

Evolution of interventional imaging in structural heart disease

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Treatments for structural heart diseases (SHD) have been considerably evolved by the widespread of transcatheter approach in the last decades. The progression of transcatheter treatments for SHD was feasible due to the improvement of devices and the advances in imaging techniques. In this setting, the cardiovascular imaging is pivotal not only for the diagnosis but even for the treatment of SHD. With the aim of fulfilling these tasks, a multimodality imaging approach with new imaging tools for pre-procedural planning, intra-procedural guidance, and follow-up of SHD was developed. This review will describe the current state-of-the-art imaging techniques for the most common percutaneous interventions as well as the new imaging tools. The imaging approaches will be addressed describing the use in pre-procedural planning, intra-procedural guidance, and follow-up.

Introduction

Transcatheter treatments for structural heart diseases (SHD) have grown dramatically in the last decades.¹ This progress has been possible thanks to the developments of new devices and/or their improved performance, as well as the innovation and evolution of the imaging techniques. The cardiovascular imaging is pivotal in the diagnosis and treatment of SHD and the imaging expert is the cornerstone of the heart team with a central role in the entire care pathway: from clinical decision-making to intra-procedural guidance and follow-up.^{2,3}

The use of imaging in the catheter-based treatment of SHD has come a long way in the past 70 years, starting with simple chest X-ray as the only modality to guide the procedures until recent advances in transesophageal (TOE) three-dimensional (3D) transducers and intracardiac echocardiography (ICE). Although the echocardiography remains the core of imaging techniques, the use of

multimodality imaging is crucial in the management of SHD that requires specific technical skill sets and advanced competencies.

The research and development are essential elements for medical advancement. The availability of new imaging tools, some of which still in pre-clinical phase and others currently used as alternative to standard techniques, is a fundamental driver to expand the borders of percutaneous treatment of SHD. This review will describe the standard and innovative imaging techniques used for pre-procedural evaluation/planning, procedural guidance and follow-up of the most common catheter-based interventions of SHD.

Transcatheter aortic valve replacement

In 2002 Cribier *et al.* reported the first-in-human transcatheter aortic valve replacement (TAVR),⁴ starting a new era in the treatment of aortic stenosis. In the last 20 years, TAVR has become the standard approach for all the patients older than 75 years old irrespective of the surgical risk.⁵ The progressive spread of TAVR has been also accompanied by improvements in the performance of

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the prostheses, in the procedural approach, in the pre-operative assessment and in the follow-up. The efficacy of TAVR induces its spreading in younger, lower-risk cohorts including the bicuspid aortic valve (BAV).

Pre-procedural planning

Multidetector computed tomography (MDCT) is the mainstay of the pre-procedural qualitative and quantitative evaluation of the aortic root and the assessment of vascular access route. In patients with high risk of nephrotoxicity or intolerance to contrast medium or in case of poor imaging quality, 3D TOE-based measurements are a valuable tool for procedural planning and prosthetic sizing^{6,7} (Figure 1).

The pre-procedural imaging assessment with transthoracic echocardiography (TTE) and MDCT could be integrated with patient-specific computer simulation to assess the interaction between the device and the native anatomy. The models include elements of the aortic root derived from MDCT, the characteristics of the prosthesis chosen, the simulation of balloon pre-dilatation and mechanical properties of the nickel titanium. Based on this assessment final frame geometry with calcium displacement and the potential for procedural complications can be anticipated. Published data showed a good correlation between the observed on MDCT post-implantation and the predicted frame dimensions (level of measurements: inflow, nadir, coaptation, and commissures) and in the qualitative comparison of displacement of leaflet calcifications after valve implantation.⁸ This technique can be valuable in BAV patients because by computer simulation it's possible to select the valve that best fits the individual patient and to optimize its positioning.

Intra-procedural guidance

In line with the prostheses development, there has also been a simplification of the TAVR procedure. The first TAVR interventions required general anaesthesia and

intra-procedural TOE monitoring to assess valve deployment, paravalvular leak, and potential complications. Nowadays the majority of TAVR procedures are performed through a minimalist approach: local anaesthesia plus sedation with TTE check after the implantation. The local anaesthesia granted a more stable patient with less need for inotropic agents and the possibility to monitor throughout the entire procedure neurological status and pain.⁹ The TTE is associated with hemodynamic parameters, and, in doubtful cases, aortography guarantees performance comparable to TOE.¹⁰ This approach provides a reduced procedural time but also a less need intensive care unit and a shorter hospital stay.⁹

Fusion imaging has a limited role in TAVR, but can be useful especially when fluoroscopy images alone can be challenging, as in case of poor calcifications or native pure aortic regurgitation.

Follow-up

TTE remains the key exam for routine evaluation and follow-up after TAVR. If a complication is suspected or in case of doubts after the TTE assessment, a TOE and/or a cardiac MDCT/positron emission tomography, MDCT and/or cardiac magnetic resonance (CMR) should be performed, depending on the type of complication identified.

Transcatheter mitral valve interventions

Transcatheter mitral valve interventions (TMVI), either repairing or replacing the mitral valve (MV), are nowadays established alternative options for the treatment of patients with mitral regurgitation (MR) who are not suitable for conventional open heart surgery.

Several devices have been conceived in order to address specific anatomical needs and target different regurgitant mechanisms:

- Edge-to-edge repair.

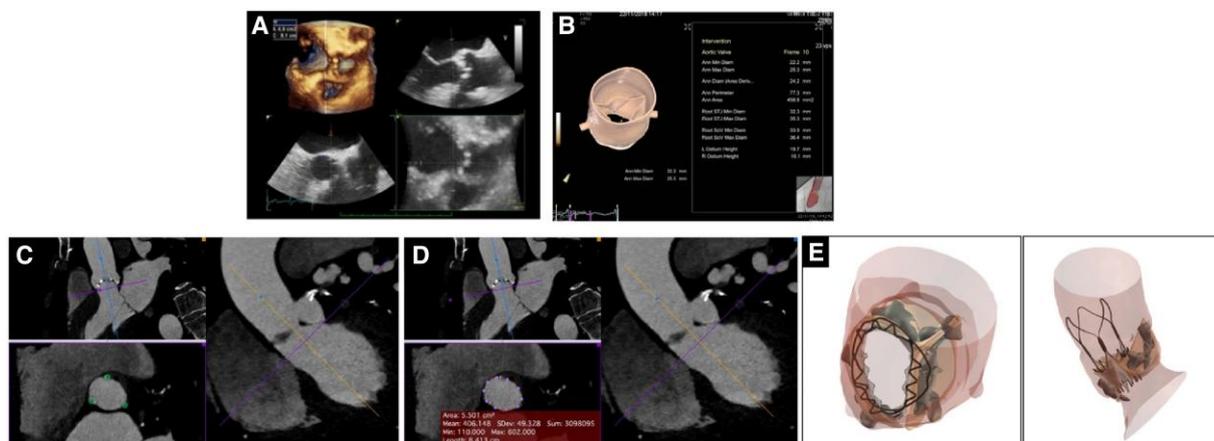


Figure 1 (A) 3D aortic annulus measurements by multiplanar reconstruction analyses. It allows for coronal and transverse plane reconstruction starting from 3D dataset. (B) Aortic root 3D static modelling, with the corresponding automated geometrical measurements concerning with annular, sinus of Valsalva, sinotubular junction dimensions, and coronary ostia height. (C) Similarly to 3D transesophageal imaging, CT multiplanar reconstruction analyses show coronal, sagittal, and transverse planes adjusted to get the true cross-sectional plane of aortic annulus: the three markers identify the annular plane/virtual basal ring for transcatheter heart valve sizing (D). (E) Prosthetic valve implantation three-dimensional simulation by a static modelling in a case of bicuspid aortic valve (FEops simulation software).

