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Echocardiographic Evaluation of Ventricular Assist Devices

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1. Introduction

Ventricular assist devices (VAD) are used to treat selected patients with severe heart failure and their role in this field is expanding. Indications for VAD insertion include bridge to transplant, bridge to decision, bridge to recovery and destination therapy. Due to their complicated mechanical structure and function and interaction with complex patients, echocardiography plays a key role in managing patients supported with a VAD. Echocardiography is integral in four areas; pre-operative assessment of potential candidates, guidance during VAD insertion, detection of complications and monitoring for cardiac recovery. Transthoracic echocardiography is the initial imaging modality used. However, trans-oesophageal echocardiography is usually required for a more detailed cardiac examination. Intracardiac echocardiography (ICE), contrast enhanced echocardiography and epicardial echocardiography may be used in specific cases.

2. Pre-operative assessment

During the selection process of suitable patients for a VAD, existing cardiac anatomy and function can significantly influence the surgical approach, choice of assist device and cannula placement. Echocardiography is optimally placed to evaluate all these variables. Native valve dysfunction may be present which can significantly affect haemodynamic support. Of particular importance is aortic regurgitation (and pulmonary regurgitation if an RVAD is required). The presence of a prosthetic valve is also a key variable affecting management of these patients. Due to the high risk of prosthetic valve thrombosis following a VAD insertion, a prosthetic mechanical valve may need to be changed over to a biological valve during VAD insertion to overcome this. The presence of intracardiac thrombus affects VAD inflow cannula positioning. Patients with severe left ventricular dysfunction may have an apical LV thrombus which the implanting surgeon will need to be aware of prior to considering any apical cannula insertion. Echocardiography is also used to assess for any intracardiac shunts, such as a patent foramen ovale or an atrial or ventricular septal defect. Assessment of the ascending aorta for atherosclerotic disease is required to help guide placement of the VAD outflow cannula. Right ventricular assessment prior to LVAD insertion is of fundamental importance to help determine whether RVAD insertion is required concurrently with an LVAD.

Ventricular Function

Echocardiography is the investigation of choice to assess right and left ventricular function prior to VAD insertion. The left ventricular ejection fraction (LVEF) is usually significantly reduced prior to LVAD insertion. Severe reduction is classified as a LVEF of less than 25%. This is typically assessed with transthoracic echocardiography, with Simpson's biplane method a common technique utilised to calculate the LVEF (1). In those patients with sub-optimal TTE images, which can account for up to 25% of patients in the critical care complex (2-5), contrast enhanced TTE can be utilised to improve calculation of the LVEF (6-9). Additionally, these patients usually undergo trans-oesophageal echocardiography, enabling improved visualisation of the endocardial border, to assess the LVEF. Coincident with LV systolic dysfunction, is the presence of diastolic dysfunction. There are numerous parameters used in echocardiography to evaluate for this. Routine measures include mitral valve inflow pulse wave Doppler, pulmonary vein flow Doppler, and mitral annular tissue Doppler velocities (usually septal and lateral annular velocities) (10). Whilst these measures may not directly influence VAD insertion, they do provide robust data on the severity of ventricular dysfunction and help predict prognosis (11).

Once left ventricular systolic function has been assessed, echocardiography is then used to determine left ventricular morphology and to evaluate for the presence of any ventricular thrombus. These points are pertinent because if a ventricular cannula is being considered, a ventriculotomy will be required and this often occurs in the region where there may be abnormal ventricular morphology or a ventricular apical thrombus. LV apical thrombi may be difficult to detect, especially if they are small or laminar. Due to imaging orientation and scan planes, transoesophageal echocardiography may not detect LV apical thrombi and transthoracic echocardiography can have a higher diagnostic yield. However, this can be related to image quality and contrast enhancement may be required to further assess for apical thrombi (12-16). Additionally, apical trabeculation (often seen in dilated cardiomyopathy) is a common mimicker of LV apical thrombi. These can be distinguished from one another using contrast enhanced TTE. However, delayed enhancement cardiac MRI is considered as the "gold standard" for detection of LV apical thrombi, particularly if they are small and laminar (17, 18).

