Review Article

Echocardiographic guidance of interventions in adults with congenital heart defects

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Abstract: Cardiac catheterization procedures have revolutionized the treatment of adults with congenital heart disease over the past six decades. Patients who previously would have required open heart surgery for various conditions can now undergo percutaneous cardiac catheter-based procedures to close intracardiac shunts, relieve obstructive valvular lesions, stent stenotic vessels, or even replace and repair dysfunctional valves. As the complexity of percutaneous cardiac catheterization procedures has increased, so has the use of echocardiography for interventional guidance in adults with congenital heart disease. Transthoracic, transesophageal, intracardiac, and three-dimensional echocardiography have all become part and parcel of the catheterization laboratory experience. In this review, we aim to describe the different echocardiographic techniques and their role in various cardiac catheterization interventions specific to adults with congenital heart disease.

Keywords: Echocardiography; guidance; interventions; adult congenital heart disease (ACHD); catheterization

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Introduction

Cardiac catheterization procedures have revolutionized the treatment of adults with congenital heart disease over the past six decades. Patients who previously would have required open heart surgery for various conditions can now undergo percutaneous cardiac catheter-based procedures to close intracardiac shunts, relieve obstructive valvular lesions, stent stenotic vessels, or even replace and repair dysfunctional valves (1). From the very first cardiac catheterization by Dr. Werner Forssmann in 1929 (2), to the early days of percutaneous treatments with balloon atrial septostomy by Dr. William Rashkind in 1966 (3), the imaging modality inherently tied to cardiac catheterization has been fluoroscopy and angiography. Over the past 20 years, however, as the complexity of percutaneous cardiac catheterization procedures has increased, the limitations of fluoroscopy and angiography have become apparent. Fluoroscopy of the heart only provides two-dimensional (2D) images of a three-dimensional (3D) structure, which can lead to incomplete spatial assessments (1). Many advanced imaging modalities, such as cardiac magnetic resonance (CMR) and cardiac computed tomography (CT), have emerged as invaluable tools for pre-procedural planning to delineate structural anatomy and function (4). Nevertheless, echocardiography, with its excellent temporal and spatial resolution (with the advent of 3D echocardiography), has become a very attractive adjunctive imaging modality during interventional procedures (1,5). Thus, as the field of interventional cardiology has grown, so has the use of echocardiography for interventional guidance in adults with congenital heart disease (1,6,7).

In this review, we aim to describe the different echocardiographic techniques and their role in various cardiac catheterization interventions specific to adults with congenital heart disease.

Table 1 The relative utility of transthoracic echocardiography (TTE), transesophageal echocardiography (TEE) and intracardiac echocardiography (ICE) in the guidance of commonly performed congenital trans-catheter interventions: patent foramen ovale (PFO) closure, atrial septal defect closure (ASD), ventricular septal defect (VSD) closure, mitral valve (MV) interventions, aortic valve (AoV) interventions, tricuspid valve (TV) interventions and pulmonary valve (PV) interventions

Imaging modality	PFO closure	ASD closure	VSD closure	MV interventions	AoV interventions	TV interventions	PV interventions
TTE	+	+	–	–	++	+	+
TEE	+++	+++	+++	+++	+++	++	++
ICE	+++	++	+	+	+	++	+++

Transthoracic echocardiography (TTE)

TTE is the workhorse of cardiology and is integral to the pre-procedural assessment of any adult congenital heart disease (ACHD) patient. Given the various different anatomical anomalies and subsequent surgical repairs/palliations, a complete echocardiographic assessment via TTE should be performed before a cardiac catheterization and after catheter-based interventions. A TTE can be useful for preprocedural planning, gauging the risk of periprocedural complications, or assessing the need for procedural support with cardiac anesthesia or the need for mechanical support in patients with ventricular dysfunction. Furthermore, it can be used to confirm or refute diagnoses in patients who have been referred for catheter-based or surgical procedures. TTE has the favorable characteristics of being cost-effective, universally available, and does not subject the patient to radiation. The use of TTE to guide intraprocedural imaging has been limited given the superiority of transesophageal echocardiography and intracardiac echocardiography (ICE) for the visualization of atrial structures and left sided valves (*Table 1*).

Transesophageal echocardiography (TEE)

Unlike the TTE, a TEE is widely considered the echocardiographic imaging modality of choice during catheterization interventions in patients with complex congenital heart disease. Cardiac fluoroscopy can be used concomitantly with TEE imaging (unlike TTE when the probe and the sonographer's hand may be in the field of view) (1). Furthermore, TEE imaging has better image resolution compared to TTE and is superior to TTE when monitoring catheter position, imaging atrial and ventricular level defects, excluding atrial thrombus, or assessing left sided valvular anatomy (6). Unfortunately, periprocedural TEE does have some drawbacks. A cardiac catheterization procedure that utilizes TEE will require two operators (the catheterizer and the echocardiographer), and thus a successful procedure will require effective communication and a high level of coordination between the operators. Furthermore, a TEE usually requires deep sedation and may require endotracheal intubation for patient comfort. Finally, the proximity of the sonographer to the X-ray tube in most catheterization laboratories also leads to an increased radiation dose to the TEE sonographer (1).

