Transcatheter interventions for structural heart disease

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Chapter 1

Introduction
Optimal Imaging for Planning and Guiding Interventions in Structural Heart Disease - A Multi-Imaging Modality Approach

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ABSTRACT

Recent advances in catheter-based interventions have provided effective alternative treatments to surgery for several structural heart diseases such as atrial or ventricular septal defects. Particularly, the advent of transcatheter valve implantation/repair techniques constitutes one of the main breakthroughs of the last decades offering an effective alternative to patients with symptomatic valvular heart disease and high mortality operative risk. In addition, the role of novel catheter-based interventions has been explored in several clinical conditions that convey an increased risk of cerebrovascular stroke such as patent foramen ovale or atrial fibrillation. Specific devices have been developed to treat all these clinical conditions. To improve the procedural success rate and minimize the frequency of complications, multimodality cardiac imaging plays a central role providing an accurate selection of patients and invaluable assistance during the procedure. Technological advances in the equipments and image post-processing softwares have provided improved accuracy of the image quality and analysis leading to an increasing implementation of these imaging techniques in the clinical practice. The present state-of-the art article reviews the role of multimodality imaging for planning and guiding interventions in structural heart disease.

Keywords: Multimodality cardiac imaging; Cardiac interventions; Structural heart disease

Abbreviations:

2D = Two-dimensional
3D = Three-dimensional
ASD = Atrial septal defect
MDCT = Multi-detector row computed tomography
MRI = Magnetic resonance imaging
TAVI = Transcatheter aortic valve implantation
TEE = Transesophageal echocardiography
TTE = Transthoracic echocardiography
VSD = Ventricular septal defect

INTRODUCTION

Recent advances in catheter-based intervention procedures have provided effective therapeutic alternatives to surgery for selected patients with structural heart disease. A large body of evidence has demonstrated that, for example, percutaneous device closure is an effective and safe treatment of hemodynamically significant atrial septal defects (ASD).[1] In addition, although technically more challenging than ASD closure, percutaneous device closure of ventricular septal defects (VSD) has been shown to have comparable results to surgery in several multicenter registries.[2] Finally, transcatheter valve implantation procedures have been one of the main therapeutic breakthroughs of the last decade and the feasibility of this treatment alternative has been demonstrated in recent experiences including over 8000 symptomatic, severe aortic stenosis patients with high operative risk.[3]

In order to achieve the highest procedural success rate with the lowest complication rate, accurate patient selection and guidance of interventions are crucial. Cardiac multimodality imaging plays a pivotal role providing an accurate selection of patients and invaluable assistance during the procedure. Two-dimensional (2D) echocardiography is the most widely used imaging technique in the pre-procedural patient evaluation. However, 3-dimensional (3D) imaging modalities (3D echocardiography, multi-detector row computed tomography [MDCT] or cardiac magnetic resonance imaging [MRI]) provide detailed information on the dimensions and spatial relationships of the cardiac structures that are crucial to anticipate the device size and the procedural approach. During the intervention, fluoroscopy remains the mainstay imaging tool to guide the procedures in spite of lacking spatial information. However, sophisticated technological developments in other imaging modalities have enabled the performance of the interventional procedures while minimizing the need for fluoroscopic control with better spatial information.

The current article reviews the role of multi-modality imaging for planning and guiding interventions in the most common structural heart diseases: aortic and mitral valvular disease, ASD and VSD. In addition, novel catheter-based interventions developed to treat cardiac conditions related with high risk of stroke (patent foramen ovale and atrial fibrillation) will be discussed.

Transcatheter aortic valve implantation

Degenerative aortic stenosis is the most common valvular heart disease in the western countries.[4] Aortic valve replacement is the only effective treatment for symptomatic, severe aortic stenosis. However, the operative risk of some patients

outweighs the benefits of aortic valve replacement and, consequently, these patients are denied for surgery. [4] The advent of transcatheter aortic valve implantation (TAVI) procedures in the last years has provided an alternative therapy for high risk patients with symptomatic severe aortic stenosis. Since the first-in-man experience in 2002, over 8000 high risk patients have been treated with TAVI.[3, 5] Currently, TAVI procedures are performed through transarterial retrograde approach (transfemoral or transsubclavian) or transapical approach. Two types of catheter-delivered prosthesis are available. The first one is the balloon-expandable Sapien Edwards prosthesis (Edwards Lifesciences Inc.,). This prosthesis is currently available in two sizes: 23-mm for aortic valve annular diameters between 18-22 mm and 26-mm for aortic valve annular diameters between 21-25 mm. These prostheses require delivery system sizes of 22-F and 24-F, respectively, for retrograde approach, and 26-F size for transapical approach. The other catheter-delivered prosthesis is the self-expandable CoreValve Revalving system (CoreValve Inc., Irvine, CA). The currently available sizes are 26-mm for aortic valve annular diameters between 20-24 mm and 29-mm for aortic valve annular diameters between 24-27 mm. The delivery systems have reduced the size and currently a 18-F sheath is used through retrograde approach.

Several single-center non-controlled studies and registries have reported short- and mid-term survival rates of TAVI that are comparable to surgical aortic valve replacement.[6-9] However, the technical challenges of this novel therapy require accurate pre-procedural patient selection and exact procedural guiding. In summary, the assessment of the procedural feasibility and exclusion of contraindications for TAVI are key issues to be assessed. Accurate sizing of the aortic valve annulus and evaluation of the peripheral arteries and thoracic aorta are crucial pre-procedural screening steps to select the prosthesis size and the procedural approach (transfemoral or transapical).

Two-dimensional transthoracic echocardiography (TTE) is the most used imaging technique to size the aortic valve annulus. However, 2D TTE may significantly underestimate the aortic valve annular size as compared to 2D transesophageal echocardiography (TEE) leading to inaccurate selection of the prosthesis size and subsequent procedural-related complications such as paravalvular regurgitation or prosthesis migration.[10] As shown by Smid et al.,[11] 3D imaging techniques may provide the most accurate measurements of the aortic valve annulus. Particularly, MDCT and MRI yield accurate 3D visualization of the aortic valve annulus, showing the characteristic oval shape of this structure (Figure 1).[11] Using as a reference perioperative measurements of the aortic valve annulus, MDCT and MRI measurements yielded smaller biases (-1.5 ± 3.5 mm and 0.7 ± 4.2 mm, respectively) than 2D TTE

or TEE (-4.5 ± 1.1 mm and -5.5 ± 2.0 mm, respectively).[11] In addition, extent and location of the aortic valve calcifications, the dimensions of the other components of the aortic root (sinus of Valsalva, sino-tubular junction and ascending aorta) and their spatial relationship with the surrounding structures such as coronary arteries can be evaluated.[12] Two-dimensional TTE or TEE provide reliable information on the valve anatomy, calcification extent and dimensions of the aortic root. However, the assessment of the relative height of the coronary ostia to the aortic valve annular plane is not feasible with these 2D imaging modalities. MDCT may provide the most comprehensive 3D evaluation the aortic root and surrounding structures of patients undergoing TAVI.[12] Particularly, the height of the coronary ostia relative the aortic valve annular plane and the risk of coronary ostium occlusion by a bulky calcified aortic leaflet during prosthesis implantation may be evaluated (Figure 2).

Figure 1. Aortic valve annulus sizing with MDCT. Multiplanar reformatting planes across the aortic valve annular plane provide the most accurate assessment of the dimensions of the aortic valve annulus. Aortic valve annular diameters can be measured at two orthogonal views (sagittal, panel A, and coronal, panel B) or at the double oblique transverse view (panel C) demonstrating the oval shape of this anatomic structure.

