Echocardiographic guidance for diagnostic and therapeutic percutaneous procedures

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Abstract: Echocardiographic guidance has an important role in percutaneous cardiovascular procedures and vascular access. The advantages include real time imaging, portability, and availability, which make it an effective imaging modality. This article will review the role of echocardiographic guidance for diagnostic and therapeutic percutaneous procedures, specifically, transvenous and transarterial access, pericardiocentesis, endomyocardial biopsy, transcatheter pulmonary valve replacement, pulmonary valve repair, transcatheter aortic valve implantation, and percutaneous mitral valve repair. We will address the ways in which echocardiographic guidance provides these procedures with detailed information on anatomy, adjacent structures, and intraprocedural instrument position, thus resulting in improvement in procedural efficacy, safety and patient outcomes.

Key Words: Percutaneous cardiovascular procedures; vascular access; echocardiographic guidance

Introduction

Echocardiography is beneficial for guiding numerous percutan-eous cardiovascular procedures of the pericardium, myocardium, and cardiac valves. It also plays an important role in guiding vascular access. The advantages of echocardiographyinclude mobility and real time imaging, which allow for assessment before, during, and after procedures. Ultrasound imaging is widely available, portable, and offers clear images to help evaluate the severity of valvular disease, surrounding structures, and the location of catheters and devices. These benefits enhance the efficiency and safety of diagnostic and therapeutic procedures. This article will address the advantages and the role of ultrasound imaging in percutaneous procedures, namely, transvenous and transarterial access, pericardiocentesis, endomyocardial biopsy, pulmonary valve repair, transcatheter aortic valve implantation, and mitral valve repair.

Transvenous access

Physicians place millions of central venous catheters (CVC) each year in the United States. Central venous access is commonly indicated for hemodynamic monitoring, hemodia-lysis, and administration of fluids, medications and nutrition. Unfortunately, the complication rate associated with the procedure exceeds 15% (1). Types of complications include infection, thrombosis, and mechanical, all of which depend on several factors such as operator experience, patient anatomy, and procedure characteristics (2,3). Common mechanical complications are arterial puncture, pneumothorax, hematoma, and hemothorax; these are reported to occur in 5 to 19% of patients (1,4,5). Complications may compromise patient safety and are expensive to treat, thus minimizing adverse events is beneficial. Ultrasound (US) guidance for the insertion of central lines, particularly through the internal jugular vein (IJ), has been shown to reduce mechanical complications, improve success rates, reduce number of attempts, and time required for insertion when compared to the technique of using external anatomic landmarks (6,9).

The internal jugular, subclavian, and femoral veins are

common sites for central venous access. Successful catheterization using the landmark technique relies on a thorough understanding of anatomic landmarks at these sites. However, there is significant variability in anatomic structures in relation to the target veins (10,11). Thus, real-time (RT) US guidance allows operators to clarify the relative position of the needle, the desired vein, and the surrounding anatomy prior to and during CVC insertions (2,3). In a meta-analysis of studies comparing RT US guidance method with the landmark method for central line placement, Randolph *et al.* observed that US guidance decreased complications during attempted CVC placements (relative risk 0.22, confidence interval [CI] 0.10-0.45), corresponding to a relative risk reduction of 78% and reduced placement failures (relative risk 0.32, 95% CI: 0.18-0.55) when compared to the landmark method (12). In addition, the mean number of attempted venipunctures was significantly reduced with US guidance (relative risk 0.60, 95% CI: 0.45-0.79), corresponding to a relative risk reduction of 40%. In a recent meta-analysis of studies comparing two-dimensional (2D) US guidance or Doppler US guidance method with the landmark method, Hind *et al.* also observed similar results. For IJ insertions, 2D US guidance reduced complications (relative risk 0.43, 95% CI: 0.22-0.87), and decreased placement failure (relative risk 0.14, 95% CI: 0.06-0.33), when compared to the landmark method (2). They also observed that fewer attempts were required for successful placement and less time needed with 2D US guidance.

Other subsequent studies also suggest that US guided IJ catheterization was associated with a higher success rate and a lower complication rate. In a randomized, prospective study of RT US guided IJ catheterization in the emergency department (ED), Leung *et al.* observed that IJ cannulation was successful in 93.9% with US guidance method compared to 78.5% with the landmark method, a significant difference of 15.4% (P=0.009, 95% CI: 3.8% to 27.0%). Of the successful US guided catheterizations, 82.0% were inserted on the first attempt compared to 70.6% of the successful landmark catheters. The complication rate was observed in 4.6% in the US guidance method compared to 16.9% in the landmark method, a difference of 12.3% (95% CI 1.9% to 22.8%) (13). In a recent randomized, prospective study, Turker *et al.* also observed similar results with the US guided method having fewer number of attempts for successful insertion and a lower complication rate when compare to the landmark method(P<0.05 and P<0.01, respectively) (14).

The operator is able to visualize the relative position of the needle, the vein, and its surrounding structures, in addition to assessing the variant anatomy and patency of a target vein with the use of US guidance. During US guidance, the carotid artery is often visualized and it is pulsatile. Conversely, the IJ is weakly pulsatile and readily compressed by pressing against the vein with the US transducer, *Figure 1A,B*. With these advantages, patients are less likely to experience a prolonged, possibly uncomfortable, and sometimes unsuccessful catheterization (2,3). Because the use of RT US guidance has been shown to be beneficial for CVC placement, the Agency for Healthcare Research and Quality has recommended US as one of their 11 practices to improve patient care (3). The National Institute of Clinical Excellence in the United Kingdom also supports the use of US guidance for CVC placement (15).

Transfemoral arterial access

The majority of diagnostic and interventional catheterizations are performed via percutaneous femoral arterial access. Annually, approximately up to 10 million arterial accesses are done worldwide (16,17). The incidence of vascular complication-sassociated with this procedure occurs in 1.8% to 4% of patients (18). Types of complications include hematomas (2-8%), pseudoaneurysm (1-2%), and arteriovenous fistulas (0.2-5%) (19-21). Risk factors for vascular complications include age, female gender, weight, previous arteriotomy at the same site, anticoagulation, renal failure, and location of arteriotomy (22). Vascular complications have been associated with increased length of hospitalization, morbidity, mortality, and healthcare costs (21,23-25). Fewer complications have been associated with arteriotomy site in the common femoral artery (CFA). In comparison, retroperitoneal hemorrhage is associated with cannulation above the inguinal ligament while pseudoaneurysm and arteriovenous fistula formation are associated with cannulation below the CFA bifurcation (26-29). Thus visualization of the vasculature and surrounding landmarks for the appropriate location of arteriotomy is important to reduce the risks and complications of femoral arterial access.

In most cases, a palpable arterial pulse is used as a landmark for access site. This is a well established, safe, and quick method for CFA catheterization (30,31). However, with significant variations in femoral vessel anatomy and if pulses are weak or nonpalpable, it may be challenging to obtain access at the appropriate site. The femoral head has been shown to be a reliable landmark for identifying the CFA and is visible with fluoroscopy. Therefore, fluoroscopy

with arterial cannulation has been recommended to potentially reduce complications (32,33). The CFA courses over the femoral head in 92% of cases and the bifurcation of the CFA occurs below the middle of the femoral head 99% of the time (34). By using fluoroscopy to locate the femoral head, the chances of successful CFA puncture in the correct location are high. However, recent randomized trials did not demonstrate improvement with the use of fluoroscopy in the rate of CFA cannulations or reduction of complications compared to the palpation method alone (35-37). Furthermore, the wide spread use of fluoroscopy to obtain arterial access vary. Reasons for the variation are the high success rates with palpation method alone, the additional time and radiation exposure associated with the use of fluoroscopy, and the lack of data regarding benefit (35).

As discussed above, US guidance has been widely used for CVC access and now has become the standard of care. In a recent multicenter, randomized, controlled trial comparing fluoroscopic guidance versus US guidance for femoral arterial access, Seto *et al.* observed that US guidance reduced the risk of vascular access complications by 59%, improved first pass success rate to 82.7%, greatly decreased the number of accidental venipunctures, and reduced the time required for access (38). *Table 1* lists the intraprocedural outcomes of this study. Ultrasound guidance improved CFA cannulation rates in patients with high bifurcations by 31%; however, it did not improve the rate of CFA cannulation in the overall population. *Figure 2A* illustrates a transducer with a needle guide and the underlying target artery. In *Figure 2B*, US guidance readily visualize the femoral artery and vein, and as the transducer is moved superiorly, the common femoral artery is clearly seen, *Figure 2C*. The benefits of US guidance method over fluoroscopy may improve patient comfort by shortening the time required for access and decreasing tissue and vessel trauma due to multiple venipunctures. Ultrasound would also be beneficial when CFA cannulation is essential, especially for high-risk patients with difficult access. It was also observed to be helpful in obese patients and patients with weak arterial pulses (31).

Pericardiocentesis

For patients suffering from pericardial tamponade (39), pericardio-centesis is a lifesaving procedure. However, until the advent of echocardiographic guidance, this procedure was essentially performed "blind". Prior to US guidance, pericardiocentesis was associated with relatively high mortality and complication rates (6% and 20-50%,

respectively) (40-42). Types of complications included pneumothorax, damage to surrounding vital organs, cardiac wall punctures, and death (39,43,44). Over the past 30 years, the incidence of pericardial effusions, as a complication of cardiothoracic surgery and perforations from catheter-based procedures, has increased the need for pericardiocentesis. Ultrasound guidance has improved the safety of this procedure in the past few decades, lowering both mortality and complication rates with direct visualization of the heart and surrounding organs.

Ultrasound guidance may be used to locate the optimal site of puncture for pericardiocentesis as well as visualize the depth of the effusion, distance from the chest wall to the effusion, and the surrounding vital organs (44). As shown in *Figure 3*, the optimal site of puncture is identified as the site where the largest fluid collection is closest to the body surface and from which the needle trajectory will avoid vital structures (40,44) The two most common entry sites for the needle are apical areas and the subxiphoid, but a parasternal location can also be used though it is used less frequently. The pericardial sac and effusion can be entered with a needle or with a polytef-sheathed needle. Continuous US guidance is generally not needed for the procedure, as it is often difficult to keep visualization of the needle tip. However, an injection of agitated saline can be used to confirm the location of the needle if bloody fluid has been aspirated or the position of the catheter is unknown (44). *Figure 4A* demonstrates a catheter within the pericardial effusion, however the fluid is bloody. In *Figure 4B*, a saline contrast study was done and it demonstrated that the contrast only appeared in the pericardial space, confirming that the catheter was within the pericardium and not within the heart. If the needle, guidewire, or sheath is not in the pericardial sac, it should be withdrawn, repositioned or another attempt should be used to enter the pericardial space. *Figure 5* shows a case example in which a guidewire was inadvertently inserted into the LV but then detected by echo to not be in the pericardial space (but in the LV). Consequently the guidewire was removed and a repeat pericardiocentesis was performed. The subcostal, apical, or parasternal views can be used to monitor the procedure to ensure that the effusion is decreasing in size during the pericardiocentesis (39). For optimal drainage, we insert a pigtail catheter, into the pericardial sac. The catheter is then attached to a Jackson-Pratt drain, and left in place for 24 hours to several days once the drainage has significantly decreased to less than 100 mL in 24 hours (45) This minimizes the chance of reoccurrence of the effusion to <20% at one year (45). The omission of extended catheter
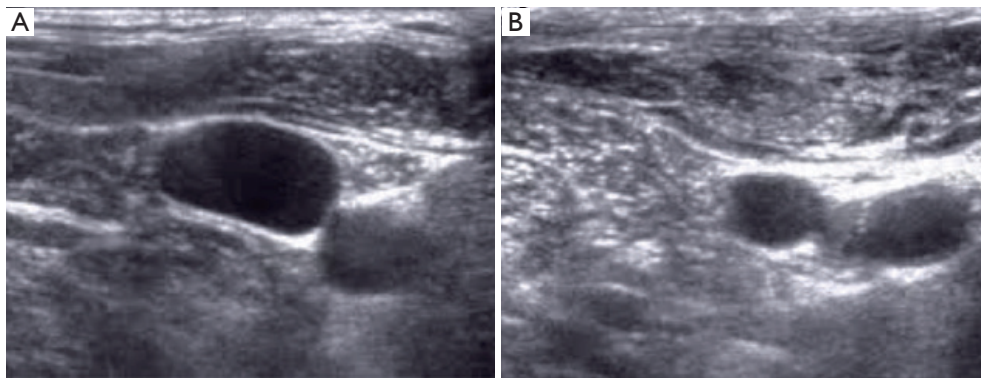
Figure 1 Anatomy of internal jugular vein. A. Normal internal jugular vein and artery; B. Internal jugular vein compressed with US transducer
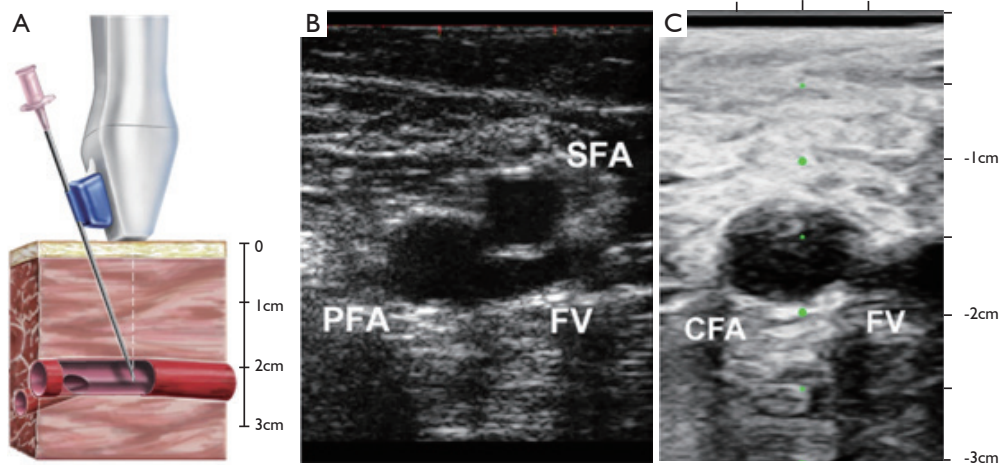
Figure 2 Ultrasound guidance technique of transfemoral artery access. A. Illustration of US transducer with needle guide and artery; B. The right femoral artery bifurcation is seen in the axial plane, identifying the separation of the profunda femoral artery (PFA), superficial femoral artery (SFA), and femoral vein (FV). Note the compressed FV, which can be differentiated from arteries; C. The transducer is moved superiorly until common femoral artery (CFA) is visualized. During needle advancement, the artery is kept under the central target line (green circles), which indicates the path of the needle. Reprinted with permission from Seto *et al*.