- Annular repair: direct or indirect annuloplasty aiming to improve leaflet coaptation by reducing annular diameters.
- Chordal implantation: adjustable transapical beating-heart artificial chordal implantation.
- Mitral valve replacement.

Pre-procedural evaluation

The MV apparatus is a complex 3D anatomical and functional unit. Its detailed pre-operative assessment is crucial to the determination of the optimal interventional approach. TTE and TOE are the first-line imaging techniques for screening e for ruling out potential candidates for percutaneous intervention. Pre-procedural evaluation, aims to assess MR severity, principal and/or multiple combined mechanisms, and the anatomy of MV in terms of localization and extension of disease, in order to choose the best therapeutic option and customize the therapeutic approach according to the risk profile of the patient. Three-dimensional echocardiography, especially TOE, has an utmost impact in this regard. It can assess mitral leaflet morphology and their coaptation quality, the mitral annular shape and diameters, and the anatomical relationship of the MV with the surrounding structures, thus guiding therapeutic approach selection and potentially predicting the complexity of the intervention. Indeed, it has the unique ability to show cardiac structures as they are in reality.¹¹

Two main 3D imaging modes are of utmost importance for detailed MV morphological characterization: simultaneous biplane view and 3D volume rendering. The first one displays simultaneously two different 2D image planes with high spatial and temporal resolution (*Figure 2 A and B*). Different 3D volume rendering are available, allowing to emphasize different MV anatomical aspects, making valve morphology assessment potentially more intuitive and effective for both operators (imager and interventionalist) (*Figure 2C*). True view rendering allows for fine and intuitive

evaluation of the morphological aspect of MV by changing light source location (*Figure 2D and E*). Transparency rendering may help in fine evaluation of regurgitant lesion and orifices evaluation after leaflet approximation for final result assessment (*Figure 2F*). Another 3D imaging tool of utmost importance is the multiplanar reconstruction (MPR): both real-time and off-line analyses allow to show three 2D orthogonal planes cropping boxes of the 3D matrix dataset (*Figure 2G*). This is a very useful tool both for pre-procedural planning and intra-procedural guidance. Moreover, advanced post-processing tools enable 3D MV reconstruction (3D modelling) with both the static and dynamic measurements of the MV anatomy (quantitative analysis of the MV morphology) including for example, in case of organic MR, the prolapse height, the prolapse volume, and the anterior leaflet surface area and leaflet length, all the parameters necessary for planning the MV repair (*Figure 2H*).

In addition, for therapeutic approaches targeting the annulus and for MV replacement scenario, MDCT evaluation is mandatory for annular sizing and evaluating morphological features in terms of calcifications, detailed spatial relationships with surrounding structures, and the risk of left ventricular outflow tract (LVOT) obstruction. Multimodality imaging indeed is nowadays the recommended approach, since MDCT scan has proved to be fundamental for patient selection and pre-procedural planning in several catheter-based procedures (*Figure 3*). In the last years, its role has been dramatically expanded mainly due to the advances in the technology with improvement in both temporal and spatial resolution. Compared with echocardiography, the main strength of MDCT is the capability to provide wide fields of view making easier to interpret the spatial relationships between the different cardiac structures and between the cardiac structures and the neighbouring organs.

Finally, in ischaemic mitral regurgitation CMR could be helpful to identify the patients who derive a survival benefit from mitral repair. Indeed, CMR examination assesses

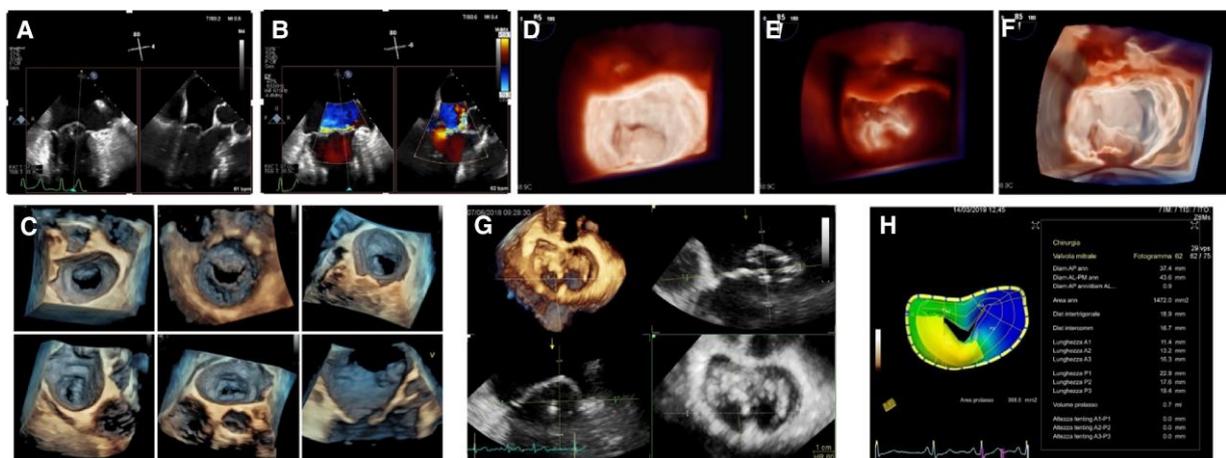


Figure 2 Prolapse/flail of P2 scallop. (A and B) Mitral valve baseline evaluation by simultaneous biplane view without and with colour Doppler; evaluation of regurgitant lesion extension. (C) Different perspective of the same 3D dataset may allow a fine evaluation of mitral valve anatomy and regurgitant lesion. (D and E) 3D surgical view of mitral valve with different volume rendering display: true view rendering may allow for fine details of the anatomy of regurgitant lesion by changing light source orientation. (F) Galss view rendering. (G) Post-processing of mitral valve by multiplanar reconstruction. (H) Post-processing software evaluation allows for mitral valve reconstruction and parametric analysis.