Intracardiac echocardiography (ICE)

ICE is a newer imaging modality compared to TEE and TTE (8). ICE has great potential to be a procedural adjunct for monitoring and guiding interventions. First described in 1981, ICE is a catheter-based steerable ultrasound probe that is introduced into the right heart chambers and displays cardiac images from inside the heart (9). As phased-array probes were developed in the early 1990s, ICE quickly gained popularity throughout interventional and electrophysiology (EP) laboratories around the world, specifically for imaging the atrial septum from a right atrial location (*Figure 1*) (10). Compared to TEE, ICE obviates the need for a second operator. There may be a learning curve, however, to understand how to deftly manipulate the probe to visualize desired structures (9). Furthermore, general anesthesia is not required for ICE imaging, and some studies have shown that ICE can shorten procedure and fluoroscopy times (6). The cost seems to be also comparable with TEE interventions (11). In patients where TEE is contraindicated or may be dangerous (i.e., patients with esophagectomy, or large esophageal varices), ICE may be an attractive imaging modality as well. ICE can also be very useful in evaluating cardiac structures when TEE imaging is not optimal, such as in the setting of a mechanical valve (causing shadowing artifact), or for anterior right-sided cardiac structures (6). Nevertheless,

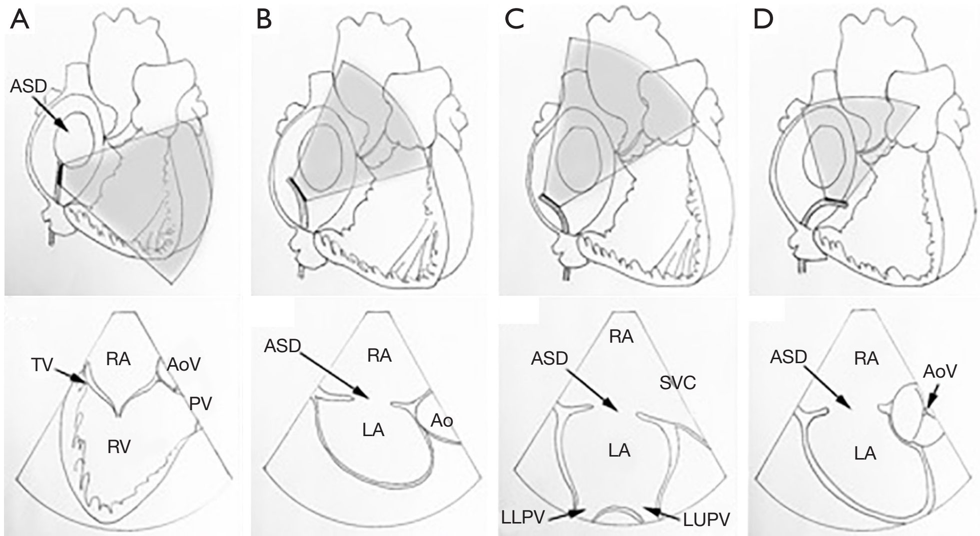

Figure 1 Intra-cardiac echocardiography (ICE) for assessment of an ostium secundum atrial septal defect (ASD). (A) Home view with the ICE catheter within the mid-right atrium (RA) and the ultrasound array facing anterior and leftward along the long axis of the heart through the tricuspid valve. The right ventricle and membranous ventricular septum can be assessed in this view. This view affords the operator a long-axis view of the tricuspid valve (TV) and of the septal and posterior leaflets. The aortic valve (AoV) and pulmonic valve (PV) can also be visualized; (B) posterior flexion and clock-wise rotation of the catheter affords a long-axis view of the ASD with assessment of the superior and inferior rims. The left atrium (LA) and aortic root (Ao) are visualized; (C) further posterior flexion with further clockwise rotation allows visualization of the superior vena cava (SVC) and left upper and lower pulmonic vein ostia (LUPV/LLPV); (D) continued clock-wise rotation eventually brings the catheter anteriorly and allows visualization of the aortic valve in short axis (AoV) and assessment of the retro-aortic rim of the ASD.

ICE is not a benign procedure and does require a second venous puncture with at least an 8 or 10 French sheath (1). Other complications include retroperitoneal bleed, perforation of venous structures, pericardial effusion from a cardiac perforation, induced atrial/ventricular ectopy and arrhythmias, and thromboembolism (6).

3D echocardiography

With the development of matrix array transducers, both TTE and TEE probes have the ability to image in real-time 3D (12). ICE catheters have also recently been developed with 3D capabilities, but have limited distribution currently given their novelty (13,14). 3D technology can accurately depict cardiac structures and visualize long segments of catheters and entire devices in one view with limited manipulation, which makes it an ideal imaging modality during interventional procedures (15). Applying 3D echocardiography during interventional procedures has led to more effective myocardial biopsies in terms of safety and efficacy, improved analysis of mitral valve pathology, and improved planning of percutaneous approaches for complex procedures such as paravalvular leak occlusion, and improved sizing of intracardiac defects such as atrial septal defects (ASDs) or ventricular septal defects (VSDs) (6). Nevertheless, 3D imaging has not become ubiquitous during catheterization procedures. Many interventional cardiologists and echocardiographers have become accustomed to working with 2D images, and carefully standardized 2D views have been established for complex structural interventional cases (15). Furthermore, unlike 2D TTE and TEE imaging, 3D imaging does not have a standardized set of views during procedures, and requires real-time manipulation of the 3D dataset acquisition (cropping, rotating) during the procedure, which may increase complexity (15). 3D TEE can be helpful in monitoring right ventricular (RV) function before and after ASD closure, and can be used to predict which patient may need closer monitoring post closure due to reduced RV function (16). Recently, the American Society of Echocardiography (ASE) and the European Society of Cardiovascular Imaging (EACVI) have released a consensus document regarding the use of 3D echocardiography in congenital heart disease. This will hopefully lead to more standardized and broad use of this useful modality during catheter-based interventions, especially for closure of ASD/VSDs and visualization of catheters/devices (7).

Echocardiography and fluoroscopic fusion imaging "EchoNavigator"

More recently, with the advent of computerized software that can enable coregistration of two imaging modalities, operators in the catheterization lab can simultaneously visualize two imaging modalities superimposed on each other instead of on two separate monitors. EchoNavigator™ (Philips Healthcare, Best, the Netherlands) is a software package that can fuse echocardiographic images (2D or 3D) with live fluoroscopy images. This allows for placement of markers on echocardiography images that can be shown on fluoroscopy images, which can help with complex structural cases and reducing radiation dose (1,17). Nevertheless, early studies using this technology have not shown a reduction in radiation dose or procedure time, but this may be biased given the initial learning curve required for this new technology (1).