Table 1 Intraprocedural outcomes for fluoroscopy and ultrasound guidance for transfemoral artery access

Characteristic	Fluoroscopy (n=500)	Ultrasound (n=502)	P Value
Number of attempts	3.0±3.2	1.3±0.9	<0.000001
First pass success	232 (46.4%)	415 (82.7%)	<0.000001
Venipuncture	79 (15.8%)	12 (2.4%)	<0.000001
Number of arterial punctures	1.14±0.43	1.09±0.36	0.076
Mean time to insertion, s	213±194	185±175	0.016
Median time to insertion, s	148 (102–242)	136 (90–212)	0.003

Values are mean ± SD, n (%), or median (interquartile range). Reprinted with permission from Seto *et al.*
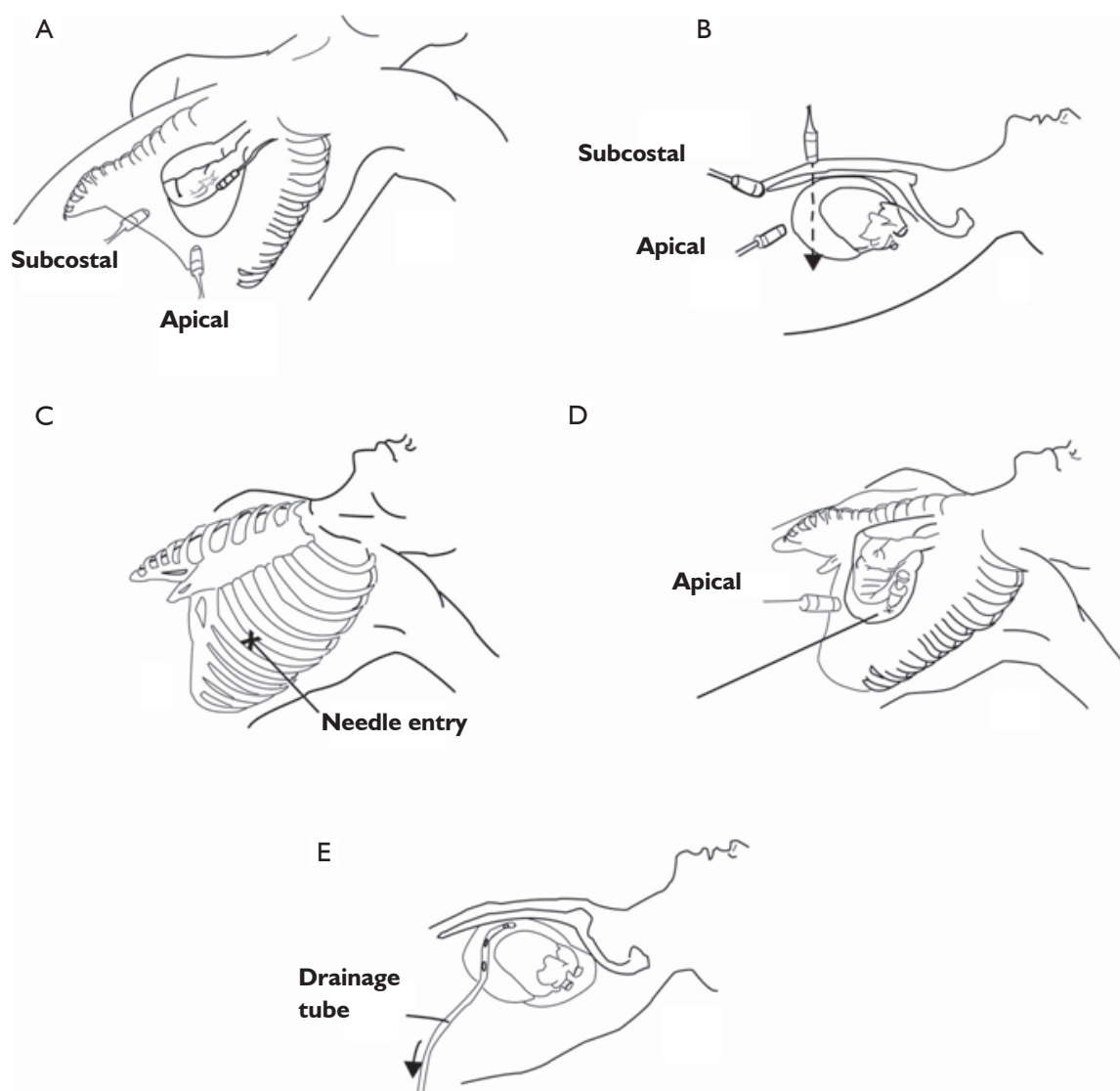

Figure 3 A-B. Patient in supine position. These figures illustrate the three windows often used for needle entry during pericardiocentesis–apical, subcostal, and parasternal access; C-D. These figures show apical entry for performance of pericardiocentesis with transhthoracic echo monitoring; E. Post-procedure illustration of pericardial catheter drainage after trans-apical pericardiocentesis

drainage has been associated with recurrence rates up to 55% (41,45). Limited repeat echocardiograms should be used to assess the residual fluid daily. If there is a change in the appearance of the fluid aspirated, chest pain, sudden increase in fluid drained, or change in vitals, the patient should be reassessed (40).

A decrease in both mortality and complication rates have been observed with US guided pericardiocentesis, as shown in *Table 2*. In 1,127 cases of US guided pericardiocentesis performed at the Mayo Clinic between 1979 and 2001,

97% of the cases were successful and 89% only needed a single attempt to gain access (41). Major complications, including chamber lacerations, pneumothorax with chest tube re-expansion, tachycardia, and death, only occurred in 1.2% of patients and minor complications, including minor pneumothorax, pleural pericardial fistula, and vasovagal responses, were observed in 3.5% of patients. With US guidance, patients have a better chance of survival and significantly lower complication rates (43). The Yonsei Clinic also achieved similar success rates. The 11-year
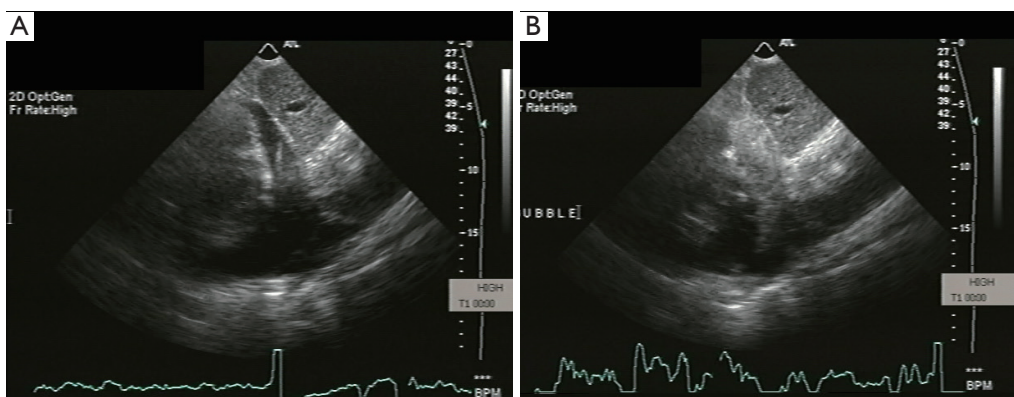
Figure 4 A. Transthoracic 2-D echo during pericardiocentesis demonstrates a catheter within the pericardial space. The pericardial fluid was hemorrhagic; B. Saline contrast study shows contrast in the pericardial space, confirming that the pericardial catheter is not intracardiac

study had an astounding overall success rate of 99% with a major complication rate of only 0.7% and 0 deaths (46). In addition, the safety of US guided pericardiocentesis has been shown in pediatric patients, cardiac perforated patients that were hemodynamically unstable, postoperative patients, and patients with malignancies (42,47,48).

With the help of US guidance, the operator can directly visualize the pericardial effusion, the surrounding structures, the wall chambers, and most importantly the best approach to access the effusion. This helps reduce the number of failed attempts, chamber and organ punctures, and other major complications. With echocardiographic guidance, this procedure can be performed safely, relatively quickly, and efficiently at the bedside in the ICU, in the catheterization laboratory, or as outpatient in the echocardiography laboratory (41). In addition, US imaging reduces the need for surgery and exposure to radiation compared to fluoroscopy. Ultrasound guidance increases safety and efficacy; thus, it has become the standard method for pericardiocentesis.
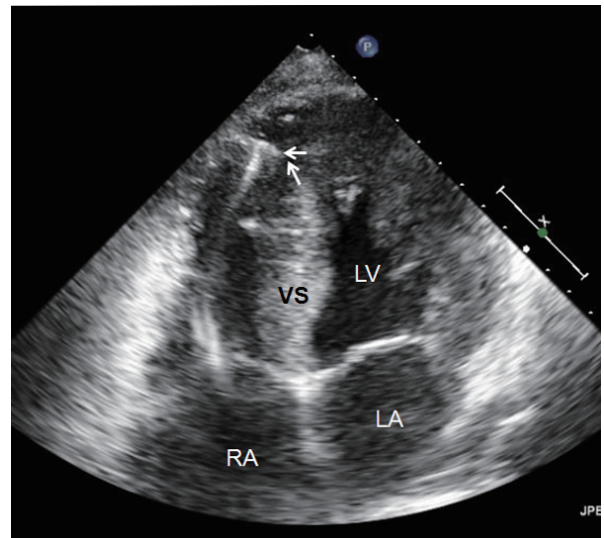
Endomyocardial biopsy

First introduced in 1962, endomyocardial biopsies have help eddiagnose a wide variety of myocardial disorders, such as infiltrative cardiomyopathy and heart transplant rejection (44,49). This procedure is usually done under fluoroscopic guidance; however, echocardiography have been used to supplement or replace fluoroscopic guidance (44,50,51). Under echocardiographic guidance, there is a wider choice of biopsy sites, including ventricular septum, RV apex, and free wall (52). Since 2D TTE provides spatial orientation and anatomic definition, the likelihood of complications

are greatly reduced, such as perforation and damage to the tricuspid valve (53). Most importantly, US guidance can assure that specimens are obtained from the septum and not the right ventricular (RV) free wall, especially since perforation of the RV or LV remains the most serious risks of the procedure (52,53). Ultrasound guidance also offers precise visualization, thus serial biopsies may be performed thereby allowing a quick procedure lasting 10-15 minutes.

