

The use of imaging in new transcatheter interventions: an EACVI review paper

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Transcatheter therapies for the treatment of valve heart diseases have expanded dramatically over the last years. The new developments and improvements in devices and techniques, along with the increasing expertise of operators, have turned the catheter-based approaches for valvular disease into an established treatment option. Various imaging techniques are used during these procedures, but echocardiography plays an essential role during patient selection, intra-procedural monitoring, and post-procedure follow-up. The echocardiographic assessment of patients undergoing transcatheter interventions places demands on echocardiographers that differ from those of the routine evaluation of patients with valve disease, and there is a need for specific expertise for those working in the cath lab. In the context of the current rapid developments and growing use of transcatheter valve therapies, this document intends to update the previous recommendations and address new advancements in imaging, particularly for those involved in any stage of the treatment of patients with valvular heart diseases.

Keywords Cath lab • Interventions • Structural heart disease • Echocardiography

Transcatheter aortic valve implantation

In 2002, transcatheter aortic valve implantation (TAVI) was introduced as an alternative treatment in patients with severe aortic valve stenosis (AS), when Cribier *et al.*¹ reported the first successful implantation of a bovine pericardial bioprosthesis mounted within a stainless steel balloon-expandable stent in a patient with severe AS who presented in cardiogenic shock. Several transcatheter valve prostheses and sizes, including the balloon-expandable and self-expandable prosthesis, have

been introduced and have received Conformité Européenne (CE) approval.^{2,3} Nowadays, percutaneous transfemoral, transapical, and transaortic approaches are commonly used.⁴ Cumulative evidence has demonstrated that TAVI constitutes an effective treatment option for patients with severe AS and high operative risk, and it has become an integral part of international guidelines for the treatment of patients with severe AS.⁵ Imaging plays a central among several steps of the procedure, including patient selection, choice of procedural access, prosthetic type and sizing, procedural guidance, and detection of early and late complications.

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Types of TAVI prostheses

First-generation valve prostheses: perspective for new devices

Although detailed previously,⁶ the first-generation valves will be revisited briefly to provide a perspective for subsequent device developments. The *Edwards SAPIEN* valve consists of bovine pericardial leaflets mounted within a balloon-expandable stent of stainless steel, which has been replaced by a cobalt–chromium stent in the following *Edwards SAPIEN XT*.⁷ The current *CoreValve* has a self-expanding nitinol frame with mounted leaflets of porcine pericardium. Further details on these valves are listed in *Table 1*.⁷ Importantly, none of them can be repositioned or retrieved, necessitating deployment of a second device or referral for surgical valve replacement in case of erroneous placement. The new valve designs aim to overcome these limitations along with the reduction in the inherent risks of stroke, vascular complications, paravalvular leaks, and conduction disturbances.

Second-generation valves investigated clinically

The *SAPIEN 3* valve encompasses bovine pericardial leaflets embodied in a cobalt–chromium balloon-expandable frame with a low delivery profile⁷ (*Table 1*). A distal flex mechanism and fine positioning control is incorporated for accurate placement.⁸ The low frame height with less protrusion into the ventricular outflow tract when compared with the previous *SAPIEN* valves is designed for reduced risk of conduction disturbances. Moreover, it has an additional sealing cuff to avoid paravalvular leak. The first-in-human experience with this valve was recently reported.⁹

The *Centera* valve is a repositionable and retrievable device with bovine pericardial leaflets incorporated in a self-expandable nitinol stent with a low delivery profile (*Table 1*). The contoured frame is designed for optimal seating and sealing in the annulus with concomitant low frame height to minimize conduction disturbances.⁸ Short- and mid-term results after implantation in 15 patients have recently been reported.¹⁰

CoreValve Evolut R is a repositionable and retrievable valve (*Table 1*), retaining the structural features of the *CoreValve* although with a shorter height.⁷ Moreover, it has a low delivery profile, a large stent design to reduce the risk of coronary orifice obstruction, and a skirt designed to reduce the risk of paravalvular leak.⁸ Furthermore, the *CoreValve Evolut R* has a new delivery system allowing retrieval after being fully deployed to ensure optimal placement and function.

The *Engager* valve has bovine pericardial leaflets mounted within a self-expanding nitinol stent (*Table 1*) with positioning arms to be anchored over the native leaflets. The device is repositionable but not retrievable. Preliminary data demonstrated successful implantation in the majority of patients but with associated complications that prompted redesign of the device system.¹¹ Its clinical evaluation is currently ongoing.

The *Direct Flow Medical* valve is non-metallic with bovine pericardial leaflets positioned between two independently inflatable polyester rings connected by an inflatable support in between them.⁸ It is repositionable and retrievable after being fully deployed (*Table 1*). The proximal and distal rings are positioned just below and above the aortic annulus, respectively. The cuffs are inflated with diluted contrast, which after successful positioning is replaced by a solidifying

material that provides a support structure for the valve leaflets. The clinical results are encouraging.

The *Portico* valve has bovine pericardial leaflets mounted close to the ventricular end of a nitinol self-expanding stent (*Table 1*) which aims to reduce sub-annular protrusion and minimize conduction disturbances. The first-in-man data have been promising.^{9,12}

The *Lotus* valve encompasses bovine pericardial leaflets within a braided, self-expandable nitinol stent (*Table 1*) which expands by shortening of its length. It is repositionable and retrievable after being fully deployed.^{10,13}

The *Symetis Acurate* valve consists of an aortic stentless porcine valve mounted in a self-expanding nitinol alloy stent (*Table 1*), also with low placement of the leaflets. It is provided with an anchoring system to facilitate optimal positioning, it is repositionable, and it has an additional cuff to reduce the risk of paravalvular leak.⁸

The *JenaValve* has a porcine root valve mounted within a nitinol self-expanding stent with low placement of the valve leaflets (*Table 1*). It has an anchoring system of three feelers designed to embrace the native cusps during implantation,^{11,14} providing a tactile feedback during deployment. The device is fully repositionable and retrievable.

Patient selection

The appropriate patient selection for TAVI includes the determination of individual risk and the assessment of the feasibility and safety criteria for the procedure by a multidisciplinary team approach, involving interventional cardiologists, cardiac and vascular surgeons, anaesthesiologists, and imaging specialists.¹⁵

According to the ESC guidelines, TAVI is recommended for patients with severe symptomatic AS, who are considered unsuitable for conventional surgery, following the evaluation performed by the heart team. Among high-risk patients, but candidates for surgery, the decision should be individualized¹⁶ using clinical judgment and considering factors such as frailty, porcelain aorta, prior significant mediastinal radiation, prior sternal infection with complex reconstruction, patent left internal mammary graft lying beneath the sternum, severe pulmonary hypertension, or right ventricular (RV) dysfunction, as these characteristics might significantly increase the risk of surgical aortic valve replacement. Likewise, TAVI clinical contraindications, such as an estimated life expectancy <1 year or unlikely improvement of quality of life because of comorbidities or severe primary associated disease, must be considered (*Table 2*). Nevertheless, more appropriate scoring systems are under development and the criteria for patient selection are still open to debate and are not considered binding. Furthermore, as the technique matures, and data on long-term valve durability become available, patient selection criteria are likely to expand to include non-high-risk surgical candidates. Studies including patients at intermediate risk have presented encouraging results,^{18,19} but randomized trials with longer follow-up, comparing TAVI and surgical aortic valve replacement in intermediate-risk patients, are needed to assess outcomes and long-term durability of transcatheter valves.

Transthoracic echocardiography

In conjunction with the clinical evaluation, echocardiography is essential in the assessment of candidates for TAVI. The severity of AS is established by transthoracic echocardiography (TTE), severe

Table 1 Main characteristics of TAVI devices (adapted from Ielasi et al.⁷)

Device	Manufacturer	Size (mm)	Aortic annulus diameter (mm)	Delivery annulus diameter (mm)	Sealing skirt material (Fr)	Access	Leaflet tissue	Frame material	Repositionable	Retrieveable	AR correction ^a
Sapien	Edwards	23, 26	18–20, 21–25	22, 24	PET	TF, TA	Bovine	BE stainless steel	No	No	No
Sapien XT	Edwards	23, 26, 29	18–22, 21–25, 24–27	18, 19	PET	TF, TA, Ao	Bovine	BE cobalt chromium	No	No	No
Sapien 3	Edwards	26		14	PET	TF, TA	Bovine	BE cobalt chromium	No	No	No
Centera	Edwards	26	20–23	14	PET	TF, TA _x	Bovine	SE nitinol	Yes	Yes	No
CoreValve	Medtronic	23, 26, 29, 31	18–29	18, 19	PP	TF, TA _x , Ao	Porcine	SE nitinol	No	No	No
CoreValve Evolut	Medtronic	23	18–20	18	PP	TF	Porcine	SE nitinol	Yes	Yes	No
Engager	Medtronic	23, 26		30		TA	Bovine	SE nitinol	Yes	No	No
Direct Flow Medical	Direct Flow Medical	23, 25, 27		18	Polyester	TF, Ao	Bovine	IF polyester FC	Yes	Yes	No
Portico	St Jude	23	≤21	18, 24	PP	TF, TA	Bovine	SE nitinol	Yes	Yes	No
Lotus	Boston Scientific	23, 27		18	PU	TF	Bovine	SE nitinol	Yes	Yes	Yes
Symetis Acurate	Symetis	23, 25, 27	21–27	Sheatless 28, 18	PP	TF, TA	Porcine	SE nitinol	Yes	Yes	No
Jena Valve	Jena Valve	23, 25, 27	21–27	Sheatless 32		TA	Porcine	SE nitinol	Yes	Yes	Yes

Ao, transaortic; AR, aortic regurgitation; BE, balloon expandable; FC, fabric cuff; IF, inflatable; PET, polyethylene terephthalate; PP, porcine pericardium; PU, polyurethane; SE, self-expandable; TA, transapical; TF, transfemoral, TA_x, transaxillary.

^aIndication as by the manufacturer.

Table 2 Contraindications for TAVI^{5,17}**Absolute contraindications**

- Estimated life expectancy <12 months due to non-cardiac comorbid conditions
- Improvement of quality of life by TAVI unlikely because of comorbidities
- Severe primary associated disease of other valves with major contribution to the patient's symptoms, that can only be treated by surgery
- Inadequate annulus size (<18 mm, >29 mm)

Other contraindications

- Bicuspid or unicuspid or noncalcified aortic valve
- Severe aortic regurgitation (>3+)
- Untreated coronary artery disease requiring revascularization
- LVEF <20%
- Left ventricle thrombus
- Hemodynamic or respiratory instability
- Stroke or transient ischaemic attack within 6 months (180 days) of the procedure
- Evidence of an acute myocardial infarction within 1 month before TAVI
- Hypertrophic cardiomyopathy with or without obstruction
- Severe pulmonary hypertension and right ventricular dysfunction
- Severe mitral regurgitation
- A known contraindication or hypersensitivity to all anticoagulation regimens or inability to be anticoagulated for the study procedure.
- Renal insufficiency and/or end-stage renal disease requiring chronic dialysis
- Echocardiographic evidence of intracardiac mass
- Stroke or transient ischemic attack within 6 months (180 days) of the procedure
- Severe incapacitating dementia

AS being defined by aortic valve area [AVA of $\leq 1 \text{ cm}^2$ ($<0.6 \text{ cm}^2/\text{m}^2$)] or a mean aortic valve gradient of $\geq 40 \text{ mmHg}$ and maximum jet velocity $>4 \text{ m/s}$.^{5,20} Nevertheless, AS severity assessment can present additional challenges in cases of low transvalvular gradients, which can occur either with reduced (pseudo-severe or severe AS) or preserved (paradoxical low-flow low-gradient) left ventricular (LV) ejection fraction. Low-dose dobutamine stress echocardiography (maximum stress dose $20 \mu\text{g/kg/min}$) can support the differential diagnosis between true severe AS and pseudo-severe AS. If the maximum jet velocity rises over 4 m/s with the dobutamine-induced increase in stroke volume and the AVA remains $<1.0 \text{ cm}^2$, the valve is truly severely stenotic and patients' survival is reported to be better with intervention.^{21–23} Conversely, if stroke volume increases with minimum rise in gradient, causing the valve area to increase significantly, the AS is likely to be mild to moderate, with the LV dysfunction due to causes other than AS. The differential diagnosis between true severe AS and pseudo-severe AS is crucial, as pseudo-severe AS has no indication for intervention. In contrast, paradoxical low-flow low-gradient AS is characterized by small LV volumes due to LV hypertrophy, preserved LV ejection fraction and stroke volume index $\leq 35 \text{ mL/m}^2$. This diagnosis can be difficult and potential sources of error should be primarily

excluded. In addition, the definite diagnosis can be assisted by the evaluation of valvulo-arterial impedance and by the aortic valve calcification load, using multi-slice computed tomography.²⁴ Comparable overall mortality rates between patients with true severe AS and those with low-flow low-gradient have been reported.²⁴ However, patients with low-flow low-gradient with severe AS with concentric LV hypertrophy and a normal LV ejection fraction have worse outcomes compared with those with higher gradients. Further studies are needed to optimize treatment strategies.²⁵ Additional less common causes of low-flow low-gradient with severe AS with preserved LVEF include concomitant mitral regurgitation (MR), atrial fibrillation (AF), or constriction.

In addition, TTE is used for the assessment of other TAVI potential absolute or relative contraindications, such as the presence of severe primary concomitant valvular disease having major contribution to the patient's symptoms, LV thrombus, haemodynamically significant LV outflow tract obstruction by septal hypertrophy, very severe LV systolic dysfunction (LVEF $<20\%$) or severe pulmonary hypertension with RV dysfunction (Table 2).²⁶

When considering concomitant valvular disease, mitral MR is frequent among patients referred to TAVI. Moderate to severe MR used to be considered a relative contraindication to TAVI, but large TAVI series have reported the inclusion of up to 48% of patients with moderate or severe MR.^{27,28} These patients usually have a worse baseline clinical profile, lower LV ejection fraction, larger LV volumes, smaller AVA, higher systolic pulmonary pressure,^{28–30} and higher overall morbidity and mortality compared with those without MR.^{28,31} However, if left untreated, patients with severe AS and concomitant moderate/severe MR have a very poor prognosis, and it remains controversial if moderate/severe MR is an independent predictor of worse outcome after TAVI,^{32,33} and which factors are definitive predictors of MR improvement after TAVI.^{31,34}

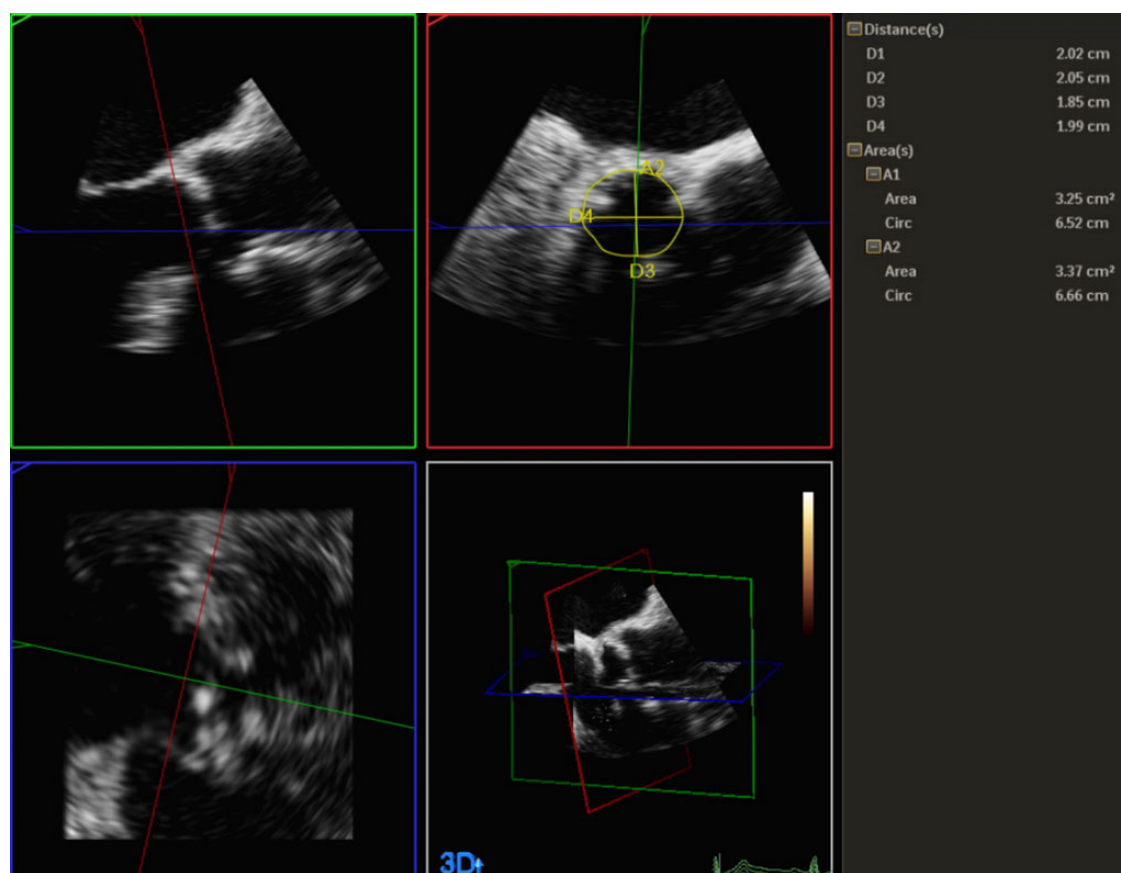
Transoesophageal echocardiography evaluation prior to TAVI

Transoesophageal echocardiography (TEE) can be useful to evaluate aortic and mitral valve morphology and function, to exclude intracardiac masses or significant aortic root aneurysmal dilatation, and to confirm AS severity by aortic valve planimetry.