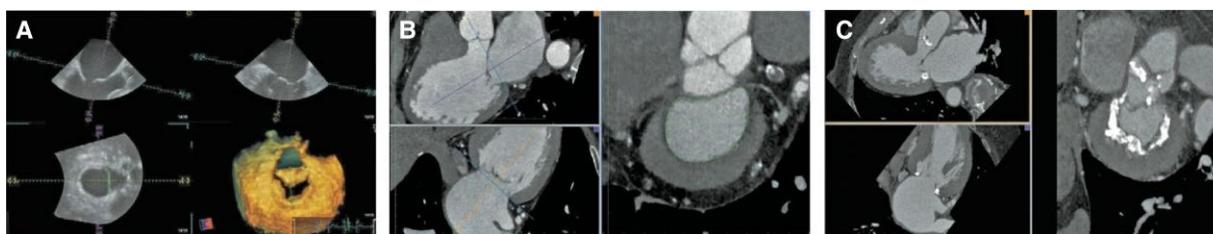


Figure 3 Mitral valve annulus sizing by multiplanar reconstruction of transesophageal 3D dataset (A) and CT-scan dataset (B). (C) Multislice computed tomography (MSCT) evaluation of mitral valve annular calcifications (degree and extension) and spatial relationships with surrounding structures by multiplanar reconstruction analyses.

both myocardial infarct size and mitral regurgitant fraction and the interaction of these two parameters emerged as a powerful predictor of adverse outcomes.¹²

Intra-procedural guidance

Nowadays, TOE both 2D and RT3DE is considered the gold standard intra-procedural imaging technique for the majority of MV procedures. Intracardiac echocardiography is emerging as new alternative/complementary technique.

The entire scenario in which most of the catheter-based procedures take place (whole left atrium and MV, with catheters/devices) can be shown in a single 3D view,^{11,13} as well as long segments of devices, can easily be intersected by the pyramidal ultrasound beam and displayed without excessive probe manipulations. Moreover, is possible to provide to operator the most effective view of the specific procedural step by changing the 3D dataset perspective, in order to make the intra-procedural guidance more intuitive and immediate.

According to the procedure and the specific procedural steps, it is useful to switch from 3D volume rendering to 2D imaging (higher spatial and temporal resolution) to optimize intra-procedural guidance. For this reason, simultaneous biplane mode is one of the most helpful and used 3D modality during intra-procedural guidance. It helps in the simultaneous visualization of anatomic structures (target lesion), guidewires, catheters, and devices during their manipulation and movements in different planes avoiding continuous changes of TOE 2D projections leading to an easier interpretation of the images by interventionists with a reduction of procedural time. Moreover, it allows proper assessment of correct orientation, angle of approach, and the fine tip positioning of the device with respect to the target lesion thanks to the possibility to get multiple views with correct angulations.

Transcatheter edge-to-edge repair

Two devices are currently available: MitraClip (Abbott Laboratories) and PASCAL devices (Edwards Lifesciences). 2D and 3D TOE are currently the most used imaging technique for intra-procedural guidance, although 4D ICE is an emerging imaging tool.

The first procedural step is the transseptal puncture (TSP) (Figure 4). Transseptal puncture is of critical importance and needs to be tailored to the procedure: the optimal TSP site should be located in the superior-posterior part of the fossa ovalis. However, multiple are the potential directions TSP catheter could achieve in a 3D space,

and despite several planes can be achieved by 2D imaging, it implies that following the intracardiac catheter and establishing its position relative to the FO may be difficult with 2D TOE and multiple views and continuous imaging adjustments are required. Thus, 3D imaging and some cases fusion imaging can have an additional value making TS approach more intuitive. Once the left atrium is achieved, catheter navigation toward MV plane, delivery system axial alignment and device orientation according to the regurgitant lesion location can be easily performed under simultaneous biplane view and 3D surgical view. Assessment of adequate leaflet insertion and approximation requires higher spatial and temporal resolution and should be monitored by focused simultaneous biplane view. The quality of leaflets insertion and satisfactory grasp is verified by observation of direct signs of leaflets insertion such as limited leaflet mobility relative to the tips of the device arms by simultaneous biplane view, together with adequate 'bridge' of tissue and occurrence of a double MV orifice, by 3D surgical view; and the indirect signs, for instance, the adequate MR reduction, the appearance of spontaneous echo contrast in left atrium and the possible presence of intra-device jet that suggests the little amount of leaflet tissue captured. Finally, the transmitral gradient and the residual MR (procedural result) should be assessed using a multiparametric approach.

Transcatheter direct annuloplasty

The Cardioband device (Edwards Lifesciences) is an incomplete adjustable surgical-like Dacron band, via transseptal access, implanted on the posterior annulus from the anterolateral to posteromedial commissure.

Direct mitral annuloplasty requires additional anatomic considerations, besides MR mechanisms and aetiology. The procedure is indeed heavily dependent on pre-procedural screening based on CT scan in order to assess:

- technical feasibility, based on the relationship between circumflex artery and posterior annulus;
- annulus sizing and thickness/shape;
- the anatomy of the left atrium (LA) and IAS (preparatory to tailored TSP);
- spatial co-ordinates for the procedure and the expected fluoroscopic projections.

The optimal site for the TSP is predefined by CT planning and must be straight above the posteromedial commissure. The steering and navigation of the implant delivery system along the posterior annulus are guided by different