Assessment of right ventricular function peri-operatively is of key importance when deciding on mechanical support. Adequate right ventricular function is not only required for adequate filling and function of an LVAD but RV dysfunction may occur following implantation of an LVAD. Up to one third of patients that have an LVAD may also require an RVAD (19-21). However, the incidence of RV dysfunction following LVAD insertion may be lower in the newer continuous flow pumps as compared to pulsatile pumps (22). The interaction between an LVAD and native right ventricle is complex. The insertion of an LVAD may result in improvement of RV systolic function or it may result in reduction in RV systolic function. It is difficult to predict prior to insertion how an LVAD will influence RV systolic function and this is an area requiring further research. Echocardiographic parameters that have been used to help predict RV dysfunction following LVAD insertion include right ventricular dilatation, right ventricular fractional area change of less than 20% and evidence of poor right ventricular performance, measured by right ventricular stroke work index and ability to generate an adequate right ventricular systolic pressure. Additionally, newer parameters such as echocardiographic derived pulmonary vascular resistance (PVR) may be of benefit in assessing the right ventricle and pulmonary haemodynamics following LVAD insertion (23).

Cardiac Shunts

Assessment for cardiac shunting prior to VAD insertion is performed to evaluate the risk of significant right to left shunting and to determine the risk of paradoxical embolisation. These shunts may be at two levels, atrial or ventricular. A ventricular shunt occurs if there is a ventricular septal defect and these may occur following an acute myocardial infarction. It is important to detect these prior to VAD insertion, as they would require closure (usually with a pericardial patch) at the time of VAD insertion. A more frequent cardiac shunt is at the atrial level, due to either a patent foramen ovale (PFO) or atrial septal defect (ASD). Both these defects have the risk of intracardiac shunting which may cause hypoxia or paradoxical emboli. A PFO or ASD can usually be accurately detected and assessed using transoesophageal echocardiography, with direct visualisation of the defect on 2D imaging and detection of flow direction using colour Doppler imaging. However, an atrial shunt is a function of the pressure differential between the right and left atria and this can be a dynamic parameter. A PFO with right to left shunting may not become apparent until after LVAD insertion, which may reduce left heart pressures and hence promote right to left shunting, particularly in the setting of pulmonary hypertension, which is relatively common in this group of patients (24, 25).

Assessment of the Ascending Aorta

The outflow cannula of an LVAD device is usually attached to the ascending aorta in an end to side anastomosis. As such, any pathology that may be present within the ascending aorta needs to be evaluated using transoesophageal echocardiography. The two main abnormalities that impact on LVAD insertion are aneurysmal dilatation of the ascending aorta and atherosclerotic disease. If there is significant dilatation of the ascending aorta (>45 mm) detected at the time of LVAD insertion, the ascending aorta is usually replaced with a Dacron graft and the LVAD cannula attached in an end to side manner to the graft. Transoesophageal echocardiography is well placed to assess for atherosclerotic disease in the ascending aorta (26). The images acquired help determine optimal siting of the outflow cannula anastomosis to the aorta. Epi-aortic echocardiography, using high frequency transducers, provide aortic images with very high spatial resolution, that can help locate and grade the severity of aortic atherosclerotic disease (27).

Assessment of Native Cardiac Valves

Echocardiography is fundamental in the assessment of native valvular structure and function prior to insertion of a VAD. Dysfunction of all four cardiac valves can have an impact on management of patients at the time of VAD insertion.

Mitral regurgitation is commonly associated with end stage heart failure. The mechanism for this is often multi-factorial, with annular dilatation and leaflet restriction due to dilation and impairment (remodelling) of the left ventricle common mediators of this valve disorder. With adequate unloading of the ventricle post LVAD insertion, there is often improvement in the degree of mitral regurgitation. Typically no specific intervention is required for mitral regurgitation at the time of VAD insertion. However, some authors recommend a modified mitral valve repair at the time of LVAD insertion (28). The rationale for this is that with pulsatile LVADs, as VAD flow is asynchronous to ventricular contraction, some VAD output may flow retrograde across an open mitral valve, resulting in pulmonary venous congestion. The presence of haemodynamically significant mitral stenosis at the time of LVAD insertion usually results in surgical correction at the same time, via either a commisurotomy or mitral valve replacement, using a tissue mitral valve (28).