The accurate measurement of the aortic annulus dictates the aortic prosthetic size, being crucial for procedure success (Table 3). An accurate measurement of aortic annulus is important to avoid or limit the possibility of post-TAVI patient prosthesis mismatch. The annulus diameter by 2D TEE is conventionally measured in systole, zooming in on the LV outflow tract, at the point of insertion of the aortic valve cusps, from tissue–blood interface to blood–tissue interface—trailing edge to leading edge.⁶ However, two-dimensional (2D) echocardiography assumes annular circularity, which may result in erroneous dimension determinations in patients with an oval-shaped annulus. Three-dimensional (3D) methods, by TEE or multi-slice computer tomography (MSCT), are superior to 2D TEE, allowing the assessment of minimal and maximal diameters, perimeter, and area (Figures 1 and 2).^{6,35} Therefore, 2D TEE is limited in the evaluation of potential candidates for TAVI, and a 3D TEE is mandatory in our days for correct decision-making in potential TAVI patients. Nevertheless, MSCT provides higher spatial resolution and evaluates aortic calcification better than TEE.³⁶

Table 3 Aortic measurements for transcatheter aortic valve prosthesis

	Prosthesis size	AV annulus	Sinus of Valsalva	Sinotubular junction
CoreValve evolut (mm)	23	17–20	≤ 25	≤ 34
CoreValve (mm)	26	20–23	≥ 27	≤ 40
	29	23–27	≥ 28	≤ 43
	31	26–29	≥ 28	≤ 43
Edwards SAPIEN (mm)	23	18–22		
	26	21–25		
Edwards SAPIEN XT (mm)	23	18–22	–	–
	26	21–25	–	–
	29	24–27		
Edwards SAPIEN 3 (mm)	23	18–22	–	–
	26	21–25	–	–
	29	24–28		

**Figure 1** 3D TEE view for the measurement of aortic annular dimension.

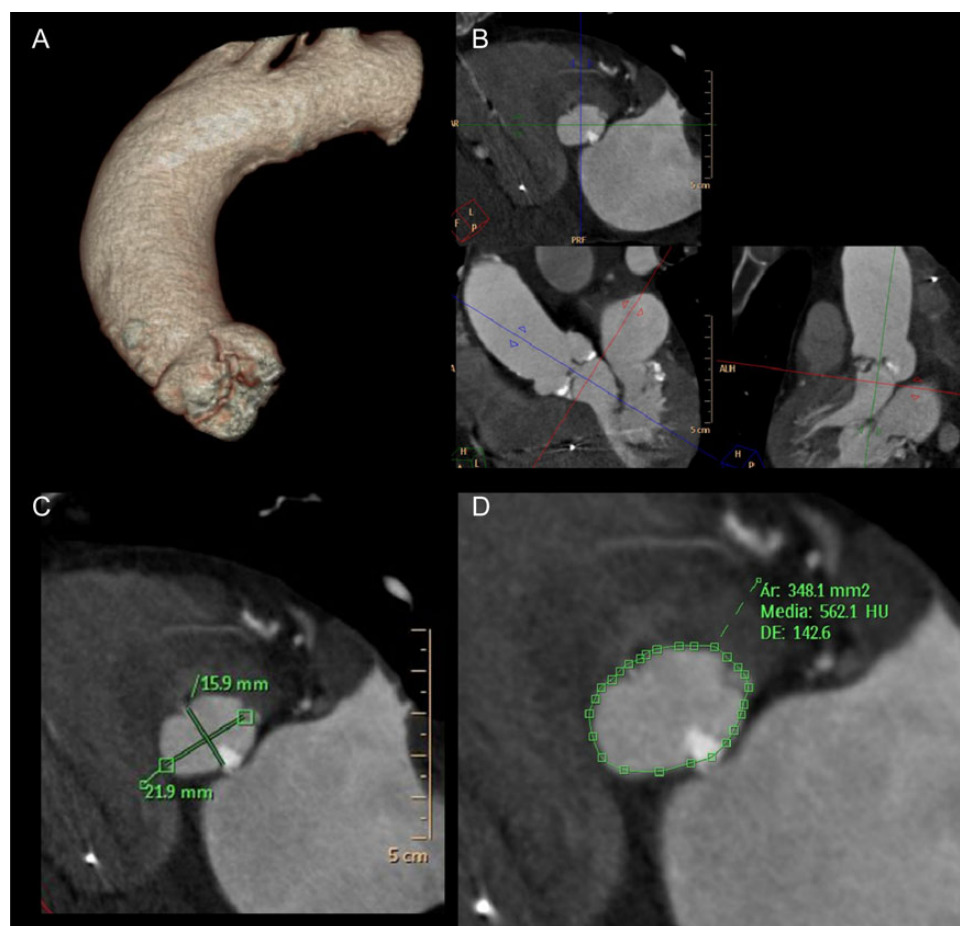


Figure 2 Multi-slice detector computed tomography reconstruction of the aortic root and ascending aorta (A); 3D orientation for aortic annulus measurement (B); aortic annulus diameters (C) and area and planimetry (D) measurement.

Before 3D TEE acquisition, a 2D image of the aortic valve at either the 45–60° mid-oesophageal, short-axis view or the 120° mid-oesophageal, long-axis view should be obtained. Multi-plane modalities may help in orientation. After the 2D image is optimized, narrow-angled acquisitions can be used to optimize the 3D image. All 3D acquisition modes can be used although ‘3D Zoom’ and ‘Live’ mode are the most conventionally used, giving priority to frame rate and imaging resolution. Multiple images may need to be recorded to ensure the entire coverage of the valve. The 3D echocardiography multiplanar reconstruction (MPR) software provides tools for 3D volume segmentation along the three axes (x, y, z) in real-time or post-processing.

3D echocardiography provides additional data on aortic valve anatomy and on aortic valve spatial relationships with the surrounding structures, and it allows en face alignment of the cut plane of the aortic annulus, irrespective of the spatial orientation of the aortic root in the body. Using MPR tools, the perfect orthogonal alignment of the LVOT and aortic annulus can be obtained. 3D echocardiography has the ability to present the real short-axis view of the annulus, after adjusting plane position using coronal and sagittal views (Figure 1) allowing the measurement of

its area by planimetry and its larger and shorter diameters, reducing the potential error occurring from the 2D echocardiography circularity assumption. Although usually located close to the sinotubular junction, the coronary orifices should also be localized to help prevent coronary flow obstruction. The determination of the right coronary annular–ostial distance is possible with 2D TEE, but the left coronary annular–ostial distance can only be measured from the coronal plane that cannot be acquired by standard 2D imaging. This requires 3D TEE multiplanar reconstruction or MSCT.

There is considerable emphasis on accurate annular sizing in order to determine the correct valve size for implantation. While annular sizing is very important, it is not and should not be the whole story. The size of the sinuses and the sinotubular junction and the likely behaviour of the leaflets during implantation are also critical. These parameters are important in order to minimize the risks of trans-/paravalvar regurgitation, aortic root rupture, and coronary obstruction.

All morphological parameters of the LVOT, aortic annulus, the aortic root, and the proximal ascending aorta can be evaluated by 3D TEE and should be reported as shown in the Table 4.

Multi-slice computer tomography

In patients with poor acoustic windows and/or with heavy calcification, MSCT permits an accurate diagnosis of bicuspid valvular anatomy.³⁷ It clearly evaluates the amount and distribution of aortic calcification, which can be associated with the risk of paravalvular aortic regurgitation after TAVI (Figure 3),³⁷ as aortic valve bulky calcification increases the risk of gaps between the external surface of the prosthesis and the host native valve, providing a substrate for paravalvular regurgitation leaks. As well, the severity and asymmetry of the device landing zone calcification may result in differences in the tension–force across the valve, which can cause asymmetric deployment of the prosthesis and increase the risk of compression of the coronary arteries ostium.

MSCT assists in the measurement of the height of the coronary ostia relative to the aortic annulus, with the minimum distance recommended between the coronary ostia and the aortic valve annular plane being ≥ 10 –11 mm for both CoreValve and the Edwards SAPIEN valves. In addition, MSCT provides aortic annulus dimensions (major and orthogonal minor diameters, perimeter and area), with the thoracic aorta evaluation completed by the measurement of the sinus of Valsalva diameters and heights and sinotubular junction and ascending and descending aorta diameters. Of note, the presence of aortic root aneurysmal dilatation is a contraindication to the use of CoreValve. Moreover, by the anatomic and

calcification evaluation of the thoraco-abdominal aorta and the ilio-femoral arteries, MSCT contributes to the selection of the best access route. While MSCT can provide information concerning coronary anatomy, this may be limited by advanced calcific disease.³⁸ Thus, coronary angiography remains a mandatory part of pre-TAVI evaluation.

Peri-procedural transoesophageal echocardiography during TAVI

While the use of TEE during TAVI generally requires the use of a general anaesthetic, there are some distinct advantages to having this additional imaging modality available during the procedure. These advantages include the assessment of aortic root morphology and valve leaflet behaviour during balloon valvuloplasty, more precise prosthesis positioning during deployment and detection/monitoring of complications that may occur.

TEE during balloon dilatation

Table 5 summarizes aspects that should be considered when using TEE during balloon valvuloplasty.

Using TEE with a matrix probe, it is possible to obtain simultaneous longitudinal and transverse images (biplane imaging) of the aortic valve, aortic root, and LV outflow tract³⁹ (Figure 4). If such imaging is performed using a long loop length to capture the entire valvuloplasty sequence performed with a known balloon size, then a considerable amount of useful information can be obtained, such as when there is an overlap in the recommended valve implant sizes for a specific annulus dimension. For example, in some cases, the manufacturer states that either a 23 mm or 26 mm TAVI valve might be suitable for an annulus size of 22 mm, so it can be unclear how to choose. Imaging the fit of a 20 mm valvuloplasty balloon into the annulus and the aortic root, and determining whether there is enough space for the leaflets to fit into the sinuses, can help the decision of which is the most appropriate prosthesis size.⁴⁰

Occlusion of the coronary ostia can occur if they are low (close to the annulus), the leaflets are long,

and the sinuses are small. The coronary ostia can be imaged during the balloon valvuloplasty and the movement of the leaflets determined to check whether they obstruct the ostia. Clearly, if this occurs during the valvuloplasty, it is likely to happen post-valve implant and this may be an indication to abandon the procedure.

Table 4 2D/3D TEE evaluation prior to TAVI

Valve anatomy
– number of cusps
– degree of calcification
– symmetry of calcification
Aortic annulus diameters, perimeter and area (3D)
LVOT diameters (3D)
Distance to coronary arteries (3D)
Aortic root dimensions (sinus of Valsalva/sinotubular junction/ascending aorta)
Presence of aortic plaques
Septal hypertrophy

3D, 3D TEE imaging is essential for the correct evaluation of these parameters; LVOT, left ventricular outflow tract.

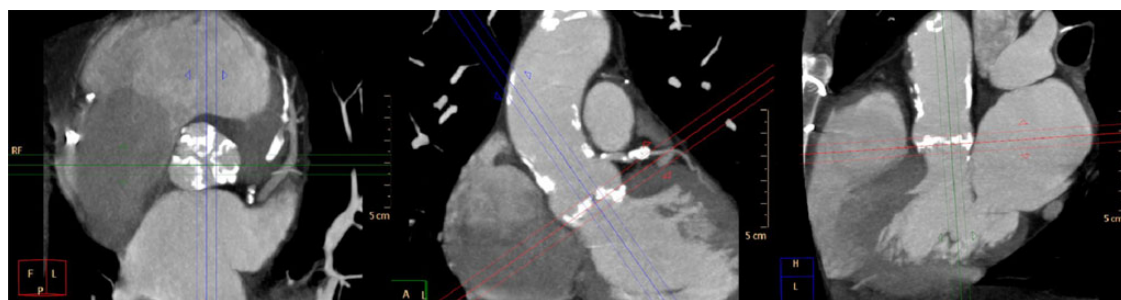


Figure 3 Multi-slice computed tomography assessing aortic valve anatomy and calcification.

Balloon valvuloplasty can result in acute severe aortic regurgitation, which can lead to rapid patient decompensation. Early detection of this complication is important and indicates the need for rapid deployment of the TAVI prosthesis. Clearly, the availability of TEE imaging post-valvuloplasty provides an instant assessment of aortic regurgitation. Although some of the imaging information obtained by TEE during valvuloplasty can also be obtained by repeated contrast injections, many patients undergoing TAVI procedures have renal insufficiency and therefore reduction of contrast dose can be important.⁴¹

TEE during valve deployment

The implications of incorrect TAVI valve positioning post-deployment are profound and the valve manufacturers make specific recommendations regarding the ideal positioning of their own valves and clearly these should be followed. If the valve is deployed too low, embolization of the prosthesis into the left ventricle may occur or it may result in paravalvular regurgitation because of incorrect apposition of the valve ring with the virtual aortic annulus. There is also the potential of damage to the anterior mitral valve

leaflet if the LV side of the valve is low enough for the leaflet to make contact with valve edge during every diastole. Conversely, if the valve is deployed too high, this may result in paravalvular regurgitation, and or embolization and indeed it may also cause obstruction of the coronary ostia. If a balloon-expandable valve is being used, then it is important that the valve is positioned high enough to cover the native aortic valve leaflets so they do not drape over the top of the valve cage. Indeed, it is often better to concentrate on imaging the top of a balloon-expandable valve, to ensure that it is positioned just above the native aortic valve leaflets, because these valves tend to shorten from the LV side, being more difficult to predict where the lower side of the valve will end up once deployed. This is particularly true for the SAPIEN 3 valve.

It is relatively easy to image self-expanding valves on TEE in a longitudinal plane. However, the details of a balloon-expandable valve can be more difficult to appreciate when it is crimped onto the balloon and 3D TEE can help by facilitating appreciation of the crimped valve cage against the deflated balloon. In order to do this, it is important that the 3D TEE imaging is performed at the highest possible frequency and that any surface rendering post-processing within the ultrasound system is turned on. In addition, the TEE gain should be kept low and the cut-plane of the 3D display should be positioned to the side of the aorta so that you are looking down on the surface of the TAVI valve, rather than cutting through it (*Figures 5 and 6*). Finally, *Live 3-D mode*, or equivalent, provides an essential real-time visualization with acceptable temporal and spatial resolution⁴ (*Table 6*).

Before the TAVI valve is deployed, it is important to rotate the 3D image to check that the valve is positioned in a co-axial plane to the native valve leaflets and the aortic root.⁴² During deployment, the image sequence should be recorded and, immediately post-

Table 5 TEE during balloon valvuloplasty
Appreciation of how a known balloon size fits into the valve annulus
Determination of space within the sinuses to accommodate calcified leaflets
Imaging of coronary ostia to determine risk of obstruction
Detection of severe regurgitation post-valvuloplasty

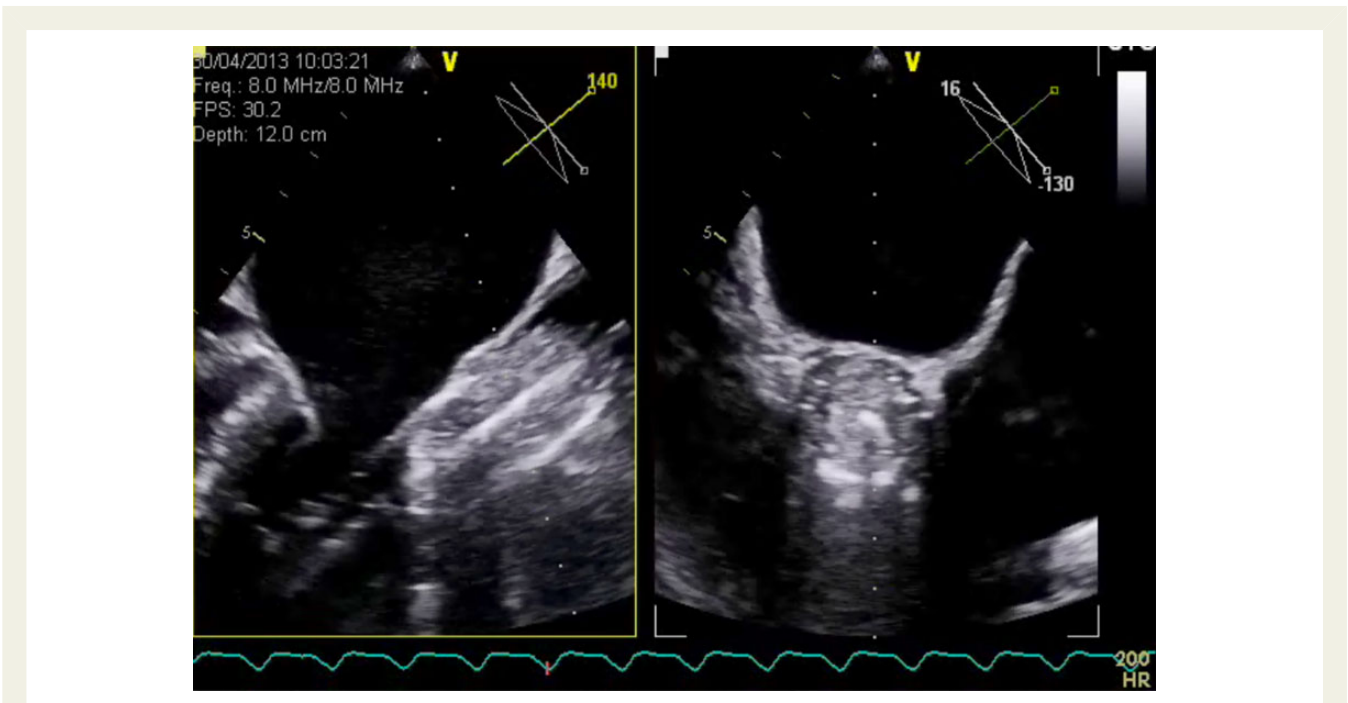


Figure 4 Simultaneous longitudinal and transverse TOE images during balloon valvuloplasty showing that the balloon completely fills the aortic annulus and sinuses, which can have implications for valve size selection.

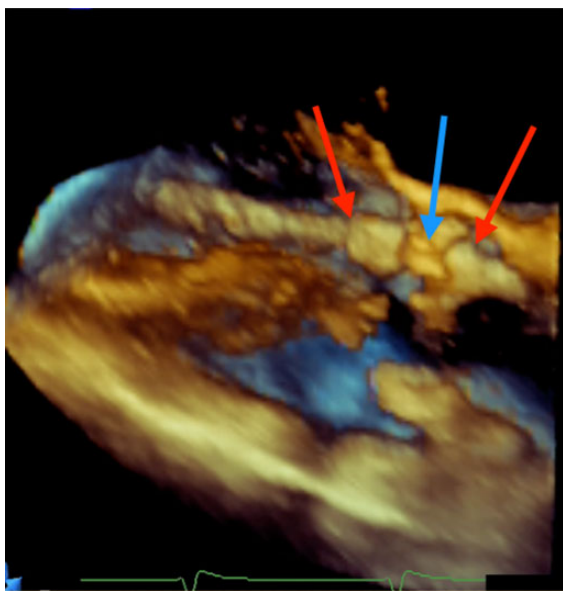


Figure 5 3D TOE image immediately prior to deployment of a balloon-expandable valve. The red arrows show the upper and lower margins of the crimped valve which can be seen as satisfactorily positioned relative to the native aortic indicated by the blue arrow.