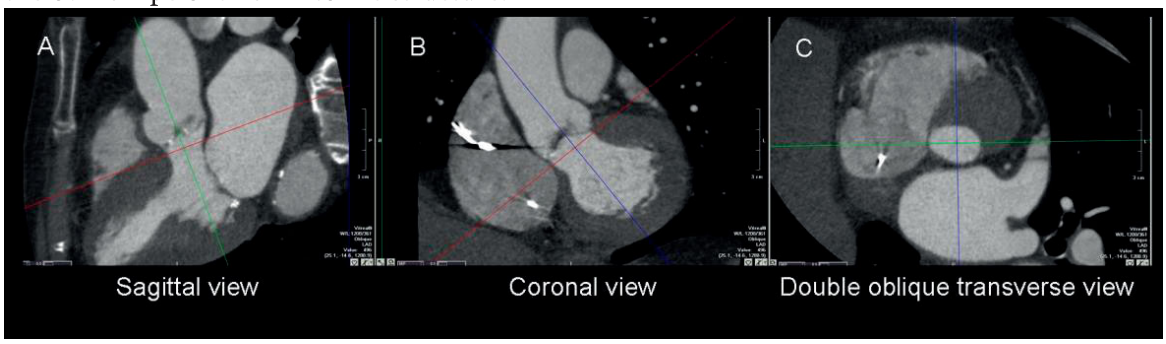
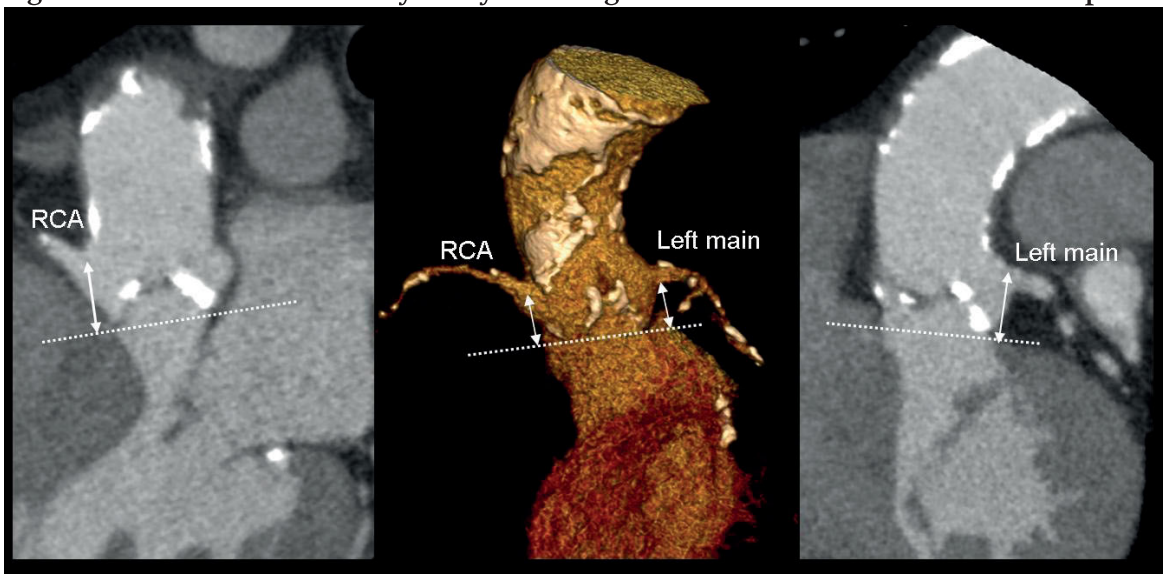


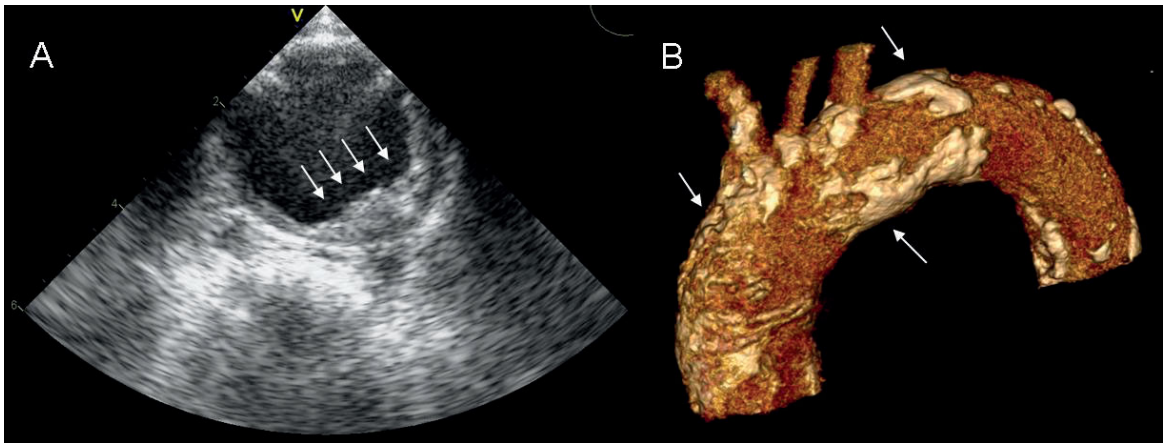
Figure 2. Assessment of coronary artery ostia height relative to the aortic valve annular plane.



Abbreviations: RCA = right coronary artery

Finally, the evaluation of the dimensions, tortuosity and calcifications of the peripheral arteries and aorta provides important information to anticipate the procedural approach (transfemoral or transapical). Invasive angiography is considered the reference method to measure the luminal diameter and the tortuosity of the peripheral arteries.[13] However, the poor soft-tissue contrast resolution of the fluoroscopy limits its accuracy to evaluate the arterial wall and, consequently, calcified, mobile plaques or mural thrombosis may be misdiagnosed with increased risk of stroke during manipulation of catheter-delivering systems inside the aorta. MDCT, MRI and TEE yield invaluable information in this regard and may assist to select the transapical approach rather than the transfemoral approach (Figure 3).[13] (PERHAPS SOME METION TO THE TORTUOSITY AND DIFFERENT ANGULATIONS OF THE VESSELS EXTENDING FROM THE GROIN TO THE AORTIC BIFURCATION WHICH CANNOT BE DEPICTED WELL IN FLUORSCOPY BY CAN BE DEFINED BY CTA OR MRI, SHOULD BE MENTIONED)

