthesia. Unlike TEE, ICE has limited imaging planes and its real-time 3D imaging is currently restricted to near-field applications, with its clinical experience limited to isolated case reports of catheter-based valvular interventions[9]. Nonetheless, ICE may be considered as an alternative to TEE in selected patients with absolute contraindications to oesophageal intubation or general analgesia[8].

Below are clinical case examples in percutaneous valvular interventions and closure of LAA, which highlight the importance of echocardiographic imaging, used in catheter-based SHD interventions performed these days in our centre.

Transcatheter Aortic Valve Replacement (TAVR)

Transcatheter aortic valve replacement has been proven to be an effective therapy for patients with symptomatic severe aortic stenosis (AS) who are deemed inoperable or high surgical risk for aortic valve surgery. From the 1-year results for Cohort B of the PARTNER trial (inoperable patients randomised to either TAVR or medical therapy including valvuloplasty), TAVR was associated with a superior 1-year survival (50.7%), compared with medical therapy (30.7%)[10]. For patients with high surgical risk, the results of Cohort A of the PARTNER trial (high-risk surgical patients with Society of Thoracic Surgeons score of ≥10 or a predicted operative mortality ≥15%, randomised to either surgery or TAVR) showed similar survival rates at 1 year[11]. Accordingly, TAVR is now a recommended standard of care for patients with symptomatic severe AS who have a prohibitive or high surgical risk[12]. Currently, the two most commonly-used valves for TAVR are: the balloon-expandable

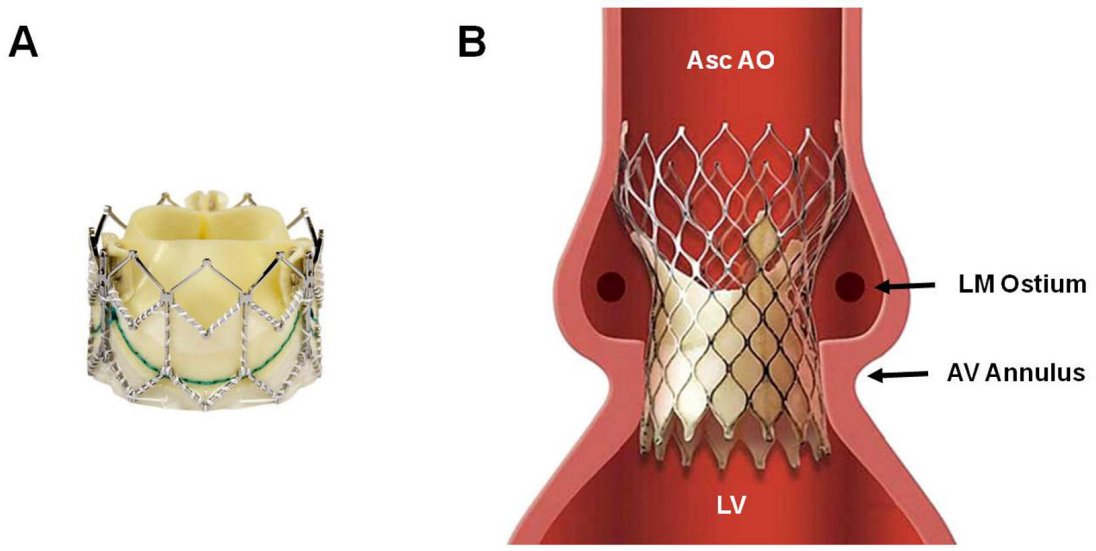

Fig. 1. Two most commonly used transcatheter valves for TAVR: (A) Balloon-expandable Edwards SAPIEN™ XT Valve (Edwards Lifesciences, Irvine, CA) and (B) Self-expanding Medtronic CoreValve™ (Medtronic, Minneapolis, MN). Reproduced with permission from Edwards Lifesciences, Irvine, CA and Medtronic, Minneapolis, MN.
Asc AO, ascending aorta; AV, aortic valve; LM, left main coronary artery

Edwards SAPIEN™ XT valve (Edwards Lifesciences, Irvine, CA) and the self-expanding Medtronic CoreValve™ (Medtronic, Minneapolis, MN) (Fig. 1).

The Edwards SAPIEN™ XT valve is a trileaflet pericardial bovine valve, mounted within a balloon-expandable cobalt chromium frame. The available sizes are 23, 26 and 29 mm for an aortic valve annulus of 18–22mm, 22–25mm, 25–28mm, respectively. The transcatheter valve can be implanted via the trans-femoral approach when the ilio-femoral arteries are adequate or via the direct aortic or trans-apical approach when the ilio-femoral anatomy is unfavourable[13]. The Medtronic CoreValve™ has a different design, characterised by a pericardial valve in a self-expanding nitinol frame, with three functional levels (the lower third exerts a high radial force and anchors within the aortic annulus and left ventricular (LV) outflow tract; the middle third includes the porcine valve and has a constraint design to avoid jailing of the coronary ostia; the upper third exerts a low radial force and stabilises the prosthesis in the ascending aorta). The available sizes for this system are 23, 26, 29 and 31 mm to accommodate for aortic annular diameters from 18 mm to 29 mm. As it has a broader upper segment that fixes to the aortic wall, this device should not be implanted in patients with ascending aorta diameter >45 mm. Unlike Edwards SAPIEN™, this valve can only be implanted retrogradely, either via the femoral or subclavian or direct aortic approach.