Echocardiographic guidance of various ACHD interventions

ASD/PFO closure

When closing a secundum ASD or PFO, the operator can choose between TTE, TEE, and ICE for procedural guidance (6). TTE has been described for closing ASDs or PFOs in adult patients (18). TTE allows for imaging in multiple planes to evaluate the device and atrial septum, but has limited views of the inferior rim post-device deployment due to device interference. One center performed a randomized trial demonstrating that TTE was as effective as TEE in terms of procedural success and sizing of the ASD closure device in pediatric patients (19). Nevertheless, given the varying degree of body habitus and possibility of poor acoustic windows in adults, most ACHD centers rely on TEE or ICE for percutaneous closure of these defects (6).

TEE is the main echocardiographic modality used for procedural guidance during ASD closures (*Figure 2*), and the pivotal trial for ASD closure device required TEE guidance for the procedure (20). TEE provides detailed and real-time imaging of the interatrial septum, surrounding cardiac structures, catheters, and the closure device. While TEE has many advantages, some disadvantages of TEE include the need for deep sedation or general anesthesia for patient comfort, as well as the need for a dedicated echocardiographer to perform the TEE (6). TEE has mostly been supplanted by ICE for PFO closure but retains an important role in the assessment of the atrial septum, atrial appendage, mitral and aortic valves as well as the aorta in patients with an embolic stroke.

ICE is a newer imaging modality that also provides comparable imaging quality of the interatrial septum and surrounding structures as TEE (*Figure 1*). ICE does not require the use of deep sedation or general anesthesia, which obviates the need for a second operator for echocardiographic guidance, and has also been shown to reduce procedure and fluoroscopy times (11). ICE still requires additional expertise in manipulating the catheter, and thus some operators may not be as comfortable with the imaging, especially of large ASDs. However, it is ideal for guidance of PFO closure and has largely supplanted TEE for this indication (6).

3D imaging, with commercially available TEE, may also be more accurate in assessing ASD size and rim adequacy than 2D alone (1). It can be helpful for assessing multiple defects, such as in the setting of a fenestrated ASD (7). 3D imaging with ICE has been described, but it is still a new technology and has not been widely adopted at the time of this review (13).

VSD closure

There are not as many studies highlighting the use of echocardiography during percutaneous closure of VSDs as compared to ASDs and PFOs. Studies detailing the efficacy of percutaneous VSD closure have described the use of both TEE and ICE during the procedure (21-24). One small study (12 patients in total) compared the use of TEE and ICE for guidance of percutaneous VSD closure and found no difference between modalities when measuring the size of the VSD or for facilitating correct device placement to close the defect (25). In our experience, the use of TEE may be limited in certain patients due to shadowing artifact from mechanical valves or other cardiac structures, and thus ICE is an attractive modality for periprocedural imaging guidance (*Figure 3*). 3D echocardiography with TEE can be used during closure procedures to monitor hardware and device deployment (7), and can also be used post-procedure to assess for any residual shunt.

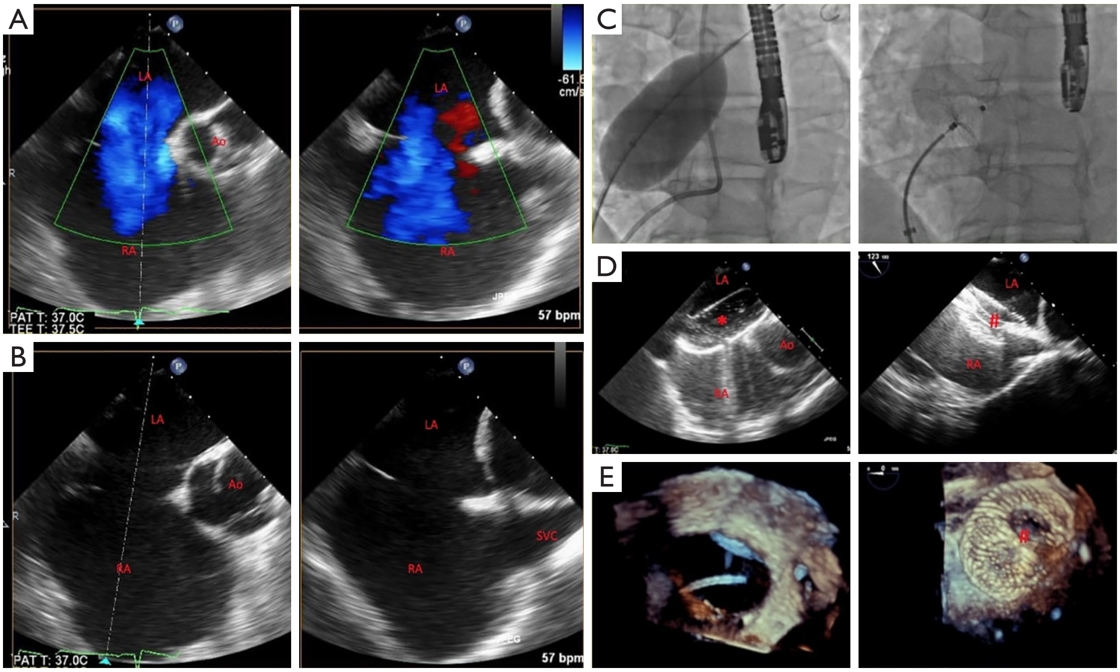

Figure 2 Percutaneous closure of a secundum ASD. (A) 2D TEE with X-plane imaging of the secundum ASD with color Doppler, in the traditional 30–60° and 90–110° view; (B) 2D TEE with X-plane imaging of the secundum ASD without color Doppler in the traditional 40–60° and 90–110° view; (C) fluoroscopic views of the secundum ASD during balloon sizing and after implantation of the 38-mm Amplatzer Septal Occluder closure device; (D) 2D TEE views of the secundum ASD during balloon sizing and after device implantation; (E) 3D TEE views of the ASD with a wire across the lesion and after device implantation. *, sizing balloon; #, ASO device. LA, left atrium; RA, right atrium; Ao, aorta; ASD, atrial septal defect; TEE, transesophageal echocardiography; ASO, atrial septal occluder.

