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REVIEW

Imaging

Why is intracardiac echocardiography helpful? Benefits, costs, and how to learn

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Current interventional procedures in structural heart disease and cardiac arrhythmias require peri-interventional echocardiographic monitoring and guidance to become as safe, expedient, and well-tolerated for patients as possible. Intracardiac echocardiography (ICE) complements and has in part replaced transoesophageal echocardiography (TEE), including real-time three-dimensional (RT-3D) imaging. The latter is still widely accepted as a method to prepare for and to guide interventional treatments. In contrast to TEE, ICE represents a purely intraprocedural guiding and imaging tool unsuitable for diagnostic purposes. Patients tolerate ICE much better, and the method does not require general anaesthesia. Accurate imaging of the particular pathology, its anatomic features, and spatial relation to the surrounding structures is critical for catheter and wire positioning, device deployment, evaluation of the result, and for ruling out complications. This review describes the peri-interventional role of ICE, outlines current limitations, and points out future implications. Two-dimensional ICE has become a suitable guiding tool for a variety of percutaneous treatments in patients who are conscious or under monitored anaesthesia care, whereas RT-3DICE is still undergoing clinical testing. Continuous TEE monitoring under general anaesthesia remains a widely accepted alternative.

Keywords Intracardiac echocardiography • Structural heart disease • Peri-interventional imaging • Guiding tools

Introduction

Intracardiac echocardiography (ICE) takes full advantage of the capabilities of echocardiography for guiding device closure of interatrial communications (IAC)[1–4] and electrophysiological ablation procedures.[5–7] It represents an alternative guiding tool for other interventional procedures[8] and can also be recommended in paediatric patients.[2] With the introduction of the 8F AcuNav™ catheter (Siemens-Acuson, Inc., Mountain View, CA, USA), ICE has become approved for intra-arterial use. The ViewFlex-Plus® (St Jude Medical, St Paul, MN, USA) is another commercially available phased-array system based on a 9F catheter. Rotational ICE devices, e.g. the UltraICE® catheter (Boston Scientific, Natick, MA, USA) are still in use, but solely for electrophysiological studies.

Long-access sheaths are recommended to avoid pelvic vein injury. For many procedures, navigation starts from the 'home view' (*Figure 1*), which depicts the right heart from the right atrium (RA). Purely fluoroscopic guidance in complex percutaneous interventions has significant limitations. Hence, complications may result from suboptimal catheter handling and device performance, from undetected thrombus formation, bleeding, and wall disruption, or simply from prolonged procedural times.[9] Intracardiac echocardiography is exclusively indicated for procedural guidance. It competes with two-dimensional (2D) and real-time three-dimensional (RT-3D) transoesophageal echocardiography (TEE). Although TEE imaging is well established and provides exceptional images, it most commonly requires general anaesthesia and may be associated with intermittent obstruction of fluoroscopic viewing.[10] Although overall risks related to ICE appear to be low, ICE is known to potentially cause transient arrhythmias.[2] However, evidence that ICE guidance can improve safety and outcome of interventional procedures is still lacking.

For what procedures is intracardiac echocardiography guidance well established?

Intraprocedural 2D and RT-3DTEE are widely accepted non-radiographic imaging modalities for many interventions.[11] Intracardiac echocardiography assistance is an attractive and increasingly

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used alternative associated with potential advantages—only some of which have been adequately studied in terms of their clinical impact; in addition, tests were limited to only a small number of interventional procedures.[2–7] Highest image resolution and compatibility with monitored anaesthesia care or local anaesthesia are the most important advantages.

Device closure of interatrial communications

With the probe positioned in the RA, ICE provides imaging of the IAC and the surrounding structures, particularly the inferior rim of atrial septal defects (ASDs). The method's safety has been repeatedly shown, and ICE is considered superior to 2DTEE.[3,4,12,13] Two transatrial standard views, i.e. the longitudinal view complemented by the perpendicular short-axis view, are recommended (*Figure 2*). Permitting unlimited echocardiographic visualization, ICE confirms adequate wire position and assists with balloon sizing,[14] placement of a long sheath, and release of the left-sided disc in the left atrium and the right-sided disc in the RA. A push–pull manoeuvre, also known as 'wiggle manoeuvre', is monitored in both standard views[9] and confirms correct disc positioning. In the short-axis view, compression of the aortic bulb can be ruled out. It makes sense to monitor device disconnection from the delivery cable by ICE as well. When released, the device will fully line up with the interatrial septum, reaching its definitive orientation. The final position of the device should be again visualized in both standard views to ascertain that the discs enclose the septal rims completely (*Figure 3*).

Intracardiac echocardiography is expected to improve safety, in particular in device closure of complex PFO and ASDs,[8,9] where significant complications are known to occur.[15] This approach seems to be beneficial in transcatheter closure of ASDs in patients with impaired left ventricular function[16] and in closure of multiple defects requiring either simultaneous or staged deployment of closure devices.[9] Compared with TEE, ICE is associated with much less procedural stress to the patient, and fluoroscopic and procedural times can be shortened.[3,8,15] Since many patients with IAC are of reproductive age or younger, reduction of radiation exposure represents an important advantage.