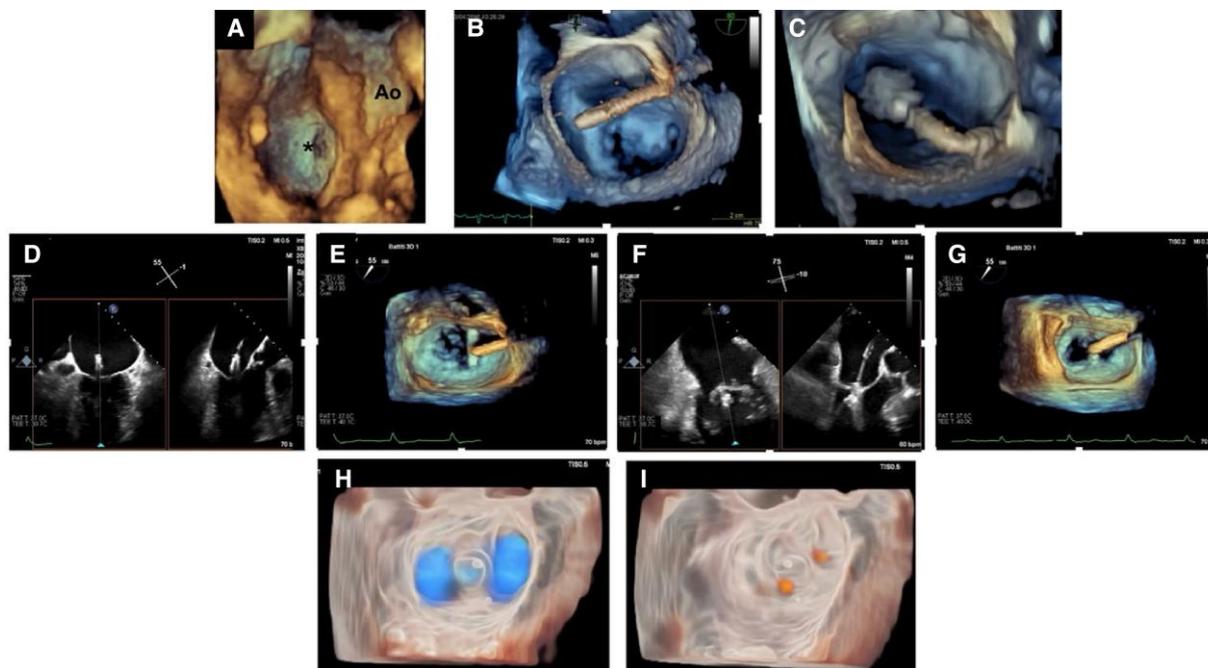


Figure 4 Transcatheter edge-to-edge repair. (A) 3D en-face view of fossa ovalis may allow for finest individuation of transeptal puncture site (asterisk). (B and C) Delivery system extrusion into the left atrium and navigation toward mitral valve plane by 3D overhead perspective of left atrium. (D) Trajectory and axial alignment of delivery system in relation with mitral valve plane, by simultaneous biplane view. (E) Device arms orientation evaluated on 3D surgical view of mitral valve. Leaflets capture and assessment of leaflet insertion by simultaneous biplane view (F) and 3D surgical view (G). 3D transparency rendering en-face view of the mitral valve with colour Doppler showing clearly the double orifice (H) and trivial residual regurgitation (I). Ao, aorta; DS, delivery system; LA, left atrium; LV, left ventricle; MV, mitral valve.

3D perspectives (3D overhead of LA) and the fluoroscopic LAO CAU views. After reaching each target point, RAO projection, several 2D and simultaneous biplane views, and extensive use of MPR, allow assessment of proper distance from the hinge point of the posterior leaflet and the device angulation for fine adjustment, and for checking proper anchoring via a push-and-pull test. Systematic coronary angiography during the procedure rules out the risk of circumflex artery injury. After the last anchor deployment and disconnection of the device, the size adjustment tool is inserted and connected to the spool of the implant that is then contracted while the reduction of MR severity and annulus size is monitored.

Transcatheter mitral valve replacement

The current available devices differ for design characteristics and anchoring/sealing mechanisms. 2D/3D echocardiography together with MDCT are crucial imaging modalities for patient screening and selection, based on a comprehensive examination of MV anatomy, MR mechanism, LV dimension in order to confirm patient eligibility according to specific anatomic characteristics and different prosthetic valve technologies. According to the technology considered, different technical/anatomical needs are addressed by CT-scan analyses, such as interatrial septum and LA size evaluation in case of transeptal approach or LV apex and LV route to MV plane, in case of transapical one.

Annular morphology, size, and calcification are the main aspects explored in the contest of pre-procedural planning in order to identify the patient suitable for transcatheter

mitral valve replacement (TMVR) procedure and identify prosthesis sizing. Study of LV dynamics is also pivotal in TMVR. Beyond the relationship of the LV wall with the annular landing zone, LVOT is an important determinant of replacement outcome. Small ventricles with hypertrophic/hyperdynamic basal interventricular septum are at higher risk of LVOT obstruction and development of systolic anterior motion (SAM) phenomena of the native anterior mitral leaflet.

Two-dimensional TTE and TOE imaging (mid-oesophageal long axis view) are of utmost importance for the assessment of the risk profile of each patient candidate for TMVR: hypertrophic LV with small cavity, AL tissue redundancy are potentially anatomical features for higher risk of post-procedural LVOT obstruction.¹⁴

Finally, a CT-based post-processing simulation to assess the neo-LVOT dimensions and the risk of obstruction after prosthesis implantation using artificial 3D shapes, is currently feasible. Recently, three-dimensional transesophageal echocardiography dataset can be used for the simulation analysis of neo-LVOT and the risk of obstruction (Figure 5).

Intra-procedural guidance relay mostly on 3D simultaneous biplane view for the delivery system proper positioning in the middle of MV and gradual prosthetic valve deployment (providing detailed 2D imaging of the annulus and the prosthesis sitting), and on 3D overhead view of MV, for proper deployment and valve orientation/rotational adjustment (Figure 5). Once deployed, effective prosthesis sealing and functioning must be assessed by 2D/3D colour Doppler imaging. Left ventricular outflow tract obstruction should be evaluated by 2D imaging: mid-oesophageal three-

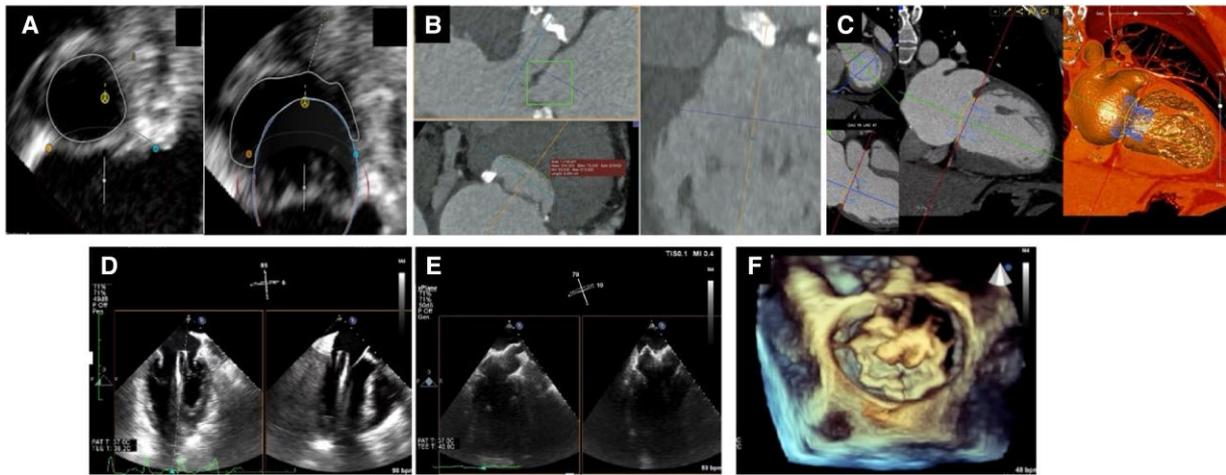


Figure 5 Neo left ventricular outflow tract assessment by multiplanar reconstruction of 3D transesophageal dataset (A) and MSCT dataset (B). (C) Simulation of prosthetic valve implantation by 3D modelling, is concordant with suitable TMVR procedure. (D) Intra-procedural guidance: the introduction of the sheath, wire, and delivery system transapically, is monitored by simultaneous biplane view, in order to properly evaluate the spatial position of the devices in terms of medial-lateral and anterior-posterior location (in particular, to exclude aorta and chordal engagement). Prosthetic valve deployment monitored by simultaneous biplane view (E) and 3D overhead perspective of left atrium (F).