Pulmonary valve disorders may also impact patient management at the time of VAD insertion, although haemodynamically significant pulmonary valve dysfunction is rare. However competence of the pulmonary valve is of key importance if an RVAD is being inserted with an end to side anastomosis onto the pulmonary artery. Haemodynamically significant pulmonary stenosis would also require surgical intervention or a valvuloplasty at the time of VAD insertion.

Aortic valvular dysfunction is clinically important in the setting of VAD insertion. Uncorrected aortic regurgitation has a negative impact on forward flow provided by an LVAD due to regurgitation of VAD flow back into the left ventricular cavity. This then results in a short length loop circuit. It is generally recommended that moderate and greater levels of severity of aortic regurgitation should be corrected at the time of VAD insertion (29). However, questions still remain as to which intervention is most appropriate. This choice in part depends upon whether recovery is expected or not and whether a continuous or pulsatile device is being considered. Options include over-sewing the valve, repairing the valve and replacing the valve (28, 29). Aortic stenosis is usually not of such clinical significance compared to aortic regurgitation. However in continuous flow devices, depending upon the configuration, aortic stenosis may limit forward flow and may need surgical replacement at the time of VAD insertion (19).

Tricuspid regurgitation is a relatively common condition in patients being assessed for mechanical support. This is typically due to right heart failure secondary to chronic elevation of the pulmonary pressures due to left heart failure. There are numerous complex factors that can influence the degree of tricuspid regurgitation post LVAD insertion. The decision to correct tricuspid regurgitation at the time of VAD insertion is a complex one. If significant tricuspid regurgitation is present and it is expected that improvement (via annuloplasty or repair but not replacement due to the risk of valve thrombosis) of this would result in improved RV function, then intervention on the tricuspid valve may be warranted (19, 28).

Assessment of Prosthetic Cardiac Valves

Patients with prosthetic valves in situ who are being considered for VAD represent a complex group in terms of their management. The key issue here is the risk of prosthetic valve thrombosis (with resultant embolisation) due to low flow states across the valve in the setting of a mechanically supported circulation. This may occur with both biological and mechanical valves, though the risk is likely to be higher with mechanical valves. If a mechanical valve is in situ at the time of VAD insertion, one approach is to remove the mechanical valve and insert a biological one instead. Another approach is to over-sew the valve completely with a Dacron patch (if it is in the aortic position). Current practice varies between institutions and there is a paucity of data to guide the clinician as to the optimal approach in this situation (28, 30, 31).

3. Guidance during VAD insertion

Echocardiography is fundamental to accurate insertion of a VAD. Intra-operative transoesophageal echocardiography is routinely performed to guide the surgical team in numerous aspects to this procedure. The key components in this evaluation are assessment of satisfactory cannulae anatomic positioning within the cardiac chambers, determination of adequate flows within the cannulae using Doppler imaging, obtaining adequate chamber decompression and excluding the presence of air within the circuit.

Cannulae that drain blood out of the heart and into the VAD can be defined as inflow cannulae (to the VAD) or access cannulae. They can be located either within the atrium or within the left ventricle. There are several anatomic and physiological parameters that will decide on atrial or ventricular cannulation. For example, the presence of a large region apical infarction would preclude satisfactory apical cannulation and a left atrial cannula would be inserted. Intra-operative transoesophageal echocardiography is used to help guide and optimise atrial and ventricular cannulation. Regardless of the location, it has to be ensured that unobstructed blood flow can be achieved into these cannulae. If placed in the left ventricle, imaging is required to ensure that the mitral valvular or sub-valvular apparatus does not interfere with adequate cannulae flow. Additionally, transoesophageal echocardiography is used to exclude the cannulae being placed into the left ventricular outflow tract, left atrium or directly against a left ventricular wall which may interfere with cannulae flow. The advent of real time three dimensional echocardiography can help in the rapid, multi-planar spatial assessment/orientation of the VAD cannulae in relation to the left ventricular structures (32). Figure 1 demonstrates 2D, simultaneous biplane and 3D transoesophageal echocardiographic images of a left ventricular cannula. If placed within the left atrium, echocardiography is also used to optimise cannulae positioning. It assists the implanting surgeon by providing real time feedback as to location in relation to surrounding structures such as the mitral valve, pulmonary veins and inter-atrial septum. If inserted into the right atrium, it provides information as to cannulae positioning in relation to the inferior vena cave, superior vena cave, tricuspid valve and the inter-atrial septum. As with ventricular insertion, optimal atrial cannulae positioning is one where it is anatomically removed from surrounding structures and where there is satisfactory flows into the cannula.