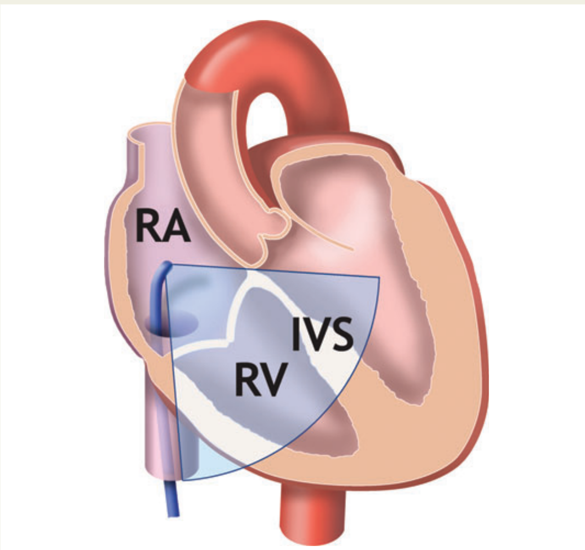

Figure 1 Home view showing the right heart, including the interventricular septum: the slightly anteflexed probe is positioned in the mid-right atrium. IVS, interventricular septum; RA, right atrium; RV, right ventricle.

Electrophysiology

The field of cardiac electrophysiology has witnessed a rapid increase in complex ablation procedures within the past decade, particularly for the growing numbers of patients with atrial fibrillation, ventricular tachycardia, and congenital heart disease. Intracardiac

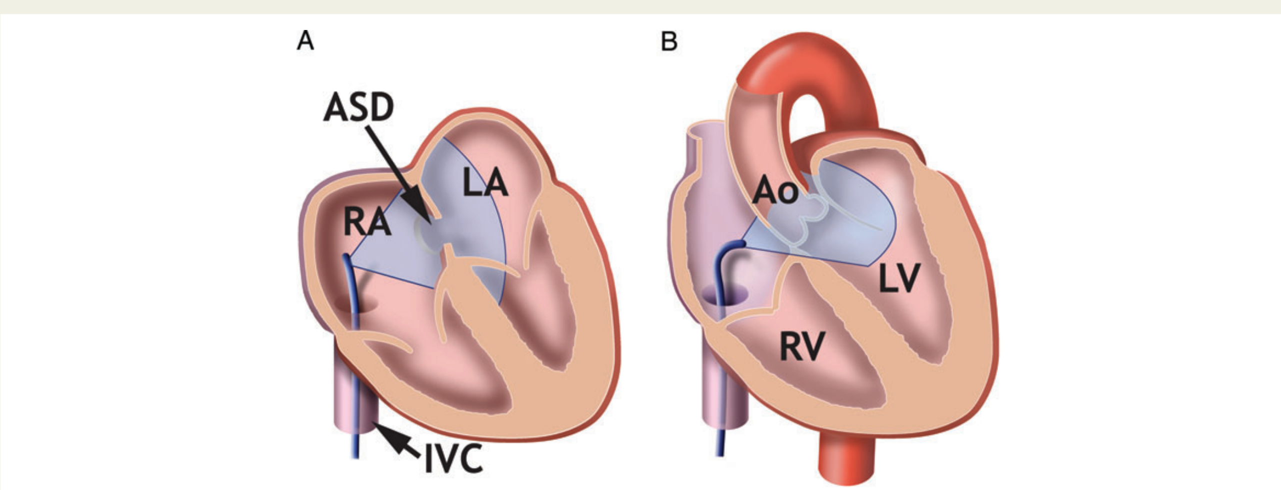

Figure 2 Standard views for device closure of interatrial communications: (*A*) longitudinal view; (*B*) short-axis view. Ao, ascending aorta; ASD, secundum type atrial septal defect; IVC, inferior vena cava; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