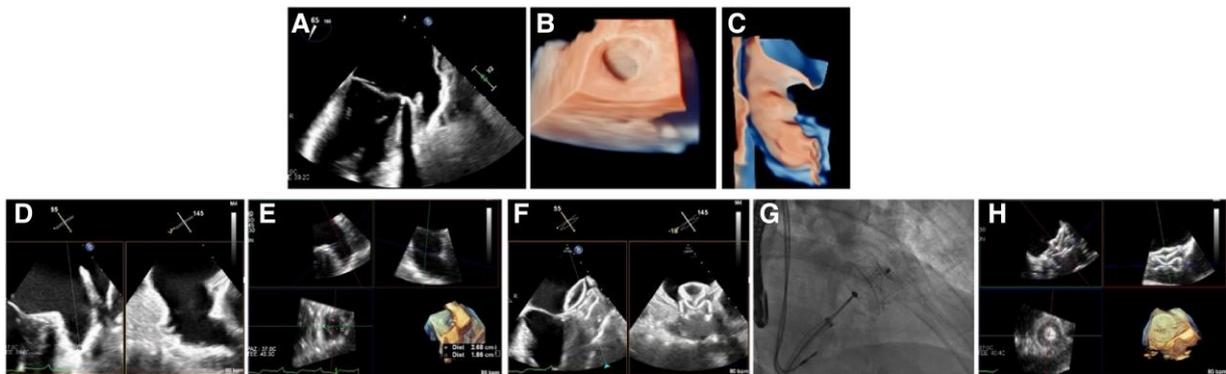


Figure 6 (A) 2D mid-oesophageal view of left atrial appendage. (B) 3D true view en-face perspective of left atrial appendage orifice. (C) 3D lateral perspective of left atrial appendage with glass rendering: it may allow for an intuitive 3D perception of left atrial appendage morphology by creating a sort of 'cast volume'. (D) Simultaneous biplane view of left atrial appendage. (E) Multiplanar reconstruction (MPR) allows for fine morphology assessment and orifice/landing zone measurement. (F) Left atrial appendage occlusion device deployed under simultaneous biplane view since 2D imaging ensures higher spatial and temporal resolution for fine monitoring of device positioning/sealing. (G) Right anterior oblique cranial fluoroscopic projection. (H) Left atrial appendage occlusion device position and sealing evaluation by in-live multiplanar reconstruction. RAO, right anterior oblique.

chamber view may evidence the presence of SAM and flow acceleration with the colour Doppler, while deep transgastric views may be necessary to measure the outflow tract peak gradient.

Left atrial appendage occlusion

Transcatheter left atrial appendage occlusion (LAAO) was developed in the early 2000 as an alternative to anticoagulants for ischaemic strokes prevention in atrial fibrillation (AF). Left atrial appendage occlusion is based on the observation that in non-valvular AF, the thrombus is in LAA in more than 90% of cases.¹⁵

The two most used devices are Watchmann (Boston Scientific Corporation) with single lobe design and Amplatzer (Abbott Vascular) with a distal lobe and a proximal disc and their evolution has improved safety and technical success rates.

Pre-procedural planning

From the earliest procedures, TOE was the standard pre-procedural imaging for LAAO, however, in the recent years CT imaging is becoming more popular providing a more accurate assessment of the LAA morphology and dimensions. The improvements in 3D TOE quality imaging and new volume rendering modalities allow contrast-less LAAO with the selection of device size completed on echocardiographic imaging only¹⁶ (Figure 6 A-C). Since patients referred for LAAO present a high prevalence of renal insufficiency, the feasibility of contrast-less LAAO abolishes the risk of developing acute kidney injury after the procedure. On the other side, in patients without renal insufficiency, the addition of pre-procedural planning with CT imaging was associated with significantly higher successful device implantation rate and less frequent change of device size.¹⁷

Intra-procedural guidance

Transesophageal and fluoroscopy are still the most used imaging techniques for intra-procedural monitoring although the intra-procedural guidance is shifting towards a minimalist approach including the use of ICE for guidance and early discharge (on the same day of the procedure) (Figure 6 D-H). Intracardiac echocardiography is an alternative to standard TOE guidance with the advantages of avoiding the general anaesthesia and the option that the ultrasound catheter can be manipulated by the interventionalist himself. Early discharge has been demonstrated safe with both TOE and ICE and in some US academic centres up to 25% of patients are discharged on the same day as the procedure.

Transcatheter tricuspid valve interventions

Tricuspid regurgitation (TR) is a frequent finding on routine echocardiography. Its prevalence increases with ageing, but moderate and severe or more than severe TR are associated with worse outcome. Evaluation of patients with TR could be challenging, and the optimal timing of intervention remains unclear, although it should be carried out sufficiently early to avoid irreversible right ventricular (RV) dysfunction.⁵

In the last years, several transcatheter techniques have emerged as alternative options to surgery in patients at high/prohibitive surgical risk. The number of patients treated with these techniques is still limited and data on long-term outcomes are slowly emerging.

Pre-procedural evaluation

Multimodality imaging is essential for patient selection as well as procedural planning, with a systematic approach for grading TR, identifying its mechanism and

determining the suitability to catheter-based interventional therapies.

As the three tricuspid valve (TV) leaflets could seldom be visualized simultaneously with 2D echocardiography, 3D echocardiography is nowadays recommended to completely evaluate the TV.

TTE is the first-line imaging test, as the anterior location of the valve permits good visualization with this approach. Transesophageal may provide additional information¹⁸: multiple views at several depths (mid-oesophageal, deep oesophageal, and transgastric), and plane angles, along with the use of simultaneous biplane imaging, are needed

In addition, parametric imaging based on specific software could increase the reproducibility and accuracy of RV and TV remodelling parameters.

Multidetector computer tomography is mandatory for patient selection and procedural planning for transcatheter annuloplasty and orthotopic or heterotopic replacement. Multidetector computer tomography is superior in the measurement of the TV annulus, assessment device landing zone and relationship between the annulus and the right coronary artery, evaluation of annular tissue quality and RV anatomical features.