Most myocardial biopsies may be performed in the catheterization laboratory with standard echocardiographic machines. A sheath is placed percutaneously in the right femoral or jugular vein (under US guidance) and the bioptome is advanced under X-ray guidance until it enters the right atrium, at which point, US guidance is continuously used (44,52,54). Once the forceps enter the right atrium, the subcostal or apical four-chamber view can be used to image the biopsy catheter (44,50,52). Ultrasound guidance helps the operating physician guide the forceps across the tricuspid and into the right ventricle. In *Figure 6*, echo can readily be used to identify the tip of the bioptome and determine its location. With US guidance, the bioptome may be repositioned along the intraventricular septum until its location is satisfactory, *Figure 7*. The position of the tip can be optimally viewed with both the apical and subcostal four-chamber views (44,52). Then the jaws of the forceps are open and the sample is excised, after which the site becomes a bit rigid. The procedure is performed repeatedly but the physician must take care to avoid performing a second biopsy at the same site. The most serious complication during this procedure is perforation of the right ventricle, a complication that has a high risk of death or morbidity (53). These complications
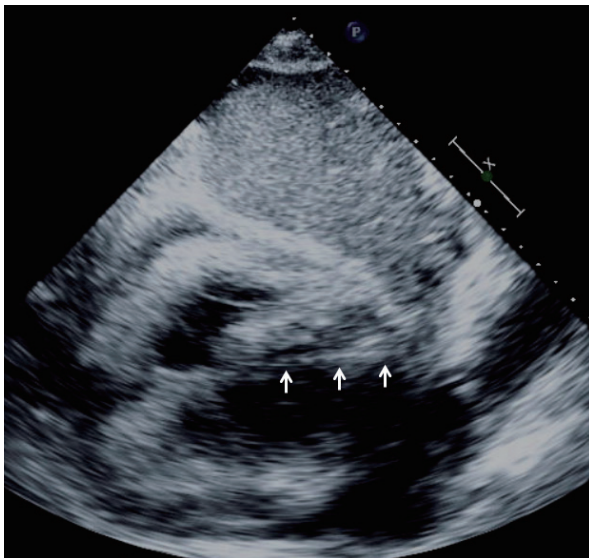
Figure 5 During echo monitoring of pericardiocentesis, it was noted that the guidewire had entered the left ventricle (arrows). The guidewire was subsequently removed and repeat pericardiocentesis performed

Figure 6 Transthoracic 2-D echo guidance during myocardial biopsy demonstrates the bioptome (arrows) is optimally positioned at the RV apex adjacent to the interventricular septum, facilitating a safe biopsy procedure
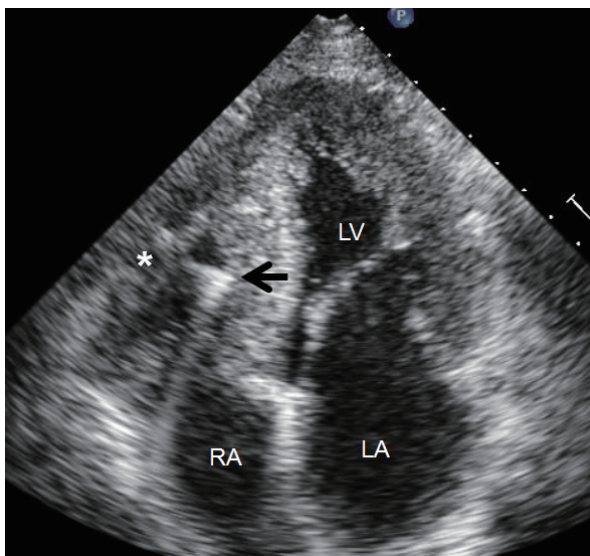
Figure 7 Echo can be used to biopsy the right side of the interventricular septum at different sites. In this example, the bioptome (arrow) is positioned at the mid portion of the septum. Asterix indicates RV free wall. RV, right ventricle; LV, left ventricle; RA, right atrium; LA, left atrium
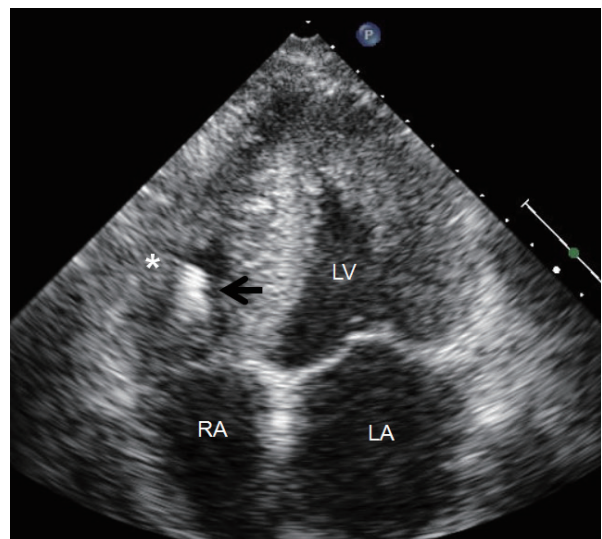
Figure 8 The bioptome (arrow) is directed towards the right ventricular free wall and it was subsequently redirected towards the septum to allow for safe biopsy sampling
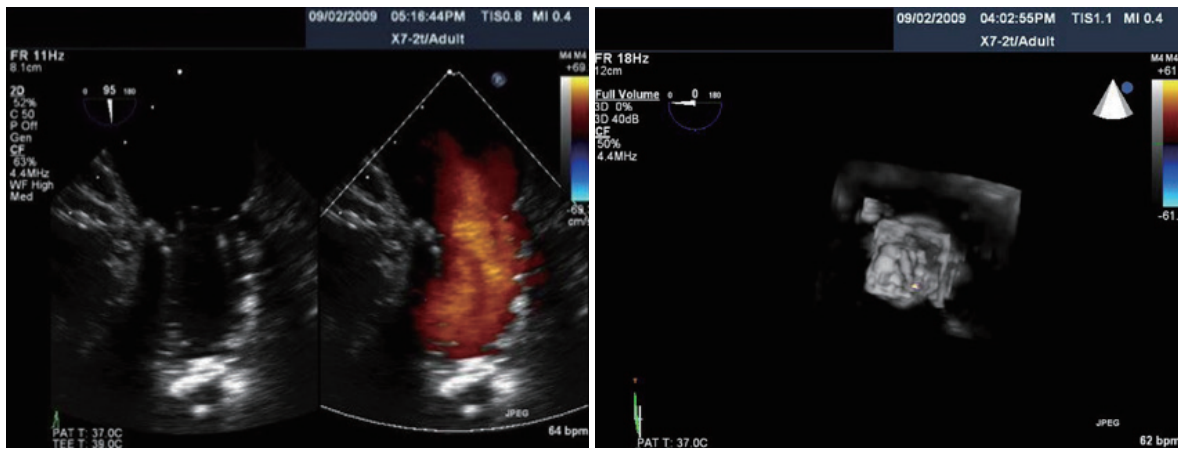
Figure 9 2D TEE view off a stented pulmonary artery with severe PR by 2D and 3D color flow doppler. PR, pulmonary regurgitation
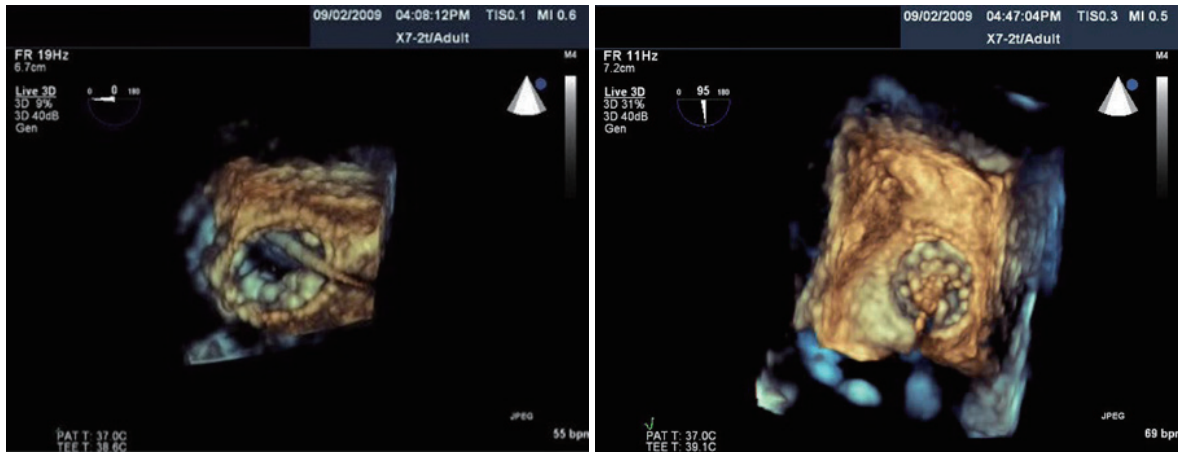

Figure 10 A catheter is clearly visualize in the stent graft
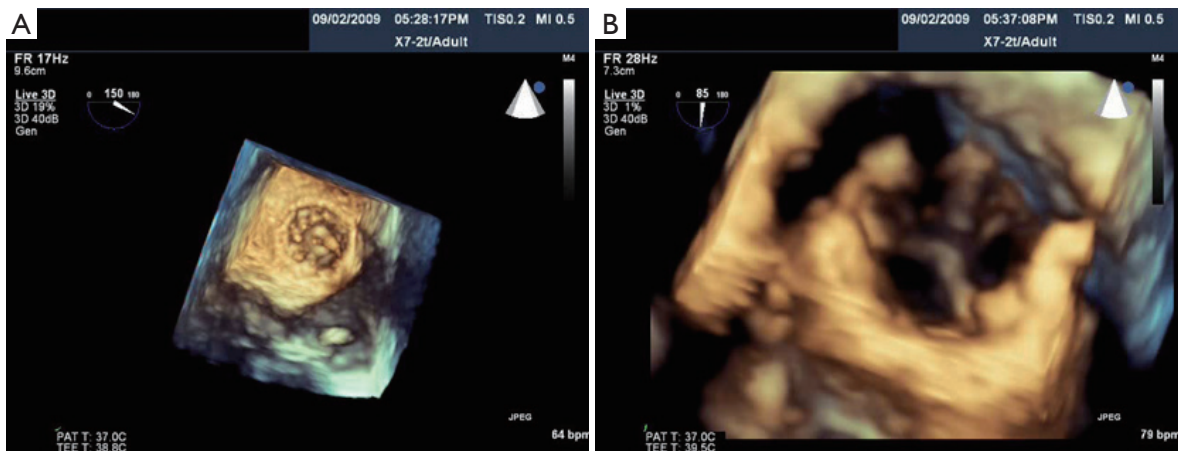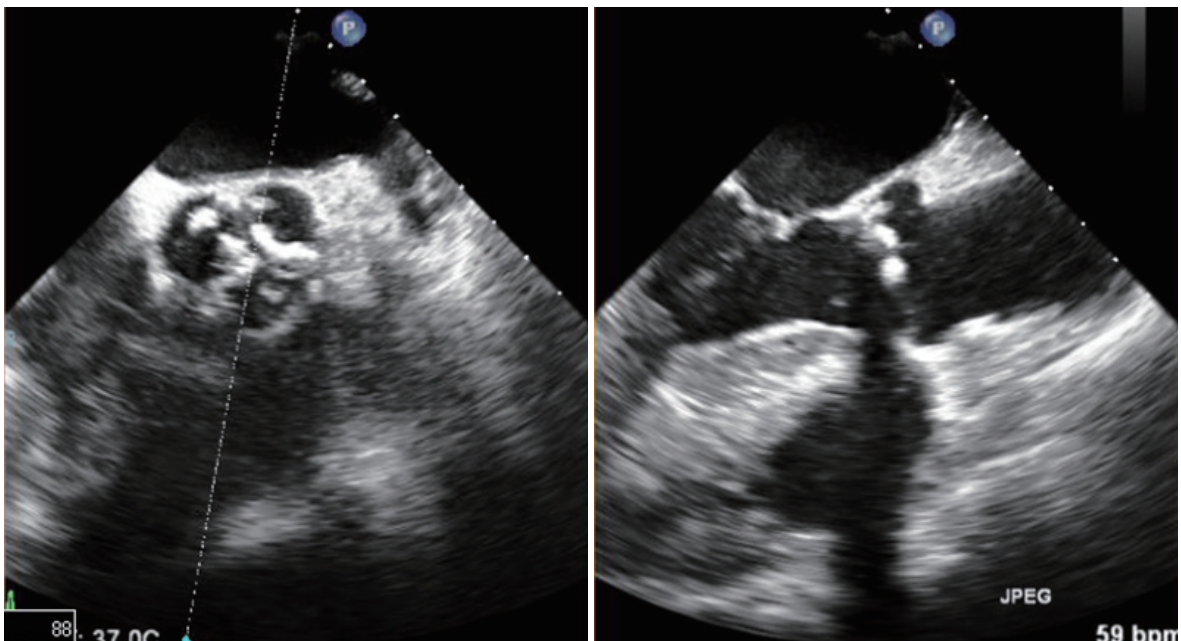

Figure 11 A. Pre-deployment echo of PV with catheter; B. Successful implantation of pulmonic valve. PV, pulmonary valve

Figure 12 CoreValve (left, courtesy of Medtronic). SAPIEN 9000 TFX (bottom right) and SAPIEN XT 9300 TFX (top right) valves (courtesy of Edwards Lifesciences Inc.)