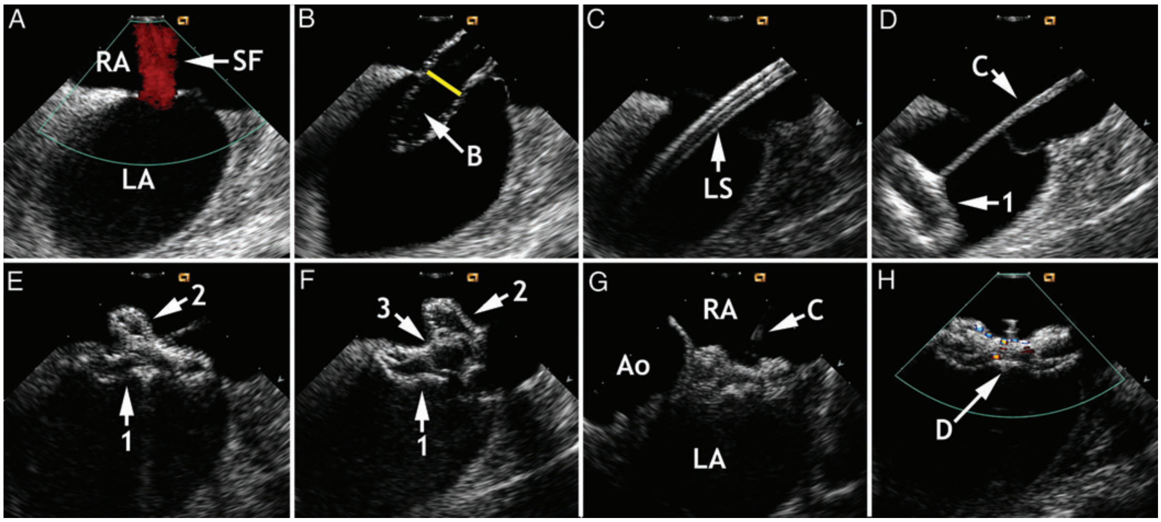

Figure 3 Atrial septal defect device closure: (*A*) longitudinal view showing left-to-right shunt; (*B*) balloon sizing; (*C*) long sheath with wire inside; (*D*) opened left-sided disc in the left atrium; (*E*) release of right-sided disk in the right atrium; (*F*) 'wiggle manoeuvre'; (*G*) short-axis view and (*H*) longitudinal view with the device in place. 1, left-sided disc; 2, right-sided disc; 3, stent; Ao, aorta; ASD, secundum type atrial septal defect; B, balloon; C, cable; D, device; LA, left atrium; LS, long sheath; RA, right atrium; SF, shunt flow.

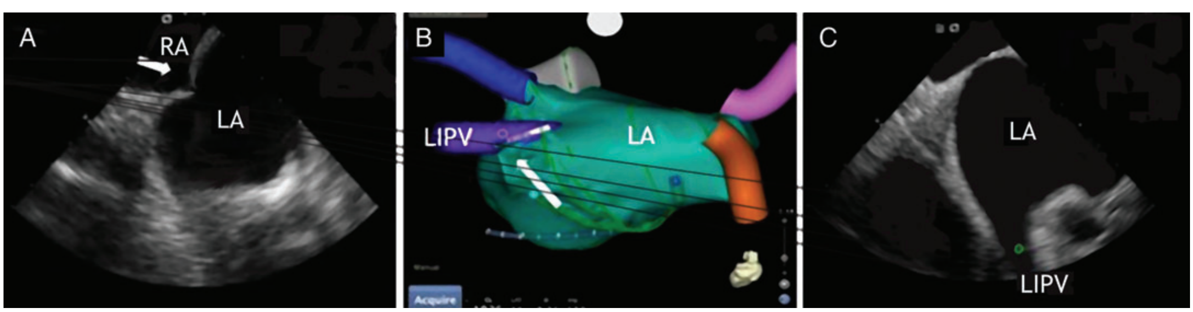

Figure 4 (*A*) Atrial fibrillation ablation procedure with desired intracardiac echocardiography image of atrial septal 'tenting' visible at the time the transseptal needle is about to cross over from the right atrium into the left atrium. (*B*) Posterior view of a registered electroanatomic + intracardiac echocardiography map of the left atrium with the ablation catheter tip in the left inferior pulmonary vein. (*C*) The circle, representative of the ablation catheter tip in (*B*), confirms intracardiac echocardiography location in the left inferior pulmonary vein. '→' in (*A*), 'tenting'; '→' in (*B*), ablation catheter tip; LA, left atrium; LIPV, left inferior pulmonary vein; RA, right atrium.

echocardiography has helped to meet the growing need for real-time monitoring of patient anatomy, catheter location, and surveillance of intraprocedural complications, such as pericardial effusion or thrombus formation.[2,17,18] Shorter procedural times cannot be necessarily expected, however.

Intracardiac echocardiography images can be collected from multiple planes and then overlaid onto existing electroanatomic maps (which may include regions where real-time data were/could not be collected), as well as onto existing computed tomography or magnetic resonance scans.[19] Thus, ICE can be used concomitantly with other imaging modalities to enhance the spatial depiction of cardiac anatomy and catheter positions.

Imaging requirements are procedure-specific. For ablation of atrial fibrillation, imaging is used to confirm catheter placement when performing transseptal puncture from the RA and to assess for complications when navigating catheters (*Figure 4*). In addition, ICE concerns the ability to see the 'quality' of contact of the catheter and the tissue surface before and while delivering the radiofrequency energy. Pertinent reference structures include the RA, fossa ovalis, left atrium, aorta, pulmonary veins, left atrial appendage (LAA), oesophagus, and pericardial space.[20] Structures important for the ablation of ventricular tachycardia include the mitral and aortic valves, left ventricular papillary muscles, ventricular scars and aneurysms, sinuses of Valsava, coronary ostia, and pericardial space.[21] For patients with congenital heart disease, ICE can help assess enlarged chambers, intracardiac baffles/shunts, and areas of scarring or severe hypertrophy.[22]

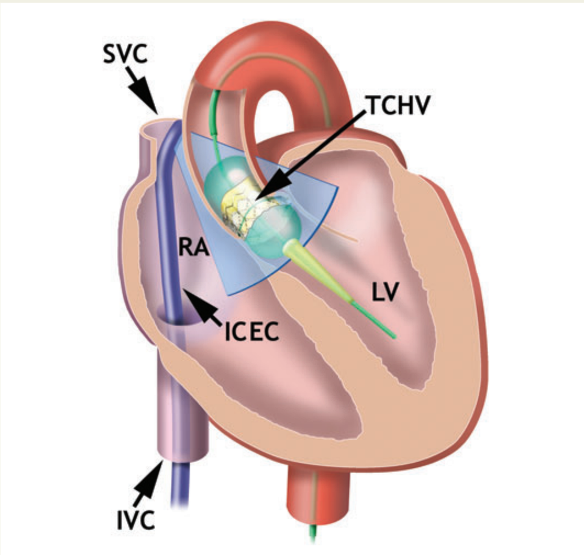

Figure 5 Longitudinal view in transcatheter valve implantation. ICEC, intracardiac echocardiography catheter; IVC, inferior vena cava; LV, left ventricle; RA, right atrium; SVC, superior vena cava; TAVI, transcatheter valve implantation; TCHV, transcatheter heart valve.