Fig. 1. 2D, simultaneous biplane and 3D transoesophageal echocardiographic images of a left ventricular cannula.

Cannulae that return blood to the native circulation and flow away from the VAD can be defined as outflow (out from the VAD) or return cannulae. These cannulae are usually fashioned as an end to side anastomosis to either the ascending aorta or pulmonary artery. Conventional transoesophageal echocardiographic views are used to image the ascending aorta (for LVAD outflow) and main pulmonary artery (for RVAD outflow).

Following assessment of satisfactory cannulae anatomic positioning, Doppler imaging (both colour Doppler and spectral Doppler) is used to determine adequate flows into and out of the cannulae. Colour Doppler imaging can assess for satisfactory flow into and out of a cannula, as well as determine whether any part of the cannula is obstructed. Cannulae usually have a large end orifice and multiple side holes. Colour Doppler helps to assess

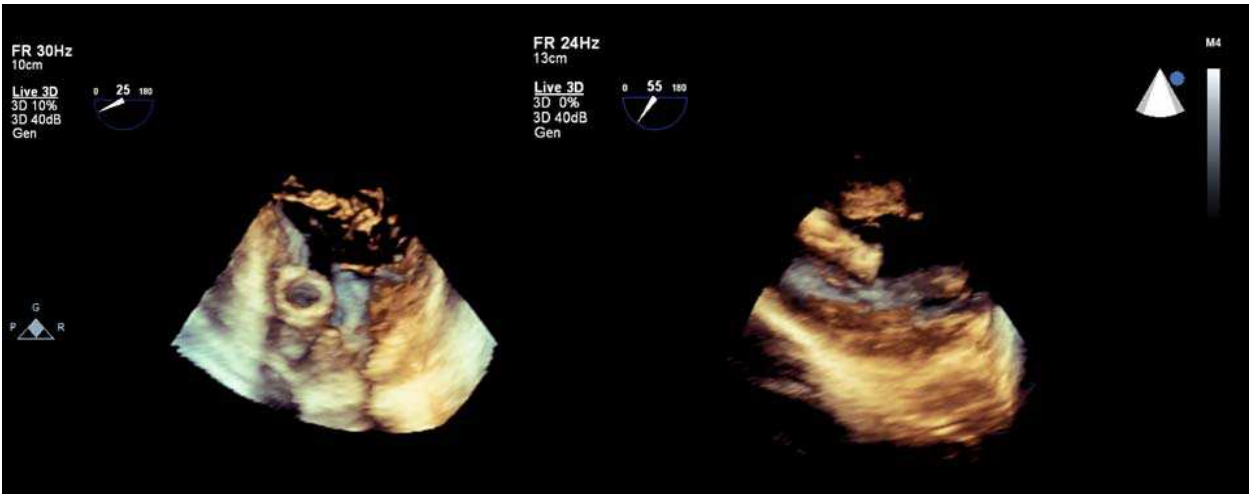


Fig. 2. Live 3D transoesophageal echocardiographic images of a left ventricular VAD cannula