Transseptal puncture guidance

Transseptal punctures are required for many EP studies or left-sided interventions. While transseptal punctures can be done with fluoroscopy alone, most operators use imaging guidance to avoid inappropriate puncture sites (15). Traditionally TEE has been the imaging modality of choice (2D or 3D methods). Usually operators choose a simultaneous biplane view (X-plane) at the mid-esophageal level to visualize the bicaval (90–110°) and the short axis view at the aortic valve (30–60°) (*Figure 4*) (5,17). Visualizing the "tenting" seen with the puncture needle may be more difficult with 3D imaging (15). Since ICE does not need additional sedation or general anesthesia, many centers are adopting ICE as the primary imaging modality during transseptal punctures when imaging is only needed for the transseptal portion of the procedure (6).

Studies have shown that use of EchoNavigator, the fusion imaging software that integrates 2D/3D TEE with fluoroscopy, during transseptal puncture can lead to shorter procedure times and can be particularly helpful in cases where there is complex anatomy of the interatrial septum, such as with an interatrial septal aneurysm or lipomatous hypertrophy (26).

Paravalvular leak

Paravalvular regurgitation is a recognized complication that affects 5–17% of all surgically implanted prosthetic heart valves (17). Currently, TEE is the most widely utilized imaging modality to guide paravalvular leak closure (*Figure 5*). TEE is used to localize defects, describe the number and size of the hole(s), guide catheters and interventional devices across the defect, and to assess the degree of reduction of paravalvular leak after the intervention. TEE also can evaluate for possible complications (pericardial effusion, prosthetic leaflet entrapment) (17). 3D echocardiography is becoming the norm for echocardiographic guidance, and is especially useful in this regard for mitral valve procedures (5). Live 3D is excellent for guiding wires and catheters across

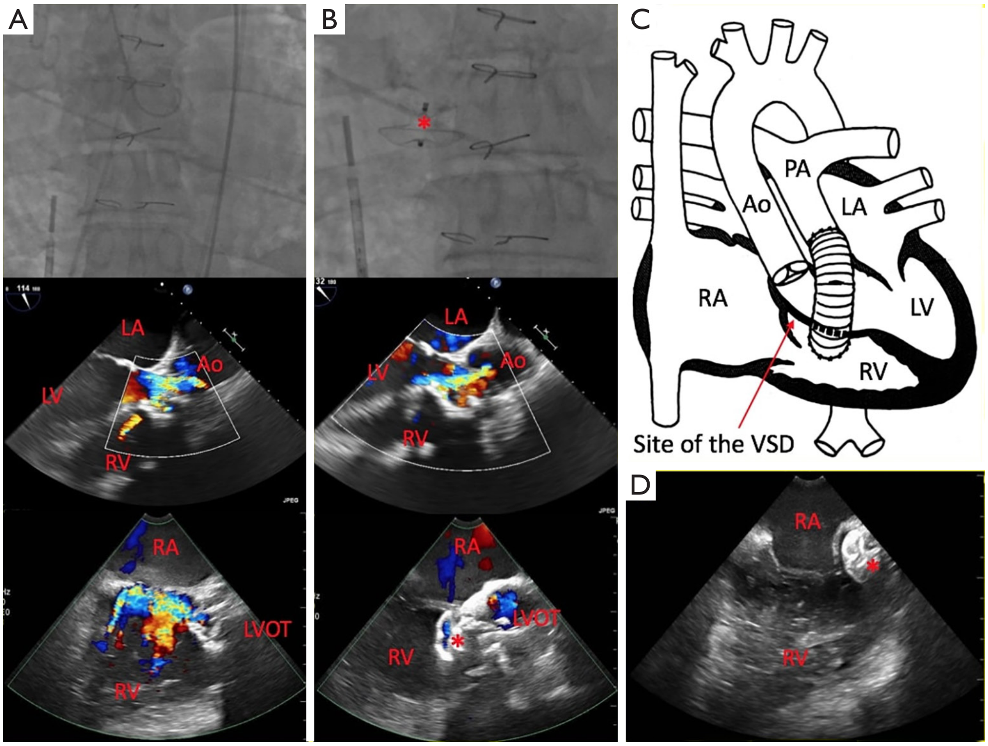

Figure 3 Percutaneous VSD closure. (A) Top to bottom: fluoroscopic, TEE, and ICE views of the VSD. TEE views were suboptimal during this procedure given the location of the defect. ICE was mainly used to guide the intervention; (B) top to bottom: fluoroscopic, TEE and ICE views after a 12-mm ASO device was placed across the defect in the VSD patch, just under the tricuspid valve; (C) representative schematic of the patient's anatomy—double outlet right ventricle status post VSD patch and RV to PA conduit, or "Rastelli Procedure"; (D) view of the ASO device via the ICE catheter in the "Home View". *, ASO device. RA, right atrium; LA, left atrium; RV, right ventricle; LV, left ventricle; PA, pulmonary artery; Ao, aorta; LVOT, left ventricular outflow tract; VSD, ventricular septal defect; ICE, intracardiac echocardiography; TEE, transesophageal echocardiography; ASO, atrial septal occluder.