Intracardiac echocardiography as an alternative or supplementary guiding tool

Transcatheter aortic valve implantation

Transcatheter aortic valve implantation (TAVI) has become an accepted alternative to surgery for high risk or inoperable patients with severe, symptomatic aortic stenosis.[23] Besides characterizing the landing zone for valve sizing, TEE has been an important supplement to fluoroscopic imaging for positioning and the primary imaging tool for the comprehensive assessment of complications following valve implantation.[10] Because intraprocedural TEE is frequently performed under general anaesthesia, it is not always an ideal tool in this patient population. Some have advocated a 'minimalist' approach to this procedure[24] with no echocardiographic guidance. Current guidelines do not address this approach but continue to advocate echocardiographic support for interventional procedures. Intracardiac echocardiography may thus be a more acceptable alternative during procedures in which TEE is not performed.[25] The main advantage of ICE imaging is its suitability for monitoring with ultra-low doses of contrast agent, an approach helpful for preserving renal function and for lowering the occurrence of acute kidney injury.[8]

Longitudinal views from the cavoatrial junction are the primary ICE views (*Figure 5*), continuously displaying the ascending aorta, native aortic valve, and aortic valve prosthesis. After valve deployment, short-axis views are obtained to rule out annulus rupture and to

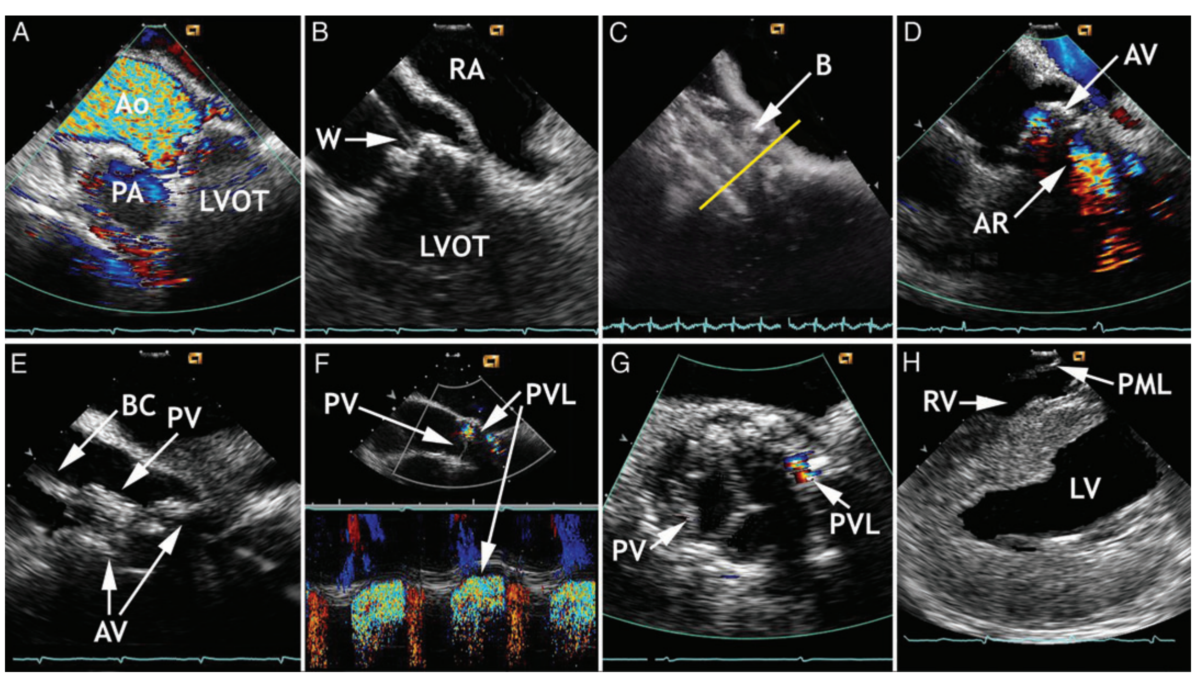

Figure 6 Procedural steps during transcatheter valve implantation: (*A*) native aortic valve and stenotic flow pattern; (*B*) crossing the valve with a wire; (*C*) predilatation (annulus denoted by yellow line); (*D*) moderate aortic regurgitation after predilatation; (*E*) crimped valve prosthesis mounted on a balloon, position too high for deployment; (*F*) moderate paravalvular leak after valve deployment; (*G*) short-axis view demonstrating small paravalvular leak; (*H*) transventricular view showing left ventricular function and ruling out pericardial haemorrhage. AV, aortic valve; AR, aortic regurgitation; B, balloon; BC, balloon catheter; LV, left ventricle; PV, prosthetic valve; PVL, paravalvular leak; PML, pacemaker lead; RV, right ventricle.