Intra-procedural guidance

Transesophageal and fluoroscopy are essential to guide transcatheter tricuspid intervention. In the case of sub-optimal transoesophageal acoustic window, multimodality imaging combining TTE, TOE, and ICE could be considered to ensure the best-quality intra-procedural guidance.¹⁹⁻²¹

Transcatheter edge-to-edge repair

TV leaflets approximation systems (TriClip (Abbott Laboratories) and Pascal systems (Edwards Lifesciences))

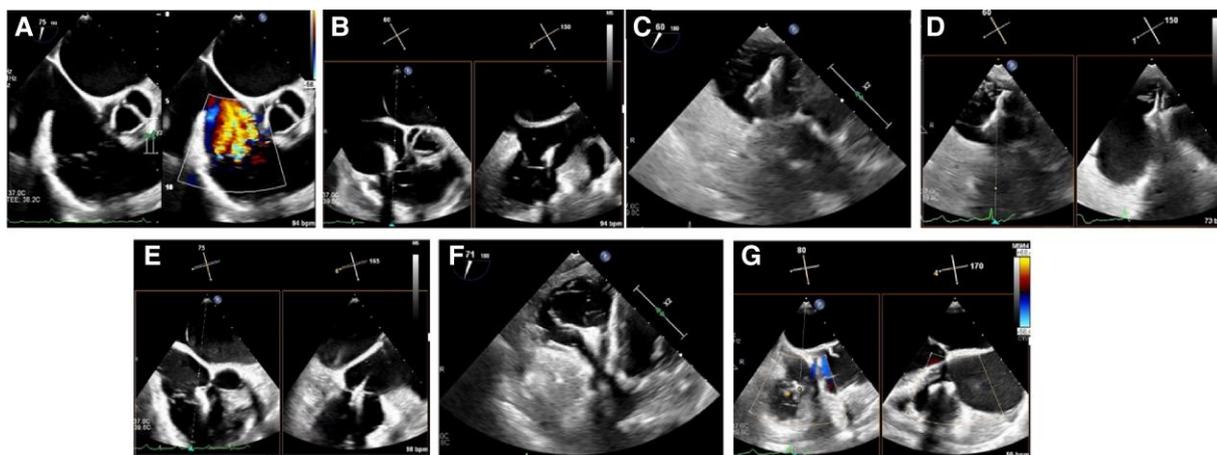


Figure 7 Tricuspid valve repair by leaflet approximation procedure monitored by 2D/3D transesophageal. (A) Baseline evaluation of tricuspid regurgitation by 2D mid-oesophageal inflow-outflow view with colour Doppler helps for spatial localization of regurgitant jet/jets in terms of anteriority (marked by aortic valve) and posteriority. (B) The same mid-oesophageal view used as reference plane for simultaneous biplane view during intra-procedural monitoring, allows for fine positioning of the delivery system over the regurgitant lesion and helps in defining the trajectory over the TV plane. (C) Transgastric short axis view of TV is of utmost importance and discriminating in the patients screening process. It allows for proper device position over the regurgitant lesion and device arms orientation in relation with coaptation line. (D) TG simultaneous biplane view showing leaflets captured by the device. Proper leaflets insertion can be then confirmed by mid-oesophageal simultaneous biplane views (E). (F) Transgastric short axis view showing device realized in the antero-septal region with approximation of leaflets. (G) Final result assessment by mid-oesophageal simultaneous biplane view with colour Doppler. ME, mid-oesophageal; DS, delivery system; TG SAX, transgastric short axis.

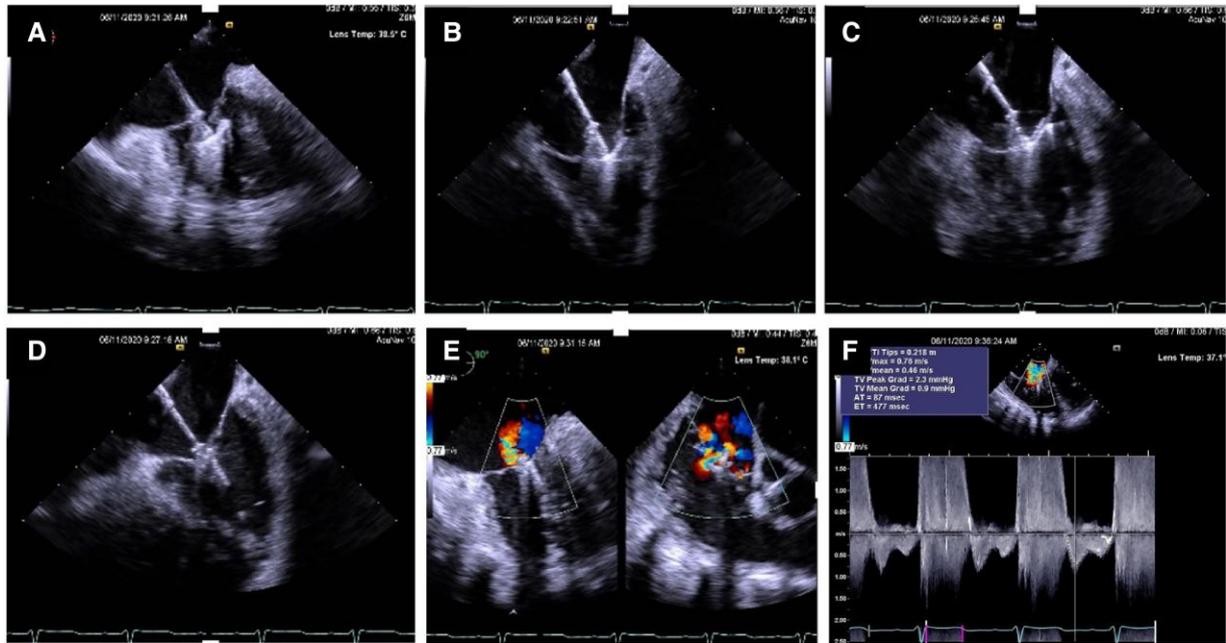


Figure 8 Tricuspid valve repair by leaflet approximation procedure monitored by 3D intracardiac echocardiography. (A) Device with open arms just below the TV annular plane. (B) Leaflets inside the device arms. (C and D) Leaflets capture. (E) Residual regurgitation evaluated by simultaneous biplane view with colour Doppler. (F) Transvalvular gradient assessment by CW. Courtesy by Mani Vannan, Marcus Heart Vale Center, Piedmont Heart Institute, Atlanta.