Echocardiography is critical in the assessment of candidates for TAVR, providing both the anatomic and haemodynamic information. Pre-procedural assessment using TTE is the initial modality to determine the presence and severity of AS. Using continuous-wave Doppler TTE assessment, severe AS is defined as peak aortic valve velocity >4 m/s or a mean aortic valve gradient >40 mmHg (Fig. 2)[12]. In patients with reduced LV ejection fraction <50%, a low-dose dobutamine stress may be helpful to distinguish true severe from pseudo-severe AS (non-stenotic aortic valve in patients with a primary cardiomyopathic disease). Patients with true severe AS will show a peak aortic velocity >4 m/s or a mean pressure gradient >40 mmHg, with an aortic valve area <1 cm^2 with dobutamine stress[12]. Once the diagnosis of severe AS is confirmed, the assessment of the aortic valve anatomy and the extent of calcification have to be assessed using echocardiography in the short-axis view (Fig. 2). Transcatheter aortic valve replacement is currently indicated for tricuspid aortic valve, while a bicuspid aortic valve is still contraindicated due to the risk of unfavorable deployment.

Next, the accurate assessment of the aortic valve annulus and the aortic root is crucial for appropriate

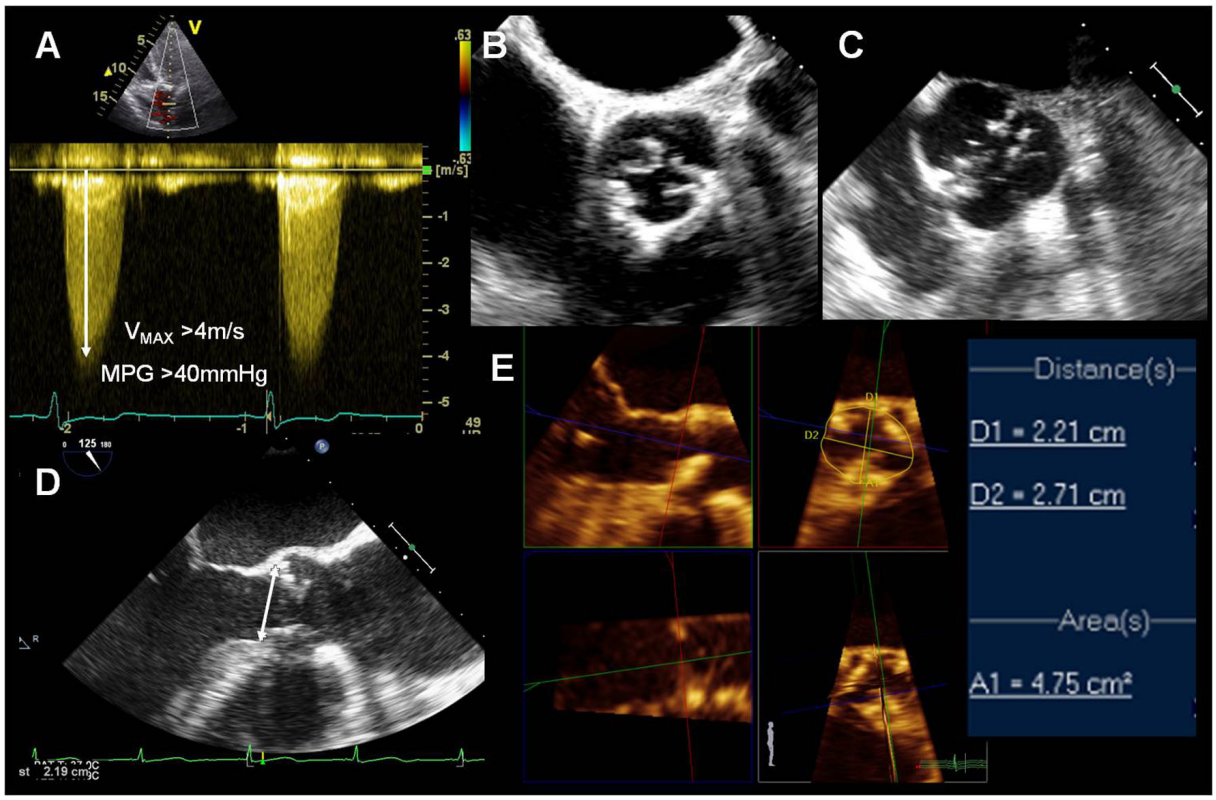

Fig. 2. Assessment of the severity of aortic stenosis, valve anatomy and aortic annulus: (A) Severe aortic stenosis is defined as a peak aortic velocity (VMAX) or mean pressure gradient (MPG) greater than 4 m/s or 40 mmHg, respectively from continuous-wave Doppler transthoracic echocardiography. Transoesophageal echocardiography (TEE) permits direct visualisation of the aortic valve: tricuspid (B) or bicuspid (C) in the short-axis view, and measurement of the aortic annulus in the long-axis view (D) 3D TEE shows the cross-sectional area of the aortic annulus, demonstrating the oval-shaped structure (E).
A1, true cross-sectional area of the aortic annulus; D1, minimal diameter of the aortic annulus; D2, maximal diameter of the aortic annulus.

selection of the prosthesis type and valve size, which impact directly on procedural success[14]. Under-sizing the valve may lead to migration of device or significant paravalvular regurgitation. Over-sizing, on the other hand, can lead to aortic annulus rupture and prosthetic under-expansion, leading to redundancy of the leaflet tissue ("pin-wheeling") that may result in central aortic regurgitation (AR). These complications can be avoided by accurate aortic annulus measurement, which is commonly measured using TEE due to better spatial resolution and anatomy delineation, compared to TTE. Recently, 3D techniques have demonstrated that the aortic annulus is in fact, not circular, but oval in shaped, thus 2D TEE tends to underestimate the maximal annulus dimension, due to off-axis imaging[15] (Fig. 2).