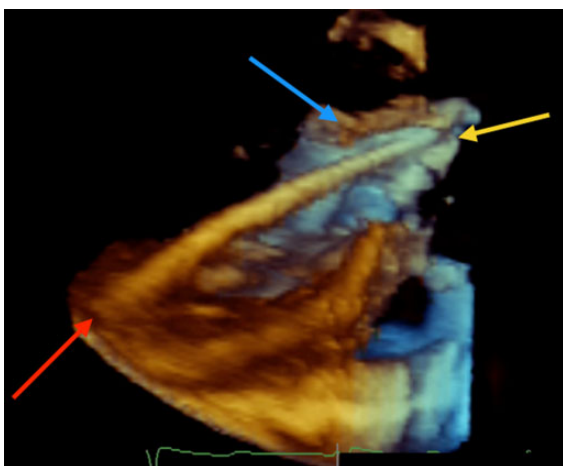


Figure 6 3D TOE image demonstrating the safe orientation of a TAVI delivery system through the left ventricle from the apex (red arrow) to the aortic valve (yellow arrow). This patient was undergoing a transapical procedure and the catheter is well away from the mitral valve indicated by the blue arrow.

deployment, TEE has an important role to play in confirming satisfactory positioning and performance of the deployed valve. In particular, the assessment of any paravalvular regurgitation should be done quickly to decide on the need for post-dilatation. Unfortunately, paravalvular regurgitation can be difficult to assess and it is

Table 6 TEE imaging during valve deployment

3D appears better than 2D TEE for visualizing balloon-expandable valves
Use Live 3D or equivalent in a longitudinal plane
Rotate probe so that the cut-plane is to the side (not through) the valve
Use high-frequency, post-processing and low 3D gain
Ensure that the top of a balloon-expandable valve cage is high enough to just cover the native valve leaflets
Rotate the 3D image prior to deployment to ensure that the valve will be deployed co-axially to the native valve structure
Record the deployment sequence

important to remember that if the blood pressure is low, which often occurs immediately post-deployment, a significant regurgitant jet may look small on colour-flow Doppler. In addition, paravalvular jets are often multiple and eccentric. A pragmatic approach seems to be to use 2D colour-flow Doppler in a transverse (short-axis) plane across the LV outflow tract immediately below the deployed valve¹⁷ (Figure 7). In that way, the circumferential extent, relative to the valve ring, of any regurgitation can be appreciated. We consider <10% of the total circumferential extent to be mild, and >30% is considered severe paravalvular regurgitation. It is also prudent to rotate the TEE probe and examine the descending aorta using pulsed Doppler to look for holo-diastolic flow reversal that, if present, may suggest significant aortic regurgitation. However, reduced aortic compliance may be associated with flow reversal in the absence of aortic regurgitation and it is therefore important to have ruled out such flow reversal pre-deployment when there typically will be none or only mild regurgitation. Clearly, these methods for determining the extent of any post-deployment valve regurgitation are not perfect. However, they do facilitate a rapid assessment and help decide whether post-dilatation of the prosthesis is necessary to improve the fit of the valve into the aortic annulus and reduce any residual regurgitation. A unifying scheme of assessing the severity of paravalvular regurgitation has recently been proposed.⁴³

TEE assessment of TAVI complications

Despite all the detailed preparation and planning of a TAVI procedure, complications do occur. When this happens, TEE imaging can be invaluable in early detection and guiding management of the complication.⁶ Table 7 indicates the range of potential TAVI complications that can be detected and evaluated by peri-procedure TEE.

The evaluation of aortic regurgitation has been discussed previously; however, it is of vital importance to detect and minimize because it is known to be associated with poor long-term outcome post-TAVI. As part of the initial TEE imaging during a TAVI procedure, it is important to document baseline regional LV and RV function. If coronary occlusion and myocardial ischaemia occur, one of the first indicators will be the presence of a new wall motion abnormality. The mid-oesophageal and transgastric views all play a key role in facilitating visualization of all myocardial segments and the TEE operator should be an expert in obtaining these images rapidly. The LV outflow tract component of the prosthesis may interfere with the anterior mitral valve leaflet, especially in patients with small

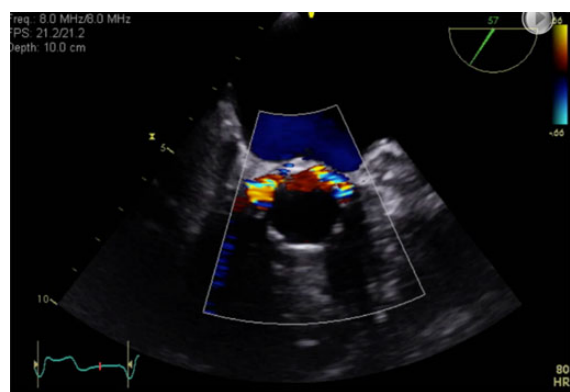


Figure 7 Transverse (short-axis) colour Doppler image of the LVOT immediately below the TAVI valve. Paravalvular regurgitation is seen from the medial to the lateral aspects of the valve involving almost 40% of the circumference.

left ventricles and cause MR. However, a more common cause of MR is interference with the subvalvar apparatus that can occur due to wire/catheter entrapment. The guidewire and guide catheter should be positioned at the LV apex and TEE is an ideal imaging modality to guide the manoeuvre. Additional care is needed when using the transapical approach, because if the guide catheter runs through the chordae en-route to the aortic valve, it may be impossible to advance the delivery system, and there is a risk of irrevocable damage to the mitral valve. TEE imaging, especially using real-time or *Live 3D* can facilitate visualization of the guidewire as it is advanced from the LV apex towards the LVOT and aortic valve (Figure 6). If the wire passes through the mitral subvalvar apparatus or into the left atrium, this will be immediately recognized. As a result, many TAVI operators prefer to manipulate the guidewire using TEE imaging guidance.

Pericardial effusions are poorly tolerated by patients with impaired LV function and/or hypertrophied 'stiff' ventricles; therefore, rapid diagnosis is usually very important. Pericardial effusion can occur secondary to partial aortic root rupture or perforation of the RV by the pacing wire. Transgastric TEE images are usually the best views to detect an effusion and they should be performed if an unexpected drop in blood pressure occurs.

Other complications detectable by echocardiography include severe aortic regurgitation secondary to prosthesis malfunction caused by a stuck leaflet, a guidewire or catheter across the valve, a native aortic valve leaflet impinging on the prosthesis leaflets or incomplete deployment of the valve. The presence and mechanism of aortic regurgitation are relatively easy to determine on TEE and the technique clearly plays an important role in guiding management.

Aortic root rupture following device deployment is usually catastrophic. However, a limited tear or puncture can occur, resulting in flow into the right ventricle, left atrium or the pericardium. Prompt diagnosis is crucial and TEE colour-flow Doppler imaging is usually the modality of choice to detect and evaluate this condition. As well, aortic dissection or intra-mural haematoma is associated complications best evaluated by TEE. In contrast, device embolization is very well seen on fluoroscopy and TEE adds little to the assessment of

Table 7 TAVI complications assessable by peri-procedure TEE

Aortic regurgitation
Trans-valvar or paravalvar
Incorrect prosthesis positioning
May lead to embolization into the LV or aorta
Paravalvar regurgitation
Myocardial ischaemia
New wall motion abnormality
Coronary occlusion
Mitral regurgitation
Damage to the valve leaflets or subvalvar apparatus
Myocardial ischaemia
Dyssynchrony secondary to pacing
Pericardial effusion
LV or RV perforation
Unmasked LV dynamic obstruction
– SAM related
– Midventricular
Aortic dissection or root rupture

this rare complication. However, it may provide additional imaging assistance during device retrieval, especially if it has embolized into the LV. Lastly, unusual complications such as excessive valve movement during deployment as a result of intermittent pacing capture (Figure 8) can be promptly recognized.

Fusion imaging

Currently, a single imaging modality is often insufficient during TAVI procedures where the use of multi-modality imaging with echocardiography for anatomical and soft tissue definition and fluoroscopy for catheter and device visualization is common. Recent technological developments have focused on structural heart disease interventions in the cath lab, and a new navigation system has been introduced. This new system allows synchronization of echocardiography and fluoroscopy images in real time, enabling fusion of both images into one, using either 2D or 3D echocardiography. The system places the two imaging modalities in the same co-ordinate system and is based on the localization and tracking of the TEE probe. After synchronization of TEE and fluoroscopy images, the system automatically tracks and follows the movements of the c-arm gantry (angiography unit arm in the shape of a c) allowing the simultaneous real-time display on one screen of an X-ray view and up to three echocardiography views. The standard TEE echocardiography view as the echocardiographer's screen shows an echocardiography image in the same orientation as the c-arm gantry, and a free image that can be rotated or cropped. A fusion image with the overlay of echocardiography and fluoroscopy images may also be obtained. Marking of structures such as the aortic annulus or coronary ostia may be performed, allowing guidance during the procedure (Figure 9). This may be especially useful in patients with less calcified valves where identification of the aortic annulus using fluoroscopy images alone can be challenging. One of the main advantages is the presentation of one single fusion image,

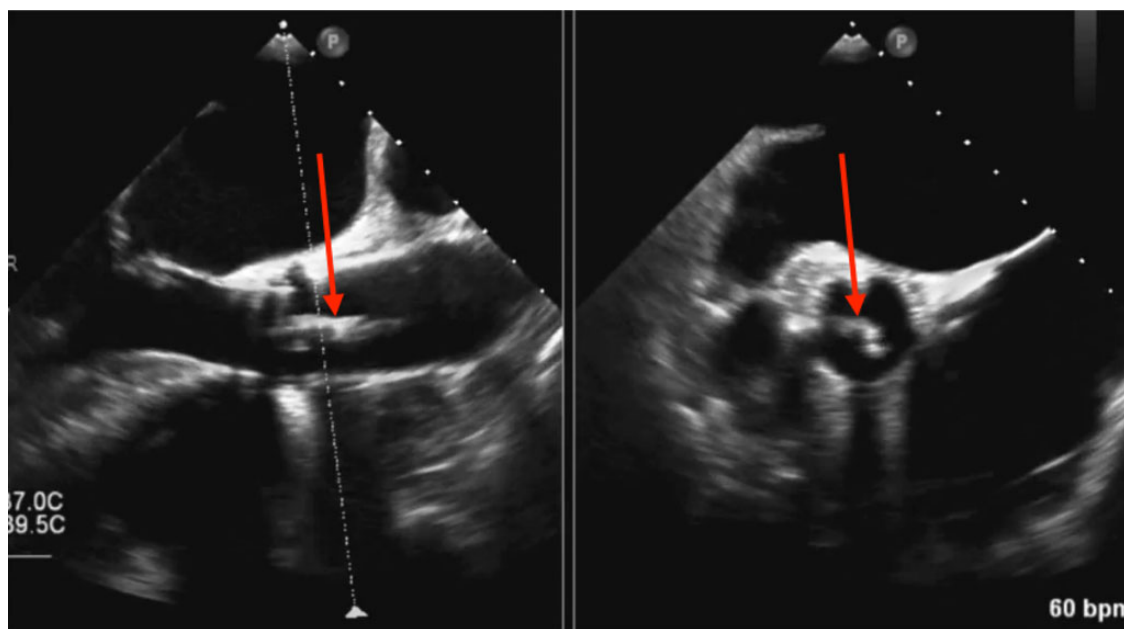


Figure 8 An unusual complication post-TAVI implant where there was excessive valve movement during deployment cause by intermittent pacing capture. The native aortic valve became disrupted and torn and it was seen as a mobile structure (red arrows) immediately above the deployed valve.

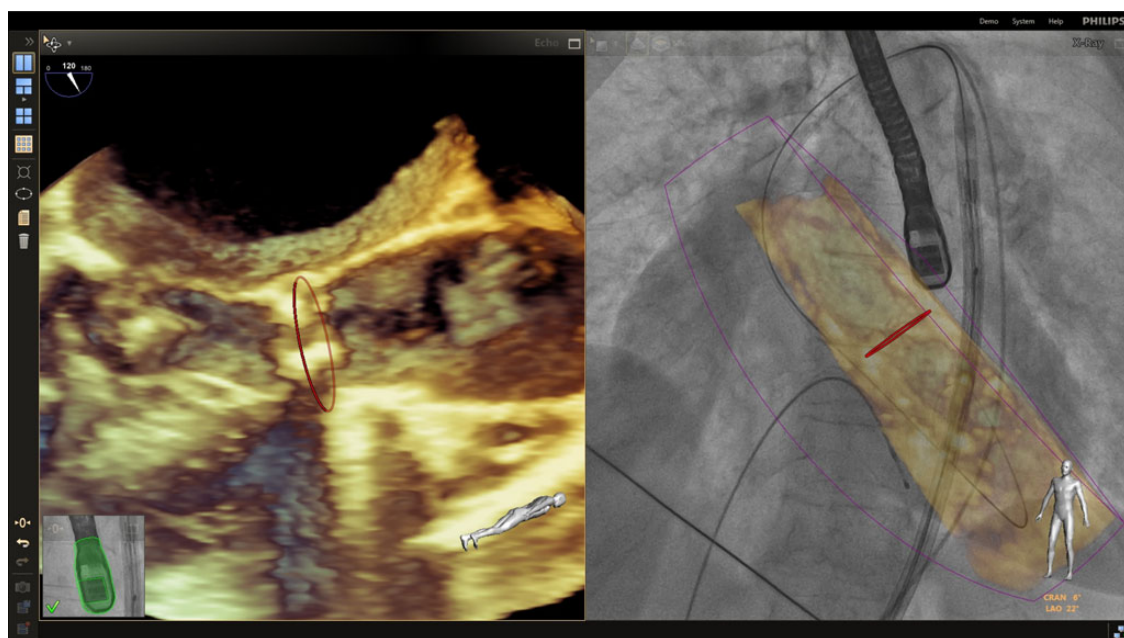


Figure 9 EchoNavigator screen image showing a 3D echocardiography image of the aortic valve and a fusion image of echocardiography in 3D and fluoroscopy of the aortic valve during a TAVR procedure.

avoiding the potential confusion from different imaging modalities and perspectives. In addition, the marking of relevant structures may help during procedure guidance and valve deployment. These

systems have recently been incorporated into cath labs with potential advantages such as minimizing radiation exposure and increasing safety for the patient and operator to be demonstrated.

Percutaneous mitral valve interventions

MR is an important cause of morbidity and mortality in developed countries.^{44,45} The most common causes of MR are degenerative and functional (ischaemic and non-ischaemic), with an age-related epidemiological burden consisting of a peak incidence in patients over 70 years of age.⁴⁴ The mechanism of MR is defined as either functional/ischaemic (secondary MR) when it is secondary to various patterns of LV remodelling in the absence of any significant intrinsic valvular lesion or as organic (primary) due to degenerative MV prolapse or flail. Open surgical correction, using mitral valve repair or replacement, is currently accepted as the best available treatment of MR. However, there is a need for alternative treatment options, as a significant number of patients with severe MR are denied surgery on the basis of age, LV dysfunction, and/or comorbidities.⁴⁶ In addition, patients with less-than-severe MR undergoing a first cardiac surgery may develop significant MR over time and be denied reoperation on the basis of increased risk. As with surgical mitral repair, the echocardiographic assessment of mitral functional anatomy and the determination of the mechanism of MR are mandatory to select patients who can benefit from percutaneous intervention and to tailor the repair strategy. Both degenerative and functional/ischaemic MR can be suitable for percutaneous valve repair through a variety of approaches including those that offer direct leaflet repair, direct or indirect annular

reshaping, and ventricular remodelling.^{47–49} Two-dimensional echocardiography supplemented by a real-time 3D imaging is also essential to guide and evaluate the effectiveness of the chosen percutaneous repair technique. Table 8 summarizes the current experience with available devices for percutaneous mitral valve repair. However, it should be noted that this is a rapidly changing field with the introduction of new devices and withdrawal/redesign of existing devices.

Echocardiographic assessment of the MV

2D TTE or/and TEE are usually sufficient for an accurate assessment of MV morphology.⁵⁰ Through multiple scan planes, and using all available acoustic windows, all components of the MV apparatus can be imaged.⁵¹ When available, 3D TTE should be used to complement the 2D TTE study in the assessment of MV morphology. 3D TEE has the advantage of higher spatial resolution and a better trade-off between temporal and spatial resolution, when compared with 3D TTE. 3D TEE has been proved to be superior to 2D TTE or TEE in describing MV morphology, especially with pathology involving the anterior leaflet or commissures, in identifying leaflet perforation and the site of vegetation attachment, as well as in detecting complex lesions. The 'en face' view of the MV from the atrial perspective can provide a view of the valve that is comparable to that of the surgeon in the operating theatre and offers a rapid and accurate understanding of the mechanism of MV dysfunction. The acquired 3D dataset can be cropped and displayed in any

Table 8 Current experience with available devices for percutaneous mitral valve repair

Therapeutic target	Device (manufacturer)	Approach	Mechanism	Current experience
Indirect annuloplasty	Carillon	Trans-jugular	Coronary sinus reshaping	In clinical trial
	Monarc (Edwards)	Trans-jugular	Coronary sinus reshaping	Clinical trial suspended
	PTMA device (Viacor)	Trans-subclavian	Coronary sinus reshaping	Clinical trial suspended
	Mitral cerclage (NIH)	Trans-jugular, femoral vein and femoral artery	Coronary sinus-right atrial encircling	Preclinical
	PS3 System (MVRx)	Trans-jugular and transseptal	Transatrial coronary sinus-atrial septal shortening	First-in-man
Direct annuloplasty	Mitralign (Mitralign)	Transfemoral	Plicating suture and pledgets through posterior annulus	In clinical trial
	AccuCinch (Guided Delivery System)	Transfemoral	Plicating anchors in ventricular side of mitral annulus	In clinical trial
	Cardioband (Valtech)	Transseptal	Plicating adjustable ring on atrial side of mitral annulus	In clinical trial
	QuantumCor (QuantumCor)	Transseptal	Radiofrequency energy shrinking annular collagen	Preclinical
	Millepiede (Millepiede)	Transseptal	Semirigid circumferential annular ring	Preclinical
	ReCor (Recor)	Transseptal	Ultrasound energy annular reshaping	Preclinical
Left Ventricular reshaping	iCoapsys (Edwards)	Subxyphoid	Transventricular reshaping	Preclinical
	BACE (Mardil)	Thoracotomy	External basal ventricular reshaping	Preclinical
Leaflet repair	MitraClip (Abbott)	Transseptal	Clip-based edge-to-edge ("double-orifice")	Clinical trial-based evidence
	Percu-Pro (Cardiosolution)	Transapical	Regurgitant orifice space occupying	Preclinical
	NeoChord (NeoChord)	Transapical	Synthetic chordae tendineae anchored to LV apex to treat mitral prolapse	First clinical trial completed, Clinical registry ongoing

desired plane, which makes morphology analysis easier. The ventricular view as well views from any other desired angles are helpful in assessing valvular morphology and provide important contributions to the understanding of the mechanism of valve dysfunction. The costs of 3D TEE are strongly balanced by the advantages provided to the interventionists in the context of MV percutaneous therapies. The major drawback for 3D TTE/TEE is the dependency on a good acoustic window, as well as potential limitations in spatial and temporal resolution, especially in patients with large annuli.