check for paravalvular leaks.[25] The severity of any regurgitation can be easily graded by a multiparametric approach.[26] Intracardiac echocardiography can be consistently used (i) to assist with guide wire passage through the native valve; (ii) to position the balloon for predilatation and to observe balloon inflation; (iii) to position the valve-carrying catheter system; (iv) to observe valve deployment and to verify adequate prosthetic valve function; (v) to rule out pericardial haemorrhage, and (vi) to ultimately check left ventricular function from the transventricular view (*Figure 6*). The ICE guiding strategy for TAVI is safe, effective, and compatible with monitored anaesthesia care.[8,25]

Rare left-to-right shunt closure procedures and transaortic intracardiac echocardiography

Intracardiac echocardiography guidance for device closure of ventricular septal defects (VSDs) is feasible, but experience is limited to the closure of peri-membranous communications.[27] Complemented by a transatrial short-axis view, a modified home view provides the best visualization of the peri-membranous portion of the interventricular septum.[2] In parallel to device closure procedures of IAC, all procedural steps should be simultaneously monitored by fluoroscopy and ICE (*Figure 7*).

Intracardiac echocardiography, more appropriately called intraluminal phased-array imaging (IPAI) if used from inside a vessel, can be beneficial for guiding the interventional closure of a patent ductus arteriosus (PDA). The ICE catheter is positioned in the descending aorta and the probe aimed at the infundibulum of the PDA, depicting continuous shunt flow and monitoring all procedural steps[28] (*Figure 8*). The advantages of ICE demonstrated for device closure of IAC, including lower radiation exposure and shorter fluoroscopy times, can be potentially transferred to device closure of peri-membranous VSDs and PDAs.

Intraluminal phased-array imaging will easily demonstrate aortic dissection, true and false lumina including entries and re-entries, as well as important side branches. Intraluminal phased-array imaging may thereby help lower the complication rate of percutaneous aortic stent-graft implantation.[29] The Doppler beam can be aligned with any flow between true and false lumen and with blood flow into small branches.[30] Furthermore, IPAI can be used to safely guide stent implantation in aortic coarctation (*Figure 9*) and percutaneous biopsies of intra-aortic masses suspected to be tumours.[31]

Intracardiac echocardiography as an investigational guiding tool

MitraClip implantation and mitral valvuloplasty

For mitral valvular interventions, 2DTEE has been generally replaced by RT-3DTEE imaging.[32] The most common device implanted at this time is the MitraClip® device (Abbott Vascular, Menlo Park, CA, USA).[33] Real-time three-dimensional TEE may improve procedural results, shorten procedural times, and reduce patient risks. It is required to assure proper positioning of the device and to evaluate procedural outcome.[34] Real-time three-dimensional TEE may be

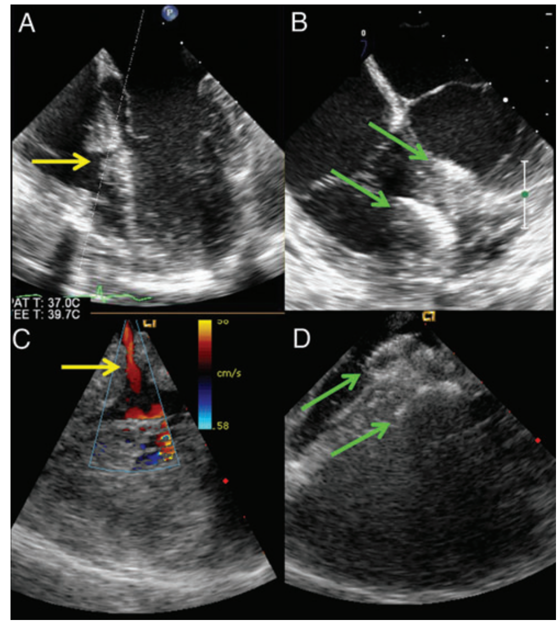

Figure 7 Ventricular septal defect device closure: (*A*) mid-oesophageal four-chamber transoesophageal echocardiographic view of ventricular septal defect; (*B*) same view as in (*A*) with a closure device deployed; (*C*) ventricular septal defect viewed by intracardiac echocardiography from right ventricular outflow tract; (*D*) same view as in (*C*) with closure device deployed yellow arrow, native defect; green arrow, closure device.

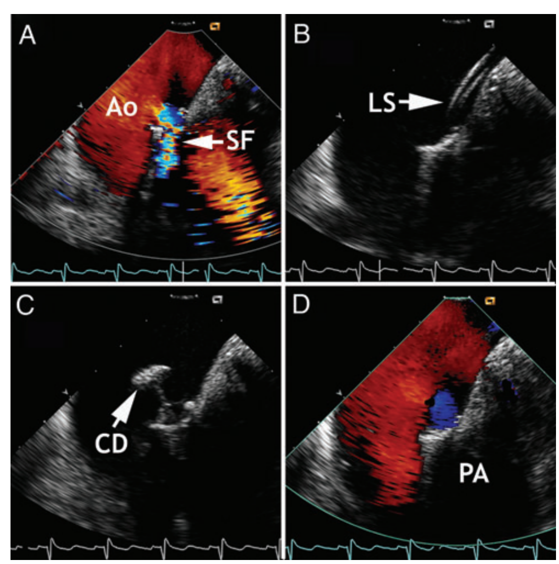

Figure 8 Patent ductus arteriosus device closure: (*A*) patent ductus arteriosus with shunt flow; (*B*) long sheath in place; (*C*) withdrawal of the partially opened closure device from the aorta into the patent ductus arteriosus; (*D*) no residual flow after patent ductus arteriosus device closure. Ao, aorta; CD, closure device; LS, long sheath; PA, pulmonary artery; SF, shunt flow.