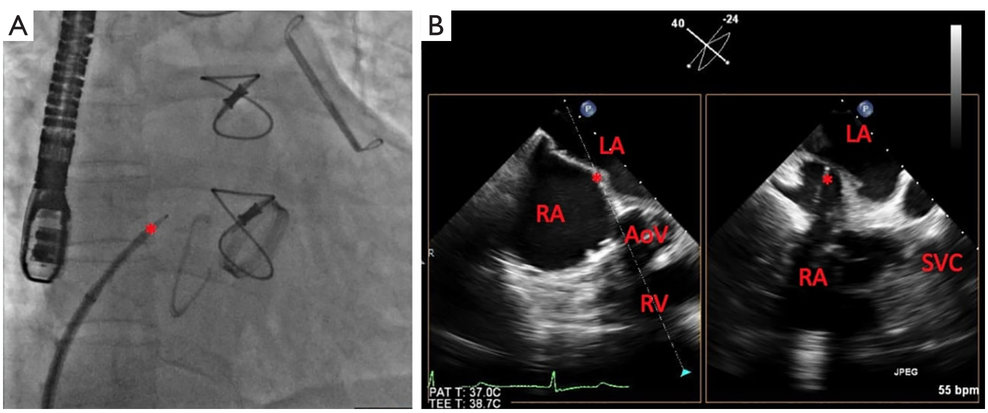

Figure 4 Transseptal puncture. (A) Fluoroscopic view of a the transseptal needle inside the sheath in the AP (anteroposterior) view; (B) 2D TEE X-plane view with the traditional mid-esophageal short axis 30–60° view and bicaval 90–110° view, demonstrating anterior/posterior and superior/inferior orientations of the transseptal needle relative to important cardiac structures like the aorta and posterior wall of the atria. *, transseptal needle. RA, right atrium; LA, left atrium; AoV, aortic valve; RV, right ventricle; SVC, superior vena cava; TEE, transesophageal echocardiography.

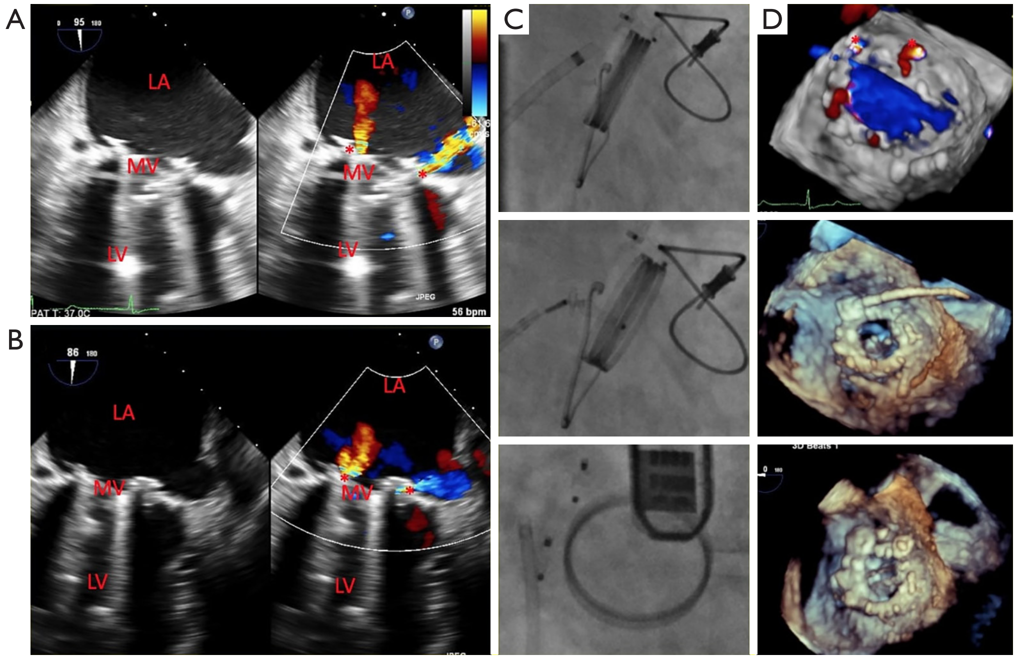

Figure 5 Paravalvular leak occlusion. (A) 2D TEE views demonstrating two areas of paravalvular leak around the mechanical mitral valve; (B) 2D TEE views after percutaneous occlusion of the paravalvular leak leading to a reduction in the severity of the leak; (C) top to bottom: fluoroscopic images during the procedure demonstrating placement of a 4-mm muscular VSD device and then a 6-mm AVP-II plug; (D) top to bottom: 3D TEE image with color to highlight the areas of paravalvular leak, and then 3D TEE images during the procedure to help show catheter position relative to the mitral valve. *, paravalvular leak. LA, left atrium; LV, left ventricle; MV, mitral valve; VSD, ventricular septal defect; TEE, transesophageal echocardiography.

a paravalvular defect (5). When closing periprosthetic aortic valve leaks, anterior defects are best seen with TTE, while posterior defects are seen best on TEE (5). ICE experience is limited during these types of procedures, but our experience has shown that anterior structures such as the tricuspid valve are more conducive to imaging with an ICE modality rather than TEE or TTE, and ICE can be effective at guiding paravalvular leak closures in the tricuspid position.

While no studies have compared the use of fusion imaging to standard TEE or ICE guidance for paravalvular leak procedures, expert operators have remarked on how beneficial having fused images and using 3D TEE-based markers can be for wiring paravalvular defects (26).