Percutaneous therapies and current experience

Percutaneous annuloplasty techniques

Percutaneous annuloplasty techniques mimic surgical annular remodelling in order to reverse mitral leaflet coaptation abnormalities and related MR. This approach is targeted to select patients with functional/ ischaemic MR and may be more effective when annular dilation/deformation is predominant. Devices aiming to reshape the mitral annulus include indirect types, which are positioned in the coronary sinus, and direct types, which are implanted in the annulus, similar to surgical annuloplasty.

The echocardiographic analysis of the MR mechanism, according to Carpentier's classification, is crucial when selecting patients for annuloplasty. Considering the surgical annuloplasty experience, common MR mechanisms that might be corrected by percutaneous annuloplasty include Type I (incomplete coaptation due to annular dilation/deformation), or Type IIIb (symmetrical leaflet tethering due to LV remodelling). Mitral valve structural abnormalities (Type II, Type IIIa), or recognized tethering shapes that are predictive of unsuccessful surgical annuloplasty (coaptation depth >1 cm, asymmetric extreme tethering of posterior leaflet with angle $>45^\circ$ or distal leaflet anterior tenting with angle $>25^\circ$)^{52,53} should be excluded from the percutaneous approach. TTE provides baseline information regarding functional anatomy of MR and annular dimension. The mitral annulus may be assessed using the 2D approach with a TTE apical long-axis view (3-Chamber), and the equivalent mid-oesophageal view for the minor axis (antero-posterior or septo-lateral). The major axis (intercommissural) annulus diameter can be measured using a modified TTE two-chamber apical view or a bi-commissural mid-oesophageal view. The presence of annular calcification or structural abnormalities of the mitral leaflets contraindicate annuloplasty device implantation. Integrated analysis of annulus shape, using MSCT and RT3D TEE, provides additional information on the feasibility and planning of annuloplasty therapy. Using 3D-TEE reconstruction models, the functional anatomy and dynamics of the mitral annulus can be quantitatively assessed. The following annular parameters may be useful to plan mitral annuloplasty: area, circumference, antero-posterior (septo-lateral) and medio-lateral diameters, sphericity index (antero-posterior/medio-lateral diameters ratio), non-planarity angle (quantifying the 'saddle shape'), annular height (the distance between the lowest and the highest points of the mitral annulus), and the angle between the aortic valve and mitral annulus along the antero-posterior annular dimension.

MSCT is essential for the evaluation of coronary sinus anatomy and adjacent coronary artery relationship, annulus shape indices, and annular calcification.

Imaging criteria for percutaneous annuloplasty suitability

MR due to annular dilation (Carpentier Type 1 or IIIb) Tenting mitral leaflet indices predicting successful surgical annuloplasty

Coaptation depth <1 cm

Tethering angle of posterior leaflet $<45^\circ$

Distal tethering of anterior leaflet $<25^\circ$

Lack of annular calcification

Anatomically normal mitral leaflets

Appropriate coronary sinus /mitral annulus match and adjacent coronary artery relationship

Indirect annuloplasty-coronary sinus techniques

Coronary sinus annuloplasty attempts to re-shape the antero-posterior annular dimension to correct the mitral leaflet apposition-coaptation abnormality underlying the MR. The rationale of this approach is based on the anatomical relationship between the coronary sinus/great cardiac vein and the posterior annulus. Several techniques have been proposed that involve placing a device within the coronary sinus/great cardiac vein to attempt septal-lateral diameter reduction and/or mitral annulus 'cinching'. To achieve therapeutic goals, trans-coronary sinus approaches should provide an appropriate degree of tension to reduce MR without slipping and fracturing. The Carillon™ Mitral Contour System (Cardiac Dimensions, Kirkland, WA, USA), which consists of two helical anchors interconnected by a nitinol bridge, is the most clinically tested device. Using right internal jugular access, the distal anchor is positioned in the great cardiac vein, and subsequent manual traction is applied to approximate the lateral and septal portions of the mitral annulus optimizing leaflet coaptation (Figure 10).

The selection of candidates for indirect annuloplasty is based on the above-mentioned echocardiographic analysis of mitral functional anatomy. MSCT is required to exclude annular calcification, abnormal coronary sinus/annulus alignment or abnormal circumflex coronary artery relationship, which reduce the efficacy and safety of the procedure.

Fluoroscopy and TEE are used to determine the final position of the annuloplasty devices during indirect annuloplasty through the coronary sinus. TEE is performed to guide annulus re-shaping and monitor related MR changes. In the event of coronary artery compromise or insufficient MR reduction, the implant should be recaptured by advancing the delivery catheter to collapse the proximal anchor, followed by the distal anchor. If the reduction of MR is insufficient, the device can be removed. The successful reduction of MR requires careful attention to loading conditions to avoid misinterpretation of procedural efficacy, while transient ischemia-related MR worsening due to left circumflex artery spasm should be excluded before considering that the trans-coronary sinus procedure has been unsuccessful. The variable distance between the coronary sinus and the mitral annulus, as demonstrated by MSCT studies, may affect procedural success. In some patients, the coronary sinus is located above the annular level in contact with the left atrial

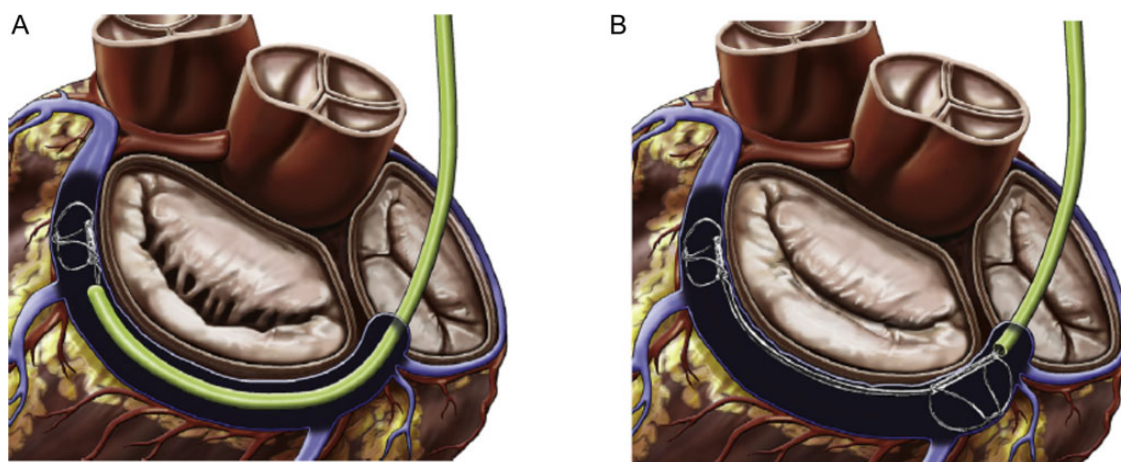


Figure 10 Carillon Device implantation through jugular venous access. (A) The device is delivered in the distal coronary sinus for release of distal anchor and subsequently proximal anchor in the coronary sinus ostium. (B) The sinus wireform cinching the mitral annulus to reduce the septal-lateral dimension and related mitral regurgitation.

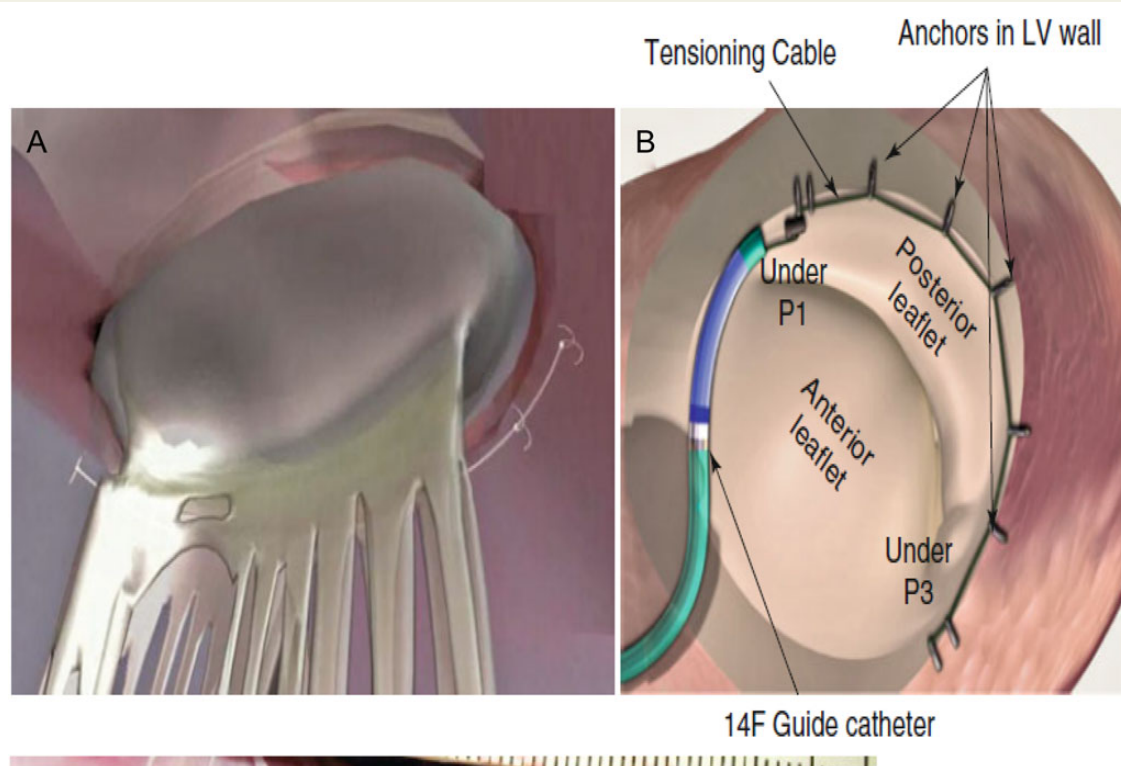


Figure 11 (A) The Accucinch (Guided Delivery System, Santa Clara, USA) can be delivered using a retrograde transfemoral approach. The device is placed using a series of anchors under the posterior mitral annulus from the right to left trigone to attempt the reduction of both annulus and basal left ventricular shape (B).

(LA) wall. Annular devices in these patients theoretically would clinch the LA wall without annular re-shaping and therefore might not reduce MR. An additional concern of indirect annuloplasty is the risk of coronary ischemic events due to the close but variable

relationship between the coronary sinus and the left circumflex artery.⁵⁴ Finally, these devices pose at least a theoretical risk of coronary sinus thrombosis or rupture. The clinical experience of CARILLON includes the AMADEUS study, which reports an

implantation feasibility in 30 of 48 patients without significant MR improvement, and a moderate risk of coronary complications (15%) and death (1 patient).⁵⁵ More recently, a redesigned CARILLON device was tested in the TITAN trial, which reports a successful implantation in 36 of 53 enrolled patients, leading to MR reduction and concomitant LV remodelling.⁵⁶

The Percutaneous Septal Sinus Shortening System (PS3 system, MVRx, Belmont, CA) uses a magnetically tipped catheter to place a suture bridge which connects 2 anchors in the coronary sinus near P2 and the interatrial septum respectively. With the application of tension to the anchor, the septo-lateral annular dimension may be reduced.^{57,58}

Direct annuloplasty

Even though currently unavailable for clinical use, some percutaneous devices that attempt favourable annular re-shaping with a direct approach have been developed for the treatment of functional/ischemic MR. There are two approaches – direct acting devices and energy/wave remodelling devices. These include transcatheter devices and hybrid devices requiring surgical implantation and subsequent transcatheter adjustment.^{47,48}

Direct annuloplasty consists of device implantation in the annulus, similar to surgical annuloplasty, using the retrograde, via the aorta into the left ventricle, or the transseptal approach. The Accucinch (Guided Delivery System, Santa Clara, USA) uses a ventriculoplasty device, which can be delivered using a retrograde transfemoral approach. The device is placed using a series of anchors under the posterior mitral annulus from the right to left trigone to attempt the reduction of both annulus and basal LV size (Figure 11).

The Mitralign device (Mitralign, Tewksbury, Massachusetts, USA) uses pairs of pledgets, which are implanted using a transaortic approach into the LV in the posterior mitral annulus, with the lateral (A1P1) and medial (A3P3) segments of the mitral valve acting as target points. The pledgets are connected with a suture, cinching the annular circumference to reduce the mitral orifice area and regurgitation⁵⁹ (Figure 12).

The Cardioband System (Valtech Cardio Ltd., Or-Yeuda, Israel) consists of a transseptal catheter device delivering a series of anchors into the atrial site of the mitral annulus under fluoroscopy and TEE guidance (Figure 13). These anchors are connected by a tensioning sleeve which can be targeted to reduce MR by intra-procedural progressive re-shaping of the septo-lateral annular dimension. A first-in-man procedure has been reported,⁶⁰ and a clinical trial is ongoing. Echo Doppler supplemented by 3D-TEE imaging is crucial to guide anchor implantation and the subsequent degree of applied tension to optimize annulus reshaping (Figure 13).

Energy-mediated Annuloplasty Systems. This technology uses transcatheter energy delivery, attempting annular length reduction by collagen shrinking. The QuantumCor (QuantumCor, San Clemente, CA, USA) is based on thermal remodelling of collagen, delivering sub-ablative radiofrequency energy using a multiple-electrode probe (Figure 14).

Animal models showed annular reshaping and the reduction of related MR, without histopathologic damage of the left atrium and mitral leaflet. Repeated application can be performed. This system has not yet been reported in a clinical context.⁶¹ The ReCor (Recor Medical, Ronkonkoma, NY, USA) consists of a transseptal balloon

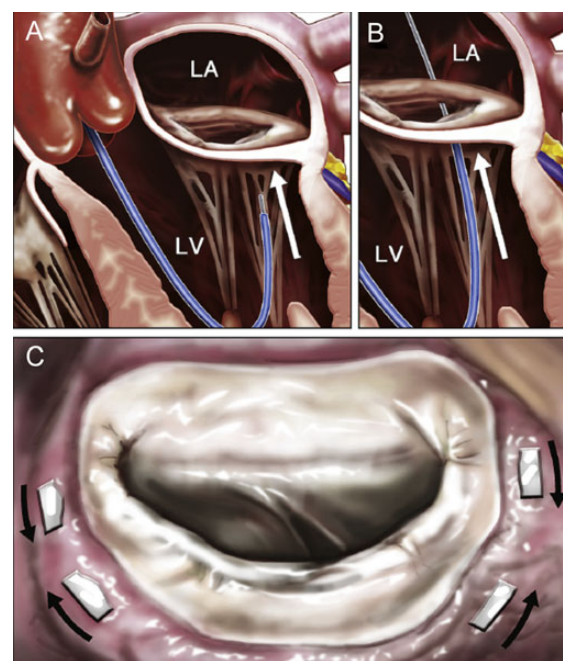


Figure 12 Mitralign annular system. (A) A retrograde aortic catheter in the left ventricle (LV); (B) a wire through the annulus into the left atrium (LA); (C) paired pledgeted sutures placed along the posterior annulus near both commissures with a final appearance of 2 × 2 annular complication.

catheter with a cylindrical piezoelectric transducer delivering ultrasound energy.⁶²

Mitral leaflet repair

Percutaneous mitral leaflet repair aims to reproduce surgical techniques of improving leaflet coaptation and reducing/eliminating MR. The tested edge-to-edge Alfieri surgical technique⁶³ is mimicked by the percutaneous MitraClip system. Other experimental approaches, including chordal replacement or cutting, are currently under development. The MitraClip system is a polyester fabric-covered cobalt–chromium implant with two arms which can be opened and closed with a steerable-guiding mechanism. The MitraClip is easily imaged with TEE permitting reliable step-by-step procedural guidance as detailed below. Under general anaesthesia, an antegrade (transseptal) approach is used with the device aligned at the A2–P2 interface perpendicular to the commissure using a sophisticated guiding/positioning system and echocardiographic/fluoroscopic guidance. The device is deployed after successfully grasping the regurgitant target zone of the mitral leaflet. If needed, an additional clip may be placed to achieve satisfactory reduction in MR. The MitraClip system is effective in select patients with either degenerative or functional MR. In degenerative MR, the percutaneous clip anchors the flail and/or prolapsed leaflet, whereas, in patients with functional MR, it improves coaptation of the tethered leaflet(s) to reduce the time and force required to close the valve. Additionally, the clip creates a tissue bridge between the two mitral leaflets. As a result, it limits annular dilatation and supports the