Figure 13 X-plane from 3D TEE system demonstrating in left panel cross section of aortic valve in a short axis view at the level of the aortic annulus; right panel, long axis view of left ventricular tract and aorta. Note: Dimension of aortic annulus is different in the short axis and long axis planes. (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)

20

**Nguyen et al. Diagnostic and Therapeutic Percutaneous Procedures**
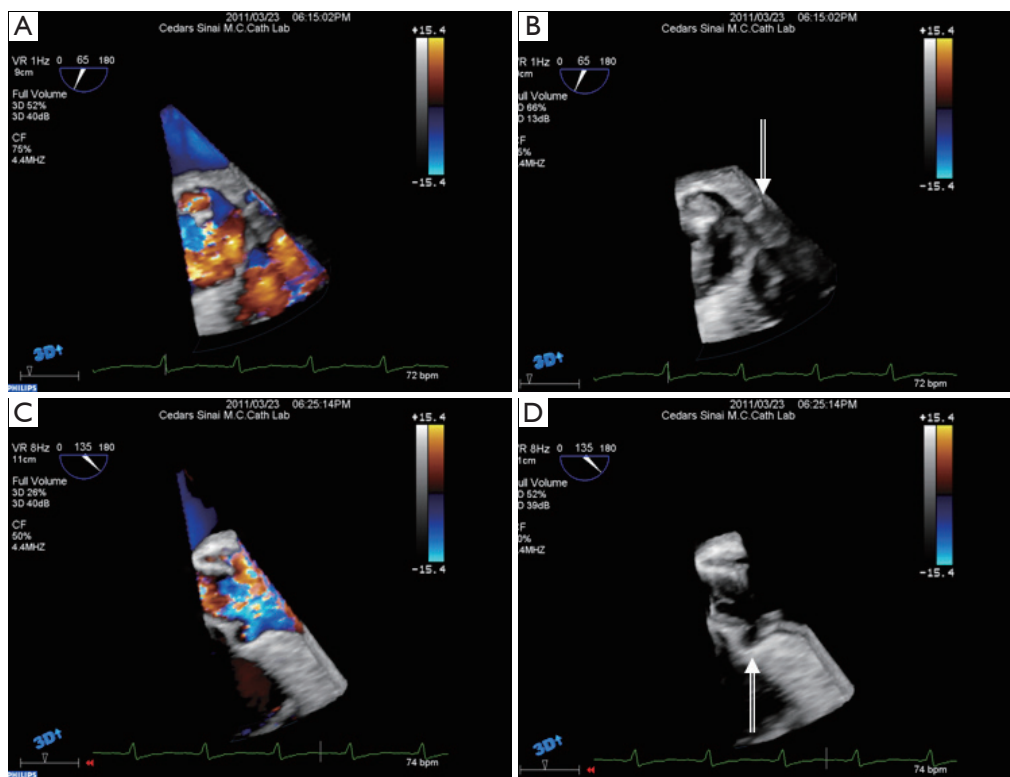
Figure 14 Assessment of the relationship of the left (panels A and B) and right (panels C and D) coronary artery ostia (arrows) to the implanted stent-valve following TAVI using 3DTEE. (From Siegel *et al*. Curr J Cardiovasc Imaging Rep 2011, in press, with permission)

Table 2 Decrease in Mortality and Complication Rates with Echocardiography Guided Pericardiocentesis

	Length of study period (years)	Total number of patients	Total number of puncture	Total success rate	Success rate on first try	Major complication rate	Minor complication rate
Mayo clinic	21	977	1127	97%	89%	1.2%	3.5%
Pediatric patients	17	73	94	99%	93%	1%	3%
Postoperative patients	19	208	245	97%	92%	2%	1.2%
Hemodynamically unstable patients (after Cath Lab procedures)	19	88	92	99%	86%	3%	2%
Yonsei clinic	11	272	291	99%	98.9%	0.7%	3%
Linkoping Heart Centre	14	120	135	96%	98%	0.7%	7%

are more likely to occur in patients with hypertrophic cardiomyopathy, endomyocardial fibrosis, or cardiac tumors (52,53). For these patients, US guidance gives optimal visualization to distinguish the septum from the RV free wall, as seen in *Figure 8*. In addition, US guidance helps to alert the physician when a complication occurs during the procedure and facilitates follow-up care with immediate detection of complications, especially pericardial effusions.
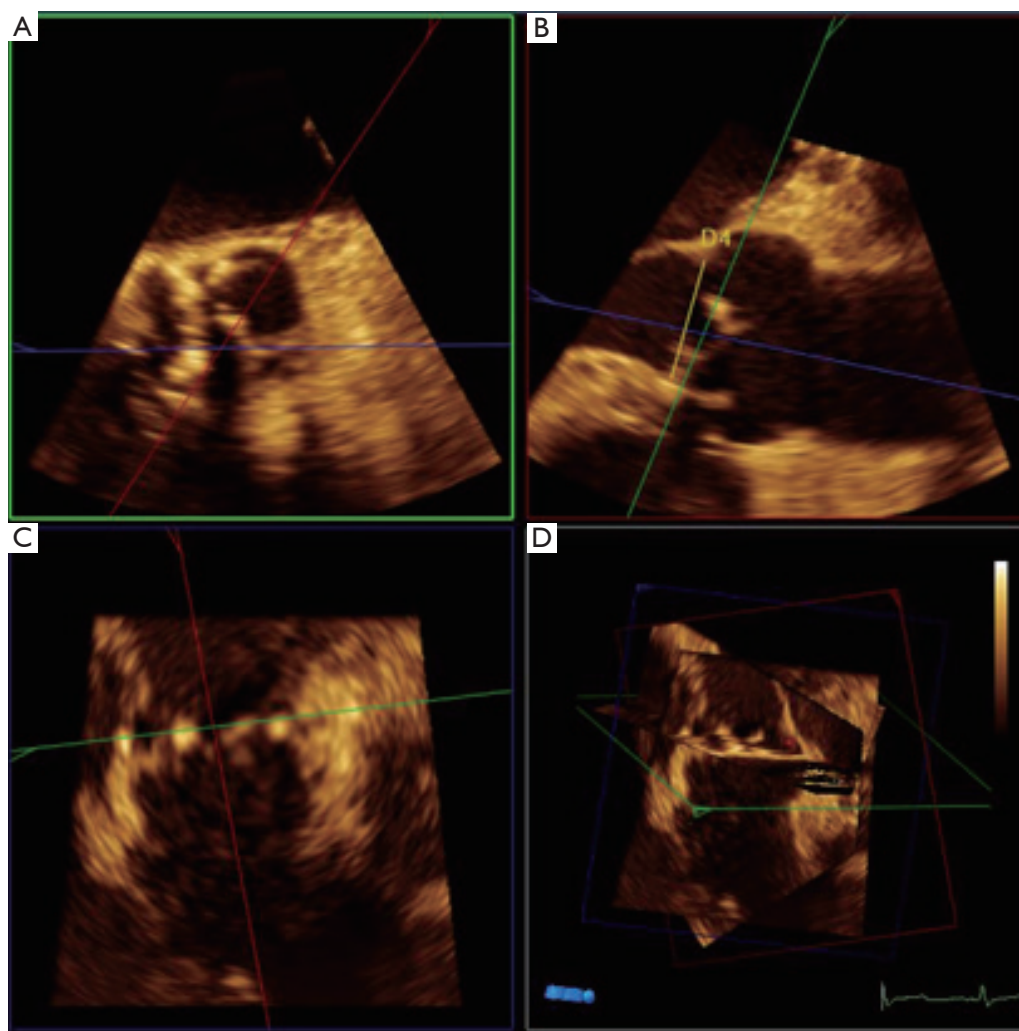
Figure 15 Multiplanar assessment of aortic annulus using 3DTEE. A. Short axis assessment of aortic valve; B. Left ventricular outflow tract view with measurement of aortic annulus diameter; C. Orthogonal measurement of the aortic annulus; D. A composite of three panels. The use of 3D TEE facilitates measurements of the aortic annulus from multiple angles. (From Siegel *et al*. Curr J Cardiovasc Imaging Rep 2011, in press, with permission)

Many different centers and physicians have had success with US guided endomyocardial biopsies. Pierard *et al*. performed 22 biopsies on 18 patients (5-6 samples each patient on average) and had a success rate of 100% with no major complications (52). Minor complications included chest discomfort, premature ventricular contractions and atrial fibrillation. They concluded that US guidance is safe and simple technique to performing biopsies. In a study by Han *et al*., 90 patients underwent endomyocardial biopsies (55). The major complication rate was 5.6% and included myocardial perforation, right bundle branch block, and hemodynamically unstable tachycardia. Also, there were three perforations but none that required pericardiocentesis and there were no procedure related mortalities. Blomstrom-Lundqvist *et al*. performed 231 endomyocardial biopsies in 74 patients (50); sixty biopsies were performed under X-ray guidance while 171 were performed with US guidance with a complication rate of 4.8% (no deaths). In five of the procedures performed, all of which were under X-ray guidance, the specimens were considered inadequate. In addition they found that the incidence of cardiac perforations was higher in x-ray guided
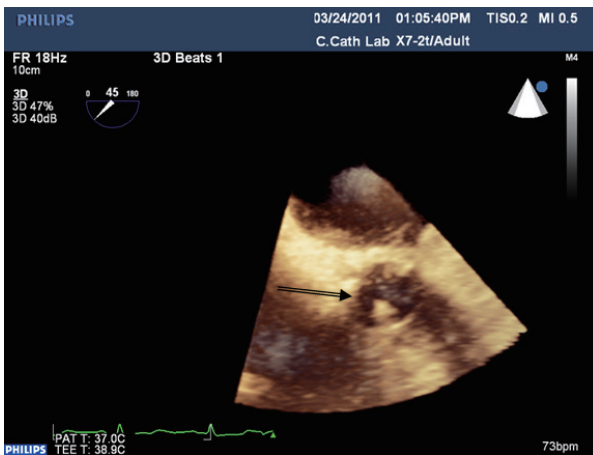
Figure 16 Demonstration of the short axis view of the left ventricular outflow tract by 3DTEE shows the shape of the LVOT to be oval in this patient with severe aortic stenosis undergoing TAVI. A catheter (arrow) is present in the LVOT. (From Siegel *et al*. Curr J Cardiovasc Imaging Rep 2011, in press, with permission)
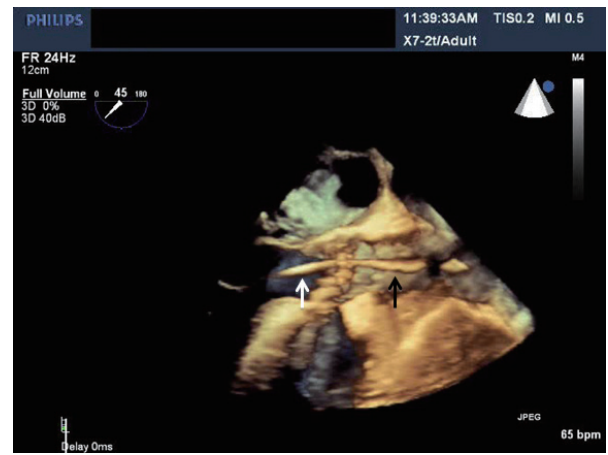
Figure 17 RT 3D TEE long axis view through mitral valve, LVOT, and aorta. View of length of catheter (arrows) from aorta traversing stenotic aortic valve and entering the LV. (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)
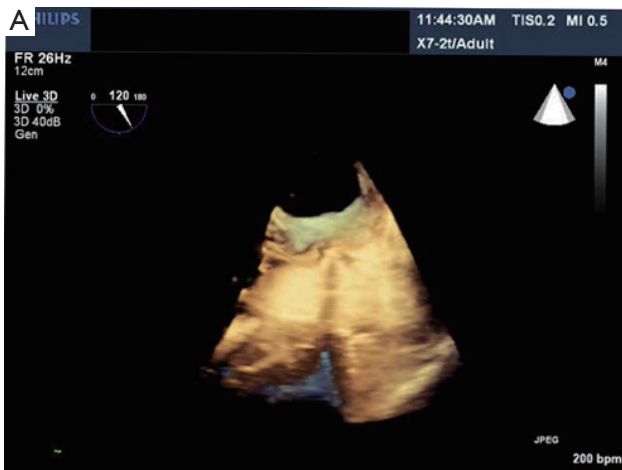
Figure 18 A. 3D view of balloon inflation during balloon valvuloplasty; B. Full volume 3D color flow showing severe aortic regurgitation after balloon valvuloplasty; (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)