Baffle leak in Mustard/Senning atrial switch patients

In patients with dextro-transposition of the great arteries (D-TGA) status post an atrial switch operation, baffle leaks are common sequelae. Baffle leaks can be identified and characterized using many imaging modalities, such as angiography, echocardiography and cardiac MRI (27). One study determined that echocardiograms (TTE or TEE) with an agitated bubble study were more effective at detecting baffle leaks than echocardiographic studies without agitated saline or cardiac MRI (28). One case series detailed their experience with TEE for procedural guidance for baffle interventions, demonstrating it as a safe and effective modality (29). While most baffle leaks are percutaneously closed using TEE for procedural guidance (*Figure 6*), 3D TEE and 2D-ICE are becoming popular as well given the sometimes difficult process of visualizing these small leaks (27). The use of ICE has become more commonplace, and one interventional group described their experience with ICE as an excellent adjunct to fluoroscopy and angiography for localizing baffle leaks and guiding the closure, especially for defects in the inferior portion of the systemic venous baffle (30). Another case series documented three reports of instances when ICE was superior to TEE or

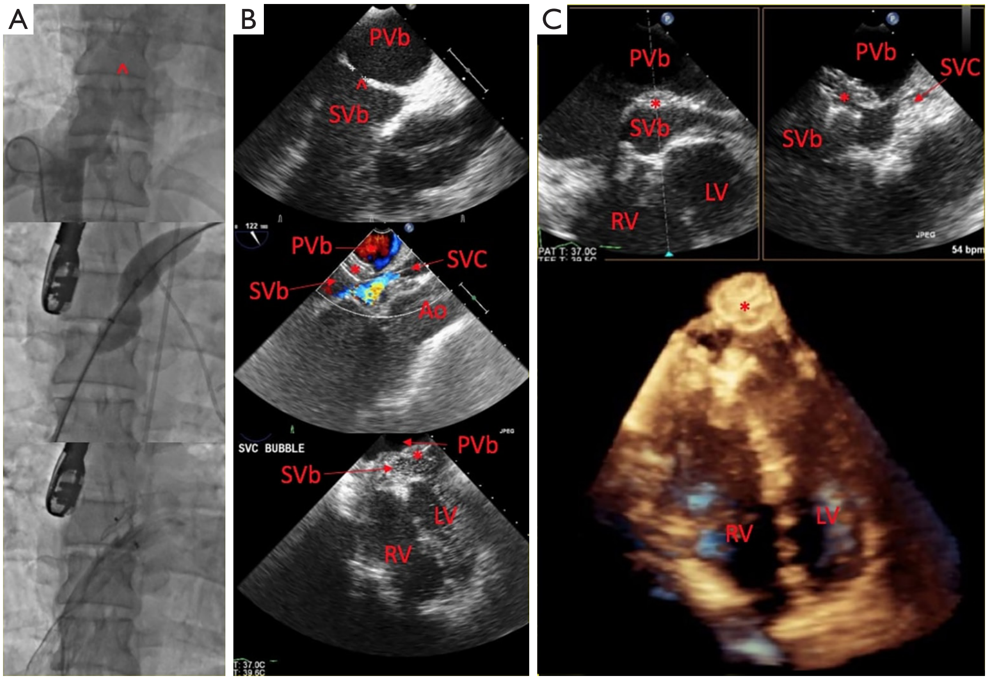

Figure 6 Occlusion of a baffle leak in a patient with D-TGA and a Mustard procedure. (A) Top to bottom: angiography of the IVC baffle demonstrating a small baffle leak (presumed cause of the patient's stroke) between the systemic venous and pulmonary venous baffles. Fluoroscopy with balloon sizing of the defect. Final angiography of the baffle after placement of a 10-mm ASO device to close the baffle leak, demonstrating no more flow across the defect; (B) top to bottom: 2D TEE measuring the baffle defect at 6 mm in diameter. 2D TEE with color Doppler demonstrating no color flow across the defect after placement of the device. Bubble study (from the SVC) with no evidence of right to left shunting; (C) top to bottom: 2D TEE with X-plane depicting the 10-mm ASO device in stable position across the defect with no obstruction of the SVC limb of the venous baffle. 3D TEE demonstrating the device in relation to the ventricles and other cardiac structures. ^, site of the baffle leak; *, ASO device. PVb, pulmonary venous baffle; SVb, systemic venous baffle; RV, right ventricle; LV, left ventricle; SVC, superior vena cava; Ao, aorta; TEE, transesophageal echocardiography; D-TGA, dextro-transposition of the great arteries; IVC, inferior vena cava; ASO, atrial septal occluder.

TTE for real-time imaging guidance for baffle leak closure, since the baffle leaks occurred in unusual orientations or were small in size (31).

Percutaneous valve replacement

Over the past decade, the number of transcatheter valve replacements, mainly for the aortic position in adults with calcific aortic stenosis, has increased dramatically (32). There is an increasing number of implants in congenital aortic stenosis and regurgitation patients as well. The use of transcatheter valves in the pulmonary position has become commonplace in the congenital population with dysfunctional RV outflow tracts (33). There is also a growing number of implants in the tricuspid and mitral positions (34).

Transcatheter aortic valve replacement (TAVR)

When performing a TAVR, the use of multimodality imaging (echocardiography, angiography, fluoroscopy) during the procedure is key to a successful outcome (17). TTE plays an important role in establishing the need for a valve replacement and can help with preprocedural planning (35). Sizing of the aortic annulus is more accurate with TEE than with TTE, and is recommended when a computerized tomography angiogram (CTA) cannot be performed (i.e., chronic kidney disease) (35). Periprocedurally, TTE can be used for locating the apex of the heart and marking the optimum point of entry on the skin for a transapical approach, as well as post-implantation assessment of valve positioning and paravalvular or intravalvular regurgitation (5). TEE use for intraprocedural guidance, whether to position the balloon during valvuloplasty, help position the prosthesis during implantation, or to assess prosthesis function post-implantation, or to detect complications, is variable (5). Since TEE may require general anesthesia and can interfere with visualizing the aortic annulus during fluoroscopy, some operators prefer not to use TEE during the procedure and rely on TTE before and after valve implantation for assessing the prosthetic valve function (5,17,35). The benefits of TTE or TEE for imaging guidance during TAVR procedures are debated in the literature (36), but the decision should be made on an individual basis depending on operator preference and patient characteristics. The use of 3D echocardiography (mainly TEE) is also very helpful in sizing the aortic annulus and determining coronary heights pre-procedure and is very effective post-procedure for evaluating paravalvular or intravalvular regurgitation (35). The use of ICE for TAVRs is not as popular due to the challenge of securing a stable adequate window during the procedure, and currently is not a first-line imaging modality (35,37). Nevertheless, a small randomized study of 50 patients demonstrated that ICE is comparable to TEE in terms of image quality and hemodynamic assessment of the aortic prosthesis post-implantation (38). One of the downsides of periprocedural echocardiography during a TAVR, however, is the positioning of the machine and the echocardiographer to allow for free movement of the fluoroscopy cameras. Furthermore, the amount of radiation exposure to the echocardiographers is always a concern (35).