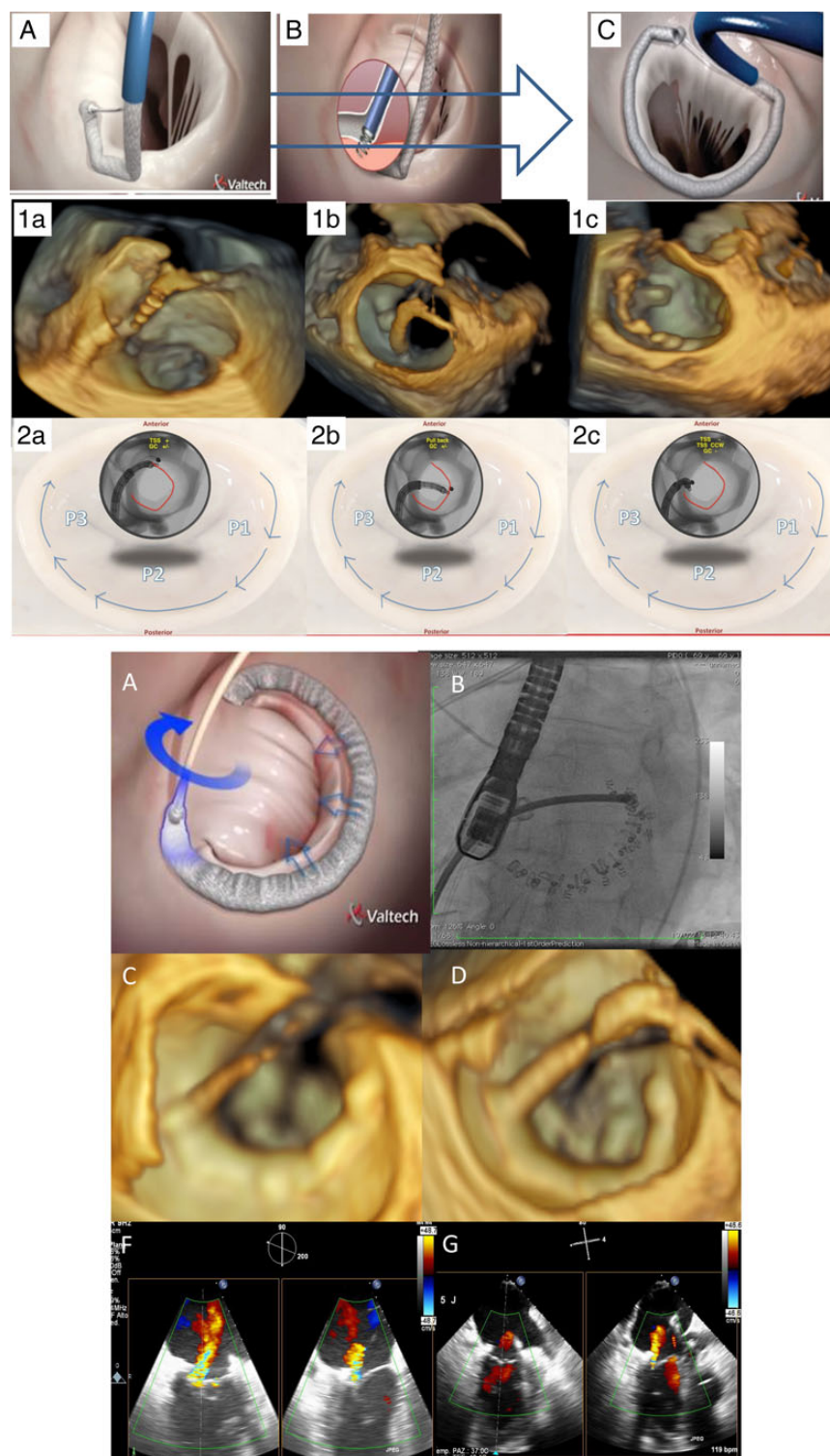


Figure 13 (A) The Valtech Cardioband. The system consists of an adjustable annuloplasty band, which is delivered via the transseptal approach into the atrial site of the posterior mitral annulus between the antero-lateral (A) and postero-medial commissures (C) with helical fixation anchors (B). The delivering phase requires step-by-step monitoring using 3-D echocardiography (Figure 1A–C) and fluoroscopy (Figure 2A–C). Starting from the antero-lateral commissure (Figures 1A and 2A), the Cardioband is progressively delivered and completed at the postero-medial commissure (Figures 1C and 2C). Fluoroscopy imaging (ventricular view) mirrors 3D echocardiography (atrial view). P1, P2, and P3 are the referral landing zones corresponding to the lateral scallop, middle scallop, and the medial scallop of the posterior mitral leaflet respectively. (B). (A) Following complete delivery, the Valtech Cardioband system ((B) fluoroscopy imaging) is adjusted under 3D echocardiography to reshape the annulus (C and D) to achieve reduction of mitral regurgitation ((F, G): colour-flow mapping at baseline and after the final adjustment, respectively).

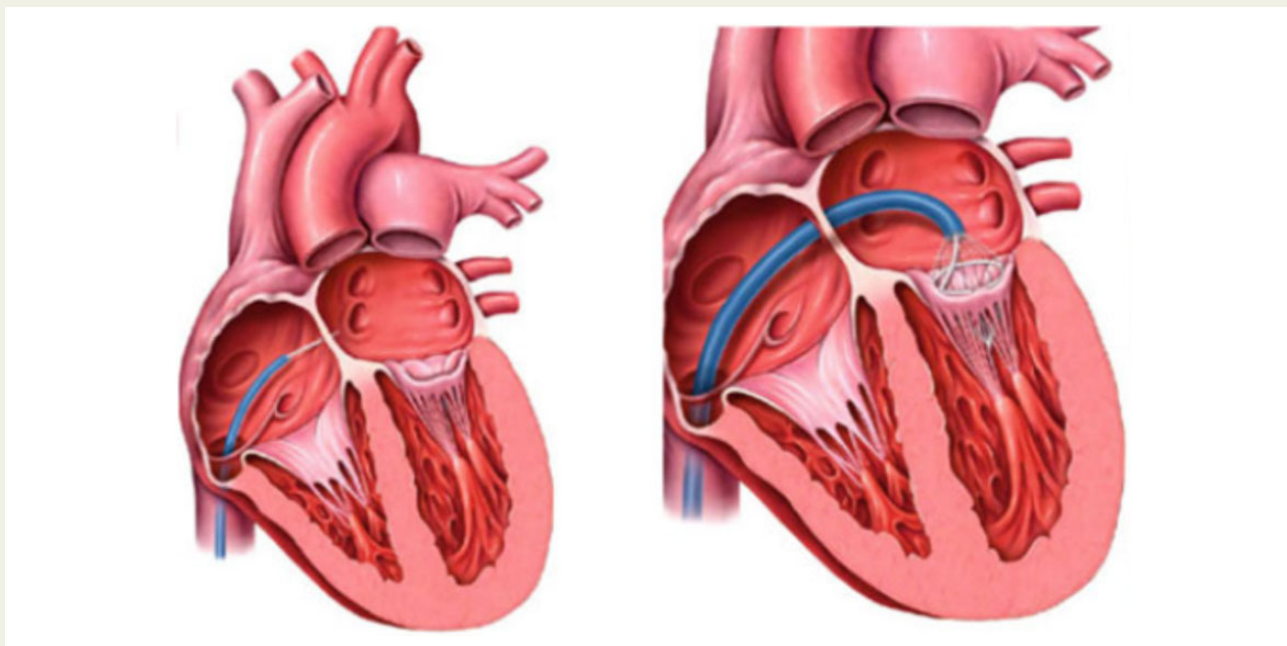


Figure 14 The QuantumCor system delivering radiofrequency energy to reshape the annulus.

Table 9 Results of clinical trial and registries of MitraClip treatment

Study	n	30-day mortality	1-year mortality	1-year freedom from surgery	% MR ≤ 2 1-year
EVEREST II	351	4.8	22.8	97.8	84
High-risk registry ^a					
ACCESS EU	567	3.4	17.3	93.7	79
TRAMI registry	1064	2.8	—	—	—
COAPT trial	Ongoing enrolment				
RESHAPE-HF	Recently interrupted				

^aData including EVEREST II High-Risk Registry and EVEREST REALISM.

durability of the repair. Finally, the clip restrains the LV wall by restricting LV dilatation and induces reverse LV remodelling, which, in patients with functional/ischemic MR, may further reduce tethering and resultant regurgitation. The procedure has been tested in the safety–feasibility EVEREST I trial that reported procedural success, defined as successful implant with reduced MR $\geq 2+$, in 79 of 107 (74%) patients.^{64,65} Most patients (73%) had degenerative MR.⁶⁵ Recently, the subgroup analysis of high-risk surgery patients in the EVEREST II trial (EVEREST high-risk study) found a favourable 1-year outcome with MitraClip with a low operative mortality (4.8% 30-day mortality).⁶⁶ Additional studies corroborated the effectiveness of the MitraClip device in patients who were deemed at high risk for surgery, or were inoperable.^{67,68} A recent meta-analysis of high-risk patients found that a high rate of successful MitraClip therapy (residual MR $\leq 2+$) may be achieved in 73–100% of patients with a favourable 1-year outcome in terms of survival (range 75–90%), clinical benefit and functional improvement. Two European multicenter registries (ACCESS)⁶⁹ and TRAMI,⁷⁰ including

567 and 1064 patients, respectively, report that in daily clinical practice MitraClip therapy is mainly performed in elderly patients with comorbidities, a high surgical risk, and functional MR with severe LV dysfunction. Table 9 summarizes MitraClip results of randomized clinical trials and registries. Two randomized trials, the RE-SHAPE in Europe (recently interrupted) and COAPT in the US (ongoing), have been addressed to evaluate the long-term outcome of MitraClip therapy over optimal medical therapy in patients with functional MR.

Transoesophageal echocardiography for edge-to-edge clip technique

Patient selection and mitral valve lesion targeting

The combined use of 2D and 3D TEE appears to enhance the confidence of the interpretation regarding MV pathology (especially in

complex lesions) compared to the usage of 2D TEE as the sole imaging modality, so 3D should always be used when possible (Figures 15 and 16).^{71,72} TEE is used to confirm the severity and to precisely define the mechanism of MR as well as the anatomic suitability for a MitraClip implantation.

This evaluation requires an integrative multi-modal approach including qualitative and quantitative parameters as recommended by European and American echocardiographic societies.^{73,74} An intervention should be indicated only in cases of moderate to severe or severe MR. It should be kept in mind that MR severity may be subject

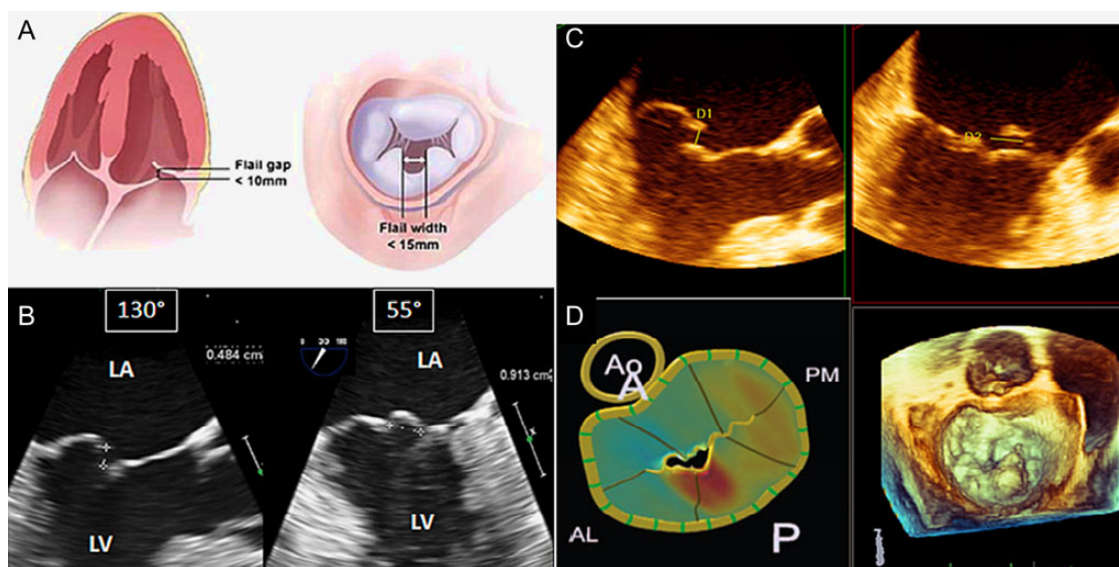


Figure 15 Echocardiographic selection for primary MR. (A) schematic representation of the requirements for MitraClip™ implantation in patients with mitral flail (reprinted with permission from Feldman et al.²⁶). (B) 2D transoesophageal echocardiography images depicting measurement of flail gap and flail width. (C) 3D multi-plane reconstruction allowing measurement of the flail gap and flail width. (D) 3D parametric colour coded image of a P2 prolapse. LA, left atrium; LV, left ventricle.

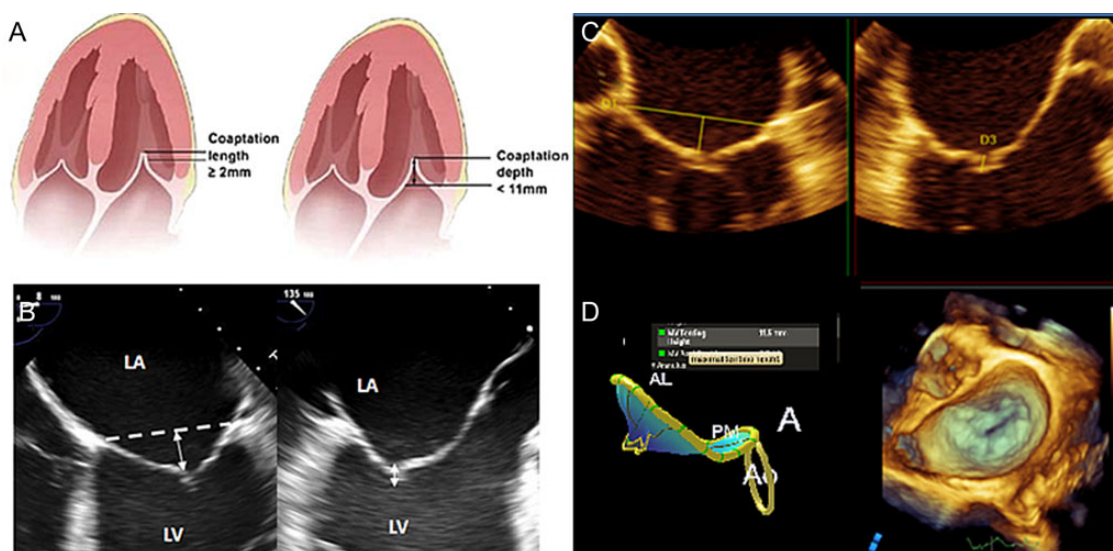


Figure 16 Echocardiographic selection for secondary MR. (A) Schematic representation of the requirements for MitraClip™ implantation in patients with functional mitral regurgitation. (Reprinted with permission from Feldman et al.²⁶) (B) 2D transoesophageal echocardiography images depicting measurement of the coaptation length and coaptation depth. (C) 3D multi-plane reconstruction allowing measurement of coaptation length and coaptation depth. (D) 3D parametric colour coded image of mitral valve tenting. LA, left atrium; LV, left ventricle.

to temporal variations especially in functional MR due its dynamic nature and to its load dependency. In particular, the severity of functional MR may be underestimated when TEE is performed under general anaesthesia due to significant hemodynamic and loading condition changes as a consequence of anaesthetic drugs.⁷⁵ Therefore evaluation of MR severity should be performed in the best hemodynamic conditions possible, with normal blood pressure and controlled heart rate.

It is crucial to assess the MV anatomy at the origin of MR (target lesion) and to confirm that leaflet tissue quality and length is adequate in this area to allow for a secure Clip placement.

For patients with degenerative MV prolapse/flail the following factors should be addressed:

- Accurate localization and evaluation of the extension of the prolapse/flail using multiple 2D TEE views. The TEE view should be aligned to demonstrate the maximal excursion of the flail segment. Typically mid-oesophageal four-chamber views (0°), intercommissural views (55–75°) and long-axis or LV outflow tract (LVOT) views (100–160°) are used for this purpose.
- Two main anatomic measurements are required: the flail gap (distance separating the tip of the flail segment from its opposing normally coapting leaflet) measured by 2D TEE in LVOT and 4-chamber views and the flail width derived from the intercommissural 2D TEE view and/or transgastric short-axis view. 3D TEE using the atrial perspective surgeon's view can also be very helpful in determining the flail width.

For patients with functional/ischemic MR, the presence of sufficient leaflet tissue for mechanical coaptation constitutes the most important factor. Two measurements are essential: the coaptation depth measured by 2D TEE in a 4-chamber view and the coaptation length measured in 4-chamber and LVOT views. In addition, the measurement of the length of the posterior and anterior leaflet is required.

2D TEE vs. 3D TEE

Real-time (RT) 3D TEE adds remarkable benefits in the assessment of MV anatomy, especially in complex lesions. RT3D TEE allows for a comprehensive visualization of the entire MV in a single en-face view from LA and LV perspectives.⁷⁶ In prolapse-related MR (primary MR), RT3D TEE imaging compared with 2D TEE alone has been shown to provide more accurate identification of mitral scallops and easier differentiation of central vs. non-central prolapses.^{71,76} In addition, RT3D TEE enables the identification of leaflet abnormalities that can impact the feasibility of a MitraClip implantation (such as clefts or perforations).⁷¹

Offline multi-plane reconstruction of 3D data sets renders a more precise quantification of anatomic measurements.⁷⁷ Despite some limitations due to a relatively slow frame rate, RT3D TEE colour Doppler provides a more accurate localization of MR jet origins than 2D TEE and may permit greater accuracy in the evaluation of MR severity.⁷¹ 3D echocardiography enables the direct visualization of the true proximal flow convergence region which is usually more hemielliptical than hemispheric, especially in functional MR.⁷⁸ RT3D TEE has been shown to be more accurate in the analysis of MR severity based on the direct delineation of regurgitant orifice areas in 3D images with or without colour Doppler.⁷⁹ Although not

performed routinely, recent advances in 3D imaging may permit direct planimetry of the anatomic regurgitant orifice area in en-face 3D images and RT 3D PISA assessment.⁸⁰ For an accurate determination of MR severity an integration of multiple parameters including newly available 3D parameters is recommended.⁷⁴

Criteria of eligibility for a MitraClip implantation

In the EVEREST studies, morphological inclusion criteria were defined that would lead to optimal procedural results. These so-called Everest criteria include a central MR origin between the A2/P2 segments and a leaflet morphology allowing for a secure MitraClip placement. For patients with primary (degenerative) MR, a flail gap of <10 mm and a flail width of <15 mm were defined and for patients with secondary (functional) MR a coaptation length ≥2 mm and a coaptation depth ≤11 mm.⁶⁵

Exclusion criteria include significant leaflet calcification in the grasping area and other features that might preclude successful device implantation such as a very short posterior leaflet, a marked loss of systolic leaflet coaptation in functional MR, rigidity of the leaflets, extensive thickening or redundancy of the leaflets (e.g. Barlow's disease), rheumatic or restrictive leaflet morphology. Other exclusion criteria include the presence of a significant cleft or a perforation of a leaflet, and a mitral valve area (MVA) <4 cm² which can lead to the development of functionally significant mitral stenosis (MS) after MitraClip implantation.^{72,75} It should be noted that beyond the above-mentioned criteria for optimal MV morphology for a MitraClip implantation, it is possible to successfully treat more difficult MV morphologies with increasingly experienced operators and the use of two or even more Clips.^{64,75} These challenging morphologies require a case-by-case analysis, and include pathologies in the P1/A1 or P3/A3 segments (carrying the potential risk of Clip entanglement in the commissural chordae), an MVA between 3 and 4 cm² with persistent good leaflet mobility, a mobile posterior leaflet length between 6–7 and 10 mm, leaflet restriction in systole, and a flail width >15 mm in patients with large rings allowing for multiple Clips to be implanted.⁷⁵

In all these situations, the most important selection criterion appears to be the ability to properly grasp both leaflets. The criteria characterizing optimal, 'conditionally' suitable and unsuitable morphological characteristics of the MV for a MitraClip implantation are summarized in Table 10.