procedures than US guided procedures. They also discovered that more epicardial and pericardial tissue in X-ray guided biopsy specimens (5.8%) than those with US guidance (0.7%). Thus, the study concluded that US guidance improves safety and efficacy compared to X-ray guidance.

US guidance can assist in the safe and accurate performance of endomyocardial biopsies. X-ray guidance is another option, however, procedural complications and

safety issues are a factor. Transesophageal echocardiography and intracardiac echocardiography may offer more optimal imaging, but have more risks and costs with patient sedation and required personnel (44).

Pulmonic Valve Implantation

Pulmonic valve disease is often associated with congenital

Figure 19 A. 2D TEE long axis view of 23mm bioprosthetic aortic valve B. 3D TEE long axis view-the stent length is too aortic and needs to be lower (more toward LVOT); C. The valve is now perfectly aligned. From Lerakis S. *et al*. JACC Vascular Imaging 2010;3:219-221), reprinted with permission
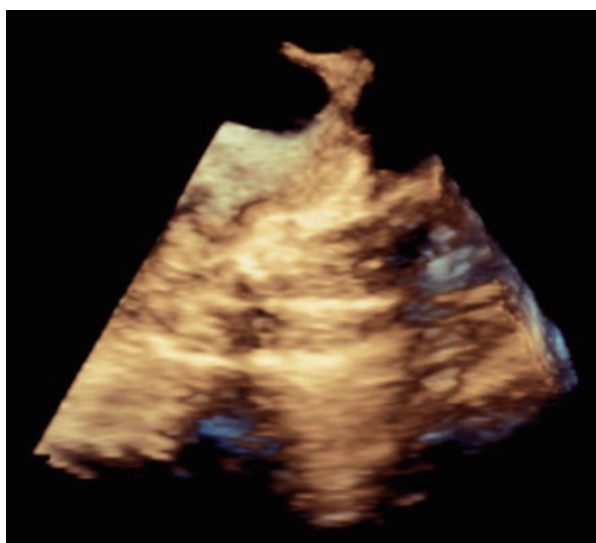

Figure 20 3D imaging during balloon inflation deploying Edwards Sapien bioprosthetic valve. (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)

heart diseases. Surgical intervention for these conditions consists of placing prosthetic valved or valveless conduits to establish continuity between the right ventricle (RV) and the pulmonary artery (PA) (56). Overtime, these prosthetic conduits are susceptible to obstruction or regurgitation leading to symptoms of exercise intolerance, arrhythmias, RV dysfunction, and an increased risk for sudden death (57-59). Patients with postoperative RV outflow tract (RVOT) dysfunction, whether from pulmonary regurgitation (PR), obstruction, or both, will need surgical intervention (60). Often, patients may undergo multiple open-heart surgeries over a lifetime to treat conduit

dysfunction (61,62). Percutaneous pulmonary valve implantation (PPVI) appears to be a promising alternative to surgical pulmonary valve replacement (PVR) (63-65). Studies have shown that PPVI reduced RVOT obstruction, provided a competent pulmonary valve, improved functional status, and peak exercise parameters (56,60,65,66).

Numerous imaging modalities are used prior to, during, and post procedure of PPVI. It is important to have a full understanding of the outflow tract anatomy because candidates for PPVI must fulfill anatomic requirements for safe anchoring of the valve (RVOT >14 mm × 14 mm and < 22mm × 22 mm) (63). Patients also undergo cardiac magnetic resonance imaging (cMRI), with 3D reconstruction, prior to the procedure to determine the maximal and minimal dimensions of the RVOT. If the results of cMRI are doubtful, then balloon sizing of the RVOT is performed at the time of cardiac catheterization. Angiography of the coronary arteries is performed to assess the risk of compression from the valve implantation. If the risk of compression remains unclear, then coronary angiography is done with simultaneous inflation of angioplasty balloon at the implantation site (65,67,68). The site for implantation is determined from angiographic studies and hemodynamic assessment of RVOT to identify the position and extent of obstruction and regurgitation (56,63,69).

Percutaneous pulmonary valve implantation is currently done under fluoroscopy guidance. Transthoracic echocardiography is used mostly to assess the conduit mean gradients, RV size and function, and severity of PR prior to, during, and post procedure in PPVI. *Figure 9* shows a 2D TEE view of a stented pulmonary artery with severe PR by 2D and 3D color flow Doppler. A catheter is well seen in the stent graft in *Figure 10*. Pre-deployment valve echo is used
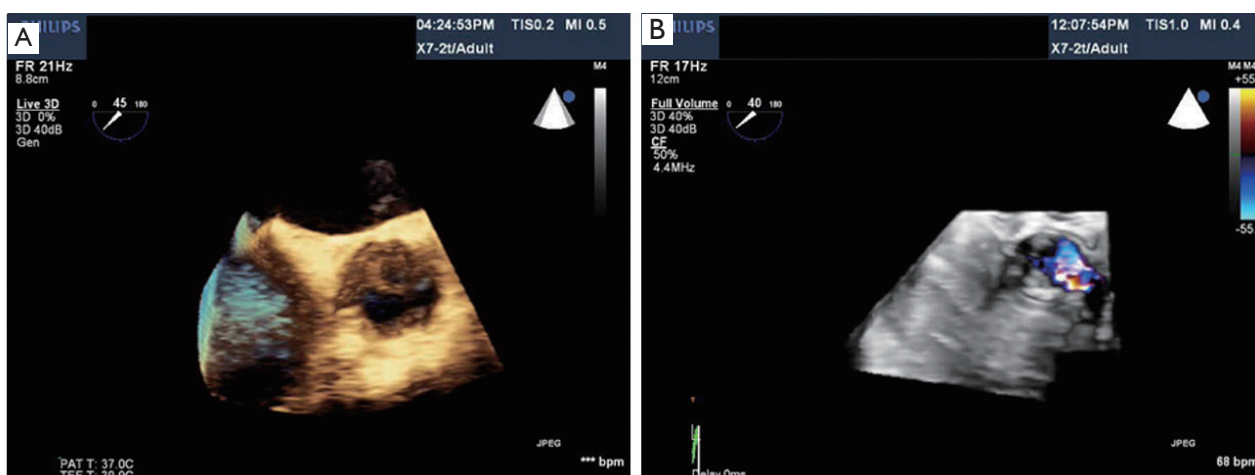
Figure 21 A. Post deployment of the bioprosthetic valve; B. Full volume color flow demonstrates site and severity of aortic regurgitation. (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)
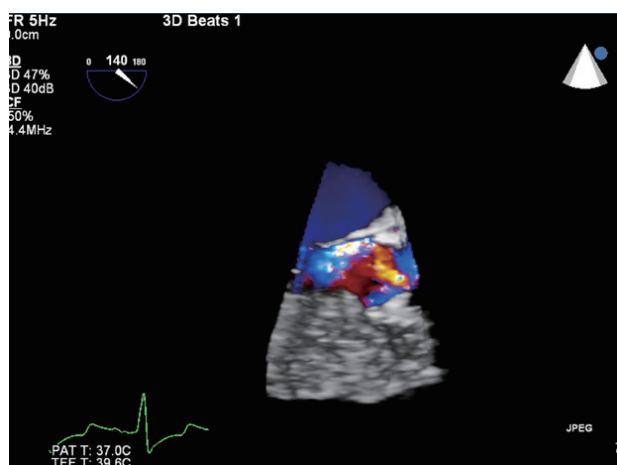
Figure 22 3D TEE color long axis view of the aortic valve demonstrating moderate peravalvular and transvalvular aortic regurgitation. (From Siegel *et al*. Curr J Cardiovasc Imaging Rep 2011, in press, with permission)

to identify the zone after implantation as seen in *Figure 11A*. *Figure 11B* shows a successfully placed pulmonic valve color flow Doppler. Two dimensional and 3D are used to further assess for PR. In this care, there was no residual PR.

As illustrated above, intra-procedural 2D and 3D transesoph-ageal echocardiography may be beneficial during PPVI by providing interventionalists and echocardiographers the ability to fully assess the size and anatomy of the RVOT, PA, and surrounding structures.

This may aid in selecting candidates with the appropriate anatomical requirements and avoid the potential risk of coronary artery compression. Other advantages may include localizing and identifying of guidewires, catheters, and balloons for precise position of valve deployment to prevent procedural complications.