Right-sided valves

For patients requiring transcatheter valve replacement of right-sided valves, such as the pulmonary valve, the use of TEE may not be ideal given the anterior location of these structures. For these procedures, when imaging guidance is needed, the use of ICE has been demonstrated to be quite effective. The ICE catheter can be manipulated into the RV and directed coaxially with the RV outflow tract and pulmonary valve, leading to excellent images of the entire region and accurate measurements of the valve gradients pre and post-implantation (37,39-41). Furthermore, angiography of valve function is limited by catheter-induced regurgitation, which is not an issue with ICE (37,39-41). Nevertheless, operators vary widely in their use of periprocedural imaging for transcatheter valve implantations.

Valve-in-valve replacement

The use of transcatheter valve implantation in existing prosthetic valves, or “valve-in-valve”, technique, has also become more popular in patients who may no longer be a surgical candidate or who prefer a transcatheter procedure over open-heart surgery (*Figure 7*). One registry of 156 patients undergoing a procedure for a transcatheter valve-in-valve tricuspid valve replacement described a wide variability in the modality of intraprocedural echocardiography. Most patients (82%) had intraprocedural echocardiography, but patients receiving a Melody valve were mainly split between TEE and ICE (48% *vs.* 38%), while those receiving a Sapien valve mainly had TEE (88%) for procedural guidance, suggesting that the decision for procedural imaging depends largely on the operator and their comfort with the imaging modality used (42).

For the mitral position, since it is a left-sided structure, TEE is the imaging modality mainly used, especially since a transseptal puncture is usually needed (43). ICE has been described for mitral valve procedures, such as MitraClip, but it remains a suboptimal imaging modality since it does not allow for adequate left atrial visualization in order to guide catheters and wires during the intervention (44). The development of 3D ICE, however, may lead to a role for ICE to help with intraprocedural guidance during transcatheter mitral valve replacements in the future (13,14,44).

Triclip/Mitraclip

The development of the MitraClip for percutaneous mitral valve repair (and the off-label use of the MitraClip system in the tricuspid position) has been beneficial for select patients requiring atrioventricular valve (i.e., mitral or tricuspid) repair who are at high surgical risk.

Mitraclip

TTE and TEE have been used for preoperative assessment of mitral valve disease. During the procedure, however, TEE is essential for procedural guidance, from the transseptal puncture, introduction of the delivery sheath and clip system, positioning of the MitraClip, grasping the leaflets, deploying the clip, and assessing for residual regurgitation and measuring mitral valve gradients (35,45). Details of the procedure the necessary TEE views have been published previously (46,47), and the use of 3D TEE is highly recommended (7,46). When patients have a

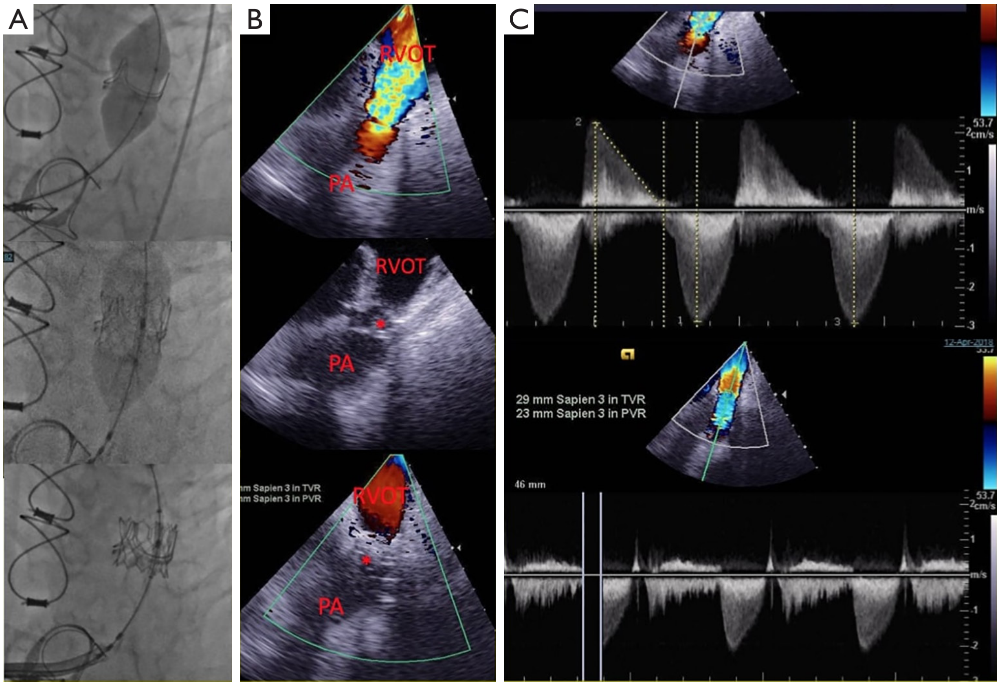

Figure 7 Transcatheter valve-in-valve replacement in the pulmonic position. (A) Top to bottom: fluoroscopy during balloon sizing, inflation of the 23-mm Edwards Sapien 3 bioprosthetic in an existing 23-mm Magna Ease valve in the pulmonic position, and post inflation; (B) top to bottom: 2D ICE with color demonstrating severe pulmonic regurgitation. 2D ICE of the 23-mm Sapien 3 after deployment inside an existing 23-mm Magna Ease valve. 2D ICE with color post procedure showing no further valvular regurgitation; (C) top to bottom: continuous wave (CW) Doppler via ICE pre-procedure with severe pulmonic regurgitation. Repeat CW Doppler post-procedure with no detectable regurgitant signal. *, 23-mm Sapien 3 bioprosthesis. RVOT, right ventricular outflow tract; PA, pulmonary artery; TVR, tricuspid valve replacement; PVR, pulmonary valve replacement.

contraindication for TEE, such as esophageal stenosis, the use of ICE is usually not sufficient, but one example of a percutaneous mitral valve repair using 3D ICE technology for procedural guidance has been reported (13).