Although we routinely use multi-detector row computed tomography (MDCT) as part of pre-TAVR workup nowadays, which provides detailed assessment of ilio-femoral anatomy for planning of vascular access, as well as the aortic annulus dimensions, 3D TEE-guided direct planimetry of the aortic annulus cross-sectional area has been shown to correlate well with results from MDCT[16] (Fig. 2). The distance of the annulus to the coronary artery ostia (especially the left main ostium) is another key measurement for the feasibility of TAVR, as a minimum distance of 10 mm is preferred to avoid coronary occlusion. This is usually obtained using MDCT, although this can also be measured on 3D TEE[17]. Hence, in patients with increased risk of contrast-induced nephropathy, 3D TEE provides a feasible option for these measurements. Finally, TEE helps in the evaluation of the aortic arch for presence and severity of the atherosclerotic plaque. Trans-femoral approach would be contraindicated in severe arch atherosclerosis, due to the increased risk of stroke and peripheral embolisation.

During the TAVR procedure, standard 2D and 3D TEE are used in addition to fluoroscopy for intra-procedural guidance. Firstly, to guide manipulation of guidewire and delivery system positioning; followed by balloon aortic valvulopasty (Fig. 3) and finally, to guide transcatheter valve positioning

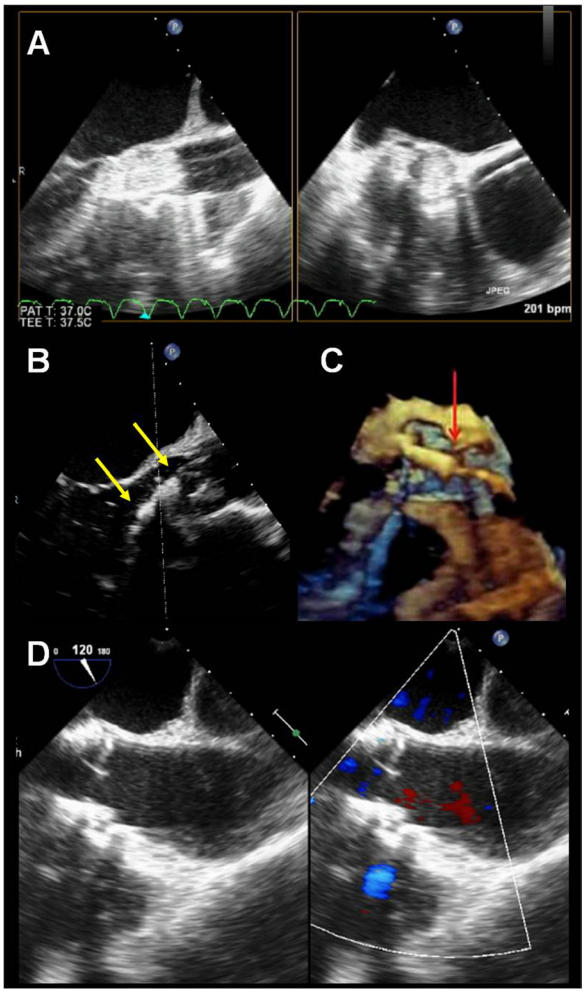

Fig. 3. Intra-procedural guidance during TAVR. Transoesophageal echocardiography (TEE) permits real-time visualisation of the aortic valve, catheter and device. Using 3D TEE technique, simultaneous bi-plane images (of the standard long-axis and short-axis 2D TEE views) can be displayed during ballooning of the native aortic valve (A). To ensure correct transcatheter valve positioning, TEE allows visualisation of the proximal and distal margins of the transcatheter valve (yellow arrows in panel B). Live 3D TEE enhances the delineation between the valve stent and the delivery balloon, showing the upper margin of the transcatheter valve at the level of the sinus of Valsalva (red arrow in panel C). Immediately post-deployment, the position and function of the transcatheter valve is assessed, showing an example of a successful deployment of Edwards SAPIEN™ valve with no paravalvular leak (D) on colour Doppler TEE.

and deployment. Real-time 2D and 3D TEE enables excellent visualisation of the proximal and distal margins of balloon-expandable transcatheter valve (Fig. 3). Too low a position risks downward transcatheter valve migration into the LV and impingement on the anterior mitral valve leaflet. On the other hand, too high a position risks upward embolisation of the transcatheter valve into the aorta, leading to paravalvular AR or even coronary ostium occlusion. Following TAVR deployment, multiple TEE views using 2D and colour Doppler imaging are performed to evaluate the transcatheter valve function and the presence and severity of AR (Fig. 3). Mild paravalvular regurgitation is common after TAVR, however, significant AR (more than mild) should be considered for repeat balloon dilatation or implantation for a second transcatheter valve. Besides procedural guidance, real-time TEE enables prompt detection of procedural-related complications, such as severe AR, mitral regurgitation (MR), coronary occlusion causing acute wall motion abnormalities, ventricular perforation or aortic rupture or dissection[1].

Percutaneous Mitral Valve Intervention

Mitral regurgitation is an important cause of morbidity and mortality in the developed nations and mitral valve surgery remains the current standard of care for severe MR[12]. A wide variety of conditions, including degenerative (myxomatous) disease, ischaemic heart disease, dilated cardiomyopathy, rheumatic disease and infective endocarditis, can cause MR. In general, MR is classified as degenerative and functional. Mitral valve prolapse is the most common cause of degenerative MR in the developed countries, resulting from both leaflet redundancy and chordal elongation[18]. In contrast, functional MR is caused by malcoaptation and tethering of the normal mitral leaflets secondary to LV remodelling, typically seen in both the ischaemic and non-ischaemic cardiomyopathy via various mechanisms, including impaired LV wall motion, LV dilatation and papillary muscle displacement and dysfunction, as well as mitral annular dilatation[12]. Although mitral valve surgery is recommended in patients with severe MR who met the indications for surgery[12], there remains a large population of patients that is currently not treated due to significant co-morbidities or advanced age, resulting in an unmet need for an alternative, less invasive treatment option for patients with high surgical risk. Over the last decade, important advances in catheter-based techniques for mitral valve repair have been made.