Transcatheter Aortic Valve Implantation

Aortic stenosis is a progressive disease. After the onset of symptoms, untreated patients are at a high risk for death. The prevalence of aortic stenosis increases with age. It is present in 2% of the population over 50 years old, 3% over 75 years old, and 4% over 85 years old (70-72). The progression rate of aortic stenosis averages 0.1 cm^2/year. Severe aortic stenosis is defined as having a maximum Doppler velocity across the aortic valve greater than 4 m/s, a valve area less than 1 cm^2, and a mean aortic valve gradient greater than 40 mmHg (73). Indications for surgical intervention include the development of symptoms such as chest pain, syncope, shortness of breath, or other symptoms associated with heart failure, or if there is evidence of LV dysfunction (LVEF <50%). Approximately one third of elderly patients with symptomatic aortic stenosis are denied aortic valve replacement (AVR) due to significant co-morbidities (73-75). For patients who are high-risk surgical candidates, transcatheter aortic valve implantation (TAVI) is a less invasive, promising alternative in the treatment of aortic stenosis.
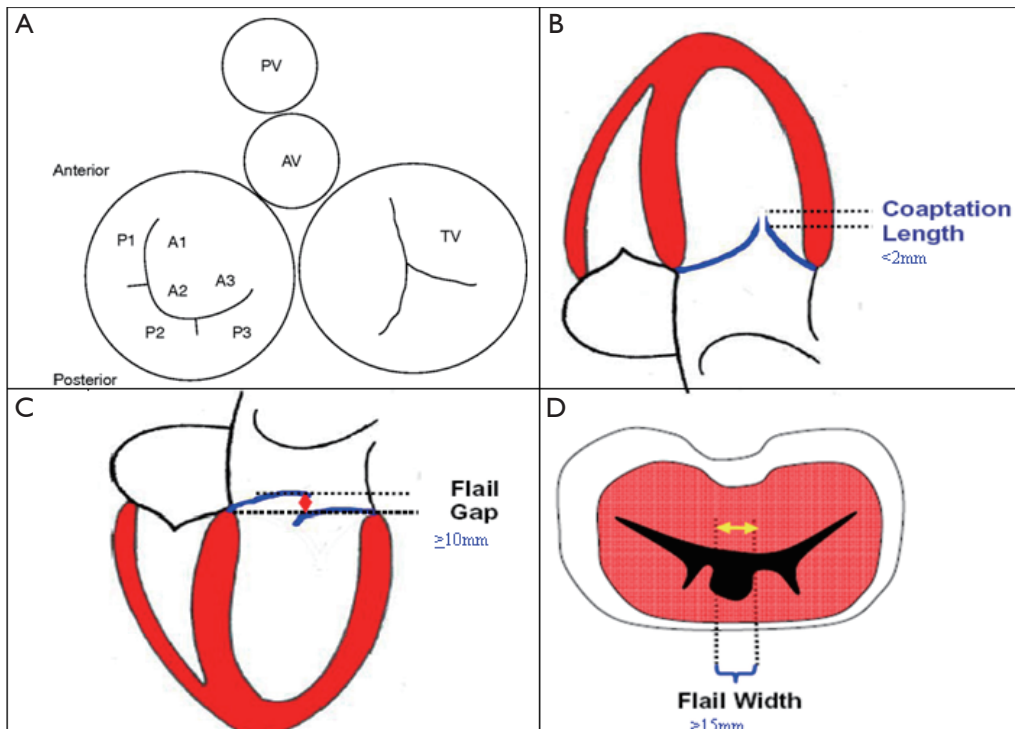
Figure 23 A. The schematic shows the Carpentier classification of the mitral valve scallops. P=posterior leaflet; A=Anterior leaflet; 1=lateral; 2=middle; 3=medial scallops; B. The measurements of coaptation length; C. flail gap, and D. flail width are shown. These are important for inclusion and exclusion criteria that need to be fulfilled prior to MitraClip placement. (From Siegel *et al*. Curr J Cardiovasc Imaging Rep 2011, in press, with permission)
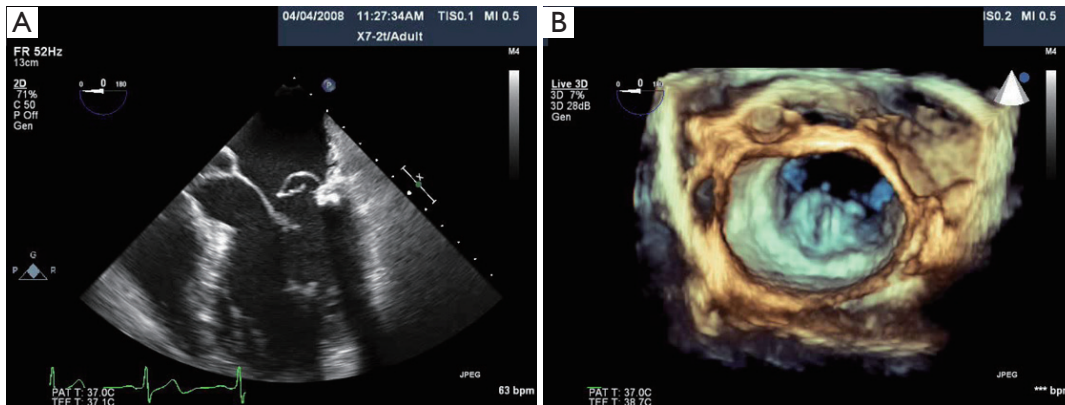
Figure 24 A. 5 Chamber 2D TEE view suggests the lateral scallop of the posterior leaflet is flail; B. 3D TEE reveals the middle scallop of the posterior leaflet is flail and that there are 2 ruptured chordae tendineae (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)

The first TAVI was performed in 2002, and since then, more than 25,000 Sapien Edwards aortic valves have been implanted worldwide (76). *Figure 12* shows the 2 TAVI devices currently used in clinical trials in the United States or commercially used internationally, the MedTronicCoreValve (Minneapolis, Minnesota) and the
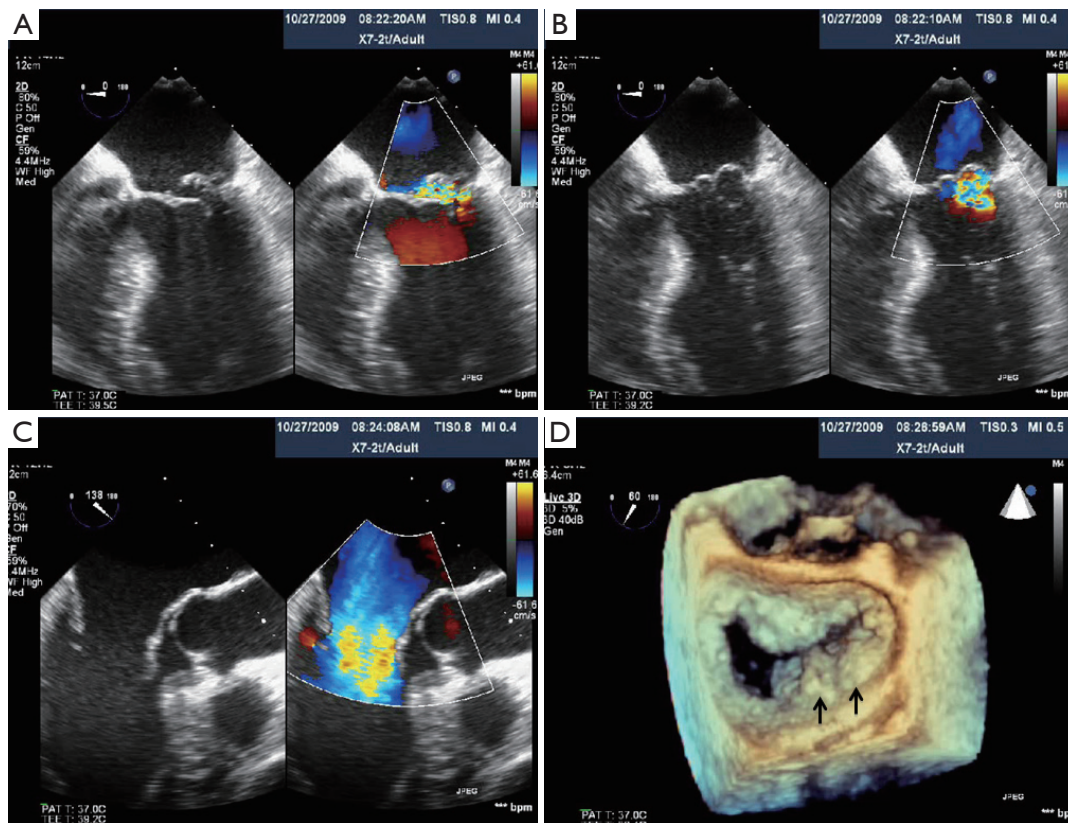
Figure 25 A-B. 2D TEE 4 Chamber views show prolapse and flail of the middle scallop (P2) with associated MR; C. 2D 3 chamber long axis view also shows middle scallop (P2) prolapse and flail; D. 3D RT TEE show flail medial and middle scallops (P2 and P3) (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)

Edwards Sapien Valve (Edwards Life Sciences, Irvine, California). The TAVI procedure consists of passing a catheter from the femoral artery up to the aorta and crossing the aortic valve. A standard balloon aortic valvuloplasty is performed to pre-dilate the stenotic aortic valve. The bioprosthetic heart valve, crimped onto a balloon catheter, is then advanced across the native aortic valve and deployed during rapid right ventricular pacing (77). TEE is used to size the aortic annulus. Concomitant TEE and fluoroscopy are used to position and deploy the valve. Successful TAVI requires selecting the appropriate prosthetic valve size and precise placement of the valve prosthesis. Intra-procedural 2D and/or 3D TEE provide interventional cardiologists and echocardiologists the ability to fully evaluate the anatomy of the aortic valve, annulus, and surrounding structures in patients undergoing TAVI. *Table 3* lists the role of TEE guidance in TAVI.

Two-dimensional and 3D TEE can visualize the aortic annulus, valve cusps, coronary arteries, and shape of the LVOT. In *Figure 13*, a 2D TEE pre-procedural X-plane image visualizes the aortic valve in cross section, in addition to the long axis view, in a patient undergoing TAVI. As shown in *Figure 14 A-D*, 2D and 3D TEE in the short axis view at the aortic level (30°-60°) often visualizes the left main coronary artery and the long axis view (110°-140°) clearly shows the right coronary artery ostium. Annular remodeling in aortic stenosis has been reported to cause a decrease in the distance between the aortic annulus and coronary ostia. With X-plane 3D TEE mode, the ostia of the coronary arteries are distinctly visualized allowing evaluation of their distance from the native and prosthetic valve. This allows safer delivery of the prosthesis by avoiding occlusion of the coronary ostia. Other complications may arise if the prosthetic valve is not deployed in the correct position. The preferred position is for the prosthetic valve to be coaxial to the native valve and
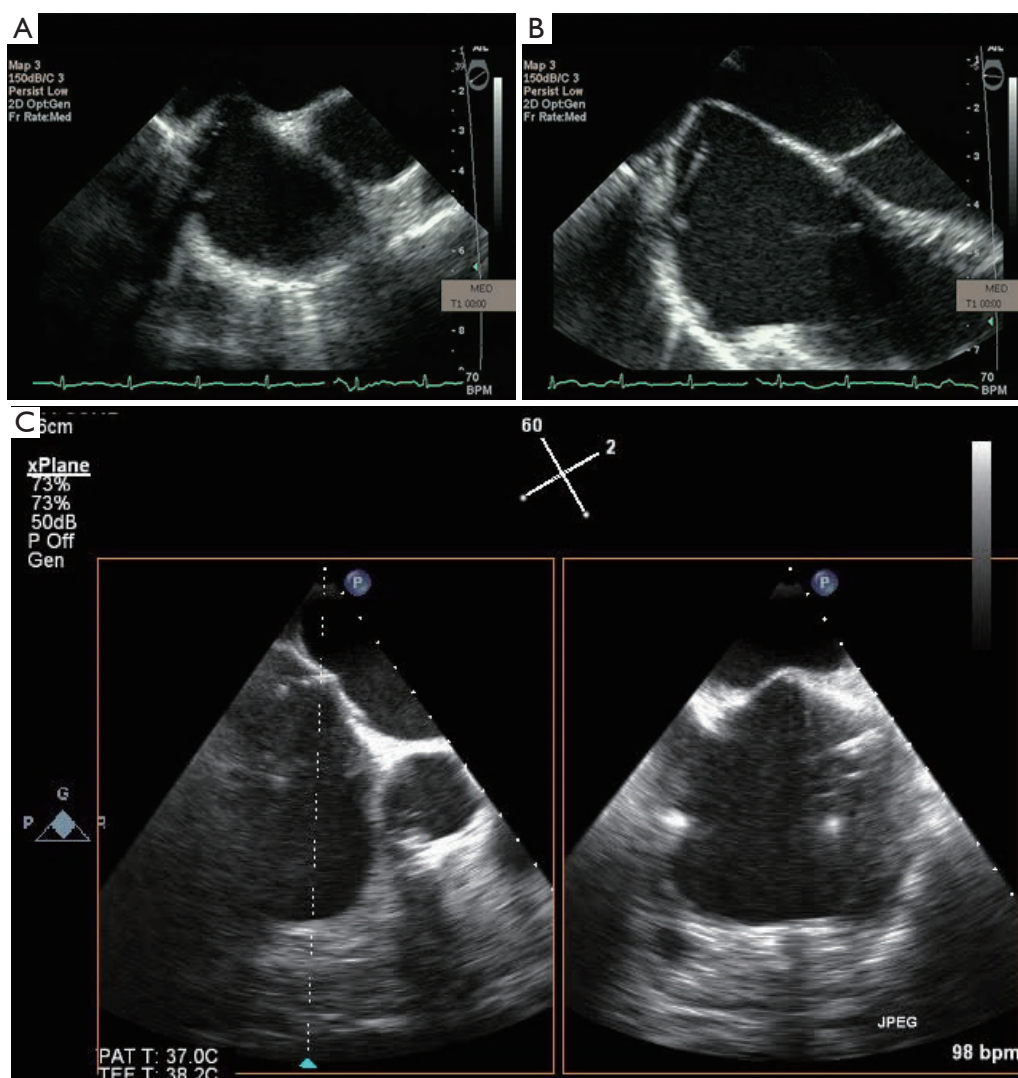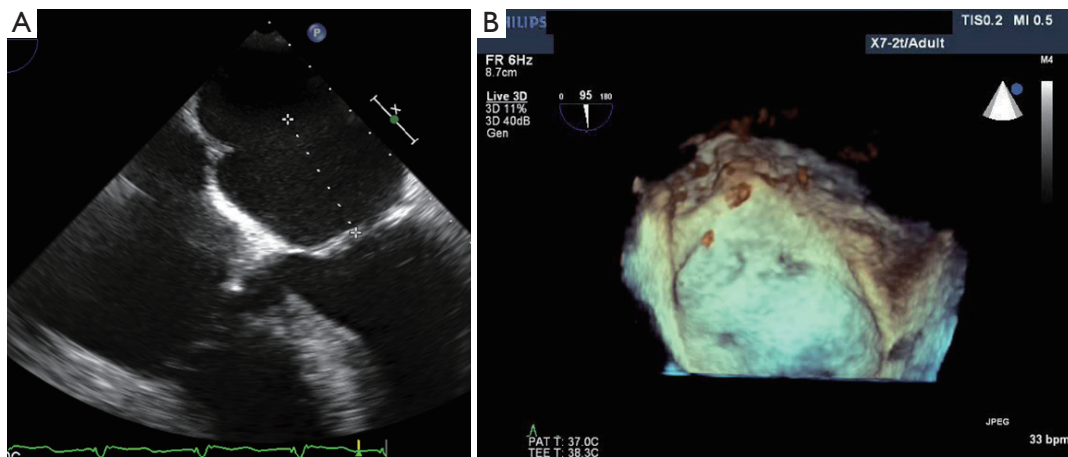
Figure 26 A. Short axis view at level of aortic valve shows transeptal catheter indenting the intra-atrial septum; B. 4 Chamber view shows transeptal catheter indenting the intra-atrial septum; C. X-plane imaging shows simultaneous views of intra-atrial septum during the transeptal puncture from the aortic short axis (left panel) and the bicaval view (right panel). (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)