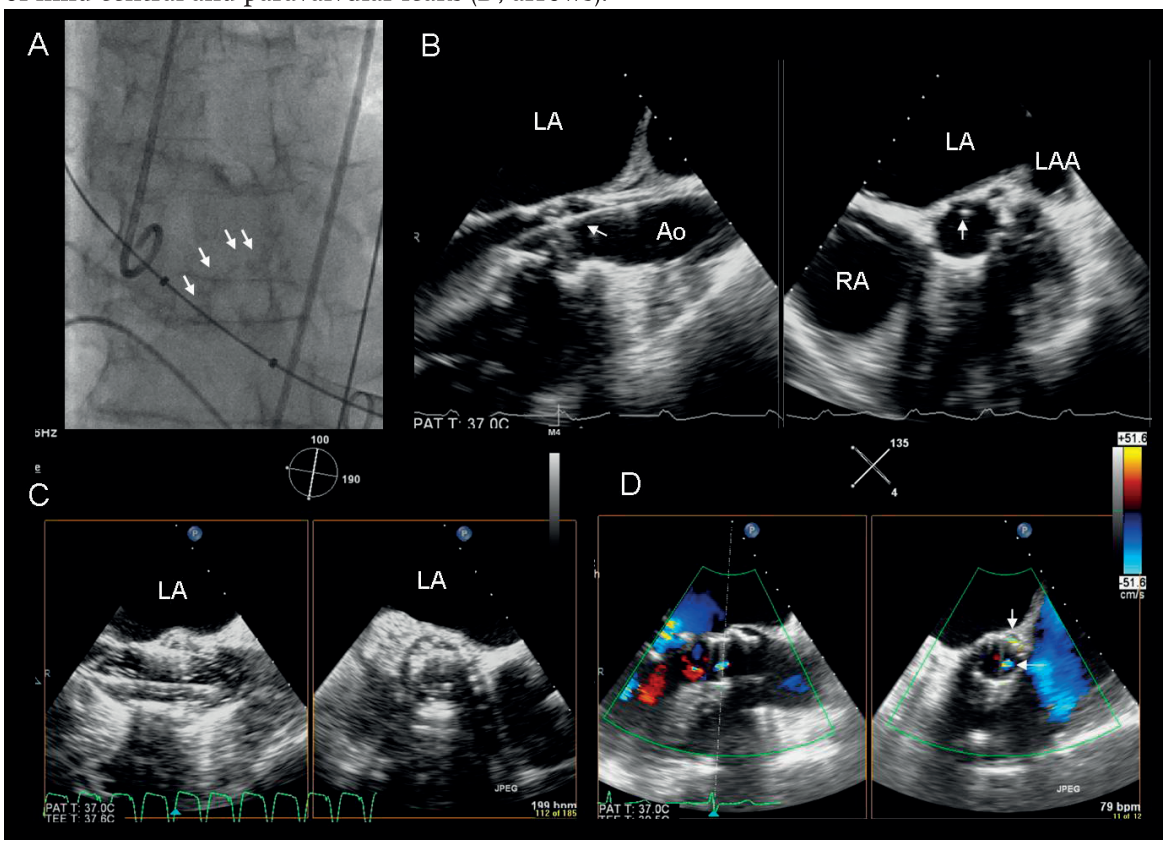
Figure 3. Aortic atherosclerosis and calcification extent. The presence of extensive atherosclerosis and calcification of the peripheral arteries or thoracic aorta may indicate a transapical approach rather than transfemoral. Panel A shows an extensive atherosclerotic plaque in the thoracic aortic wall as evaluated with TEE. Panel B demonstrates an extensively calcified aortic arch as assessed with MDCT.



During TAVI procedure, fluoroscopy and TEE play a central role to guide the sequential procedural steps. There is limited experience using intracardiac echocardiography to guide the procedure.[14] Crossing the aortic valve with the guide wire and positioning the waist of the balloon at the aortic valve annular level are usually guided with fluoroscopy, using as landmarks the calcifications of the non-coronary leaflet, or with direct visualization of the valve with TEE (Figure 4A,B). Afterwards, exact positioning and deployment of the prosthesis are crucial to minimize complications such as paravalvular regurgitation (Figure 4C). Combination of fluoroscopy and TEE may provide the most accurate guidance to position the prosthesis (WHAT

ABOUT THE OVERLAY OF FLUORO-CTA OR THE 3D-VOLUME RENDERED CINE-ANGIOGRAPHY). Finally, after prosthesis deployment, the results can be evaluated with TEE providing valuable information on transvalvular gradient reduction and on aortic valve regurgitation. The presence of mild paravalvular regurgitation is rather common (up to 50%).[9] In contrast, significant valvular regurgitation is infrequent and suggests the presence of misdeployment of one of the leaflets or overexpansion of the prosthesis.[15] Orthogonal color-Doppler views of the prosthetic valve permit differentiate paravalvular and valvular regurgitation whereas fluoroscopy may have limitations to differentiate them (Figure 4D). In addition, TEE permits the detection of other potential procedural-related complications such as cardiac tamponade, aortic dissection or occlusion of the coronary ostia by bulky calcified leaflets immediately after prosthesis deployment.

Figure 4. Transcatheter aortic valve implantation. The procedure is usually performed with fluoroscopic and 2D or 3D TEE guidance. With fluoroscopy, calcifications of the coronary leaflets (arrows) are used as landmarks to guide the wire crossing the valve and to position the balloon (A). With X-plane TEE images, the guide wire is directly visualized crossing the valve in two orthogonal planes simultaneously (arrows) (B). After aortic valve ballooning, the prosthesis is deployed (C) and the positioning and the function can be assessed immediately after deployment, evaluating the presence of valvular leaks (D). In this example, the arrows indicate the presence of mild central and paravalvular leaks (D, arrows).



Abbreviations: Ao = aorta; LA = left atrium; LAA = left atrial appendage; RA = right atrium.

In summary, multimodality imaging combining echocardiography and MDCT or MRI may constitute the most accurate approach to evaluate the candidates to TAVI and to define the procedural feasibility. During the procedure, combination of fluoroscopy and TEE is crucial to achieve the highest procedural success rate with the lowest complication rate. (SHOULD YOU ALSO MENTION THE IMAGING ASPECTS FOR THE SELF-EXPANDING AORTIC VALVE PROSTHESIS?)

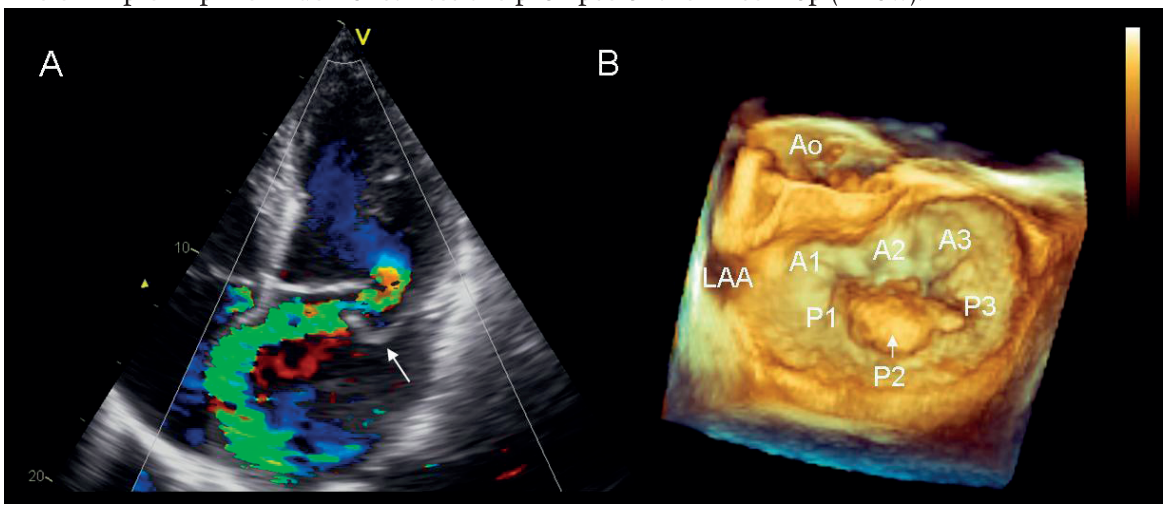
Transcatheter mitral valve repair

Contemporary registries have demonstrated that mitral regurgitation is the second most prevalent valvular hart disease.[4] Surgical mitral valve repair, combining leaflet repair techniques and restrictive ring annuloplasty, remain the treatment of choice for symptomatic severe mitral regurgitation. In the last decade, elderly patients have benefited most of recent advances in surgical repair techniques.[16] However, the presence of depressed left ventricular systolic function or associated co-morbidities increase the mortality operative risk and, consequently, the denial of surgery in this subgroup of patients rises up to 50%.[17] Several transcatheter mitral valve repair techniques have been developed in order to provide an effective and less invasive alternative to surgery. These techniques include leaflet repair (edge-to-edge), coronary sinus annuloplasty or direct mitral annulopasty, and direct remodeling.[18] The complex anatomical and functional interactions between the mitral valve apparatus, left ventricle and left atrium challenge transcatheter mitral valve repair techniques. Exact characterization of the mitral valve anatomy and mitral regurgitation mechanism is crucial to select the appropriate transcatheter mitral valve repair technique. Accordingly, imaging plays a central role in the pre-procedural screening and during the procedure.