In this regard, the MitraClip™ device (Abbott Vascular, Abbott Park, IL) is the most extensively studied device used for catheter-based treatment of MR. This technique mimics the surgical edge-to-edge repair of Alfieri stitch, which works on the principle of improving leaflet coaptation by suturing a segment of anterior leaflet to the posterior leaflet, creating a double-orifice valve. The EVEREST I (Endovascular Valve Edge-to-Edge

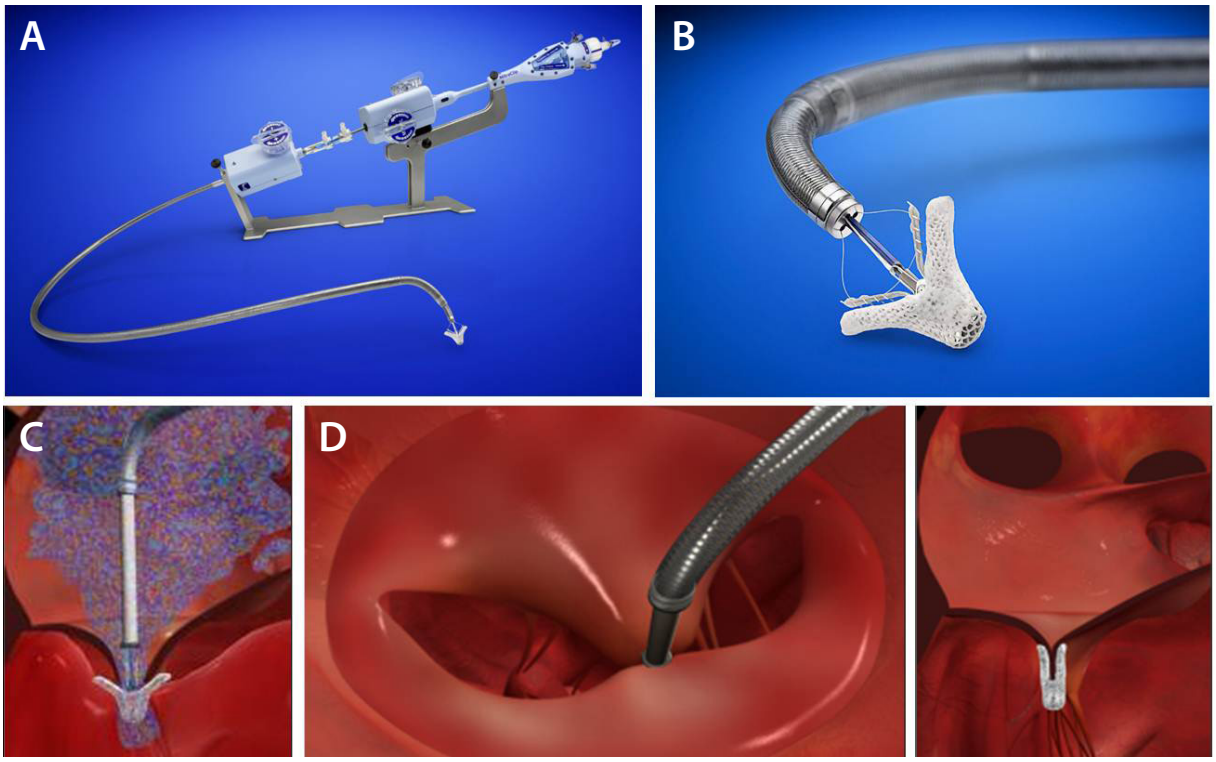

Fig. 4. The MitraClip™ Percutaneous Edge-to-Edge Repair System. The MitraClip™ delivery system (Abbott Vascular, Abbott Park, IL) showing a steerable guide catheter, a clip delivery system and the MitraClip™ device (A). The MitraClip™ device is a polyester-covered cobalt-chromium implant with two arms, while the U-shaped grippers are placed in the inner portion of the clip that helps with leaflet fixation (B). The clip delivery system exits through a guide catheter, to grasp the mitral valve leaflet at the site of MR (C). When the clip is closed, the leaflet tissue is secured by the clip arms on ventricular side and by the grippers on the atrial side, creating a double-orifice valve (D). Reproduced with permission from Abbott Vascular, Abbott Park, IL.

Repair Study) trial has established the initial safety, feasibility and haemodynamic improvements in patients with moderate to severe MR[19]. Although the results of the EVEREST II trial (patients randomised to either the percutaneous MitraClip™ or conventional surgery), showed less effective MR reduction with MitraClip™ than surgery, the MitraClip™ procedure was associated with superior safety[20]. Importantly, the MitraClip™ group showed significant clinical improvement at 1 year, in terms of quality of life, functional class and LV dimensions from baseline, which was non-inferior to surgery[21]. For those with high surgical risk (estimated surgical mortality rate of ≥12%), the subgroup analysis of the EVEREST High Risk study, showed a significant reduction in the rate of repeat hospitalisation and improvement in LV dimensions at 1 year, when compared to the concurrent control group treated with medical therapy, albeit no difference in survival[22]). Accordingly, the recent guideline states that percutaneous mitral valve repair maybe considered for severely symptomatic patients with chronic severe MR who has a reasonable life expectancy but a prohibitive surgical risk, due to severe comorbidities[12].