the ventricular edge of the aortic valve should be 2-4 mm below the aortic cusps allowing the post deployment position of the prosthesis to be 1-2 mm below the insertion points of the native valve cusps. Deployment of the valve too low in the LVOT may result in impingement of the anterior mitral leaflet. However, if the valve is deployed too high, then the prosthetic valve may occlude the coronary ostia or embolize into the aorta.

Pre-procedural TTE and intra-procedural TEE are used to assess the diameter and size of the aortic annulus.

CT is often used to measure the aortic annulus prior to the procedure. During TAVI, TEE is used to corroborate the procedural measurements. For the Edwards Sapien valve, if the aortic annulus is 18-23 mm, then a 23 mm prosthesis is used for implantation, whereas, a 26 mm prosthesis is selected if the annulus is 23-26 mm. The annulus diameter is measured at the lowest portion of the hinge point of the aortic valve cusps.

However, the annular diameter measurements may vary because of the shape of the annulus is often oval rather

Figure 27 A. 2D TEE 4 Chamber view shows transeptal catheter indenting the intra-atrial septum; B. 3D TEE transeptal catheter indenting the intra-atrial septum from the left side of the septum. (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)
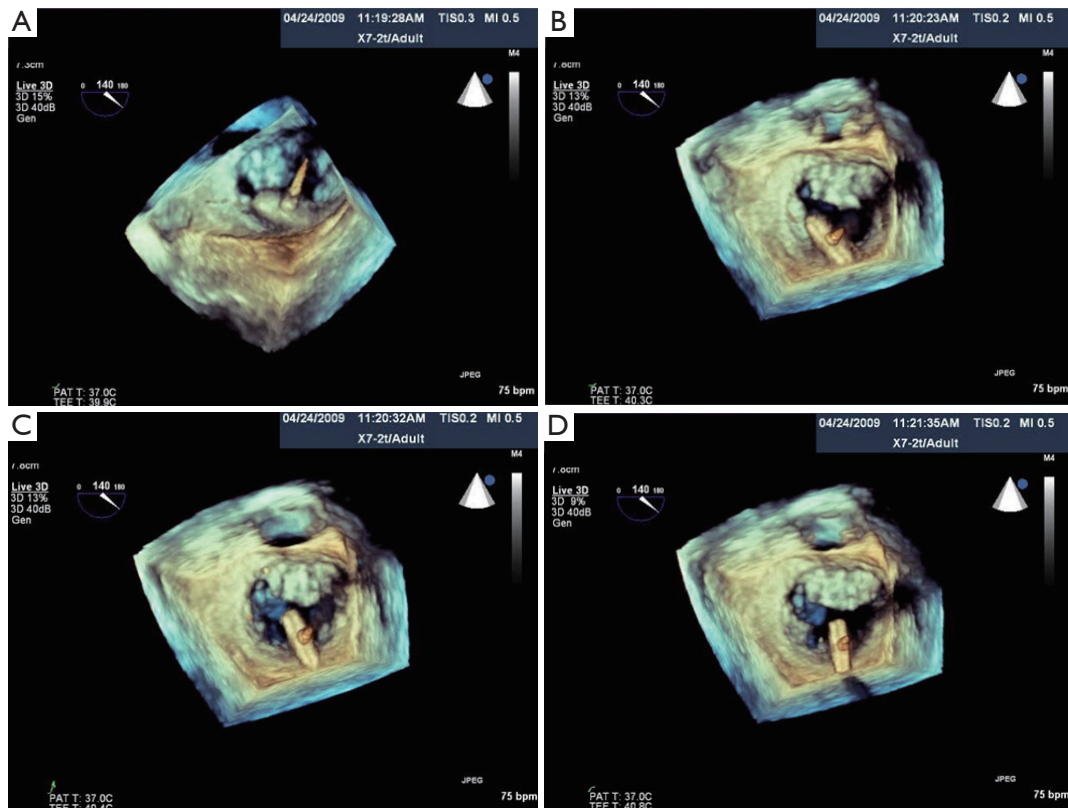
Figure 28 A-D. Serial 3 D images show how the open MitraClip is progressively re-oriented to that the clip is at the mid-portion of the mitral valve (above A2-P2) and perpendicular to the line of MV coaptation. (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)

than circular (78), depending on whether measurements were taken from a coronal or a sagittal plane. As shown in *Figure 15A*, X-plane imaging from a 3D TEE system allows for measuring the aortic valve annulus in orthogonal views. In *Figure 16*, 3D TEE imaging reveals that the aortic annulus is not circular but oval in this patient. Of note, 3D
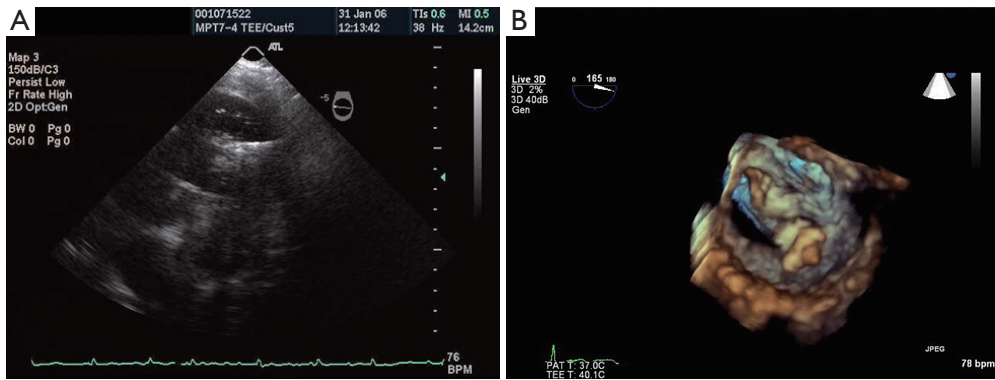
Figure 29 A. 2D TEE transgastric view shows from the LV that the clip is perpendicular to the MV line of coaptation and near the central portion of the valve; B. 3D view from LV shows clip is at the mid-portion of the mitral valve (below A2 P2) and perpendicular to the line of MV coaptation. (From Siegel *et al*. Int Cardiovasc Imaging 2011, in press, with permission)
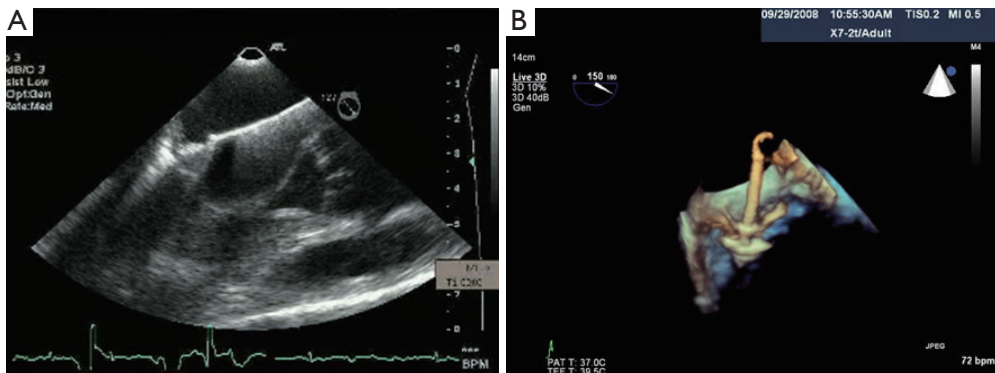
Figure 30 A. 2D TEE long axis view shows the MitraClip grasping the anterior and posterior leaflets; B. 3D TEE shows the MitraClip grasping the anterior and posterior leaflets (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)
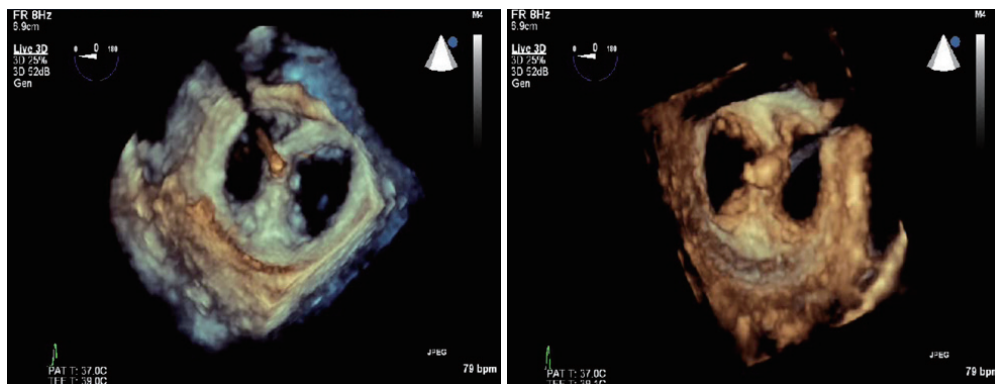
Figure 31 3D TEE evaluation of size and the shape of the dual mitral orifices after MitraClip deployment. (From Siegel *et al*. Int J Cardiovasc Imaging 2011, in press, with permission)

Table 3 The Role of TEE Guidance in Transcatheter Aortic Valve Implantation (TAVI)

1.	Assessment of aortic annular diameter with 2D and 3D
2.	Determine LV and RV systolic function; identifying other associated valve disease or cardiac abnormalities
3.	Guide and confirm coaxial alignment of the delivery catheter within LVOT and aortic root
4.	Identify the ventricular and aortic ends of the prosthesis prior to deployment of valve to aligne with the aortic valve cusps
5.	Optimize bio-prosthetic valve position before deployment
6.	Assess severity of aortic regurgitation post valve deployment
7.	Assess the complications including LV dysfunction, coronary obstruction, valve embolization, pericardial tamponade, or aortic annular rupture

TEE has less underestimation of annular size and narrower limits of agreement then 2D TEE. Correct determination of aortic annular size is necessary to avoid complications such as post-procedural paravalvular aortic regurgitation if the prosthesis is too small or aortic annulus rupture if the prosthesis is too large.

Aortic annulus may also vary in size depending on which imaging modality is used. Several studies have compared the measurements of the aortic annulus obtained by TTE, TEE, and cardiac CT in patients undergoing TAVI. Differences in measurements observed between the modalities include underestimation of annular size by TTE (79), disparity by approximately 1.4 mm between TTE and TEE (80), and underestimation of annular diameter by 2D TEE when compared between 3D TEE and MDCT (81).