flow into these parts of the cannula. Continuous wave Doppler can then be used if the ultrasound beam can be aligned with the flow. The type of signal obtained (both for colour and spectral Doppler) is dependent upon which type of VAD device is inserted. A pulsatile device will result in an intermittent flow profile (usually asynchronous with the ECG rhythm) whilst a continuous flow pump will provide a lower velocity continuous signal. However, there may be a degree of pulsatility to the continuous flow outflow signal due to variation in filling if there is native heart contraction as well. There is a paucity of data that has been published regarding normal reference ranges for VAD cannulae Doppler flow assessment. Obtaining baseline haemodynamic data can help in the serial evaluation of cannulae flow. The actual velocities obtained can vary depending upon the cannulae diameter, preload, afterload and contribution of native cardiac function. Inflow velocities into a VAD cannula are usually below around 2 metres/second (33). Velocities above this usually indicate pathology within or around the inflow cannula, such as partial obstruction with a thrombus or impingement from a surrounding structure such as a papillary muscle or atrial wall.

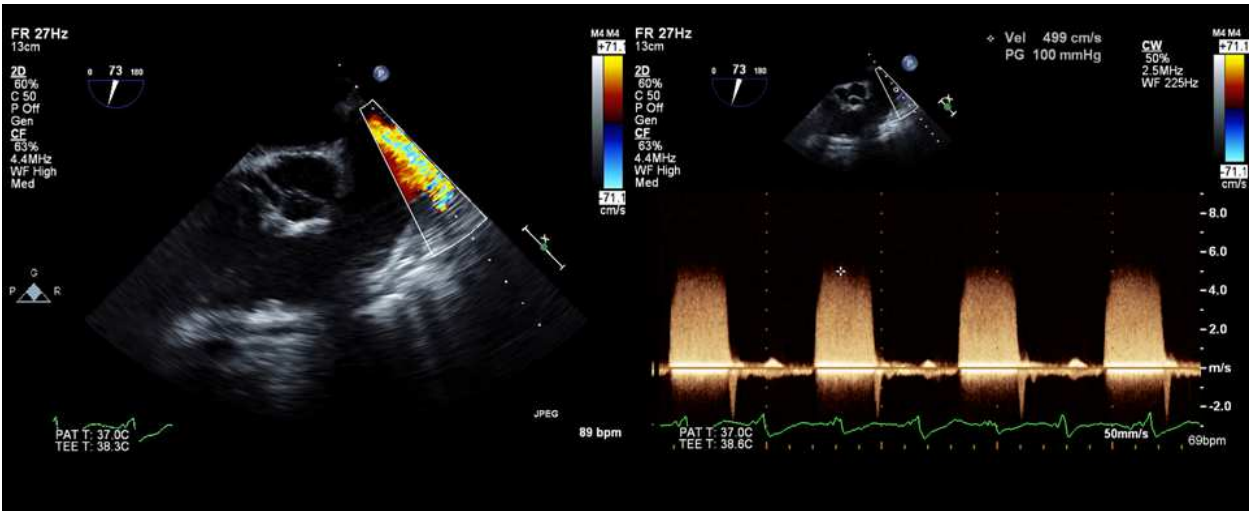


Fig. 3. Colour Doppler (left) and continuous wave Doppler (right) imaging of an RVAD outflow anastomosis onto the main pulmonary artery

Doppler imaging of the outflow cannulae is also important. It enables assessment of satisfactory flow out of the VAD. Due to the higher velocities present, continuous wave spectral Doppler is often needed to interrogate these flows. Again the normal velocities can vary depending upon the type of pump used and the loading conditions. Outflow from a continuous flow device has a continuous flow pattern with a flow velocity of usually less than 2 metres/second (34). Outflows from a pulsatile pump can be higher, with velocities up to 4 metres/second for an Abiomed AB5000 being normal (35). However, outflow velocities of 2 metres/second are normal for the Heartmate VE or Heartmate XVE. The outflow velocities were lower in those patients who had inflow valve regurgitation (36). Higher flows than this usually indicate obstruction within the outflow cannula, usually by a thrombus. Additionally, external compression or kinking of the cannula can also cause an increased velocity detected on spectral Doppler imaging. This may occasionally be detected with transoesophageal echocardiography by careful and thorough evaluation of the cannulae as they course through the mediastinum.