The MitraClip™ system has three main subsystems: a steerable guide catheter, a clip delivery system and the MitraClip™ device (Fig. 4). After gaining femoral venous access, it is followed by a trans-septal puncture through the fossa ovalis, and the distal tip of the guide catheter is advanced into the left atrium (LA). The clip delivery system is then advanced through the guide catheter, with the clip attached to its distal end. The clip is a polyester-covered cobalt-chromium implant with two arms that are opened and closed by control mechanisms on the clip delivery system. It is designed to grasp the mitral valve leaflet (at the site of MR), while the U-shaped grippers are placed in the inner portion of the clip that appose and stabilise the leaflet tissue against the clip arms. When the clip is closed, the leaflet tissue is secured by the clip arms on ventricular side and by the grippers on the atrial side (Fig. 4). In addition, the clip can be repositioned to achieve the best possible result before final deployment.

As the goal of MitraClip™ is to bring together the middle scallops of the mitral valve, creating a double-orifice mitral valve, to achieve MR

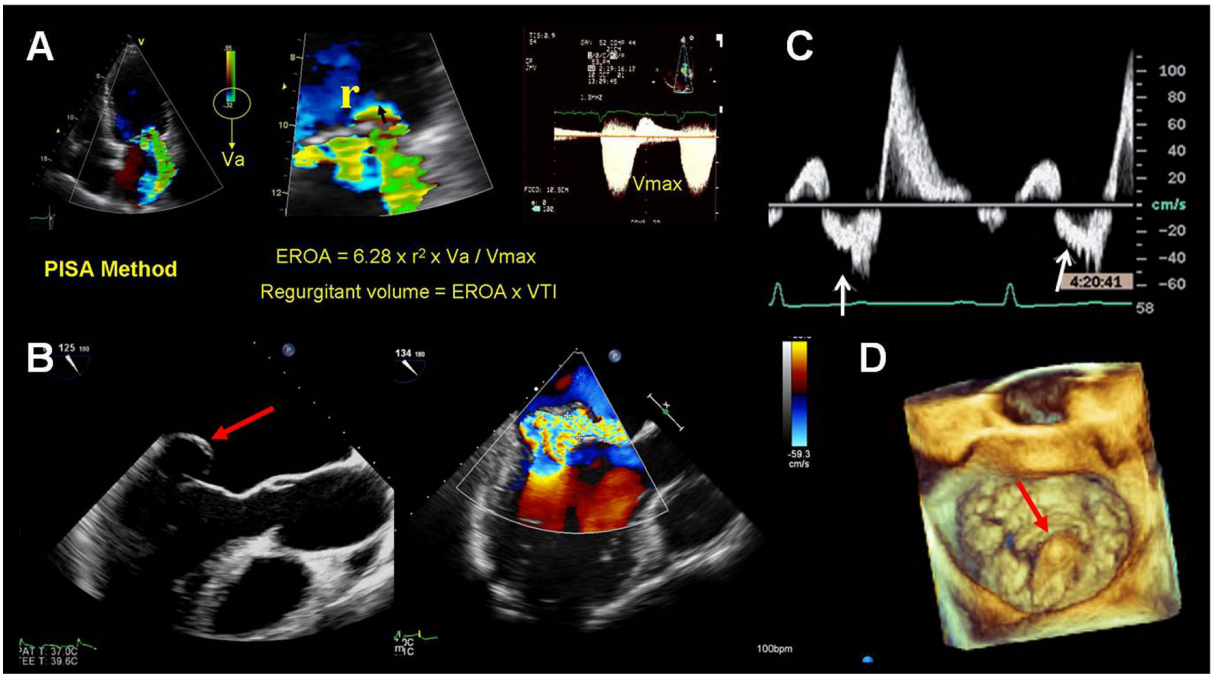

Fig. 5. Assessment of the severity of mitral regurgitation (MR) and its etiology. Quantitative assessment of MR by the proximal isovelocity surface area (PISA) method to calculate the effective regurgitant orifice area (EROA) and regurgitant volume using transthoracic echocardiography (A). Transoesophageal echocardiography (TEE) permits detailed anatomy delineation of the mitral valve, showing severe MR (B) caused by a large mitral valve prolapse of the P2 scallop (red arrow). Colour Doppler study further confirms systolic flow reversal in the pulmonary veins (white arrows), indicative of severe MR (C). Real-time 3D TEE zoom view provides an en face visualisation of the diseased, mid mitral leaflet segment (red arrow in panel D), which is deemed suitable for MitraClip™ therapy.

reduction, the selection criteria of patients for MitraClip™ mirrors that used in the EVEREST trials[19]. Patients with degenerative MR with either prolapse or flail of the A2 and/or P2 scallops are suitable for MitraClip™. Similarly, patients with functional MR, can also be eligible for MitraClip™ if the MR jet arises predominantly from A2 and P2. The key anatomic exclusion criteria include patients with contraindications to TEE or inadequate TEE image quality for the procedure, rheumatic mitral valve disease, active endocarditis, mitral valve area of <4 cm^2, severe mitral annular calcification, previous mitral valve replacement or intracardiac thrombus. In addition, patients with functional MR with a coaptating surface length <2 mm and/or a coaptation depth of >11 mm, are excluded. For degenerative MR, patients with a flail height of >10 mm and a flail width of >15 mm are also excluded[1].

Echocardiography plays a central role in the pre-procedural assessment to determine anatomic suitability for the MitraClip™ device, and to exclude contraindications. Transthoracic echocardiography is used as an initial screening to assess the severity of the MR and its etiology. Besides the standard 2D and colour Doppler TTE evaluation, quantitative assessment of MR severity by calculation of the effective regurgitation orifice area by the proximal isovelocity surface area (PISA) method, and subsequent calculation of the mitral regurgitation volume (Fig. 5) is currently the recommended approach[23]. Other methods such as the Doppler volumetric measurement of the regurgitation volume by measuring the mitral inflow volume and forward stroke volume are time consuming and less reproducible[1]. Other supportive parameters, which are routinely assessed using TTE, including chamber sizes, estimation of pulmonary artery pressure and LV function, should be used to fully evaluate MR severity and its haemodynamic consequences. Nonetheless, TEE is crucial to confirm anatomic eligibility before the MitraClip™ procedure (Fig. 5). Due to its superior image resolution to TTE, TEE allows precise measurement of the coaptation length and depth in for patients with functional MR, to ensure sufficient valve tissue for mechanical coaptation by the MitraClip™ for optimal results. For degenerative MR, leaflet grasping is more favourable when the flail gap and width are not too wide for optimal leaflet grasping.