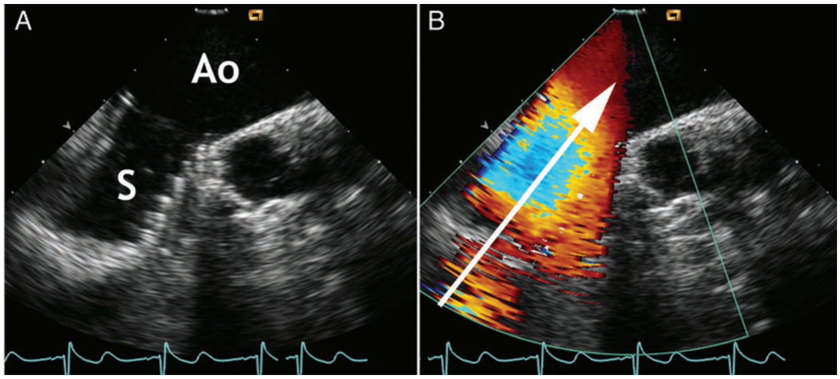

Figure 9 Stent implantation in aortic coarctation: (*A*) implanted stent; (*B*) flow after implantation. The arrow shows direction of flow. Ao, aorta; S, stent.

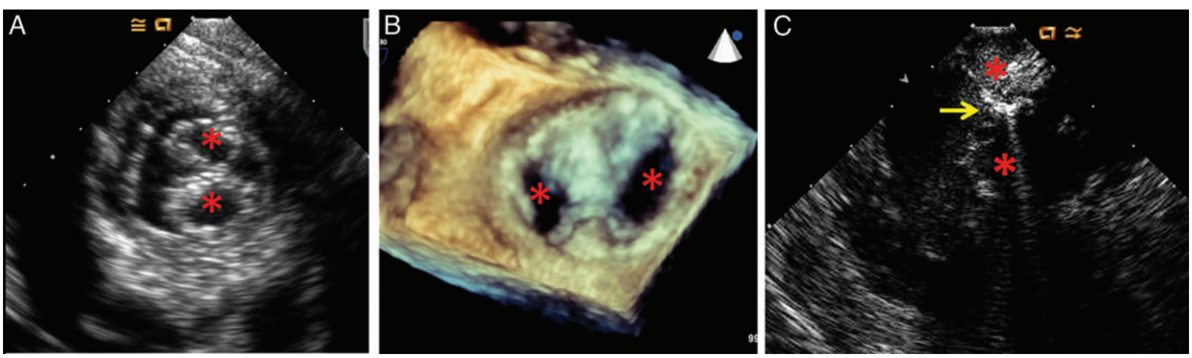

Figure 10 MitraClip® implantation: (*A*) transgastric short-axis two-dimensional transoesophageal echocardiographic view; (*B*) en-face real-time three-dimensional transoesophageal echocardiographic view; (*C*) intracardiac echocardiographic view from the right ventricular outflow tract. '*', double mitral valve orifice; '→', clip.

the key to accurate intraprocedural assessment of regurgitation following transcatheter interventions. The advantages of RT-3D colour Doppler TEE for direct planimetry of the vena contracta area include improved accuracy compared with 2D methods and no reliance on flow or geometric assumptions.[35]

Intracardiac echocardiography imaging can be used for transseptal puncture, depicting advancement and steering of the clip delivery system as well as leaflet grasp. However, alternating between perpendicular image planes to depict one area is challenging with 2DICE (*Figure 10*). In contrast, the transventricular longitudinal view is useful for monitoring mitral valvuloplasty.[36]

Left atrial appendage closure

Similar to imaging of the mitral valve, RT-3DTEE is useful for showing the specific anatomy of the LAA, its relationship to the pulmonary vein orifices, and any thrombus.[37] Currently marketed intracardiac LAA closure devices require measurement of the dimensions of the ostium and of the length or depth of the appendage. Real-time three-dimensional TEE can document device release and the final result.[37] For the extra-cardiac approach, these inside dimensions are rarely important. Here, the maximum length of the LAA in the anterior–posterior direction should not exceed the maximum diameter of the snare.

Intracardiac echocardiography imaging can be used for guidance during LAA closure procedures and for excluding thrombi.[38] Right atrial views are rarely sufficient to visualize the complex anatomy of the LAA. In addition, positioning of catheters or devices and colour Doppler assessment of peri-device flow frequently require near-field imaging (*Figure 11*). Therefore, ICE imaging from the left pulmonary artery might be an alternative.[39]

Closure of paravalvular leaks

The imaging requirements for this procedure are numerous and demanding. The initial assessment should include the number and precise location of the defects, a requirement that can be met by comprehensive 2D imaging. Real-time three-dimensional imaging of the sewing ring has made this assessment even easier and more accurate.[40] Following characterization of the defects and after determining the suitability for transcatheter closure, a number of decisions should be made. Precise information about the shape and dimensions of the defect as depicted by RT-3DTEE lets the interventionalists decide which type, size, and number of devices to select. The affected