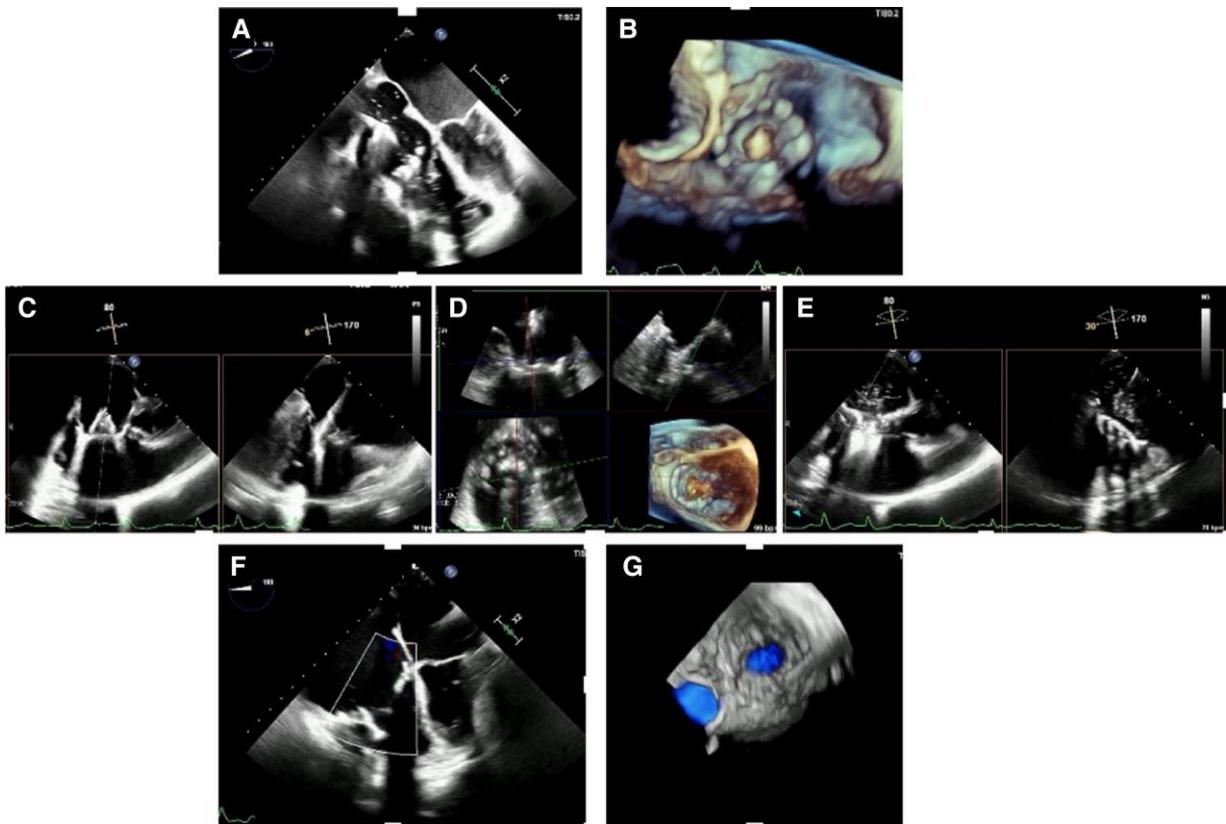


Figure 9 Transcatheter TV replacement with CardioValve prosthesis. The device delivered and oriented over the valve plane evaluated by 2D mid-oesophageal view (A) and 3D overhead perspective of right atrium (B). (C) Mid-oesophageal simultaneous biplane view of the device pulled back toward TV, entrapping the leaflets. (D) 3D multiplanar reconstruction allows for fine evaluation of the leaflet grasping. Once the proper entrapment of the leaflet is confirmed the atrial portion of the device can be safely realized under mid-oesophageal simultaneous biplane view (E). Final result assessment of the prosthesis completely released, by 2D (F) and 3D (G) imaging with colour Doppler, showing no paravalvular leak and normal antegrade flow. ME, mid-oesophageal; RA, right atrium; PVL, paravalvular leak.

aims to restore coaptation between leaflets reducing the regurgitant orifice area. Transesophageal is currently the most adopted imaging technique for intra-procedural guidance using specific echocardiographic tools according to the procedural steps (Figure 7). TTE is used as an alternative or complementary to TOE in case of suboptimal quality of TOE imaging. Intracardiac echocardiography is emerging either as a complementary or an alternative imaging technique in patients in whom TOE is contraindicated or suboptimal, or in some centres as a primary intra-procedural imaging choice (Figure 8). Various approaches for guiding TV interventions have been described even though imaging planes are not standardized due to the complex and variable anatomy of the TV, requiring individual adaptations.

Direct annuloplasty

During the implantation of annuloplasty devices, it is essential to visualize the annulus. For Cardioband™ implantation, TOE is essential to identify the angulation between the anchors and the annulus and the muscular tissue where the screw is implanted. Intracardiac echocardiography is emerging either as a complementary or an alternative intra-procedural imaging technique to TOE.

Orthotopic valve implantation

Intra-procedural TOE guidance and fluoroscopic monitoring are of critical importance for correct orthotopic valve implantation in TV position and procedural success (Figure 9). Transesophageal, based on 2D and 3D, is fundamental for navigation inside the right atrium towards the annular plane imaging, positioning of the delivery system, and to achieve the best orientation and axial alignment, and for final assessment bioprosthetic functioning and residual paravalvular regurgitation.

Innovation in imaging techniques for structural heart diseases interventions

In line with the developments of new devices, novel or refinements of imaging tools have emerged to improve the pre-procedural and intra-procedural guidance.

Intracardiac echocardiography represents one of the major progresses in cardiac imaging and it has been adopted in a variety of percutaneous interventional and electrophysiology procedures like atrial septal defect closure, LAAO, TV procedures, and ablations of arrhythmias (Figures 8 and Figure 10). Intracardiac echocardiography is recorded through a catheter placed in the right