During the Mitraclip™ procedure, TEE is the primary imaging modality used at all stages for real-time navigation, which complements fluoroscopy as

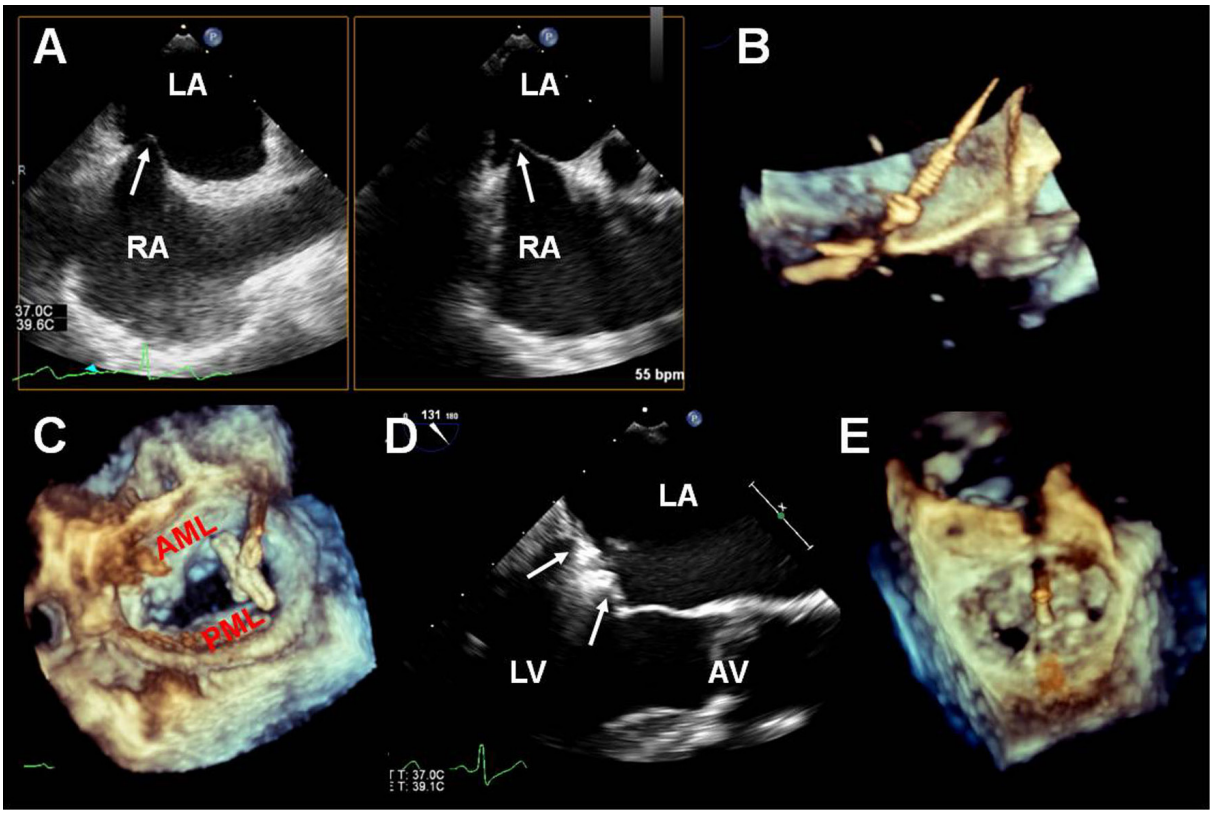

Fig. 6. Intra-procedural guidance during MitraClip™ Percutaneous Edge-to-Edge Repair. Transoesophageal echocardiography (TEE) permits localisation of the puncture site of the inter-atrial septum. Tenting of the septum at the fossa ovalis, caused by the trans-septal catheter is clearly appreciated on the simultaneous bi-plane view (the standard bi-caval and the short-axis aortic 2D TEE views in panel A). Constant TEE guidance is necessary for safe manoeuvering throughout the procedure. Real-time 3D TEE depicts clearly the whole guide catheter and dilator (spiral structure) assembly, crossing the septum, away from the surrounding structures (B). Importantly, 3D TEE visualises the mitral valve from the left atrial aspect during positioning of the MitraClip™ above the valve leaflets, to ensure perpendicularity with the coaptation or closure line of the valve for optimal mitral leaflets grasping (C). Adequate grasping of both the mitral leaflets (white arrows) is the key and should be clearly demonstrated on the 2D long-axis TEE view (D). Final appearance is that of a double orifice valve and perpendicularity should be confirmed again using 3D TEE, before full release of the clip (E).