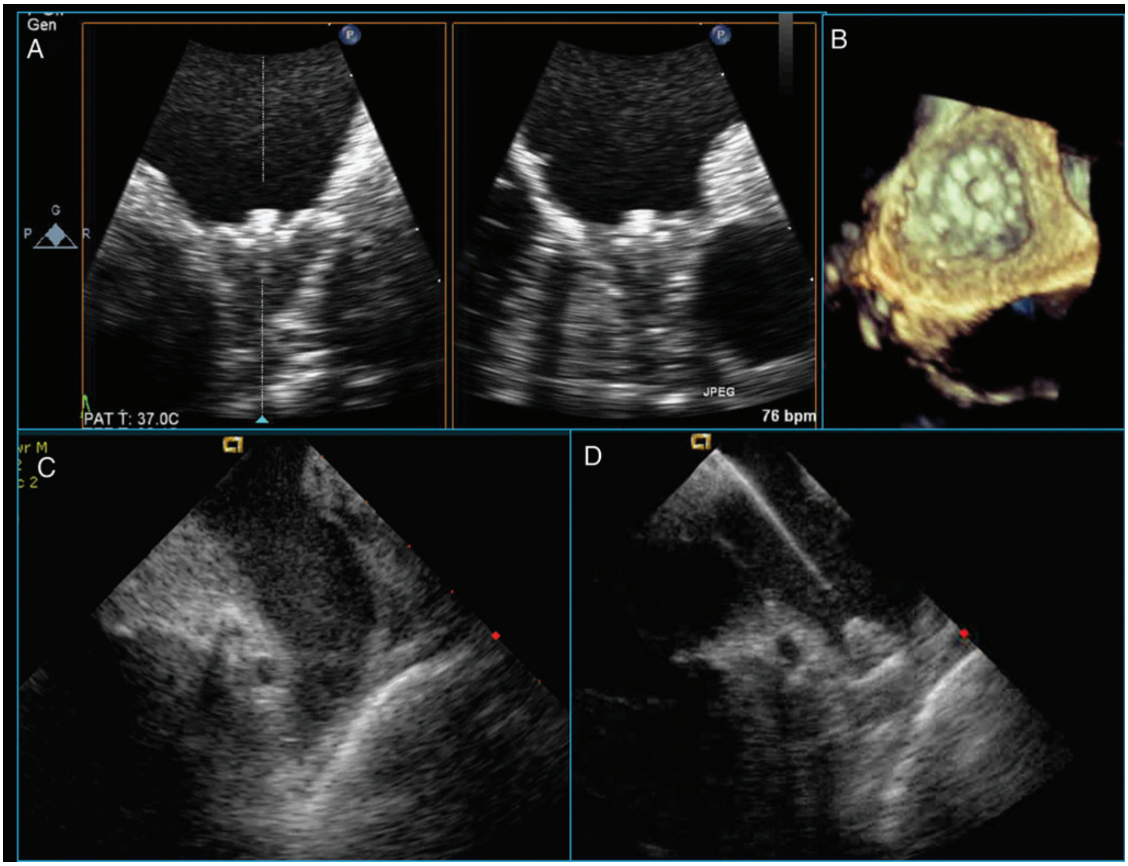

Figure 11 Left atrial appendage device closure: (*A*) mid-oesophageal biplane transoesophageal echocardiographic view; (*B*) real-time three-dimensional transoesophageal echocardiographic view; (*C*) transatrial intracardiac echocardiographic view without closure device; and (*D*) with device being deployed.

valve, the specific defect location, and its relationship to surrounding structures determine the interventional approach.

Owing to the complex nature of the jets, the relatively large region of the sewing ring to be imaged, and the required imaging reproducibility, RT-3DTEE is ideal for monitoring the closure of paravalvular leaks, which is challenging with current ICE probes. However, ICE imaging for this procedure has been reported to be feasible and advantageous.[40,41] Aortic prostheses will often lead to acoustic shadowing of the anterior sewing ring during TEE imaging, but this region can be imaged by ICE from the right ventricular outflow tract, which is adjacent to the aortic root. Acoustic shadowing of the posterior sewing ring of an aortic prosthesis or the posterior/medial sewing ring of a mitral prosthesis remains a significant limitation of ICE imaging.

Real-time three-dimensional intracardiac echocardiography

Experience with RT-3DICE is limited to isolated case reports[42] and animal studies.[9] No clinical investigations are available on this technique yet. The recently introduced AcuNav® V catheter (Siemens, Inc., Mountain View, CA, USA) represents the only commercially available RT-3DICE system. The first clinical impressions on RT-3DICE for TAVI guidance are promising. In particular, this technique appears to facilitate precise final positioning of the valve-carrying balloon immediately before the deployment of the valve prosthesis (*Figure 12*). Initial experiences suggest that RT-3D capabilities can augment the advantages of ICE in TAVI. Real-time three-dimensional ICE may also facilitate device closure of IAC, especially ASD closure.[42] Tracking thin wires, catheters, and devices with RT-3DICE is generally easier compared with 2DICE.[9]

The 10F catheter carries a matrix transducer providing a $22^\circ \times 90^\circ$ real-time volume image. This small volume represents the main limitation, particularly in near-field applications.[9] Depicting bigger devices in their entirety, e.g. ASD occluders, is challenging. The benefits of imaging are related to the distance between transducer and target region. The lack of continuous wave and M-mode capabilities is an additional drawback. Stronger reverberation artefacts than with 2DICE make structures behind devices more difficult to visualize. The need for an additional echocardiographic operator who adjusts appropriate anatomic RT-3D views nullifies an important advantage of 2DICE. Randomized multi-centre trials are desperately needed to tally such limitations against potential benefits.