During the TAVI procedure, both 2D and 3D TEE help identify intracardiac catheters, the valvuloplasty balloon, and the bioprosthetic valve. As shown in *Figure 17*, 3D TEE clearly shows the catheter across the calcific aortic valve in the aorta and LV. During predilation with balloon valvuloplasty, the balloon can be clearly visualized as seen in *Figure 18A*. After balloon deflation, echo is used to assess for complications. *Figure 18B* demonstrates that 3D color is also useful to assess the severity of aortic regurgitation post valvuloplasty. Prior to deployment of the bioprosthetic valve, the valve should be coaxially aligned in the LVOT and at the right level to avoid implanting the valve at an angle, which may result in paravalvular regurgitation. To achieve proper alignment, the ventricular edge of the valve should be approximately 4 mm below the aortic cusps, as shown in *Figure 19A-C*. In panel 19B, the bioprosthetic valve is placed too far into the aorta relative to the aortic cusps, whereas in panel 19 C after adjustment, the bioprosthetic valve is in the appropriate position across the native aortic valve between the LVOT and aorta. *Figure 20* was obtained during rapid RV pacing during inflation of the balloon and deployment of the

bioprosthetic valve with RT 3D TEE. Three-dimensional imaging illustrates how well the valve is seated as shown in *Figure 21A*. Color-flow 3D TEE permits assessment of both the severity and precise origin of the aortic regurgitation, whether paravalvular or central, and if the regurgitation is coming from multiple sites, as seen in *Figure 21B*.

Aortic valve regurgitation is common after TAVI, occurring in 88% of cases (80). It is usually paravalvular regurgitation, which can be trivial to severe, and is generally along the posterior aspect of the prosthetic valve. Less commonly, the regurgitation can be transvalvular and often diminishes over time. In a recent study, moderate or severe paravalvular aortic regurgitation was present in 11.8% of the patients in the TAVI group at 30 days and in 10.5% at 1 year (82). The presence of moderate to severe paravalvular regurgitation after TAVI has been reported to have a 3.79-fold higher risk of 1-year post-procedural mortality (83). Paravalvular regurgitation should always be assessed by color flow Doppler interrogation of the aortic annulus immediately post procedure. *Figure 22* shows an example of post-procedural transvalvular and paravalvular aortic regurgitation that is moderate in severity. Other possible complications are listed in *Table 4*.

The benefits of 2D and 3D echocardiography for percutaneous AVR include a more accurate assessment of aortic annulus shape and size, visualization of catheters during the procedure, and efficacy of the procedure. Echocardiography is also used to evaluate post procedure complications. These benefits contribute to operator confidence during the procedure and successful implantation of the bioprosthetic valve.

Mitral Valve Repair with MitraClip

Mitral regurgitation (MR) is a progressive disease associated with left ventricular dysfunction and congestive heart

Table 4 Possible complications from TAVI
Aortic annulus rupture
Prosthesis embolization
Stroke
Myocardial infarction
Cardiac tamponade
Transient LV dysfunction
Coronary obstruction
Mitral regurgitation
Aortic regurgitation
Major vascular complications

Table 5 Echo doppler criteria for mitraclip repair of MR
Inclusion
Grade 3-4+ (moderate-severe or severe) MR
MR originating from the central 2/3 of the valve (A2, P2)
Degenerative of functional etiology
Sufficient tissue for mechanical caption of the valve
Exclusion
Rheumatic MR
MVA area <4 cm^2
Flail gap >10 mm
Flail width >15 mm
LV systolic internal dimension >55 mm
LV ejection Fraction <25%

Table 6 Transesophageal Echo-Guided MitraClip Placement (12 steps)	
1.	Transseptal puncture
2.	Introduction of guide catheter sheath into left atrium (LA)
3.	Insertion of clip delivery system into LA
4.	Open clip in LA just above mitral valve (MV)
5.	Orient MV clip perpendicular to line of MV coaption at mid-portion of valve
6.	Advance clip into left ventricle (LV)
7.	Confirm clip orientation remains at line of MV coaption at mid-portion of MV
8.	Grasp leaflets
9.	Confirm leaflet insertion
10.	Assess for adequacy of MR reduction. If not adequate consider moving clip or placing second clip.
11.	Confirm MV gradient <5 mmHg
12.	Deploy clip

coaptation within the LV, however this can be difficult, as shown in *Figure 29A*. However, 3D MitraClip orientation in the LV can often be obtained, as seen in *Figure 29B*.

Next, the operator is set to capture the MV in the mid-portion of the MV leaflets. This step is generally guided by 2D TEE from the long axis view that shows the A2 P2 segments (angle 110°-140°) or combining with a 3D system X-plane view where the operator has a long axis view and a 2D bi-commissural view (60°-90°). This enables the operator to image P1-3 segments as well as A2 (*Figure 30A,B*). After MV leaflet capture, 2D TEE is used to assess leaflet insertion with multiple views including 4 chamber, bicommissural (2 chamber), and long axis (3 chamber) views. Three-dimensional TEE provides important adjunctive information regarding MR, such as identifying if there is more than 1 MR jet, which can sometimes be missed by 2D

imaging. More interrogation with 2D color and spectral Doppler is performed if a second or third regurgitant jet is found. If a second clip is needed, 3D TEE color Doppler is helpful in identifying the site of the largest jet as well as the jet origin. After successful leaflet capture and satisfactory reduction of MR, Doppler is used to assess residual gradient across the MV to ensure the absence of mitral stenosis. A gradient of 5mmHg would be considered unacceptable and a gradient of 3 or 4 mmHg might preclude from using a second MitraClip. As *Figure 31* shows, 3D TEE is useful after the deployment of MitraClip to evaluate the size, shape, and symmetry of the dual mitral orifices.

To date, over 3,000 MitraClip procedures have been performed worldwide and no intra-procedural mortality has been reported. Of the 128 cases performed in our institution, the post-procedure complications include 1

failure. Patients with severe MR have a 5-year survival rate of 40%. If untreated, symptomatic patients may have a yearly death rate of greater than 5% (84). Surgery is recommended for symptomatic patients with severe MR or asymptomatic patients with evidence of left ventricular dysfunction (73). Mortality rates for mitral valve (MV) surgery have been reported to range from 1-2% for low-risk, young patients to 25% for high-risk, elderly patients undergoing MV replacement (85,86). In 2001, Alfieri *et al.* developed a modified, surgical MV repair technique which involves suturing the middle scallops of the anterior and posterior MV leaflets at the origin of the regurgitant jet to create a double-orifice MV (87). This was mainly for degenerative MR and the procedure is usually performed with an annuloplasty ring. In 2003, percutaneous MV repair was introduced with the first MitraClip implantation (88). This is an endovascular approach that approximates the anterior and posterior MV leaflets creating a double-orifice MV with a mechanical implant, the MitraClip (MitraClip System, Abbott Vascular Structural Heart, Menlo Park, CA). A recent study observed that the procedure was associated with increased safety, had similar improvements in clinical outcomes, and similar rates of reduction in MR at 12 and 24 months when compared with conventional surgery (89). The MitraClip implant may benefit patients who have met several important inclusion and exclusion criteria prior to clip placement (*Table 5* and *Figure 23A-D*).

To optimize communication regarding MV morphology and anatomy among echocardiologists and interventional cardiologists, we use the classification of Carpentier (87). As shown in *Figure 23A*, we use the Carpentier nomenclature to describe the MV in the surgical view when using 3D TEE imaging. Although 2D TEE is helpful to assess MV morphology, 3D provides important additional information and details regarding morphology. For successful MV clip repair, the structural abnormalities and MR needs to be central. With degenerative MR due to prolapse or flail, the abnormality has to be limited to the central portion of the valve at the anterior leaflet (A2) and posterior leaflet (P2). Three-dimensional TEE, which can be done in live 3D TEE, Zoom mode or full volume imaging, provides an accurate en face anatomic definition of the MV. As demonstrated in *Figure 24A*, 2D TEE can be misleading as to which scallop is prolapsed. In this 5-chamber view, the 2D TEE appears to show prolapse of the posterior lateral scallop or P1 prolapse, whereas on 3D TEE, the prolapse is central (P2), as seen in *Figure 24B*.

We have found that 3D TEE clarifies the site of MV prolapse in cases that are ambiguous by 2D TEE. To date, we have screened more than 900 patients for MitraClip, and currently, 125 patients have had MV clip repair at our institution (Cedars-Sinai Medical Center, Los Angeles, CA). Insufficient MR severity is the most frequent cause of exclusion from the trial. However, detection of lateral (A1 or P1) or medial (A3 or P3) prolapse on the screening 3D TEE may occur that was not clearly seen by 2D TEE. As shown in *Figure 25A-D*, the flail scallop appears to be the middle scallop (P2) on 2D TEE, but on 3D TEE, the flail is actually in both the middle and medial scallops (P2 and P3, respectively). Thus, this patient did not meet the criteria for MitraClip as the MR was due to a non-central MV leaflet prolapse and flail.

The MitraClip System is a catheter-based device that is inserted percutaneously via the femoral vein to the right atrium. *Table 6* summarizes the steps of the procedure. As demonstrated in *Figure 26A-C*, X-plane view is used for trans-septal punctures to identify simultaneously the site of puncture from a bicaval and aortic short axis view. This allows confirmation of the puncture site relative to the fossa ovalis, in addition to its relationship to the aorta. Before the trans-septal puncture, the distance of the trans-septal needle in relation to the plane of the mitral valve is assessed with a 4-chamber view. The puncture site should be more superior along the intra-atrial septum so that there is more distance between the trans-septal catheter and the plane of the MV annulus; this is preferred for MV prolapse, especially bi-leaflet prolapse. After the MitraClip-guided catheter enters the left atrium, the guide catheter should be oriented towards the mitral valve apparatus, as shown in *Figure 27A,B*. Real-time 3D TEE imaging helps to orient the catheter in a way not possible by 2D TEE. The alignment and directionality of the catheter can be evaluated in the three dimensions of the heart. Three-dimensional TEE can also identify the locations of the guide catheter, the device, mitral valve, and left atrial appendage. Two-dimensional TEE can visualize the advancement of the MitraClip towards the MV; however, clip orientation within the LA can be problematic. The MitraClip should be located at the mid-portion of the MV (A2 and P2 segments) and oriented perpendicularly to the line of MV coaptation prior to the entry into the LV. With 3D guidance, as shown in *Figure 28A-D*, the clip can be directed to the mid-portion of the MV and adjusted perpendicularly to the line of MV coaptation. Once in the ideal position, the MitraClip is advanced into the LV. Two-dimensional TEE trans-gastric view can adequately assess the MitraClip orientation perpendicular to the line of MV

cardiac tamponade, 1 hemothorax, and 1 large right to left shunt. Both the pericardial tamponade and hemothorax cases were drained without complications and each had successful MitraClip placement. The case with severe right to left shunting across the atrial septum after the trans-septal puncture was associated with severe tricuspid regurgitation. An ASD closure device (Amplatzer) was used to close the shunt. Thus, if a patient has severe tricuspid regurgitation, especially in the setting of pulmonary hypertension, there may be a higher risk of developing a substantial right to left shunt across the atrial puncture site.

Percutaneous mitral valve repair with the MitraClip System has shown to be a promising method for a noninvasive treatment of severe MR. Real-time 3D TEE has been shown to be beneficial and is useful for optimal guidance of the MitraClip procedure (90). The addition of 3D TEE with 2D TEE has been reported to improve confidence of the echo interpretation (P<0.001) (91). In our experience, 3D enhances the confidence for the assessment of mitral valve morphology, localization of guiding catheters, and MitraClip placement. In addition, RT 3D TEE was associated with reduction in procedure time by 40 minutes (P=0.35).

Conclusion

In conclusion, echocardiographic guidance and monitoring of interventional procedures has transformed cardiovascular therapeutics as demonstrated in this article. Echo is not only useful but increases the safety of percutaneous access procedures for arterial and venous access. It has been found to enhance the safety of both pericardiocentesis and myocardial biopsy by allowing the operator to identify the location of catheters and avoiding unnecessary complications. Recent advances in cardiovascular catheter technology have seen the development of percutaneous valves, as well as valve repair devices such as the MitraClip. Current data demonstrates echo guidance of transcatheter procedures of valve interventions improves device delivery and patient outcomes.

Acknowledgements

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36

Nguyen et al. Diagnostic and Therapeutic Percutaneous Procedures

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