Mitral regurgitation can be divided into primary or secondary (functional) according to the underlying pathophysiologic mechanism.[19] In primary mitral regurgitation, the mitral valve itself is affected and leaflet coaptation failure results of derangements of one or more components of the mitral valve (leaflets, tendineous cords or annulus). In contrast, in functional mitral regurgitation the mitral valve is preserved whereas the left ventricle is damaged. Prior left ventricular myocardial infarction or dilated cardiomyopathy induces dysfunction and displacement of the papillary muscles towards apical and posterior levels, mitral annulus dilatation and finally tethering of the mitral leaflets resulting in coaptation failure. Two-dimensional TTE is the first imaging technique to evaluate the cause and severity of mitral regurgitation. Barlow's disease and fibroelastic deficiency are the most common causes of primary mitral regurgitation.[19] Both diseases result in excessive motion and prolapse of one or more scallops of the mitral leaflets and varying grades of mitral regurgitation

but commonly with characteristic eccentric regurgitant jets (Figure 5A). In contrast, functional mitral regurgitation is characterized by restrictive motion of the mitral leaflets. Current recommendations of the American Society of Echocardiography advocate quantitative assessments of mitral regurgitation by means of vena contracta width, regurgitant volume or effective orifice area by proximal isovelocity surface area method.[20] However, eccentric regurgitant jets challenge mitral regurgitation quantification with 2D imaging techniques. In addition, systematic examination of the mitral valve and accurate identification of the scallops with 2D TEE requires high experience. Real time 3D TTE yields an improved accuracy in the estimation of the mitral regurgitation by direct visualization of the vena contracta without geometrical assumptions.[21, 22] Current 3D transesophageal echocardiographic probes incorporate novel matrix-array transducers with approximately 3000 elements that provide superb image quality and display of the mitral valve, either from the left atrial view (surgeon's view) or from the left ventricular view (Figure 5B). Interventional procedures on mitral valve demand accurate visualization of the mitral valve to select the most suited repair technique and to guide the procedure. Technical features of the different transcatheter mitral valve repair procedures require tailored imaging approach to evaluate the procedural feasibility. In addition, fluoroscopy may be insufficient to guide the procedure due to its poor soft-tissue contrast resolution. Therefore, combination of fluoroscopy and TEE (2D or real-time 3D TEE) may be ideal to accurately guide the sequential procedural steps while minimizing the radiation exposure.

Figure 5. Transcatheter mitral valve repair: pre-procedural evaluation. Echocardiography is the mainstay imaging modality to evaluate the mitral regurgitation mechanism (primary or secondary). Panel A shows the example of a patient with primary mitral regurgitation due to prolapse of the posterior mitral leaflet (arrow). Real-time 3D TEE provides the surgical view of the mitral valve and accurate anatomical segmentation in scallops and commissures (panel B). The example in panel B demonstrates the prolapse of the P2 scallop (arrow).

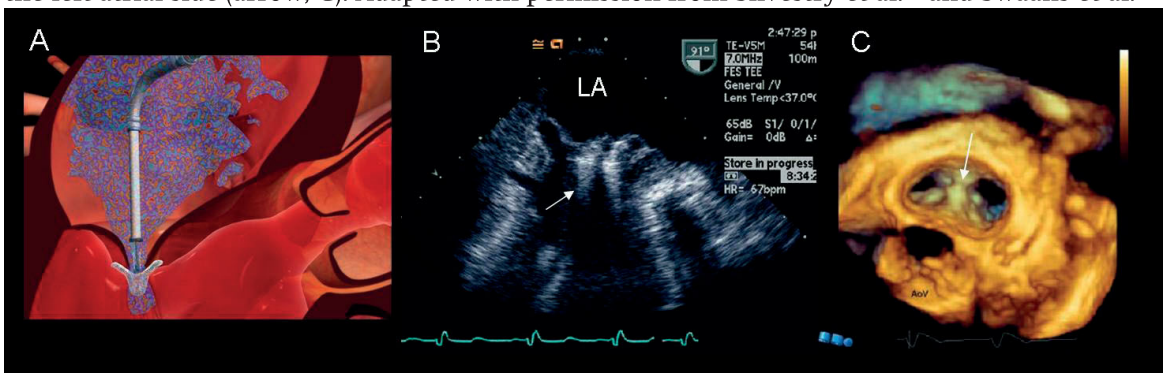


Abbreviations: Ao = aortic valve; LAA = left atrial appendage.

Transcatheter leaflet mitral (edge-to edge) repair mimics the surgical edge-to-edge repair pioneered by Alfieri and coworkers two decades ago.[23] This technique improves the leaflet coaptation by suturing a segment of the anterior mitral leaflet to the posterior leaflet, resulting in a double-orifice mitral valve. The MitraClip device (Evalve Inc., Menlo Park, CA) provides the largest body of evidence in this field. The safety and mid-term durability results of the initial Endovascular Valve Edge-to-Edge REpair STudy (EVEREST) cohort have been recently reported with a 74% acute procedural success rate (placement of 1 or more clips resulting in a discharge mitral regurgitation severity of ≤2+).[24] In addition, the 1-, 2- and 3-year survival rates were 96%, 94% and 90%, respectively, whereas the freedom from mitral surgery rates were 86%, 83% and 76%, respectively.[24] To maximize the procedural success rate, accurate patient selection is crucial. This procedural technique may be suitable for patients with degenerative (primary) or functional moderate-to-severe or severe mitral regurgitation who fulfil the following key anatomic criteria: regurgitant jet origin at the middle scallops of the mitral valve (A2-P2) in the absence of severe dilatation of the mitral annulus, and for patients with leaflet flail, a flail gap <10 mm and flail width <15 mm, and for patients with functional mitral regurgitation, a coaptation length ≥2 mm and a coaptation depth <11 mm. [24] As mentioned before, real-time 3D TEE yields a comprehensive and accurate evaluation of these patients. However, other 3D imaging modalities such as MRI or MDCT may provide invaluable information on mitral regurgitation quantification and mitral valve geometry, respectively.[22, 25-27] During the procedure, TEE plays a central role guiding the puncture of the posterior and superior portion of the interatrial septum and guiding the advancement and positioning of the catheter-delivery devices. Initial experimental studies have also shown the usefulness of intracardiac echocardiography to guide the procedure.[14] After transseptal puncture, the MitraClip is steered, aligned perpendicularly to the mitral coaptation line and centered over the origin of the regurgitant jet. The two arms of the device are opened and the clip is advanced into the left ventricle below the mitral leaflets. Then, the clip is retracted until the two leaflets are grasped and then closed to coapt the mitral leaflets (Figure 6). The immediate reduction in mitral regurgitation can be evaluated with TEE.