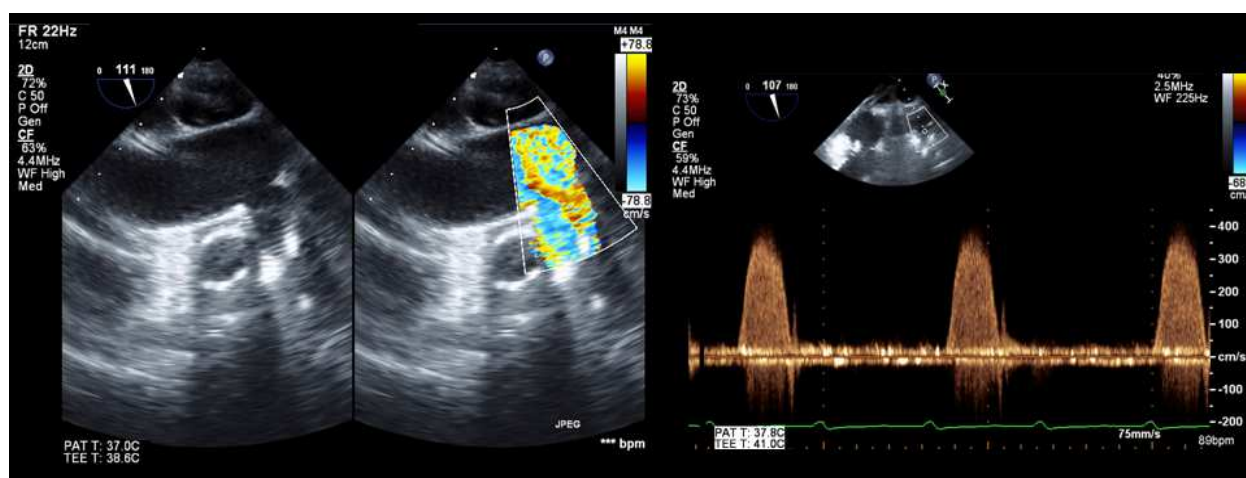


Fig. 4. Simultaneous biplane transoesophageal echocardiogram with colour Doppler (left) and spectral Doppler (right) image of an LVAD outflow anastomosis onto the ascending aorta.

During insertion and initiation of VAD support, de-airing of the circuit is of crucial importance. Air can enter the circulation and circuit from numerous sources, including inadequate priming of the pump and lines, from the bypass pump or from entrainment around the cannulae insertion. Systemic air embolisation from any of these sources can result in significant morbidity or mortality. Echocardiography is usually able to detect the presence of air within the circulation. This can be manifest as either a small amount of bubbles or in the worse case, an air lock within the heart or circuit. A large collection of air has the appearance of a localised echo-intense region (32).

4. Detection of complications

VAD complications have a significant impact on both the morbidity and mortality of these complex patients. Echocardiography plays a fundamental role in determining the presence of these complications. Bleeding (cardiac tamponade), thrombus formation (both intra-cardiac and intra-device/cannulae), infection (cannulae endocarditis), aortic dissection and air entrainment/embolisation are significant complications that can be detected using