Monitoring the procedure

The success of a MitraClip procedure is heavily dependent on the imaging quality rendered by TEE as the mitral leaflets are not visible by fluoroscopy. Therefore, a patient with considerably impaired imaging quality should not be considered as a suitable candidate for MitraClip implantation. In principle, the procedure can be guided by 2D TEE imaging alone. However, 3D TEE adds substantial information and is therefore recommended for the guidance of the procedure in addition to 2D TEE.⁷¹ RT3D TEE allows for the acquisition of pyramidal datasets that can be used to visualize the size, shape, and movement of cardiac structures from multiple perspectives. During a MitraClip procedure RT3D TEE provides en-face views of the MV from the LA and the LV side, thus optimizing the assessment of MV morphology and pathology. Wires, catheters, the Clip delivery system** (CDS), the MitraClip device and the target region

Table 10 Morphological mitral valve characteristics for a MitraClip implantation. Adapted from the EVEREST criteria¹² and the German recommendations⁸¹

Optimal valve morphology (adapted from the classical 'EVEREST' criteria)	'Conditionally' suitable valve morphology	Unsuitable valve morphology
<ul style="list-style-type: none"> Central pathology in the A2 and/or P2 segments No leaflet calcification MVA > 4 cm² Flail width ≤ 15 mm (primary MR) Flail gap < 1 mm (primary MR) Coaptation depth < 11 mm (secondary MR) Coaptation length ≥ 2 mm (functional secondary MR) Mobile length of the posterior leaflet ≥ 10 mm Normal leaflet strength and mobility 	<ul style="list-style-type: none"> Pathology in segments 1 or 3 of the posterior and anterior leaflet Mild calcification outside of the target lesion (grasping zone) MVA between > 3 cm² with persistent good leaflet mobility Flail width > 15 mm in cases with large MV rings allowing for multiple Clips to be implanted Coaptation depth ≥ 11 mm Mobile posterior leaflet length between 6–7 and 10 mm Leaflet restriction in systole (Carpentier IIIB) 	<ul style="list-style-type: none"> Perforated MV leaflet or cleft Severe calcification in the area of the target lesion (grasping zone) Haemodynamically significant mitral stenosis (MVA < 3 cm², TMPG > 5 mmHg) Barlow's disease with multi-segment flail leaflets Gap between the leaflets > 2 mm Insufficient mobile length of the posterior leaflet for secure Clip insertion Rheumatic leaflet thickening and restriction in systole and diastole (Carpentier IIIA) or endocarditic valve disease and diastole (Carpentier IIIA) or endocarditic valve disease

MVA = mitral valve area; MV = mitral valve; MR = mitral regurgitation; TMPG = transvalvular mean Doppler pressure gradient.

of the MV can be visualized in one single view and in relation to each other, thus facilitating procedural steps namely transseptal (TS) puncture, steering of the CDS in the LA towards the MV and proper MitraClip alignment perpendicular to the line of coaptation at the site of the pathology of the MV. It has been demonstrated that the usage of both imaging modalities in combination leads to a remarkable reduction of nearly 30% in procedure times.⁷¹ The implantation of a MitraClip is a technically demanding procedure that requires specific imaging approaches and active imaging support during each procedural step as described in detail hereafter. In addition, knowledge of the MitraClip details and the Clip dimensions is needed to guide a procedure successfully.

Transseptal puncture

Access to the LA and the MV is gained via a transvenous, transseptal (TS) puncture using standard techniques and equipment. The determination of the optimal TS puncture site is of major importance for a MitraClip procedure as a suboptimal TS puncture often requires additional steering manoeuvres to correct the position of the entire MitraClip delivery system. This results generally in an increase in the complexity and duration of the procedure which should be avoided whenever possible. Three 2D TEE planes are primarily used to precisely define the preferred puncture site, which is located in the superior-posterior part of the fossa ovalis:

- A short-axis view at the base (~30–50°) which allows for anterior–posterior orientation
- A long-axis view (bi-caval) at ~90–120° which allows for superior–inferior orientation
- A four-chamber view (~0°) is used to determine the correct height above the MV

The position of the tip of the TS needle can be identified by a tent-like doming of the interatrial septum (IAS) towards the LA ('tenting'). In this context 3D x-plane imaging facilitates the TS puncture by presenting a short-axis view and a long-axis view simultaneously

thus providing anterior–posterior and superior–inferior orientation in one single view (Figure 17A). Once a correct posterior and superior position is confirmed, the height above the MV is evaluated in a four-chamber view (Figure 17B). The optimal height above the MV differs for primary (degenerative) and secondary (functional) MR. In patients with primary MV disease the puncture site should be 4–5 cm above the mitral annulus thus providing enough space to adequately manoeuvre the MitraClip delivery system within the LA. In patients with secondary MR extensive tethering results most often in a shift in position of the line of coaptation to below the mitral annulus. In such cases, the puncture site needs to be more inferior (~3.5 cm above the annular plane). A patent foramen ovale cannot be recommended for access to the LA. Even if the entry into the LA would be superior, it is too anterior and therefore suboptimal for this procedure. Access via an interatrial septal defect (ASD) is also not recommended, even if the defect is located superiorly and posterior in the fossa ovalis, as the size of the defect generally does not match the size of the Steerable Guide Catheter (SGC). Therefore, in most cases a stable position of the SGC cannot be achieved and the risk of IAS rupture is increased.

Steerable Guide Catheter (SGC) Insertion into the LA

After TS puncture the SGC and dilator assembly are gently advanced into the LA over a super stiff exchange length guidewire which is preferably placed in the left upper pulmonary vein. The dilator can be identified by a typical echogenic appearance of striation at the cone-shaped tip. The tip of the SGC is marked with a radiopaque echo bright double ring structure and can also be identified by TEE. The insertion of the SGC should be carefully monitored with the aid of 2D and 3D TEE (short-axis, long-axis, and four-chamber views are recommended) and fluoroscopic imaging to avoid injuries of the LA wall. Once the SGC is in place and secured (~2–3 cm within the LA cavity) the wire and the dilator will be removed (Figure 17C).

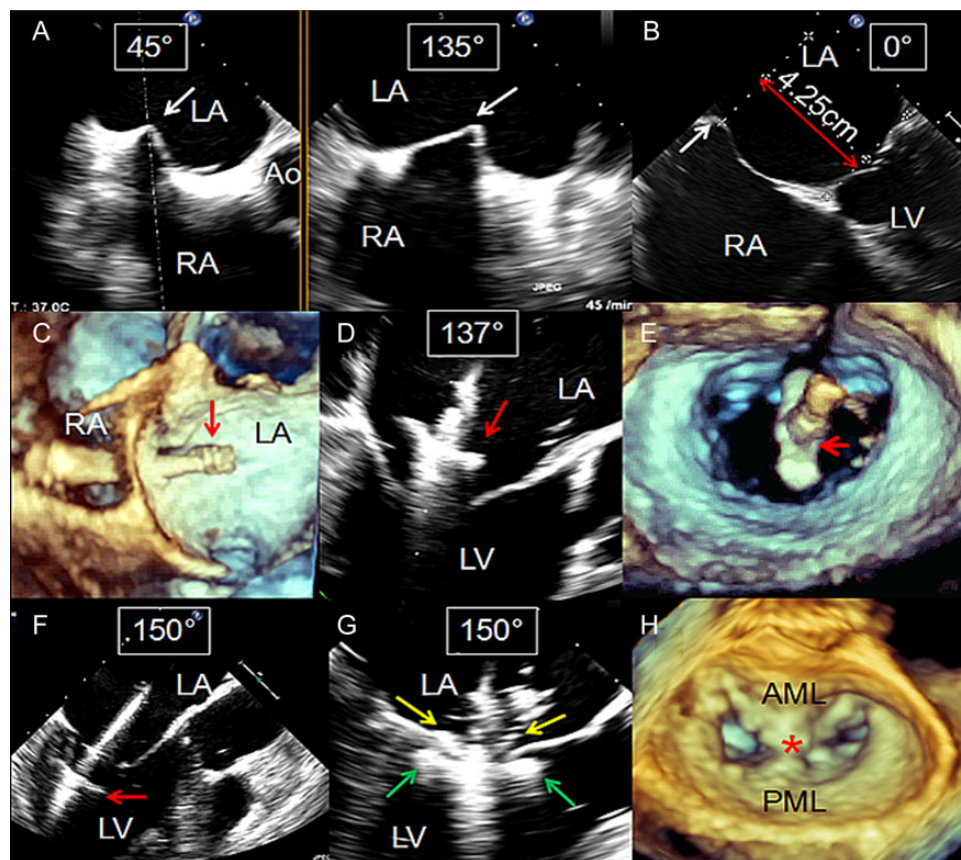


Figure 17 Procedural steps. (A) x-Plane imaging of the interatrial septum is shown. The tip of the transeptal needle is identified by a tent-like doming of the interatrial septum (marked with a white arrow) in a short-axis view (left) and in a long-axis (bicaval) view (right). (B) Height above the MV is measured in a four-chamber 2D TEE view (in this case 4.25 cm above the mitral annulus, which is appropriate). The white arrow marks the 'tenting' in the interatrial septum. (C) Steerable guide catheter (SGC) is positioned in the LA. The tip of the SGC is marked with a red arrow. (D) MitraClip device is positioned above the mitral valve. In this long-axis view both Clip arms can be seen in full length. (E) The correct orientation of the Clip (red arrow) perpendicular to the line of coaptation in an LA 3D enface view. (F) The Clip (red arrow) in the LV in a LVOT view with both leaflets freely moving above the Clip. (G) The grasping of the leaflets is shown. The leaflets can be identified between the Clip arms (green arrows) and the grippers (yellow arrows). (H) The final result is seen in a 3D enface view from the LA. The newly created tissue bridge is marked with a red star. Two orifices can be identified medial and lateral. LA, left atrium; RA, right atrium; LV, left ventricle; LVOT, left ventricular outflow tract; MV, mitral valve; AML, anterior mitral leaflet; PML, posterior mitral leaflet; TEE, transoesophageal echocardiography.

CDS Insertion into the LA

The CDS is then advanced through the SGC under fluoroscopic guidance until the tip of the Clip reaches the tip of the SGC. The CDS is then further advanced into the LA under fluoroscopic and TEE guidance. X-plane views and 3D TEE views are particularly useful to confirm that the Clip is free from the LA wall and valve tissue. 2D TEE short-axis views presenting the complete length of the SGC and 3D TEE views are useful in addition to ensure that the SGC is maintained in the LA.

MitraClip positioning in the LA

To position the CDS with the Clip above the mitral leaflets, the medial deflection and posterior torque of the system are needed. In many cases, the retraction of the whole system is required in addition. A series of steering manoeuvres is generally needed to achieve a central position of the Clip ≥ 1 cm over the MV with respect to

anterior–posterior and medial–lateral directions and to orientate the Clip arms perpendicular to the line of coaptation of the MV. Two orthogonal 2D TEE imaging planes are mainly involved during these steps: a mid-oesophageal intercommissural view ($\sim 60^\circ$) in which both commissures can be adequately identified to perform medial–lateral Clip adjustments and a long-axis view at $\sim 150^\circ$ (LVOT view) to monitor anterior–posterior Clip adjustments. In a correct Clip position no Clip arms are seen in the intercommissural view whereas both Clip arms are visible in full length in the LVOT view (Figure 17D). X-plane imaging facilitates these adjustments considerably by providing both imaging planes (intercommissural and LVOT views) simultaneously. If only 2D TEE imaging is available for procedural guidance, short-axis transgastric views have to be performed to confirm that the Clip arms are perpendicular to the line of coaptation. Gentle movements of the TEE probe are required to avoid gastric lesions. If 3D TEE is available, transgastric imaging

can usually be avoided. A single 3D TEE LA en-face view enables the determination of whether the Clip is positioned centrally above the MV and whether it is orientated perpendicular to the MV coaptation line (Figure 17E). Colour- Doppler should be used in addition to confirm an adequate Clip alignment over the regurgitant jet. The Clip should split the regurgitant jet thus indicating a correct position above the pathology of the MV. The tip of the Clip should point towards the largest PISA. The opening of the Clip and the position of the Clip is also confirmed by fluoroscopy.

MitraClip positioning in the LV

The MitraClip system is then advanced distally across the MV into the LV under fluoroscopic and TEE guidance (most commonly with a fully opened Clip) to a position approximately 2 cm below the MV (Figure 17F). This movement is best observed using x-plane images in which the intercommissural and the LVOT view can be seen simultaneously. As the Clip may rotate during the passage across the MV, 2D TEE (intercommissural and LVOT views) and 3D TEE views are used to reconfirm a correct Clip orientation. Substantial Clip arm orientation adjustment ($>90^\circ$ in each direction) in the LV should be avoided as this may lead to an entanglement of the Clip in subvalvular structures (e.g. chordae tendineae) and may make it difficult or even impossible to remove the Clip. In order to prepare for a successful grasp perpendicular to the line of MV coaptation, correct positioning should be verified by ensuring that both mitral leaflets move freely above the Clip arms and that the Clip splits the MR jet in the intercommissural and LVOT views.

Grasping of the leaflets and verification of adequate leaflet insertion

Once the MitraClip is in a good position, leaflet grasping is done by slowly retracting the system back towards the LA to allow the leaflets to come to rest on the Clip arms. The Clip arm angulation is usually $\sim 120^\circ$ during grasping. If the grasp appears satisfactory, then the grippers are lowered onto the leaflets (Figure 17G). This step is usually monitored by a 2D TEE LVOT view in addition to fluoroscopy. The acquisition of a longer loop is helpful as the grasp can be re-evaluated whenever needed. 3D TEE has no clear advantage during this step of the procedure. Initial closure of the Clip until the Clip arm angle is $\sim 60^\circ$ is recommended. Fluoroscopically, the Clip should maintain a distinct 'V' shape. Echocardiographic imaging using multiple planes is used to verify proper insertion of both leaflets into the Clip. Leaflet immobilization, limited leaflet mobility relative to the tips of the Clip arms, adequate MR reduction, and the occurrence of a double MV orifice in most cases is verified. Adequate insertion of the posterior leaflet is usually best seen in an LVOT view. For assessment of proper anterior leaflet insertion, a four-chamber view can be helpful in addition. Entrapped chordae tendineae may be visible at the free edges of the leaflets in an intercommissural view. 3D TEE is particularly helpful to assess the new geometry of the MV, which presents a double MV orifice in most cases (Figure 17H). A haemodynamic assessment including transvalvular mean Doppler pressure gradients (TMPG) must be performed in addition to using imaging assessment (direct planimetry by 3D) to exclude mitral stenosis. When the Clip position, as well as leaflet insertion and MR reduction without inducing MS, appear satisfactory, the Clip can be fully closed.

Assessment of result before clip deployment

Before a Clip is released, adequate leaflet insertion has to be re-evaluated and the grade of MR and MS has to be assessed. This is usually done by TEE as the probe is still in place at the end of the procedure. To make results comparable regarding MR grading, it is of major importance to perform measurements pre- and post-Clip implantation under similar haemodynamic conditions. The initial evaluation post-procedure is usually performed under general anaesthesia before the Clip is released. At this moment, MR severity may be influenced by the depth and type of anaesthesia and the administration of specific medications (e.g. inotropes, vasopressors, vasodilators) as these may influence pre- and afterload and consequently LA and LV filling patterns. In addition, the ultrasound machine settings (particularly colour scale and gain) should be identical for each evaluation of MR pre- and post-Clipping. The implantation of one or more MitraClips creates a new geometry of the MV with a double MV orifice in most of the cases. It is evident that the evaluation of residual MR needs adjustment after the placement of a MitraClip as quantitative Doppler evaluation cannot be used reliably in these patients. Currently, there are no consensus guidelines or validated studies available on how to best evaluate residual MR after Clip placement. Following the recommendations for the evaluation of native valves^{20,74} a multi-modal approach seems the most suitable and appropriate to characterize and quantify MR adequately in this specific situation.

Table 11 gives an overview of echocardiographic and other additional parameters to evaluate MR after Clip implantation. Findings in case of effective MR reduction as well as advantages and limitations of each modality in MR evaluation post-MitraClip implantation are summarized. In addition, MS has to be evaluated after the placement of each Clip. For this purpose, the diastolic TMPG is usually assessed by continuous-wave (CW) Doppler. It has been demonstrated that TMPG has the same validity in assessing double-orifice mitral valves as a single-orifice MV.⁸² A limitation is that Doppler measurements are highly influenced by heart rate, cardiac output and residual MR.⁸² Nevertheless, Biaggi et al.⁸³ showed that TMPG assessed by CW Doppler is quickly performed, feasible in all patients and superior to direct peri-interventional assessment of mitral valve area (MVA) [including different methods for 3D evaluation using the Qlab software (3DQ and MVQ); Philips]. A post-interventional TMPG of ≥ 5 mmHg best predicted elevated TMPG at discharge.