The spatial relationship between the coronary sinus and the mitral annulus has promoted the development of **percutaneous coronary sinus annuloplasty** techniques that simulate the surgical restrictive ring annuloplasty. By placing anchors or stents at the distal coronary sinus or the great cardiac vein and at the ostium of the coronary sinus connected by a bridging device, the coronary sinus is constrained and the cross sectional area of the mitral annulus is reduced with consequent improvement of the mitral leaflet coaptation. Several devices have been tested in the last years.[18]

Figure 6. Transcatheter edge-to-edge mitral valve repair. The MitraClip device (Evalve Inc., Menlo Park, CA) (A) is a 4-mm wide cobalt/chromium implant with 2 clip arms covered with polyester fabric to promote tissue ingrowth. The distal gripping elements secure the leaflet fixation (arrow, B). Real-time 3D TEE demonstrates the final double-orifice mitral valve viewed from the left atrial side (arrow, C). Adapted with permission from Silvestry et al.[54] and Swaans et al.[55]



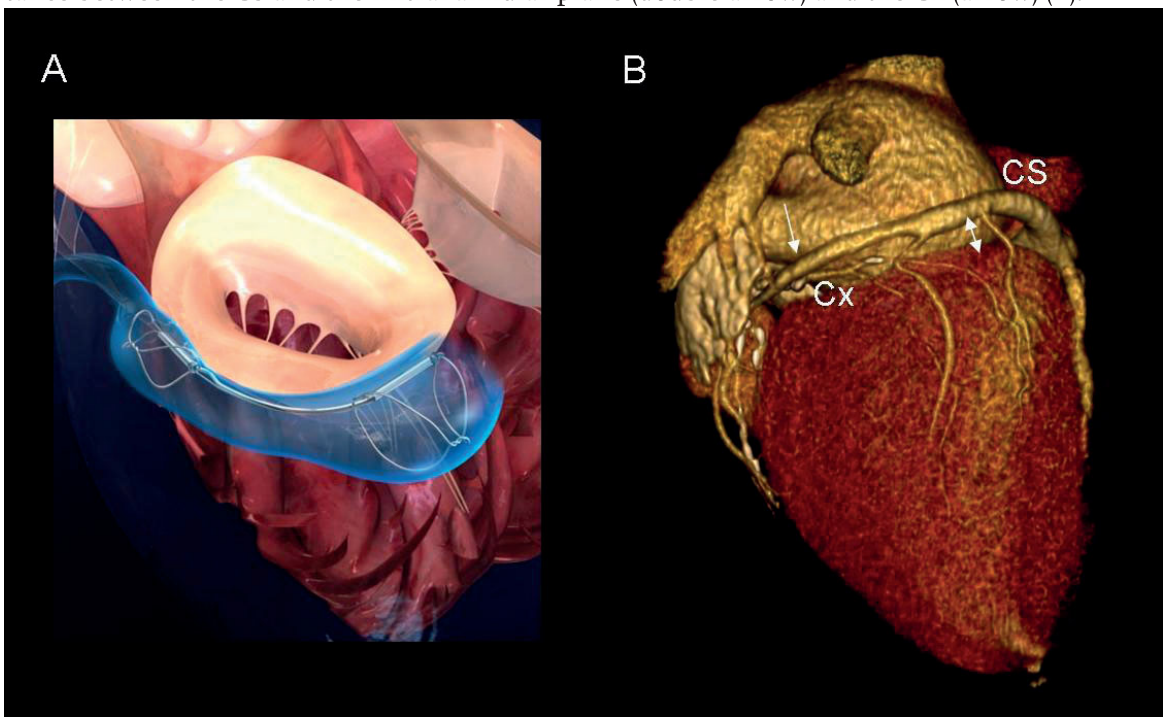
Abbreviations: AoV = aortic valve; LA = left atrium

Recently, the results of the CARILLON Mitral Annuloplasty Device European Union Study (AMADEUS) trial have demonstrated the feasibility of this interventional procedure in 48 patients with moderate or severe functional mitral regurgitation.[28] The CARILLON Mitral Contour System (Cardiac Dimensions Inc., Kirkland, WA), consists of a fixed-length, double-anchor, nitinol device and, as advantages, this device can be removed or adjusted at the time of implantation. The CARILLON device could be implanted in 30 patients with significant and sustained reductions in regurgitant volumes at 6 months follow-up.[28] This technique is challenged by the location of the coronary sinus relative to the mitral annulus and to the circumflex artery. MDCT provides 3D visualization of these anatomical structures and may constitute a valuable pre-procedural screening tool to select the patients amenable for this repair technique.[29, 30] Recently, Tops et al.[30] studied these anatomical relationships with 64-row MDCT in 105 patients, including 34 patients with functional mitral regurgitation.[30] In the majority of the patients, the coronary sinus coursed superiorly to the mitral annulus and, therefore, the effectiveness of the percutaneous coronary sinus annuloplasty in reducing mitral regurgitation severity may be limited (Figure 7). In addition, in 68% of the patients, the circumflex artery coursed between the coronary sinus and the mitral valve annulus, increasing the risk of arterial impingement and myocardial infarction.[30] These anatomical relationships should be also taken into account during the procedure. The implant procedure is performed with fluoroscopy and echocardiography guidance. First, a venogram is performed to assure the luminal dimensions of the coronary sinus and the great cardiac vein. The positioning of the distal anchor is guided with fluoroscopy and, during deployment of the anchor, an arteriogram is performed to assure patency of the circumflex artery. Once, the distal anchor is deployed, the delivery system is manually tracked to reduce the

cross sectional area of the mitral annulus. Reduction of mitral regurgitation severity is evaluated with echocardiography and finally, the proximal anchor is deployed.

(PERHAPS LESS EMPHASIS ON THE PROCEDURE ITSELF AND CLINICAL RESULTS – BOTH FOR THE TAVI AND FOR THE MVRp – AND MORE EMPHASIS ON THE DETAILS OF THE DEIFFERENT IMAGING TECHNIQUES WOULD BE BEST FOR THIS PAPER, SINCE THERE WILL BE OTHER PAPERS ON THE SAME SUPPLEMENT THAT WILL ADDRESS THEM)

Figure 7. Transcatheter coronary sinus annuloplasty. The CARILLON Mitral Contour System (Cardiac Dimensions Inc., Kirkland, WA) is designed to be implanted within the coronary sinus (CS) or the great cardiac vein to reduce the cross sectional area of the mitral annulus and, subsequently, to reduce the functional mitral regurgitation (A). The procedural feasibility and the effectiveness of this device to reduce mitral regurgitation severity depend on the anatomical course of the coronary sinus in relation to the mitral annular plane and the circumflex artery (Cx). MDCT provides 3D visualization of these spatial relationships and enables the relative distance between the CS and the mitral annular plane (double arrow) and the Cx (arrow) (B).