fluoroscopy lacks soft tissue delineation. There are several key procedural steps that cannot be performed without TEE guidance. Firstly, the precise site of puncturing the inter-atrial septum is critical, which should be performed through the posterior-mid aspect of the fossa (Fig. 6) and at a recommended height of 3.5–4.0 cm from the mitral annulus, so as to provide adequate space for manoeuvering of the clip delivery system in the LA. Once the septum is crossed, the next step is to dilate the inter-atrial septum with a dilator for passage of the delivery system and clip towards the mitral valve (Fig. 6). Next, steering the clip delivery system towards the mitral valve requires 3D TEE views that display the spatial relationship of the delivery system with the LA wall and mitral valve. These views are, particularly appreciated by the interventionalists as they can maneuver the catheters safely in the LA, avoiding contact with the LA wall. Moreover, the 3D TEE zoom view has greatly facilitated the procedure, by providing an en face visualisation of the mitral leaflets and optimal positioning of the approaching clip (Fig. 6), whose arms should be opened and rotated until they are perfectly perpendicular to the coaptation line, immediately above the regurgitant orifice. This is of paramount importance as lack of perpendicularity may result in a failure to capture or inadequately grasp one or both leaflets. Once the orientation is achieved, the clip can enter the LV. While in the LV, the clip arms open and the device is pulled back to grasp the leaflets with the device grippers. This step is exclusively guided by 2D TEE, as the spatial resolution of 3D TEE is currently inadequate to image thin leaflets between arms and grippers (Fig. 6). If either leaflet is inadequately captured, the clip is reopened and re-advanced into the LV and the process is repeated. Once both leaflets are clipped, a quick assessment of the residual MR is performed, using colour Doppler TEE. At this point, it is important to exclude mitral stenosis, by measuring the gradient with continuous-wave Doppler and

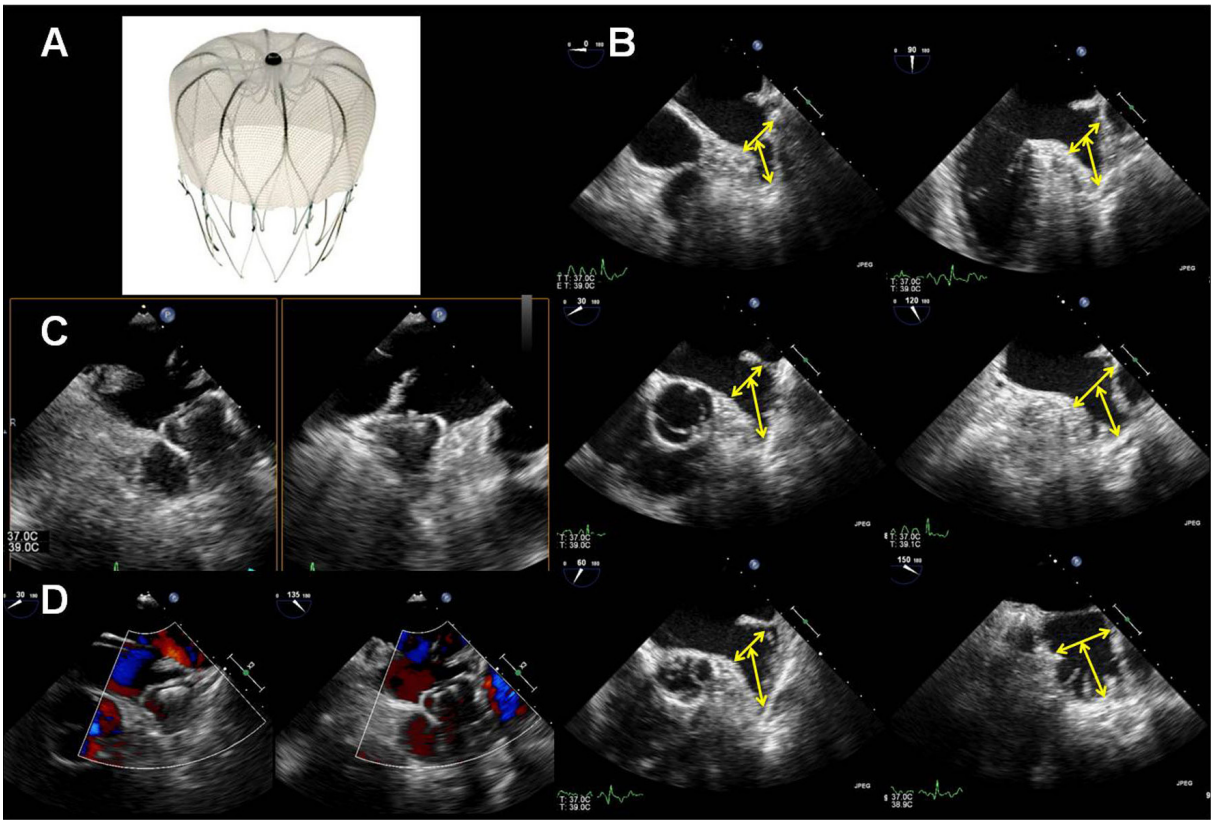

Figure 7: Percutaneous closure of left atrial appendage (LAA). The WATCHMAN™ device (Boston Scientific, Natwick, MA) is made of a self-expanding nitinol frame with fixation barbs and a permeable, polyester fabric covering, which is delivered through a sheath placed within the LAA (A). Pre-procedural transoesophageal echocardiography (TEE) is used to fully evaluate the diameters and the lengths of the LAA, using multi-plane 2D imaging for appropriate sizing of the device (B). Intra-procedurally, TEE is used to confirm the correct positioning and stability of the LAA closure device in multiple views (C). Importantly, colour Doppler TEE is used to show no residual blood flow around the margins of the device, confirming proper seal is achieved, before final deployment (D).

planimetering the two orifices using 3D TEE or 2D transgastric short-axis views. Only when the MR reduction is satisfactory and the mean transmitral gradient ≤5 mmHg, the clip can then be fully deployed. After deployment, a final assessment of the MR is performed. If there is further residual MR that is amenable to further clipping, decision to insert a second clip should be considered, using the first clip as a reference point[1].

Besides procedural guidance, TEE allows early detection of any potential complications during the MitraClip™ procedure, which may include atrial wall perforation, pericardial effusion, chordal or leaflet tears caused by multiple attempts at leaflets grasping and partial detachment of the clip after initial deployment. As for follow up of patients after a successful MitraClip™, TTE is best suited to assess the presence of any residual or recurrent MR, using an integrated, multi-parametric approach[23] and the extent of reverse LV remodelling, in terms of reduction in LV volumes and dimensions[1].