In addition, planimetry of the MV should be performed, preferably by using 3D echocardiography, which allows for multiplanar reconstruction of the MVA.⁸⁴ Alternatively, 2D planimetry should be performed in mid-diastole in short-axis views (transgastric when TEE is used). The edges of the MV leaflets should be clearly seen. The inner edge of each orifice is then traced and the areas combined to calculate the total MVA. An MVA ≤ 1.5 cm² and a TMPG ≥ 5 mmHg were considered criteria to indicate significant MS in the EVEREST studies.⁸¹ After successful Clip implantation without creating significant MS, it has been demonstrated that patients did not develop clinically relevant MS during 2 years of follow-up. This result was independent of the number of Clips (1 or 2) and the aetiology of MR (primary or secondary).⁸⁵ In addition, it has to be taken into consideration that TMPG during MitraClip implantation measured by TEE underestimates the hemodynamic impact of daily life with exercise, of which operators should be aware when deciding on

Table 11 Multi-modal approach for evaluation of residual mitral regurgitation (MR) post-MitraClip implantation

	Findings in case of effective MR reduction	Advantages	Limitations	Recommended for evaluation
Echocardiographic parameters for evaluation of residual MR post-MitraClip implantation				
Colour jet area (cm ²)	A central colour jet area <10 cm ² and a jet expansion <40% of LA area indicates non-severe MR (larger measurements indicate severe MR) Moderate MR = variable findings A central colour jet area <4 cm ² and a jet expansion <20% of LA area indicates mild MR	Residual MR is easily detected and jet direction can be evaluated Able to exclude MR Small persistent colour jets, even if multiple, are congruent with mild MR	Qualitative The area of colour jets is larger with multiple jets which occurs more commonly after MitraClip implantation than if there is a single jet (this may lead to overestimation of residual MR) ⁴⁹ Artifacts created by the Clip/Clips may alter the findings Depends on gain/scale settings and loading conditions Eccentric jets underestimate MR severity	Yes (be aware of limitations)
Pulmonary vein flow	Relevant MR reduction leads to an elimination of pulmonary vein flow reversal Pulmonary vein systolic flow reversal (if present) should disappear and the 'S' wave should become more pronounced or even dominant	Easy to perform, particularly with TEE Pulmonary vein systolic flow reversal is specific for severe MR Independent of MV morphology	Semi-quantitative Influenced by the presence of atrial fibrillation and elevated LA pressures	Yes (be aware of limitations)
2D Vena contracta (VC) (mm)	<7 mm (8 mm biplane) indicates that MR is not severe (larger measurements indicate severe MR) 3–6.9 mm = moderate MR <3 mm = mild MR	Quick evaluation Independent of jet direction	Semi-quantitative Not validated for multiple jets Differences in DMR vs. FMR due to shape of regurgitant orifice area (ROA) Assuming circular regurgitant orifice area (ROA) Single frame measurement Hemodynamic variations	Yes in case one jet is present (be aware of limitations) Not reliable in presence of multiple jets
2D PISA (proximal isovolumetric surface area) method for effective regurgitant orifice area measurement (EROA) (mm ²)	EROA < 20 mm ² = mild MR; 20–39 mm ² = moderate MR; ≥ 40 mm ² = severe MR	Quantitative	Not validated for multiple jets nor for the newly created MV orifice (1–3 orifices) Dependent on valve morphology	No
Volumetric evaluation of regurgitant volume and fraction (total stroke volume- stroke volume derived from the LVOT) (mL)	Regurgitant volume ≥ 60 mL = severe MR; 30–59 mL = moderate MR; <30 mL = mild MR	Quantitative Independent of valve morphology	Not suitable in case of aortic regurgitation or shunt through a VSD Measurement errors (Annulus measurements, Doppler signal, sample volume placement, foreshortening of the LV when 2D imaging is used)	Yes (be aware of limitations)

Table I | Continued

	Findings in case of effective MR reduction	Advantages	Limitations	Recommended for evaluation
New echocardiographic parameters for evaluation of residual MR post-Clip implantation				
3D vena contracta area (VCA)/Direct delineation of ROA (mm ²)	A 'cut off' of <41 mm ² indicates non-severe MR ⁵⁰ (larger measurements indicate severe MR)	Can be used when the regurgitant orifice has an irregular shape or when multiple orifices are present 3D VCA correlated better with ERO derived from Doppler measurements than 2D VC measurements ²⁰	Low spatial resolution To date no validated reference standards on 3D quantification are available Artifacts may influence measurements	Yes (be aware of limitations)
Additional non-echocardiographic parameters for evaluation of residual MR post-MitraClip implantation				
LA pressure measurement ('V'-wave)	A decrease or even normalization of LA pressures is observed in case of effective MR reduction	Easy to obtain as the system is already placed in the LA	A left-to-right shunt (e.g. ASD) influences the measurement The measurement is also influenced by the compliance of the LA and the pulmonary veins and the systemic resistance Medications that decrease the LV afterload reduce the 'V'-wave	Yes (be aware of limitations)
Stroke volume measurements (via right-heart catheterization (thermodilution) or Picco-catheters)	An increase in stroke volumes can be expected in case of effective MR reduction ⁵¹	Easy to obtain by positioning a catheter in the pulmonary artery	If tricuspid regurgitation is present, stroke volume and cardiac output are overestimated A left-to-right shunt (e.g. ASD) influences the measurements Technical measurement errors may occur	Yes (be aware of limitations)
LV angiography (to assess the amount of regurgitation by judging the density and the expansion of the MR jet in the LA)	Reduction of MR jet density and expansion into the LA	Easy to perform via arterial access (Pigtail catheter in the LV)	Qualitative Need for additional administration of iodide contrast agents (may be problematic in patients with renal insufficiency)	Can be considered when other parameters are doubtful

2D, 2-dimensional; EROA, effective regurgitant orifice area; LA, left atrium; LV, left ventricle; LVOT, left ventricular outflow tract; MR, mitral regurgitation; MV, mitral valve; ROA, regurgitant orifice area; VC, vena contracta; VSD, ventricular septal defect.

implanting one or even multiple Clips.⁸⁵ The final geometry of the MV and the assessment of the final size of the newly created orifices have also to be judged and is best evaluated by using 3D TEE enface views (Figure 17H). It should be ensured that each Clip is placed symmetrically on both leaflets and that the Clip is not biased towards one of the leaflets. Excessive distortion of the leaflets should be avoided as this may lead to unbalanced traction on the leaflets which can potentially cause partial Clip detachment or leaflet rupture during follow-up.

Clip release

In case of a satisfactory Clip position and effective MR reduction, the Clip is detached from the catheter shaft. A stable Clip position has to be reconfirmed and the grade of residual MR should be reassessed as minor changes can occur when the tension transferred via the CDS disappears. The final Clip deployment is then performed by removing the gripper line.

Detection of complications

Percutaneous MV repair using a MitraClip is a safe procedure with good haemodynamic tolerance even in high-risk patients and is associated with only a few major complications.^{65,69} However, serious complications may occur and can be identified accurately and quickly by echocardiography during the procedure. Acute severe hypotension may be caused by cardiac tamponade, acute aggravation of LV dysfunction, or sudden worsening of MR. Pericardial effusion and cardiac tamponade may occur due to a perforation of the atrial free wall during TS puncture. TEE may promptly identify this complication and pericardiocentesis can be performed under echocardiographic guidance. Different mechanisms may lead to MR aggravation: e.g. acute worsening of LV dysfunction or leaflet or chordal tears due to entrapment of chordae tendineae by the Clip. Depending on the underlying cause, acute MR may require emergency circulatory support (intra-aortic balloon counter pulsation) and/or bail-out MV surgery. Other Clip-related complications are rare (<5%). A partial Clip detachment may occur as a consequence of inappropriate leaflet insertion. A complete Clip detachment and embolization is a very rare event. An accurate intra-procedural TEE evaluation of leaflet insertion (including 3D-volume TEE multi-plane reconstruction) may prevent this complication. The creation of MS is also uncommon and may be prevented by a careful assessment of the MVA and TMPG after implantation of each Clip. A TMPG < 5 mmHg and an MVA > 2.5 cm² are generally well tolerated.⁸⁶ Persistent ASD flow at the septal puncture site is frequent after a MitraClip procedure and does not represent a true complication. Persistent ASDs occur at a rate which is comparable with reports after other transseptal interventional procedures and generally do not appear to be haemodynamically significant.⁸⁷

Echocardiographic outpatient follow-up

TTE is generally sufficient for follow-up examination as it permits an adequate evaluation of residual MR and possible LV remodelling and/or improvement of LV function.⁸⁸ An additional TEE is indicated in cases in which further information is needed. There is no consensus on how to assess residual MR after MitraClip implantation as the presence of more than one orifice complicates this evaluation

(Figure 18). As with native valve regurgitation, an integrated approach is essential for the assessment of residual MR severity.⁷² TTE should assess the presence, number, location, and extension of regurgitant jets. Although small MR jets generally correspond to mild MR, semi-quantitative assessment based on regurgitant jet dimensions is limited by factors affecting the size of the regurgitant area. Quantitative commonly used 2D parameters such as vena contracta and EROA by the PISA method have not been validated for post-procedural double-orifice MV morphology.⁸⁹ Semi-quantitative techniques based on Doppler volumetric methods are theoretically applicable even in case of multiple jets. In the absence of aortic regurgitation, RV may be obtained by subtracting LVOT systolic outflow from 2D TTE or 3D TTE (preferable) measured total stroke volume. 2D and 3D TEE may add significant information where residual MR appears to be more than mild. A promising new approach for the evaluation of MR severity is the assessment of MR regurgitant volume by colour Doppler 3D TEE as the product of vena contracta areas defined by direct planimetry of each orifice and velocity time integral using CW Doppler.⁸⁹

MS is a rare event following MitraClip therapy. However, assessment of MVA and MV gradients should be performed systematically during TTE follow-up examination. MVA can be assessed with 2D TTE by measuring the planimetry of each orifice. The pressure half time method is not validated.

Assessment of reverse LV remodelling

2D and 3D TTE assessment of LV volumes should be performed during follow-up to assess positive LV reshaping effects and improvements in LV size and function after MV edge-to-edge repair.⁸⁸

Chordal implantation

Percutaneous leaflet repair may be obtained using adjustable chordal implantation systems. Several devices are currently under development. The NeoChord (NeoChord Inc., MN, USA) uses a mini-thoracotomy transapical approach for leaflet capture, guided by four fibre-optic channels with corresponding indicator lights on the device monitor. Using 3D TEE guidance, the expanded polytetrafluorethylene (ePTFE) chords attached to the leaflets are subsequently adjusted to optimize MR reduction, then tightened to the LV myocardium and fixed to the apex.

Degenerative MR due to middle scallop prolapse of the posterior leaflet is the ideal lesion for correction with this system. A prolapsing segment over-riding the opposite leaflet by at least 9 mm suggests coaptation leaflet reserve and correlates with a successful outcome of the procedure. After a preliminary animal study, a clinical trial (TACT trial) on 30 selected patients showed good results regarding safety, and a high rate (75%) of efficacious MR reduction at 12-month follow-up when multiple chordae were implanted.⁹⁰ An ongoing prospective multicentre European registry (TACT registry), already including 120 patients undergoing multiple chordal implantation (4–5 chordae), reports good results (efficacy rate 80–100%) (Giovanni Speziali, personal communication). Real-time 3D TEE is crucial to identify the prolapsing target segments and to guide chordal insertion and length adjustment in order to correct MR.

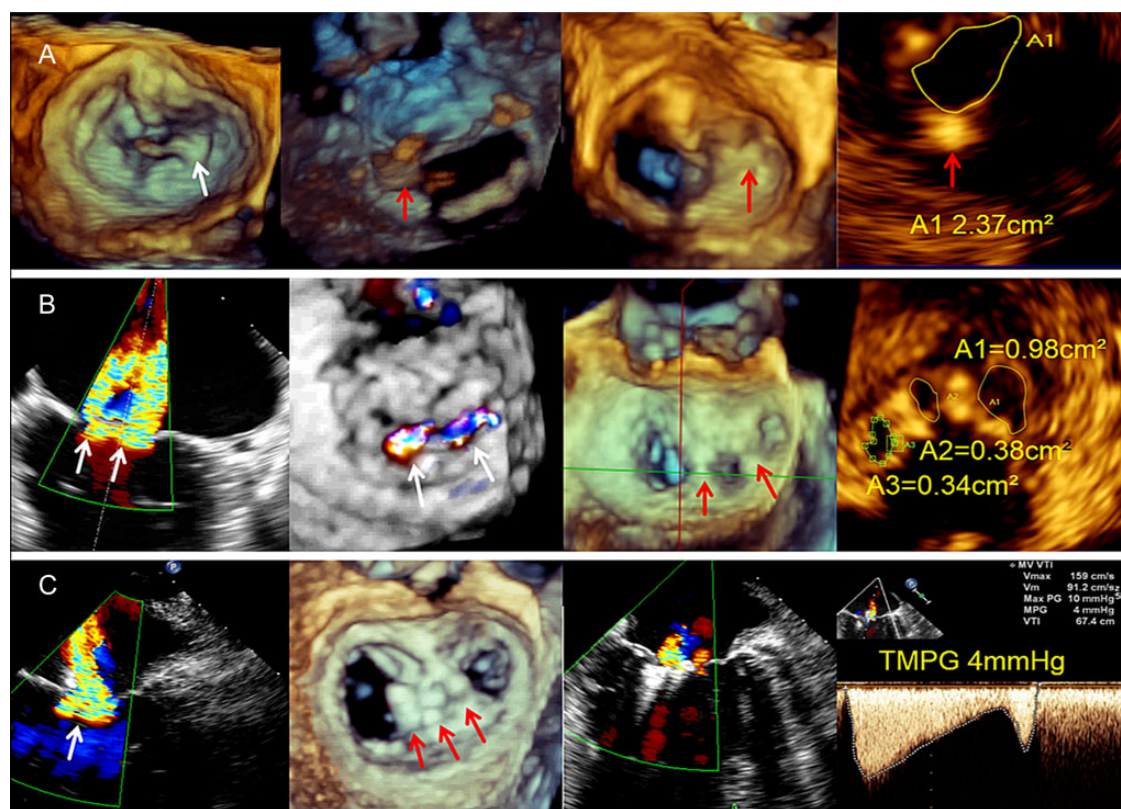


Figure 18 Specific case examples. (A) A case with a P3 prolapse is shown. The pathology can be identified in a 3D LA enface view in the first image on the left side (the prolapse is marked with a white arrow). The second image on the left shows the Clip (red arrow) in medial position from the LV side in a 3D view. The third image shows the newly created geometry of the MV with a single lateral orifice from the LA side. The tissue bridge in the medial part of the MV is marked with a red arrow. 3D planimetry (Qlab software, Philips) of the single orifice is seen in the image on the right side. The position of the Clip is marked with a red arrow. (B) A case with two large jets medial and lateral in the central segment is shown. The image on the left shows an intercommissural view at 60°. The two jets are marked with white arrows. In the second image on the left an LA aspect of the MV is seen in a 3D enface view with colour Doppler. The origin of the two jets is marked with white arrows. The third image shows the result after placement of two Clips in the target regions in a 3D LA enface view. This resulted in a triple orifice MV. In the image on the right-side planimetry of the three orifices is demonstrated (Qlab software; Philips). The total MVA is 1.7 cm² in this case. The mean TMPG was 5 mmHg (not shown) which was borderline, but acceptable. (C) A case with functional MR is demonstrated. A broad jet in the central part of the MV can be seen in an intercommissural 2D TEE view in the first image on the left side. The Vena contracta width was 12 mm in this case (not shown). After placement of three Clips in the central part of the MV which can be seen in the second image on the left side (3D LA enface view; each red arrow marks the position of one Clip), residual MR was considered to be mild as shown in the third image from the left in an intercommissural 2D TEE view at 65°. The TMPG after positioning of the third Clip was acceptable (4 mmHg) as shown in the image on the right side. LA, left atrium; LV, left ventricle; MV, mitral valve; MR, mitral regurgitation; 2-/3D, two-/three-dimensional; TMPG, transvalvular mean pressure gradient; MVA, mitral valve area.

Leaflet space occupier

The Percu-Pro system consists of a Mitra-Spacer balloon acting as a 'buoy' to fill the mitral regurgitant orifice. The system is anchored to the LV apex.

Ventricular remodelling

Devices based on the concept of ventricular remodelling have been designed in recognition of the fact that abnormal ventricular geometry with displacement of the papillary muscles is an important element in the pathogenesis of functional MR. The iCoapsys system (Edwards, Irvine, CA, USA) is based on the surgical subxiphoid placement of two epicardial pads (anterior and posterior) that are connected by flexible suture-like chordae. Subsequent chord shortening attempts to reverse LV remodelling and reduce related MR.

The RESTOR-MV trial showed significant sustained LV remodelling and MR reduction, together with improved survival compared with mitral annuloplasty.⁹¹ The BACE device (Basal Annuloplasty of the Cardia Externally, Mardil INC., Morrisville, North Carolina) consists of a circular silicone band with inflatable chamber, which is implanted around the atrioventricular groove on a beating heart via mini-thoracotomy and subsequently inflated by saline adjusting the LV volume to attempt mitral valve remodelling (Figure 18).⁹²

LAA closure

AF is associated with an increased risk of embolic stroke that mainly results from thrombus formation in the LAA.⁹³ The risk of stroke is markedly reduced by oral anticoagulation, although this treatment is

Table 12 Indications and contraindications for LAA closure

Indications	Contraindications
1. When anticoagulation is not possible: Patients with high thromboembolic risk (CHA ₂ DS ₂ VASc score ≥ 2) but contraindication to systemic anticoagulation.	Valvular AF Visible left atrial thrombus Estimated life expectancy <12 months
2. When oral anticoagulation is possible: Patients in whom OAC or NOAC are considered to pose an unacceptable bleeding risk (HASBLED ≥ 3), but with high stroke risk (CHA ₂ DS ₂ VASc score ≥ 2), should be considered for LAA occlusion.	
3. As a complement to anticoagulation Could be an option for patients with embolic events despite adequate antithrombotic therapy, provided there are no other plausible causes.	

complicated by risk of bleeding, drug interactions, administration logistics, and patient compliance.⁹⁴ LAA closure provides another therapeutic approach, and recently, new devices have enabled treatment through a percutaneous approach.^{93–95} However, despite 90% of LA thrombi being found in the LAA,⁹⁶ the presence of hypercoagulability⁹⁷ or aortic plaques in patients with AF also represent potential sources of embolism,^{95,98} and about one third of cerebral emboli in patients with AF might originate from sites other than the heart.⁹⁹ However, evolving data indicate that significant stroke prevention may be accomplished by LAA closure and the European guidelines for the management of AF, currently recommend that percutaneous LAA closure may be considered in patients with a 'high risk of stroke and contraindications for long-term oral anticoagulation' (Table 12).^{93,100} This technique also has potential importance in particular settings of patients such as those with chronic renal insufficiency where the use of anticoagulant drugs is difficult.

Percutaneous therapies and current experience

Patient candidates for device therapy may be identified by risk scores for ischaemic stroke and for bleeding complications of anticoagulation.⁹³ Of note, risk factors such as hypertension, previous stroke, and age >65 years are common for both risk scores. Thus, patients at greatest risk for stroke may also be at highest risk for complications of anticoagulation, and might therefore benefit from LAA closure.⁹³ Several devices for LAA closure have been evaluated and all are introduced by femoral vein access, with subsequent transseptal delivery and deployment in the LAA.

The *WATCHMAN* device (Atritech, Plymouth, MN, USA) consists of a self-expanding nitinol cage with fixation barbs and a permeable polyester fabric covering its face towards the left atrium. PROTECT-AF was a randomized non-inferiority study evaluating

the *WATCHMAN* device's efficacy in preventing embolism with chronic warfarin therapy as the comparator.¹⁰¹ The study results from a subsequent non-randomized registry showed a significant decline in adverse events with increased operator experience,¹⁰² and data from the randomized study (PREVAIL)⁹³ demonstrated successful implantation in 95% of patients, with major adverse events in 2.2%. Four-year follow-up in PROTECT-AF demonstrated a 40% relative risk reduction with 96% probability of superiority.⁹³ This device treatment might provide an alternative to chronic anticoagulation, taking into account the evolving safety results added to the randomized and long-term clinical data.