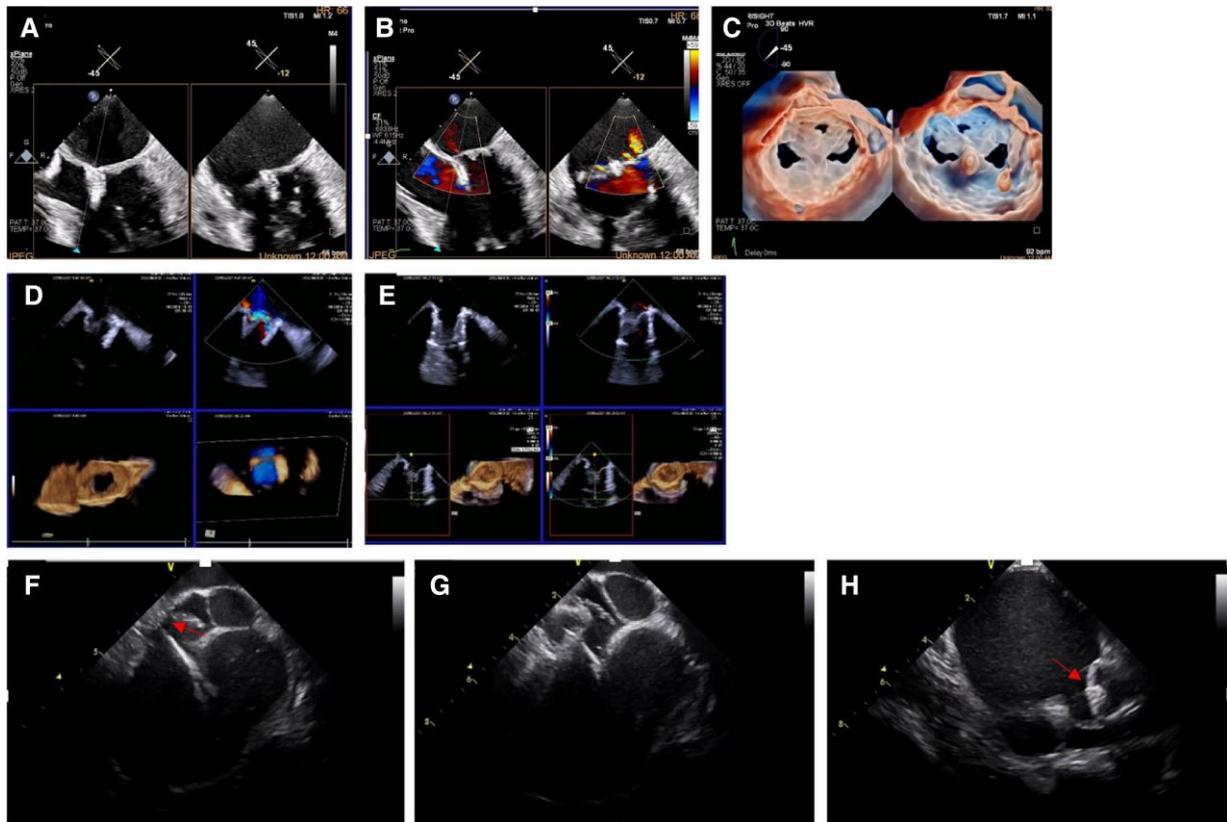


Figure 10 ICE intra-procedural monitoring of different transcatheter procedures. Transcatheter edge-to-edge mitral valve repair. final assessment by simultaneous biplane view without and with colour Doppler (A and B) and 3D en-face perspective from left atrium (left) and left ventricle (right) (C) through transparency volume rendering. Transcatheter valve-in-valve procedure. (D) Baseline evaluation of mitral bioprosthesis dysfunction by 2D and 3D imaging with and without colour Doppler. (E) Final assessment by 2D and 3D imaging with and without colour Doppler. Courtesy by Mani Vannan, Marcus Heart Vale Center, Piedmont Heart Institute, Atlanta. Left atrial appendage occlusion. (F) Initial device deployment (arrow). (G) Device deployed. (H) Device anchored finally released (arrow). MV, mitral valve; LA, left atrium; LV, left ventricle.

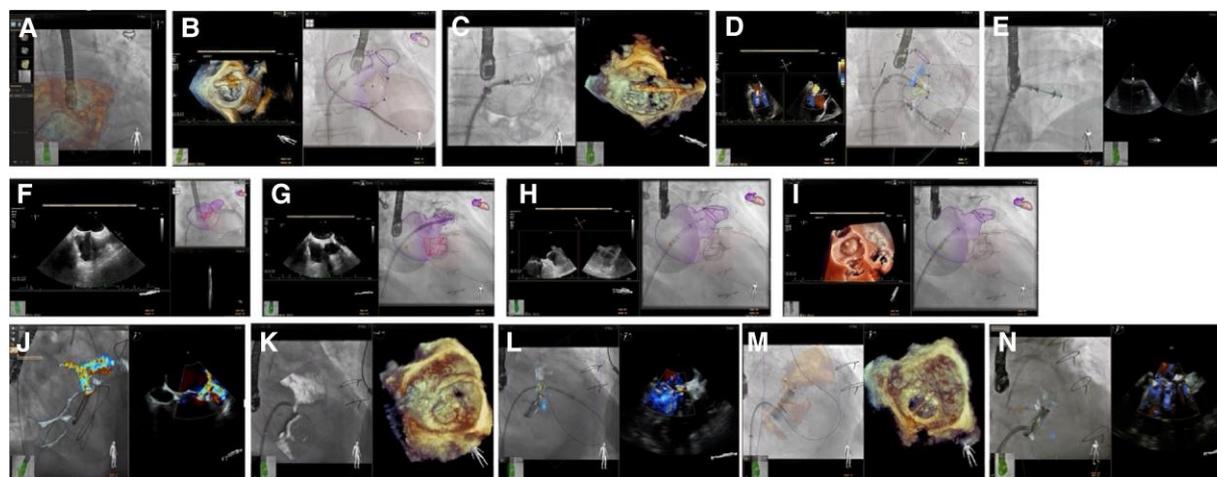


Figure 11 Fusion imaging in different transcatheter procedures. (A-E) Transcatheter edge-to-edge mitral valve repair. (F-I) Left atrial appendage occlusion. (J-N) Percutaneous mitral paravalvular leak closure.

atrium or right ventricle with a transducer at the tip and can be performed under conscious sedation directly by the interventionalist without the need for endotracheal intubation. This technique has undergone great improvements during the last years now providing all conventional echocardiographic modalities and including 4D with wider acquisition volumes and real-time MPR.²² The limits of this imaging modality concern its invasive nature, the limited field of view and reduced depth penetration and the high costs of the catheter.

The fusion imaging technique is able to acquire imaging data from both fluoroscopic and TOE images, and align them in terms of 3D space and in time, putting X-ray and echo onto the same co-ordinate system. The result is a sort of hybrid image, which has the advantage of providing an immediate degree of confidence to interventionists since soft tissues are displayed superimposed to the ‘familiar’ fluoroscopic images. Fluoroscopic-echocardiographic fusion imaging supports both live 2D echocardiography with or without colour Doppler, simultaneous multiplane imaging, live 3D volume rendering and partial-thickness of 2D slices derived by 3D dataset, heart model derived from artificial intelligence algorithm which can be moved from near-to-far in the direction of the fluoroscopic beam. Furthermore, since fluoroscopic-echocardiographic fusion imaging is bridging the world of X-ray and echocardiography, potentially simplifying SHD scenario²³⁻²⁵ (Figure 11). It allows the user to improve the understanding of anatomical structures imaged by TOE providing the ability to reproduce new and unusual echocardiographic projections by manipulating the images at the table site. However, in our opinion, the fusion imaging has the greatest clinical utility in two scenarios: to guide the paravalvular leak closure and to monitor the valve-in-valve and valve-in-ring procedures in presence of radiolucent prosthesis. A potential disadvantage is an excess of information that could distract an inexperienced operator during the intervention.

Finally, Cardiac 3D printing is a new emerging tool that enables the production of patient-specific cardiac anatomical replicas based on imaging data. Cardiac 3D

printing was already explored in the pre-procedural planning for transcatheter interventions granting a real interventional simulation. The widespread of this technique is hampered by lack of standardization, the imperfect physical properties of these models and its cost.²⁶ Probably the future development of augmented reality technologies will quickly make this new technique obsolete.

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Data availability

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