TriClip

The off-label use of the MitraClip system in the tricuspid position has been reported for patients with severe tricuspid regurgitation who are too high risk for surgical repair/replacement (48-50). TEE imaging was used to guide the operators when orienting the clip on the tricuspid valve, utilizing deep transgastric views, esophageal views, as well as 3D echocardiography (48,50). Patients in these studies were preselected for adequate visualization of the valve prior to the procedure however, and thus TEE may not be the best imaging modality for this type of procedure (49). Since the tricuspid valve is an anterior structure, TTE may be effectively used. In fact, 25% of patients in a large case series had received TTE in addition to TEE due to insufficient image quality for clip placement or grasping by TEE alone (49). One patient in a case series had to also receive ICE for procedural guidance (49,50).

EP procedures/lead extraction

For patients with atrial fibrillation undergoing pulmonary vein isolation, TEE is necessary to exclude the presence of a left atrial appendage thrombus prior to the procedure (17). During the procedure, TEE is very helpful for transseptal punctures and for delineating pulmonary vein anatomy and can help locate catheter position relative to important cardiac structures (17). Nevertheless, ICE has been demonstrated to be a safe and effective adjunct to fluoroscopy during transseptal puncture (17,37). Furthermore, for patients with complex congenital anatomy, ICE can help identify the pulmonary vein antrum and allow for more precise ablations and fewer complications, such as pulmonary vein stenosis (37). ICE can help improve the contact between the mapping/ablating catheter and the myocardial tissue, and help visualize cardiac structures that have an electrical interest as well (9). ICE can also monitor for procedural complications, such as cardiac tamponade, in a real-time fashion (9,37). When trying to diagnose right-sided pacemaker lead infections or thrombosis, ICE is superior to TEE since these are anterior cardiac structures. ICE can also be helpful during lead extractions as well (9).

Endomyocardial biopsy

As the ACHD population ages there is a growing need for heart (plus other organ) transplantation in those with irreversible heart failure. Following heart transplantation, endomyocardial biopsy to assess for rejection is indicated. While many endomyocardial biopsies are performed with fluoroscopy alone, some centers utilize 2D TTE to complement fluoroscopy (6). TEE or ICE can also be an optimal imaging tool to guide the procedure. With ICE, the operator can have direct visualization of the biopsy site and can monitor for procedural complications in real-time (9). If the operator is trying to biopsy a specific area like an intracardiac mass, ICE can be invaluable. All modalities, however, have their disadvantages. TTE may be difficult to perform on supine patients who have difficult windows due to body habitus or chronic lung disease. TEE may need extra sedation and anesthesia support. ICE has increased costs and requires a second vascular access site, typically in the femoral venous region (6). Thus, the choice of adjunctive imaging modality during an endomyocardial biopsy will depend on operator comfort, patient characteristics, and availability of ancillary support (6).

Pericardiocentesis

TTE is the main echocardiographic modality used for performing a pericardiocentesis. A large series out of the Mayo clinic has demonstrated its safety and efficacy, with major complications in only 1.2% of cases (51), and the ASE has recommended that a pericardiocentesis should be performed with TTE guidance (6). The proper technique for an echocardiography-guided pericardiocentesis is to locate the ideal needle entry site and trajectory for the needle. The entry point should be at the largest collection of fluid that is closest to the body surface where a straight needle trajectory would avoid vital structures (6). The typical pericardiocentesis sites are via the left chest wall or the subcostal approach.

Future directions/recommendations

The development of fusion imaging in ACHD has led to potentially safer and quicker procedures (26), but data are lacking evaluating its effectiveness compared to standard adjunctive imaging techniques at this time. As new technology emerges, such as the use of virtual or augmented reality in the catheterization lab (52), fusion imaging may become more commonplace.

The use of three-dimensional ICE is also a promising development in the field of interventional ACHD. The use of multiplanar ICE and full volume acquisitions with an ICE catheter may allow for lower sedation needs and improved spatial resolution, which would lead to more successful complex procedures (13,14). We are hopeful that with multi-planar and 3D ICE becoming more commercially available there will be less of a need to use TEE for closing large ASDs and paravalvular leaks.

The recent guidelines for 3D TEE for congenital heart disease acknowledge a lack of standardization for training in 3D echocardiography (7). They propose more formalized programs, including training courses in acquisition and post-processing of 3D echocardiographic images, as well as a minimum number of at least 50 3D volumes analyzed as a core competency requirement (7). Nevertheless, efforts are being made to try and codify and standardize proper 3D imaging techniques and create a standard set of 3D views, such as the “en face” views of the atrial septum or surgeon’s view of the mitral valve (7,15).

As structural and adult congenital catheter-based interventions become more complex, the reliance on echocardiography for real-time imaging guidance will only continue to increase. A dedicated echocardiographer who is willing to undergo rigorous training to become adept with these imaging techniques will become an integral team member in the catheterization laboratory. Being able to provide valuable information on the fly to the adult congenital interventional operator will be paramount to the success of these types of procedures.

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Footnote

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