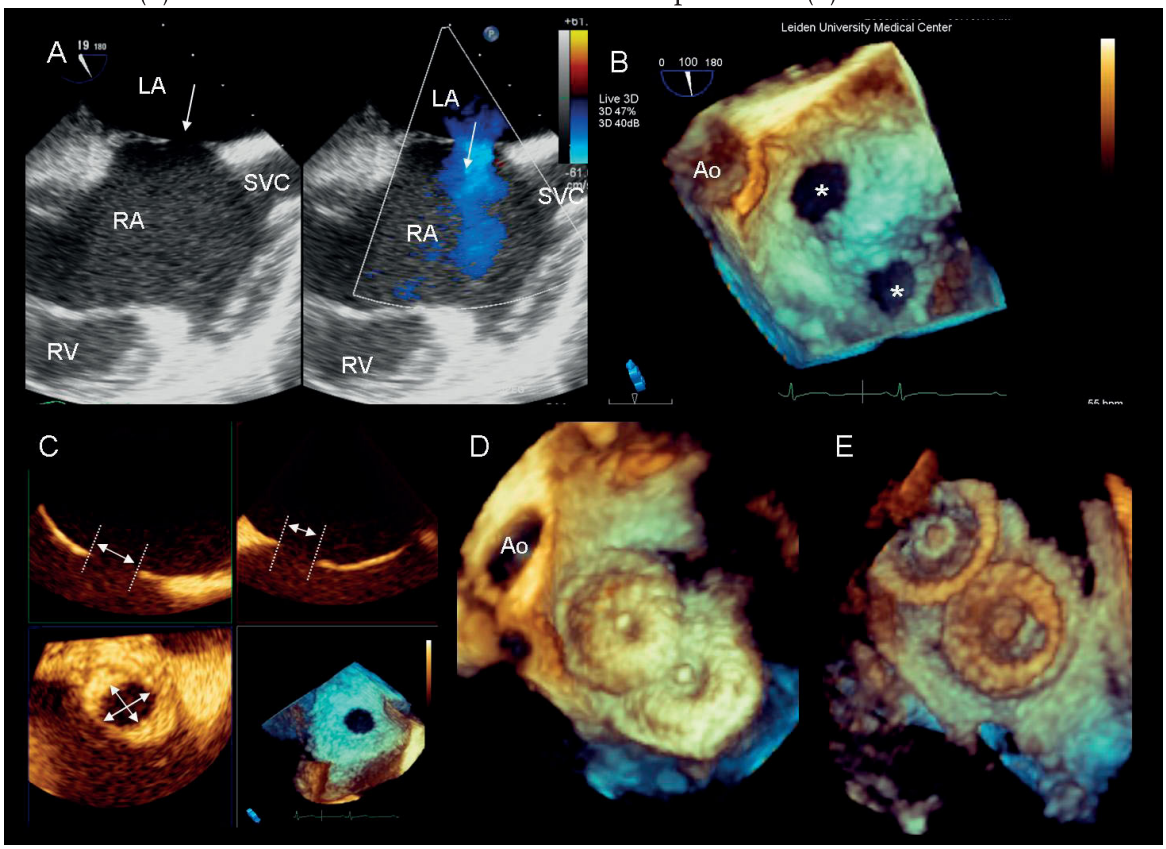
Transcatheter closure of ASD and patent foramen ovale

Transcatheter closure is a well-established treatment for secundum type ASD in children and adults. Compared to surgery, transcatheter closure procedures provide similar hemodynamic benefits and favourable cardiac remodeling while minimizing the hospital stay and recovery.[1] In experienced hands, the procedural success rate is 95% with a low rate of major complications such as cardiac perforation or device embolization (<1%).[31] The indications for transcatheter closure of ASD are the

same than for surgery: presence of hemodynamically significant left-to-right shunt (a ratio of pulmonary blood flow [Qp] to systemic blood flow [Qs] of >1.5:1.0) and/or enlargement of right chambers with an ASD of >10 mm and without significant pulmonary hypertension.[32] However, there are several additional features that define the candidates for transcatheter closure. Secundum type ASD amenable for transcatheter closure should be smaller than 36-40 mm diameter and have adequate septal rims (> 4mm) for stable anchoring of the occluder device.[32] In addition, the procedural feasibility depends on the presence of abnormal pulmonary vein drainage and the exact position of the ASD relative to other structures such as atrioventricular valves, coronary sinus or inferior vena cava. The presence of abnormal pulmonary vein drainage or close relation to any of the aforementioned structures indicate preferably surgical treatment. Therefore, in the pre-procedural screening, cardiac imaging plays a central role with echocardiography as the imaging modality of reference. Two-dimensional echocardiography permits the evaluation of all the aforementioned issues (Figure 8A). However, recent advances in real-time 3D TEE have provided en face ASD images with improved accuracy in real-time estimation of the defect size and morphology (Figure 8B,C).[33] Recently, using as a reference sizing balloons, Taniguchi et al.[34] demonstrated that real-time 3D TEE provided more accurate ASD dimensions than 2D TEE.[34] In addition, the intra- and inter-observer variability for maximal ASD diameter estimation was significantly lower with the use of real-time 3D TEE than 2D TEE (3.6% and 4.8% vs. 8.9% and 9.9%, respectively; $p<0.0001$).[34]

Among several ASD occluder devices, the Amplatzer Septal Occluder (AGA Medical Corporation, Golden Valley, MN) is the most commonly used. This device consists of two, self-expandable, nitinol alloy wire-mesh discs joined at a waist. Transcatheter ASD closure is performed through an antegrade approach, via the femoral vein, with fluoroscopic and echocardiographic (transesophageal or intracardiac echocardiography) guidance. The ASD is imaged by echocardiography and with the use of a sizing balloon, the dimensions of the septal defect are measured to select the most appropriate device size. The defect is crossed with a semistiff wire and the delivery system passes orthogonally through the septal defect. Thereafter, the left and the right discs are sequentially unfolded and before the device is released, the exact positioning of the occluder should be ensured. In this key step, real-time 3D TEE may provide a superb on-line view of the device position in the interatrial septum and its spatial relationship with surrounding cardiac structures (atrioventricular valves or coronary sinus) (Figure 8D,E). Finally, the presence of residual shunting should be evaluated. Hemodynamically non-significant shunts are often observed at the end of the procedure but most of them close spontaneously within the first year.[1]

Figure 8. Transcatheter atrial septal defect closure. Echocardiography is the first choice imaging modality to localize and evaluate the dimensions of the atrial septal defect (A). Doppler echocardiographic techniques permit the assessment of the left-to-right shunt (A). During the procedure, real-time 3D TEE may provide a more accurate visualization and measurement of the ASD (B). The presence of multiple ASD may be rather common (stars, B) and real-time 3D TEE enables the en face view of the entire atrial septum and the spatial relationship between the defects. This imaging modality permits also multiplanar reformatting planes to accurately measure the size of the defect (C). Finally, 3D reconstructions from the left atrial view (D) and the right atrial view (E) illustrate the final result of the device implantation (E).



Abbreviations: Ao = aortic valve; LA = left atrium; RA = right atrium; RV = right ventricle; SVC = superior vena cava.