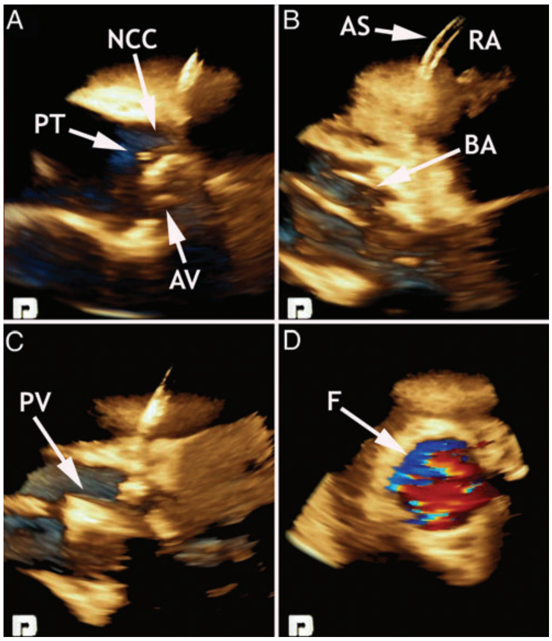

Figure 12 Three-dimensional intracardiac echocardiography in transcatheter valve implantation: (*A*) native valve with pigtail catheter placed in the non-coronary cusp; (*B*) predilatation; (*C*) final positioning of the prosthetic valve; (*D*) systolic flow after deployment of the prosthetic valve. AS, access sheath in the right atrium containing a pacemaker lead; AV, aortic valve; BA, balloon; F, systolic flow throughout the prosthetic valve; NCC, non-coronary cusp; PT, pigtail catheter; PV, prosthetic valve; RA, right atrium.

The cost–benefit ratio

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From an economic point of view, possible savings from shorter procedural times, from avoiding general anaesthesia and complications, i.e. advantages translating into shorter hospital stays, need to be weighed against the cost of the ICE catheter.[8] If the interventional operator is familiar with echocardiography in general and with ICE in particular, an additional physician reading the images may not be required. Health insurance agencies do not cover the costs of ICE catheters; high costs remain, therefore, a limitation of ICE. In many countries, a conventional IVUS procedure can be billed instead. Re-sterilization and re-use of ICE catheters, both permitted only in Germany and in eastern Europe, lower the costs. One also needs to consider the costs of ICE in relation to the overall costs of the interventional procedure. In TAVI, the ICE catheter contributes $<$10% of the total costs, but 30–50% of the overall costs in IAC closure procedures.

USA

If an interventional cardiologist performs ICE imaging, global hospital and physician charges are similar when using ICE or TEE (US$34 861 $\pm$ 43 759 vs. US$32 812 $\pm$ 2656, respectively, $P = 0.107$).[43] Catheterization laboratory time is significantly shorter with ICE than with TEE imaging (92 $\pm$ 18 vs. 50 $\pm$ 12 min, $P < 0.001$). The shorter turn-around time resulting from the use of local vs. general anaesthesia may add to the relative value of ICE imaging. Intracardiac echocardiography can also significantly reduce interventional procedure time, but the clinical impact of this is probably less pronounced.

Monetary cost, although the easiest to quantify, is probably the least important factor. A comprehensive cost-effectiveness analysis should also include the relative risks of each imaging modality, differences in imaging accuracy and reproducibility, differences in procedural complication rates as well as differences in outcome. Disadvantages of ICE imaging include the need for insertion of a second venous sheath, the danger of potentially provoking transient atrial arrhythmias, a limited field of view (particularly for 3D imaging), catheter motion within cardiac chambers, and the need for supplemental training.

How to learn intracardiac echocardiography

After a brief learning curve, interventional cardiologists familiar with echocardiography can fully benefit from the advantages of ICE, particularly if they are familiar with intraprocedural TEE. Cardiologists not familiar with echocardiography will benefit from a team approach, i.e. the presence of a non-invasive or second cardiologist in the catheterization laboratory who manipulates the ICE catheter from the opposite side of the table. The distributor of the system offers educational courses including hands-on training in an animal laboratory. Sitting in on procedures performed at an experienced institution represents an alternative. When first starting out with ICE, it is recommended to initially use this technique in device closure of PFOs, since this is a comparatively simple intervention. In a second step, one might advance to ICE in ASD closure and radiofrequency ablation procedures and later to ICE for TAVI and other percutaneous treatments of structural heart disease.

Conclusions

Although accepted as the guiding tool of choice for percutaneous IAC device closure procedures and for electrophysiological catheter-based ablations, randomized multi-centre trials on ICE in this context are lacking. The main advantages of ICE shown in more than a decade of single-centre experiences are unique: safe guidance of percutaneous interventional treatments plus avoidance of general anaesthesia and reduction of radiation exposure. These factors provide direct benefits to patients. On the other hand, the additional costs and the need for specific operator skills remain limitations. Nonetheless, further studies comparing the accuracy, reproducibility, and outcomes of ICE guidance vs. guidance by TEE and pure fluoroscopy need to be performed prior to adopting ICE imaging as the primary non-radiographic imaging modality for structural heart disease procedures. The direct clinical impact will be finally more important than any monetary costs or savings.

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