Percutaneous Closure of Left Atrial Appendage

Atrial fibrillation (AF) is the most common arrhythmia in the adult population and is associated with substantial morbidity. The main risk associated with AF is the increased risk of ischaemic embolic stroke, even after adjustment for other factors. Oral anticoagulation is the best available therapy to reduce the risk of thromboembolism[24,25]. However, major concerns to long-term therapy with oral anticoagulants include the hazard of major bleeding, noncompliance, side effects and the lack of an available antidote in the case of the novel oral anticoagulants. The LAA is the most common site of thrombus formation in patients with nonvalvular AF and stroke, thus transcatheter closure of the LAA has emerged as a potential alternative to oral anticoagulation for AF patients at high risk for stroke but with contraindications for chronic oral anticoagulant.

Currently, the LAA closure device used locally is the WATCHMAN™ device (Boston Scientific,

Natwick, MA). The safety and clinical efficacy of the WATCHMAN™ have been examined in two randomised clinical trials. In the PROTECT-AF trial (707 patients with CHADS2 score ≥1 randomised to either device implantation or warfarin), the WATCHMAN™ was non-inferior to warfarin for combined cardiovascular death, stroke or systemic embolism[26]. In the smaller PREVAIL trial (407 patients with CHADS2 score ≥2 or 1 plus an additional stroke risk factor), the combined primary end points were numerically similar between WATCHMAN™ and warfarin, although the device did not reach the pre-specified non-inferiority margin statistically, possibly due to lower than expected event rates and relatively short duration of follow-up[27]. In the absence of more clinical efficacy data, the current indication for device implantation is for high risk AF patients who are not candidates for long-term oral anticoagulation, and not simply indicated as an alternative to oral anticoagulant therapy[28].

The WATCHMAN™ consists of a self-expanding nitinol frame with fixation barbs and a permeable, polyester fabric covering (Fig. 7), which is delivered through a sheath placed within the LAA, guided by TEE and fluoroscopy. Prior to the procedure, TEE is the modality of choice to fully assess the anatomic suitability and to exclude contraindications for the device implantation. The size of the LAA orifice, length of appendage and the diameter of the orifice at all angles need to be measured accurately, using multi-plane 2D TEE imaging, to ensure appropriate sizing (Fig. 7). With real-time 3D TEE, direct visualisation of the LAA opening is possible, such that the true shape and area of the LAA opening can be measured[29]. In addition, the absence of LAA clot prior to the procedure should be confirmed before the procedure[2].

During the procedure, TEE (including real-time 3D imaging) is essential to guide the intra-cardiac course of the catheters, after puncturing the inter-atrial septum, and to confirm the correct positioning of the LAA closure device at the LAA orifice. Prior to deployment, proper seal of the LAA opening can be confirmed by visualising the 3D en-face view of the LAA opening, and to ensure no residual blood flows around the margins of the WATCHMAN™ device using colour Dopper TEE (Fig. 7). If the device placement is suboptimal, re-capture and re-positioning can be performed until a proper seal is achieved, before final deployment is done. Transoesophageal echocardiography is repeated once again to ensure stability of the device and to look out for any procedural complications, such as haemopericardium, before the delivery system is withdrawn into the right atrium and removed[2].

For follow up of these patients, echocardiographic surveillance with TEE is recommended. Transthoracic echocardiography may also be considered in those with good echocardiographic windows. However, TEE is the preferred modality, due to its superior resolution to TTE, to ensure stability of the implant and to detect any evidence of migration, erosion or encroachment of adjacent structures such as the left upper pulmonary vein and mitral valve[30]. Importantly, the atrial-facing side of the device should be assessed for evidence of smooth healing or presence of thrombus development[30]. Colour Doppler TEE imaging is used to screen for presence of any residual leak around the device or any persistent shunt across the inter-atrial septum following the trans-septal puncture.

LIMITATIONS OF ECHOCARDIOGRAPHY

Although there are established practical advantages of 3D over 2D TEE in SHD interventions, we do not recommend it as the sole imaging technique, as there are currently several limitations with 3D TEE. In particular, the frame rate of 3D TEE is still not optimal, especially when a large volume of interest is imaged. Similarly, its spatial resolution is still inferior when compared to that of 2D TEE. Moreover, dropout artifacts may appear (in cases of thin structures such as the interatrial septum), which may resemble "real holes" and may lead to misinterpretation of the 3D images. Other artifacts created by highly reflective structures such as the metallic part of catheters or devices may also cause reverberations and shadowing. Ongoing technological improvements, together with proper training and interpretation of the 3D datasets will further enhance the adoption of this modality in SHD, to adequately guide transcatheter interventions.

CONCLUSION

Percutaneous therapy for treatment of SHD is rapidly evolving, as the technology continues to develop and the results of ongoing trials continue to shape the field of structural heart intervention. Besides, it requires a true integration of a multi-disciplinary team, the so-called 'structural heart disease team' that improves understanding and coordination between the interventionists, surgeons and

imaging specialists, so as to deliver the best optimal catheter-based therapies for patients with SHD. Accurate visualisation of cardiac anatomy is critical for optimal success of these catheter-based interventions. In this regard, echocardiography plays an essential role prior to, during and after the percutaneous interventions. The advent of real-time 3D TEE imaging has significantly improved the visualisation and characterisation of the cardiac structures, ideally suited during catheter-based SHD interventions. It provides real-time guidance, thus ensuring safe manipulation of catheters, wires and devices deployment to achieve the highest success rates, while avoiding potential complications, potentially reducing radiation exposure, and/or shortening procedural times.

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