The number of transcatheter patent foramen ovale closure procedures has increased dramatically in the last years. Over 1100 patients have received an Amplatzer PFO occluder (AGA Medical Corporation, Golden Valley, MN) for secondary prevention of stroke.[35] The prevalence of patent foramen ovale in the general population is rather high (15% to 27% according to echocardiography- or anatomy-based series) and frequently, is associated with an atrial septal aneurysm.[36] Diagnosis of patent foramen ovale relies on echocardiography demonstrating an interatrial communication with right-to-left transit of contrast microbubbles within 3 or 4 beats after opacification of right atrium.[32] Atrial septal aneurysm is diagnosed by the visualization of a redundant and hypermobile portion of the interatrial septum with more 10 mm excursion from the centreline during the cardiac cycle.[32] During the last decades, several observational, non-controlled studies have related the presence of a

patent foramen ovale to increased risk of cryptogenic cerebral stroke or paradoxical thromboemlism.[35] In the Patent Foramen Ovale in Cryptogenic Stroke Study (PICCS) a patent foramen ovale was present almost 39% of the patients with a cryptogenic stroke vs. 30% of the patients with known cause of stroke.[37] Pooled data from non-randomized studies favour transcatheter closure of patent foramen ovale over medical therapy, with reduced 1-year rates of recurrent neurological thromboembolism (0-5% vs. 4-12%, respectively) and with a mean frequency of major complications of 2.3%.[38] Nevertheless, current guidelines recommend transcatheter closure of patent foramen ovale only in patients with recurrent cryptogenic stroke despite optimal medical therapy (class IIB, level of evidence C).[35] Ongoing randomized, controlled trials will provide the best evidence on the safety and efficacy of transcatheter patent foramen ovale closure relative to antithrombotic therapy.[35]

Although highly experienced centers have demonstrated successful transcatheter closure of patent foramen ovale with only fluoroscopic guidance,[39] the combination of fluoroscopy and echocardiography (transesophageal or intracardiac) may constitute the best approach to achieve the highest success rate while minimizing the complications rate.[40] The interventional procedure is similar to the ASD closure procedure. With fluoroscopy, the so-called Pacman sign may be visualized before the device is released.[39] The cranial halves of the left and the right discs should appear as open jaws biting the thick septum secundum. However, the goal of the patent foramen ovale closure is to eliminate the shunt between right and left atria, abolishing, therefore, the risk of recurrent paradoxical thromboembolism. In patients with tunnel defects, atrial septal aneurysm or who require large occluder devices, the risk of residual shunting is higher and therefore, the use of echocardiography during the procedure may be helpful to accurately measure the defect, select the most appropriate device size and to help in the positioning and delivering of the occluder device.[41]

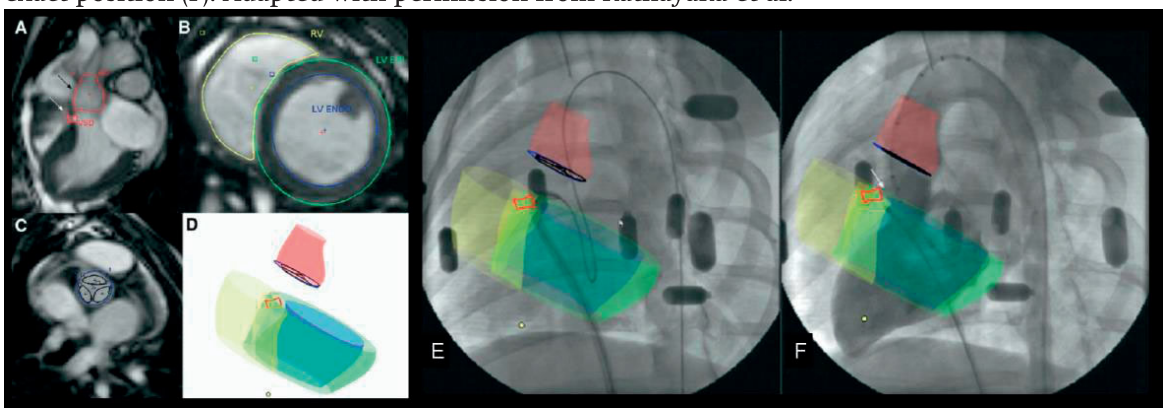
(AGAIN, I THING THE EMPHASIS SHOULD BE MORE ON THE IMAGING RATHER THAN DESCRIBING DEVICES OR RESULTS. HOW TO BEST DEFINE THE 5 SEGMENTS OF THE ASD RIMS, 2D-TTE, 2D-TEE, ICE AND RT-3D TEE)

Transcatheter closure of VSD

Ventricular septal defects account for 20% of the congenital heart disease.[2] In up to 70% of the patients, the location of the VSD is perimembranous whereas muscular VSD are observed in 15%.[2] Supracrystal or multiple VSD are rarely observed. Indications for VSD closure include heart failure symptoms, enlargement of left cardiac chambers or history of endocarditis.[2] Surgical closure remains the first choice

treatment of VSD. However, in highly experienced centers, transcatheter closure of both perimembranous and muscular VSD compares favourably to surgical (NOT SO FOR THE PERIMEMBRANOUS) closure with procedural success rates around 95% and limited number of complications.[2] Compared to transcatheter closure of ASD, closure of VSD is more challenging due to the contraction of the interventricular septum. (UNDERSTANDING THE SPATIAL CONFIGURATION OF THE RV RAPPING ARROUND THE LV AS WELL AS THE CONCRETE ANATOMICAL LOCATION OF THE VSD - APICAL, ANTERIOR, INLET, OUTLET, SUB-ARTERIAL ETC, IS PRIMORDIAL TO SELECT WHICH PATIENTS ARE AMENABLE TO CLOSURE BY CURRENT DEVICES) Particularly, the closure of perimembranous VSD faces an increased risk of complete atrioventricular block with the subsequent need for pacemaker. Accurate morphologic assessment and location of a hemodynamically significant VSD are crucial preprocedural screening steps. Echocardiography constitutes the imaging technique of choice to evaluate all these parameters. Specifically, transcatheter closure of perimembranous VSD is feasible when a rim of at least 1 mm separating the aortic valve from the VSD exists.[42] Patients with infundibular defects, perimembranous VSD and prolapse of one of the aortic leaflets or malalignment are not amenable for transcatheter closure and should be referred to surgery. The interventional procedure is performed with fluoroscopic and echocardiographic guidance. First, a left ventricular angiogram helps to localize the septal defect and echocardiography helps to accurate measure the maximum diameter of the defect. According to the size and the location of the defect, the occluder device size and type will be selected. Different occluder devices exist for each type of VSD: muscular (Amplatzer mVSD) and perimembranous (Amplatzer pmVSD) (AGA Medical Corporation, Golden Valley, MN). An antegrade approach is commonly used to advance the delivery system and to cross the muscular VSD.[43] Once the left ventricular disc is deployed and pulled against the septum, the correct position of the occluder device is confirmed with echocardiography or fluoroscopy. Thereafter, the right ventricular disc is deployed and the device is released. In contrast, a retrograde approach is preferred to close the perimembranous VSD since there are no fluoroscopic landmarks to cross the defect.[42] Subsequently, the right ventricular disc of the device is deployed and pulled against the septum and finally, the left ventricular disc is deployed and the device is released. Recently, advances in image fusion have facilitated the antegrade approach to percutaneously close the perimembranous septal defects.[44] Ratnayaka et al. demonstrated that fluoroscopy image fused with magnetic resonance imaging roadmaps permits antegrade approach reducing the radiation exposure compared to conventional retrograde approach (Figure 9).[44] Finally, the results can be evaluated with echocardiography with special attention to the residual shunt.