The *Amplatzer Cardiac Plug* (ACP) (St Jude Medical, MN, USA) is a double disc device with a self-expanding nitinol mesh containing polyester patches.¹⁰³ The distal lobe is anchored to the inner wall of the LAA by stabilizing wires and is connected by a central waist to the proximal disc which seals the orifice of the appendage. Randomized data on procedural safety and efficacy of this device are not yet available, though different series of treated patients have demonstrated a successful implantation rate of 95 to 99%.¹⁰⁴ The rate of major adverse events was 7% in the first of these series, while lower event rates were observed in the subsequent ones. Another treatment system, by means of the *LARIAT* device (SentreHEART Inc., Palo Alto, CA, USA) for suture ligation of the LAA, employs a more complex procedure requiring a combined endocardial and pericardial approach.¹⁰⁵

In summary, percutaneous closure of the LAA may be considered as an effective and acceptably safe alternative to drug prevention of stroke, particularly in patients at high risk for major bleeding complications during chronic anticoagulation.^{93,100,106} However, LAA closure as an alternative to anticoagulation, when anticoagulation is not an option, is the only indication currently based on randomized data and was recently approved by the FDA panel.¹⁰⁶ The latest European consensus document states that when patients are eligible for anticoagulation without increased risk for bleeding, the option of LAA occlusion should be mentioned to the patient while oral anticoagulation currently remains the standard of therapy.¹⁰⁶

Assessment of functional anatomy of LAA

The LAA is a multifaceted tubular hooked structure, lined with trabeculations on the inner surface. The volume of the LAA varies widely from 0.7 to 19.2 mL; the orifice size can have a diameter from 5 to 40 mm. The length of the LAA can vary from 16 to 51 mm. Of note, cases with prior electrocardiographic evidence of AF have been reported to have larger LAA, with more orifices and fewer branches than those without AF. This was also seen in TEE studies of LAA function.^{107,108}

The evaluation of thrombus in the LAA is accurately performed with TEE.¹⁰⁹ LAA thrombus is most often correlated with enlarged LAA size/LAA area, reduced or absent LAA inflow and outflow velocities, and low LAA ejection fraction.¹¹⁰ Large thrombi (>1.5 cm) and those that are pedunculated or mobile are at higher risk of embolism.¹¹¹ The shape of the LAA may be relevant depending on the device chosen. The LAA can have various morphologies, which have been described in terms of a variety of shapes: cactus, chicken-wing, windsock, and cauliflower.¹¹² There are mixed results on the association between LAA shape and risk of stroke. The

chicken-wing shape has been reported to have an increased¹¹³ or decreased¹¹⁴ risk of stroke and a cauliflower LAA can be an independent risk predictor.¹¹⁵ These shapes are important for sheath positioning in the case of endocardial devices; these can be prohibitive for epicardial devices.

The LAA closure procedure is intimately tied to the functional anatomy of the left atrial appendage. Pre-procedural imaging for LAA closure must fulfil certain criteria. This is dependent on the device used, but in general terms, this includes the ability to rule out thrombus, describe the ostium, landing zone, and number and location of lobes as well as relation of important structures. For epicardial devices, it is important to track the approach to the LAA as well as the relationship to the pulmonary artery.

Transoesophageal echocardiography in patient selection

Imaging is necessary for patient selection prior to LAA closure. All LAA should be free of thrombus before closure. The number of lobes is important to understand the position of the device as well as to make sure all lobes are covered (Figure 19). A measurement of the ostium, landing zone, and length should be performed in multiple views, at least 0°, 45°, 90°, and 135° views (Figures 20 and 21). The landing zone is measured as the distance of the LAA at the level of the left circumflex coronary artery to roughly 2 cm away from the edge of the pulmonary ridge. The 135° view often requires extreme flexion of the probe. In general practice, the largest ostium or landing zone measurement should be recorded and used for sizing. The landing zone and

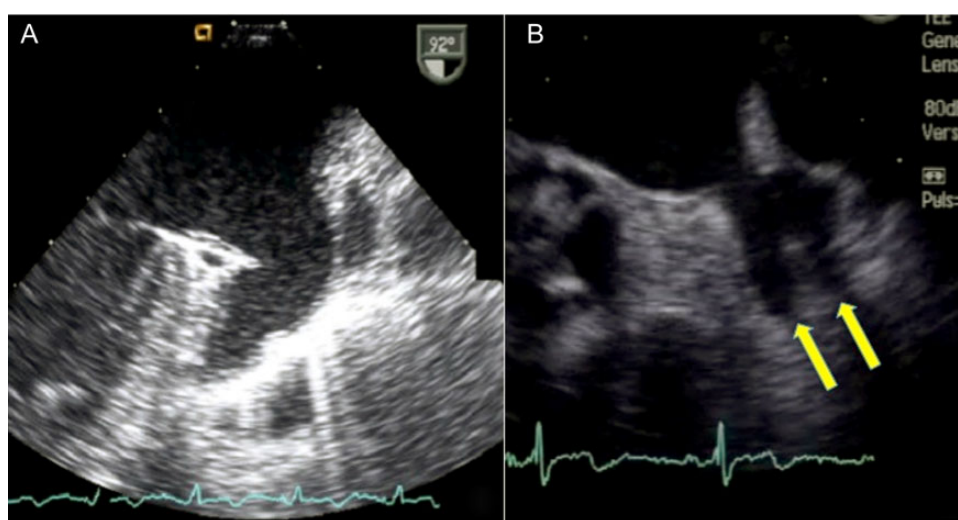


Figure 19 Two views of the left atrial appendage. (A) The appendage has one lobe; (B) we see the appendage with two lobes.

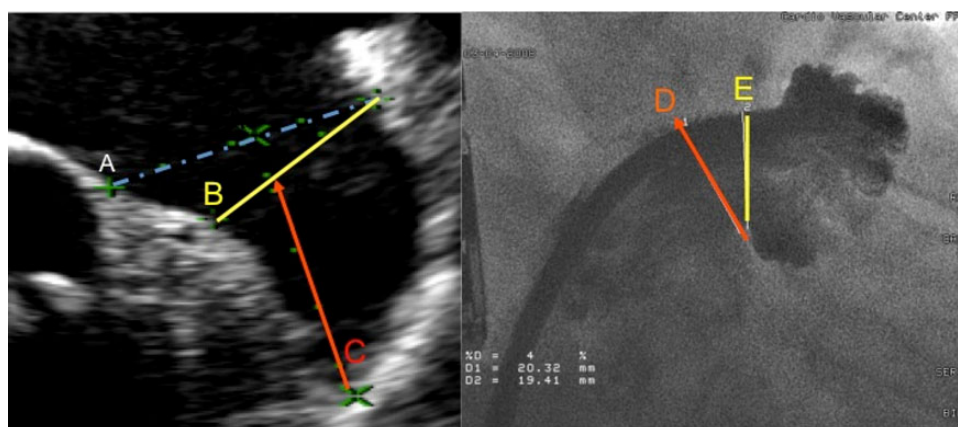


Figure 20 On the left-hand-side echocardiographic view, we see the ostium (A), landing zone (B), and length (C). The landing zone extends from the left circumflex artery to the other side of the LAA with 1 cm below the start of the pulmonary ridge. On the right-hand-side angiographic view, we see the ostium (D) and landing zone (E).

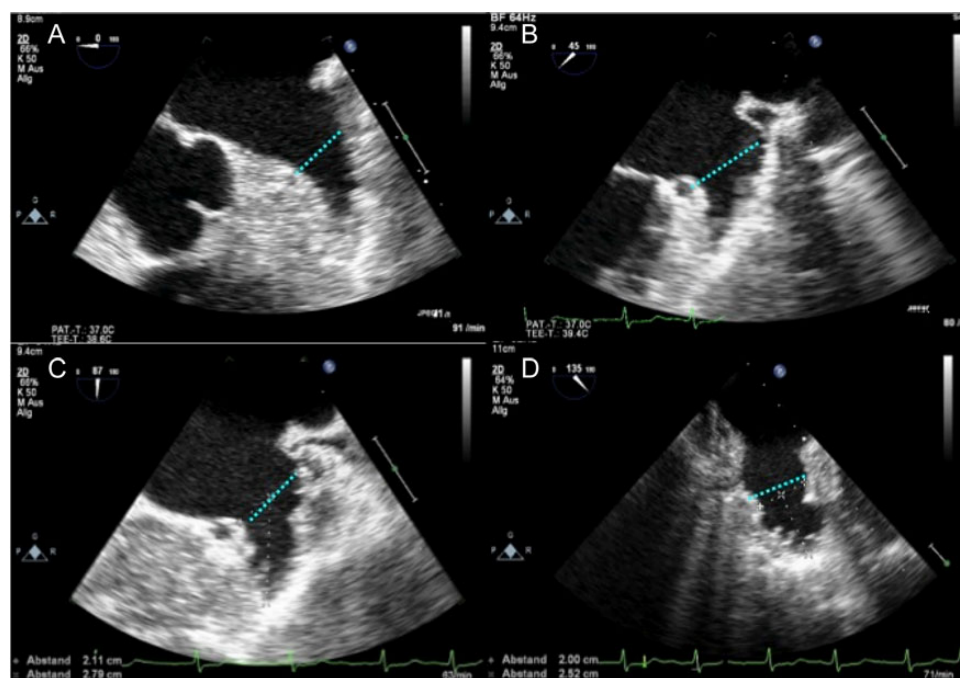


Figure 21 There are four views of the left atrial appendage 0° (A), 45° (B), 90° (C), and 135° (D). The landing zone is marked in each with the dashed line.

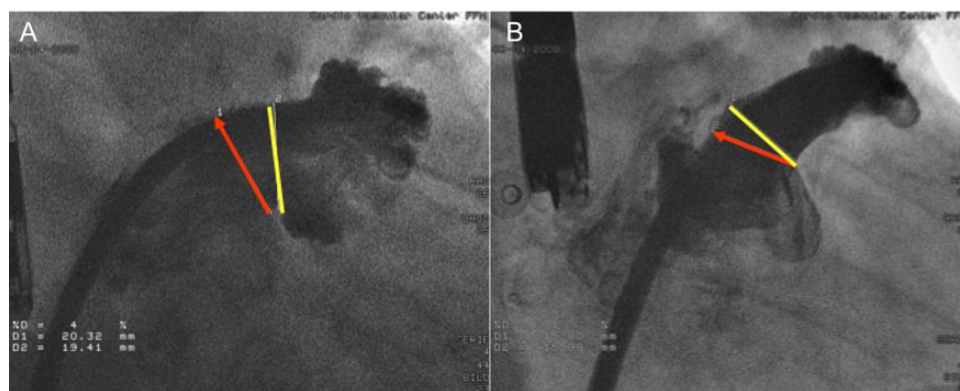


Figure 22 Here are two angiographic views of the left atrial appendage. (A) The RAO caudal view, we see the ostium (arrow) and landing zone (straight line), with the landing zone measuring 19.4 mm. (B) The RAO cranial view, we see the ostium (arrow) and landing zone (straight line), with the landing zone measuring 16 mm.

ostium correspond to views seen on angiography (Figure 22). The use of 3D echocardiography adds 3D measurements of the ostium and is useful in ruling out thrombus.¹¹⁶

MSCT can also be used for pre-procedural imaging. It can be helpful in detecting thrombus,^{117–119} with sensitivity from 93 to 100% and specificity from 85 to 92%, and shows the relation between the LAA and important structures, such as the left superior pulmonary vein, left aortic sinus, and the pulmonary artery. This is especially important for epicardial devices, e.g. LARIAT. In addition, MSCT

clearly shows the shape of the LAA and the number of lobes. However, there are significant barriers to its use, including contrast, need for an additional patient visit, cost and the need to time correctly for good opacification in patients with AF.

Procedural monitoring and assessment of results

Transoesophageal echocardiography is the imaging modality of choice for procedural monitoring. At the beginning of the

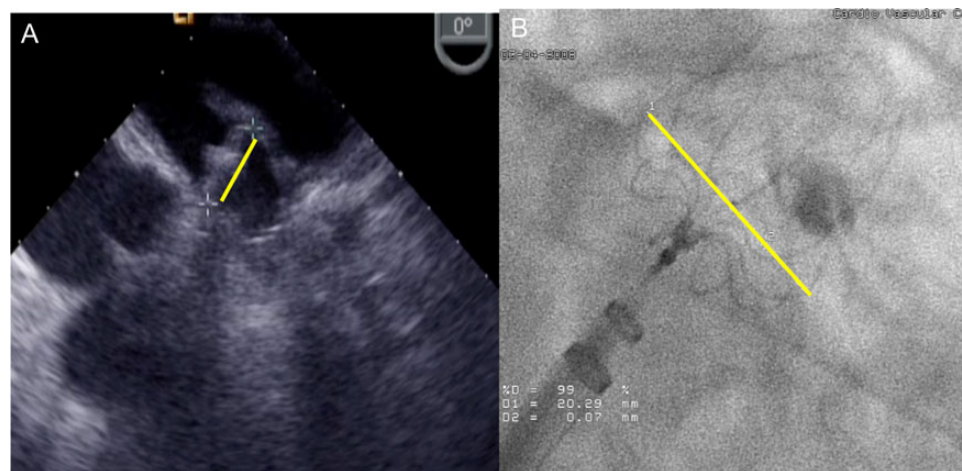


Figure 23 Compression test. For some devices, compression measurement is important. This 24 mm Watchman device is measured on echocardiography as 19.3 mm and angiography as 20.3 mm. This is between the recommended 80–94% compression.

procedure, it is important to re-measure the ostium, landing zone, and length of the LAA, as well as the number of lobes. These may change compared with earlier measurements based on loading conditions. In addition, it is important to assess for baseline pericardial effusion as well as to evaluate for other potential sources of cardiac emboli.

Transseptal access is necessary for access from the right atrium to the LAA. Although some operators use a patent foramen ovale for access,¹²⁰ the vast majority of operators use an inferior and posterior access point for easier access to the LAA. This is obtained using a long-axis 110° view of the septum (for superior/inferior positioning) and short-axis 30° view of the septum (for anterior/posterior positioning). The biplane view is helpful in this regard. After transseptal access, the echocardiogram can be used to monitor the placement of the wire, pigtail, or sheath into the LAA. During device delivery, it is important to confirm that the endocardial device is well seated inside the LAA. The exact ideal implant depth is device-specific. If the device is not in an adequate position, then it can be recaptured and redeployed. In addition, there should be an evaluation of the device stability with a pull test under echocardiography, as well as evaluation for peri-device leak. Leak evaluation requires interrogation in multiple views (at least 0°, 45°, 90°, and 135° views) with low Nyquist limit (<40 cm/s). Correct device placement for an endocardial device usually requires fulfilment of multiple criteria, which include correct depth, device compression, stability under tug test, and absent or minimal leak. An example of device compression is seen in Figure 23. For an epicardial device, the leak evaluation is most relevant; unlike endocardial devices where the leaks are more often peri-device and at the border of the LAA, epicardial device leaks are more likely central in nature.

There are multiple potential complications of LAA closure that can be monitored by TEE. Procedure-related stroke may occur, with a 0.9% rate in one major trial.¹⁰² TEE can potentially see air emboli or missed cardiac embolus. Pericardial effusion occurs at a rate of 4.3% across studies,¹²¹ with pericardial tamponade requiring

pericardiocentesis at a lower rate of 3.4% (down to 2.2% with experience).¹⁰² For this reason, baseline TEE evaluation of pericardial fluid is important, and this should be periodically monitored during the case and checked immediately in case of blood pressure drop. Device embolization can occur, with a reported rate of 0.6%.¹⁰² The device may stay within the left atrium, move to the left ventricle, be caught in the LV outflow tract, or move to the aorta. TEE should be performed to locate the device, evaluate for cardiac or valvular injury, and guide for percutaneous device retrieval, when clinically indicated. In case of devices with a large disc, harmful interaction with the left upper pulmonary vein and the mitral valve should also be evaluated prior to release.

Complications can occur during the procedure and during the immediate post-procedural period. It is important that emergency TTE is available during this time period. A TTE should be performed at 24 h to rule out device migration or embolization, which may be asymptomatic.

Echocardiographic outpatient follow-up

The outpatient follow-up after LAA closure should be performed regularly. According to a large trial¹²² with the Watchman device, the TEE follow-up is performed at 45 days, with the decision to remove warfarin dependent on absent or minimal leak and no thrombus on the device. Afterwards, the TEE follow-up was performed at 6 and 12 months, with additional TEE at the discretion of the physician. Another strategy is to perform TEE at 1 month and again at 6 months. This can vary, but TEE is important to evaluate device stability and leak, with the latter not well seen by TTE. A leak seen on follow-up TEE is seen in Figure 24.

During the TEE follow-up, it is important to evaluate device position, presence of leak (in multiple views), presence of thrombus on the device, and effusion if present. For epicardial devices, the follow-up consists of evaluation of leak and effusion if present.

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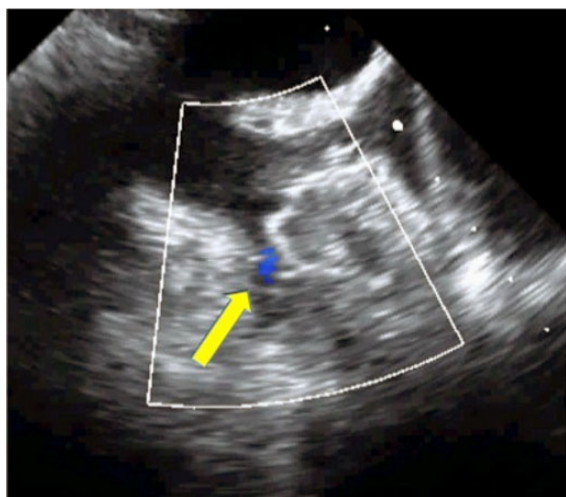


Figure 24 Residual leak. The residual leak around the left atrial appendage device is shown. For better sensitivity views, turn down the Nyquist limit to 30 cm/s.

served as speaker for Abbott; M.M. served as speaker for Philips and Edwards Lifesciences, and received research support from Philips and St Jude Medical; L.D.G. reported Core Lab contracts with Edwards Lifesciences and Medtronic, and served as consultant for Edwards Lifesciences.

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