Figure 9. Novel image fusion technologies to assist transcatheter VSD closure. Antegrade transcatheter closure of perimembranous VSD assisted by X-ray fused with MRI roadmaps (XFM). First, from a long-axis 3-chamber steady-state free precession MRI the contours of the aortic root (in red) and the perimembranous VSD (in red) are traced (A) whereas the endocardial borders of the right (in yellow) and left (in green) ventricles are traced from the short-axis views (B). In addition, the aortic root and the aortic leaflets contours are traced from the short-axis views (C). These MRI-derived contours provide the data to render the aforementioned structures in three dimensions (D). During the procedure, the VSD is identified with XFM guidance. Through an antegrade approach, the delivery system is directed towards the left ventricular apex (E) and confirmatory XFM ventriculography demonstrates the deployment of the occluder device in the exact position (F). Adapted with permission from Ratnayaka et al.[44]



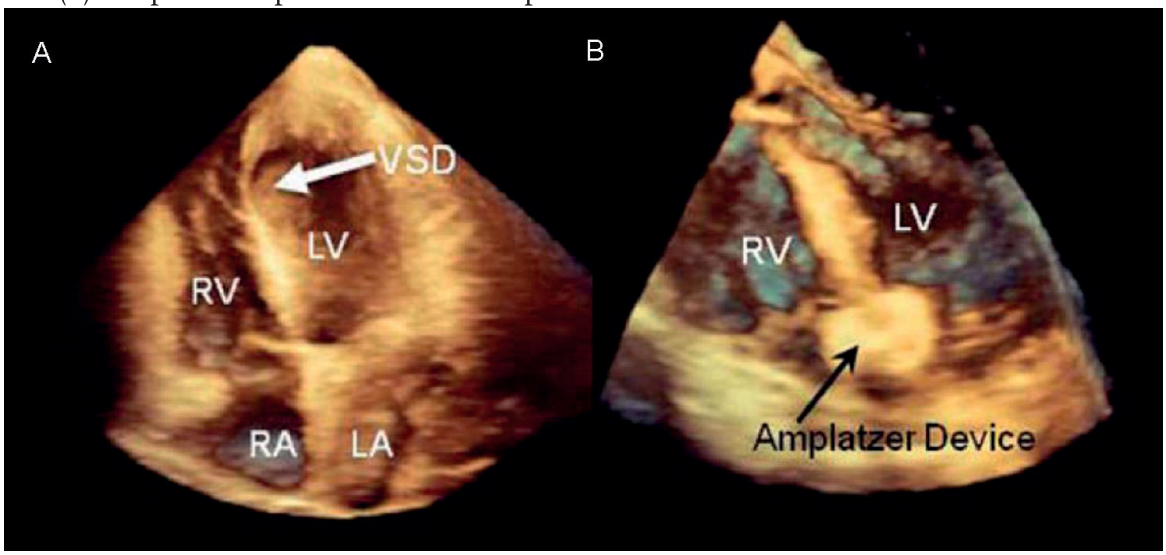
Limited experience exists on transcatheter closure of post-myocardial infarction ventricular septal rupture.[45, 46] With primary coronary intervention, this complication is currently rather uncommon and when it occurs, surgery is the preferred treatment. However, in high-risk patients such as elderly patients or with associated co-morbidities, transcatheter closure of ventricular septal rupture may be an alternative option. Limited registries and several case reports have demonstrated the feasibility of this intervention.[45, 46] Ischemic ventricular septal ruptures show usually a complex morphology with multiple orifices and tunnels. Real-time 3D echocardiography may be a valuable imaging technique to assist the procedure. As mentioned previously, real-time 3D echocardiography provides accurate information on the location and size and morphology of the septal defect (Figure 10).[45] However, the still high 30-day mortality rate (28%) after the procedure warrants further studies before this technique is widely implemented in the clinical practice. (AGAIN, LESS EMPHASIS ON DEVICES AND RESULTS, AND PERHAPS MORE ON IMAGING DETAILS WOULD BE PREFERABLE)

Transcatheter left atrial appendage closure

Atrial fibrillation is the most common sustained cardiac arrhythmia with a prevalence of 6 millions of individuals in United States.[47] Atrial fibrillation is related to an increased risk of stroke (5%/year).[48] Despite the efficacy of anticoagulation to

prevent future strokes, recent registries demonstrated that only 50% of the patients who would benefit of long-term warfarin are treated with it.[49] Based on anatomical and echocardiography series, the left atrial appendage is the site of thrombi formation and embolism in 90% of the patients.[50, 51] Therefore, the closure of this anatomic structure in patients with non-valvular atrial fibrillation may prevent future strokes. The Percutaenous Left Atrial Appendage Transcatheter Occlusion (PLAATO) trial demonstrated the feasibility and the safety of the occlusion of the left atrial appendage with the PLAATO system (Appriva Medical Inc., ev3, Sunnyvale, CA).[52] This non-randomized trial was the first in reporting significant reductions in the annualized stroke/transient ischemic attack rate (3.8% vs. the 6.6% expected rate based on the $CHADS_2$ score) with limited procedure-related complication rates.[52] Recently, the randomized PROTECT AF (WATCHMAN Left Atrial Appendage System for Embolic Protection in Patients with Atrial Fibrillation) trial have extended these results and confirmed the non-inferiority of the occluder device (Atritech Inc., Plymouth, MN) against chronic warfarin therapy.[53] Successful implantation of the device was achieved in 88% of the patients whereas the procedural complication rate was relatively low (4.8%).[53]

Figure 10. Transcatheter closure of post-myocardial infarction muscular VSD. Real-time 3D TTE demonstrates the apical septal thinning and ventricular septal defect (A). After the transcatheter closure, real-time 3D TEE demonstrates the final position of the deployed occluder device (B). Adapted with permission from Halpern et al.[45]



Abbreviations: LA = left atrium; LV = left ventricle; RA = right atrium; RV = right ventricle; VSD = ventricular septal defect.

Cardiac imaging plays a central role in the pre-procedural screening with TEE as the mainstay imaging technique. The orifice of the left atrial appendage should be measured in two orthogonal views to select the most appropriate device size. Therefore,

real-time 3D TEE may improve the accuracy of the measurements by providing en face views where the left atrial appendage orifice could be visualized and measured without geometric assumptions. However, to date there is no experience with this imaging technique. In addition, echocardiography is a valuable imaging modality to rule out the presence of procedural contraindications (significant mitral or aortic stenosis, moderate or severe mitral regurgitation, mobile or planar clot in the left atrium or atrial appendage and enlarged left atrium [>65 mm]). During the procedure, combination of fluoroscopy and transesophageal or intracardiac echocardiography provides the most accurate guidance. A left atrial appendogram (APPENDAGE ANGIOGRAM) is performed to measure the dimensions of the left atrial appendage and to select the size of the device (usually 10-20% larger than the diameter of the left atrial appendage). After transseptal puncture the delivery system is positioned into the left atrial appendage. Once satisfied, the device can be released and the final position is confirmed by cineangiography or with color Doppler echocardiography to evaluate potential leaks around the implant's edges.

CONCLUSIONS AND FUTURE PERSPECTIVES

Accurate visualization of different cardiac structures is mandatory to maximize the success rate of current catheter-based intervention procedures. Recent advances in cardiac imaging modalities such as real-time 3D TEE, MDCT or MRI have improved significantly the visualization and characterization of cardiac structures and have facilitated the dissemination of several transcatheter procedures. Some procedures are challenging and require high experience. However, combination of fluoroscopy and, most frequently, echocardiography yields an accurate procedural guidance to achieve the highest success rate with the lowest complication rates. Current catheterization laboratories may evolve to hybrid operating rooms with sufficient space to hold multi-modality imaging capabilities (3D echocardiography, MDCT and MRI). This is particularly of interest in the emerging field of transcatheter valve implantation. However, other procedures such as transcatheter closure of perimembranous VSD may be facilitated by novel image-fusion technologies that require MRI or MDCT. Ongoing research will provide novel tools to increase the number of catheter-based procedures to treat several structural heart diseases that remain currently in the surgery domain.

DISCLOSURES

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