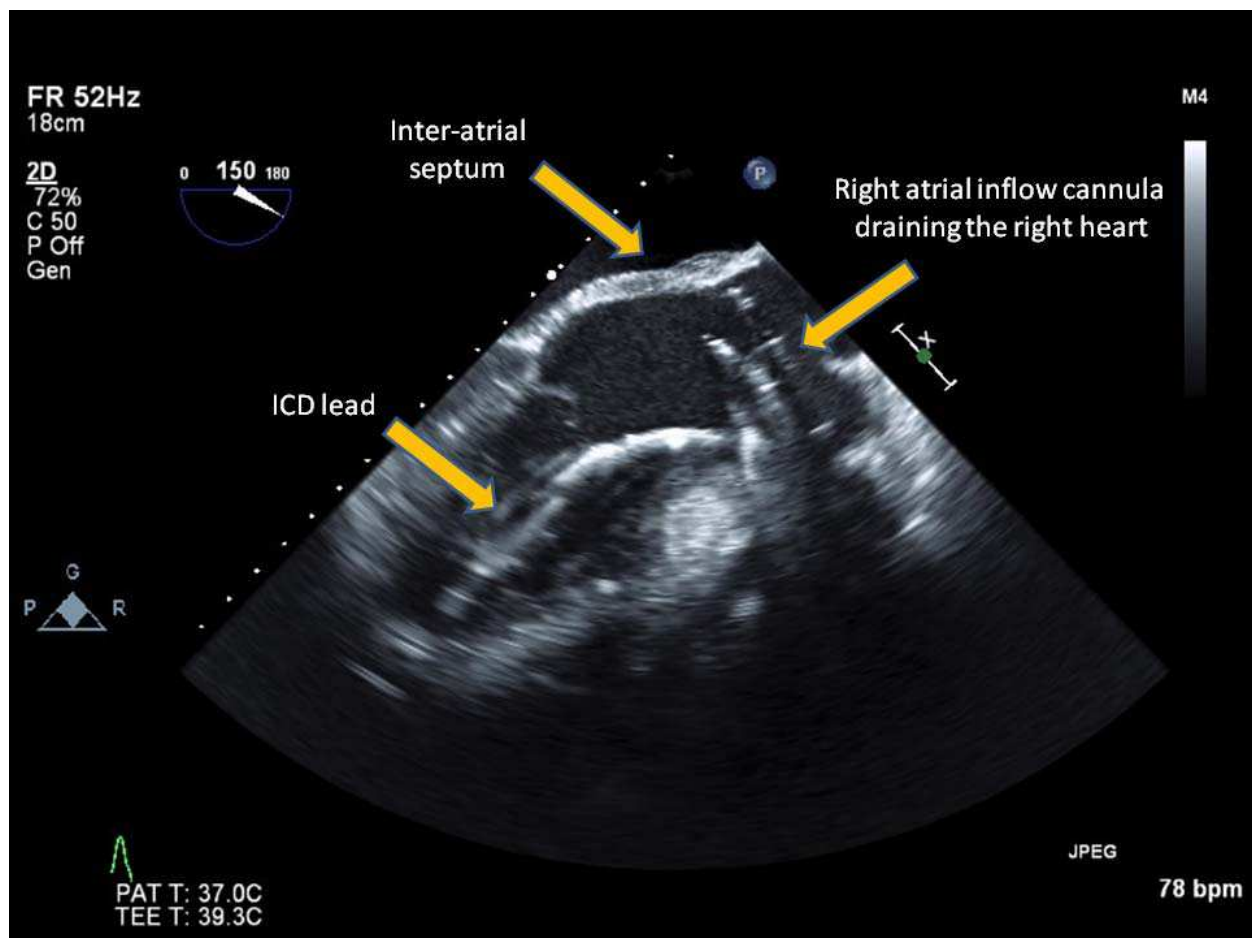


Fig. 5. Right atrial cannula draining the right heart

echocardiography. Sub-optimal VAD function can also be determined with echocardiography by determining volume status and cannula obstruction due to “suck-down” or opposition of the cannulae against other cardiac structures.

Post operative bleeding is very common in these patients, particularly in the early post operative period (first 24-48 hours). So much so that systemic anti-coagulation is usually withheld in this early period. However, significant bleeding may also occur at a later stage (37, 38). Factors which promote bleeding include recent cardiopulmonary bypass, critical illness, thrombocytopenia (both from consumption and heparin induced thrombocytopenia) and transfusion associated coagulopathy. However, the incidence of bleeding can vary and may relate to the type of device being inserted, level of illness prior to insertion, surgical experience and peri-operative management. In the REMATCH trial, which studied a pulsatile device, the frequency of bleeding was quoted at 42% at 6 months (39). In a recently published trial, compared pulsatile versus continuous flow VADs (40), bleeding requiring surgery occurred in 30% with continuous flow pumps and 15% with pulsatile pumps ($p=ns$). Bleeding requiring transfusion occurred in 81% with a continuous flow VAD and in 76% with a pulsatile VAD ($p=0.06$).

Bleeding can cause cardiac tamponade which will result in haemodynamic instability. In VAD supported patients, tamponade is often difficult to diagnose with TTE and a transesophageal echocardiogram is usually required to confirm diagnosis. Even with a TOE,

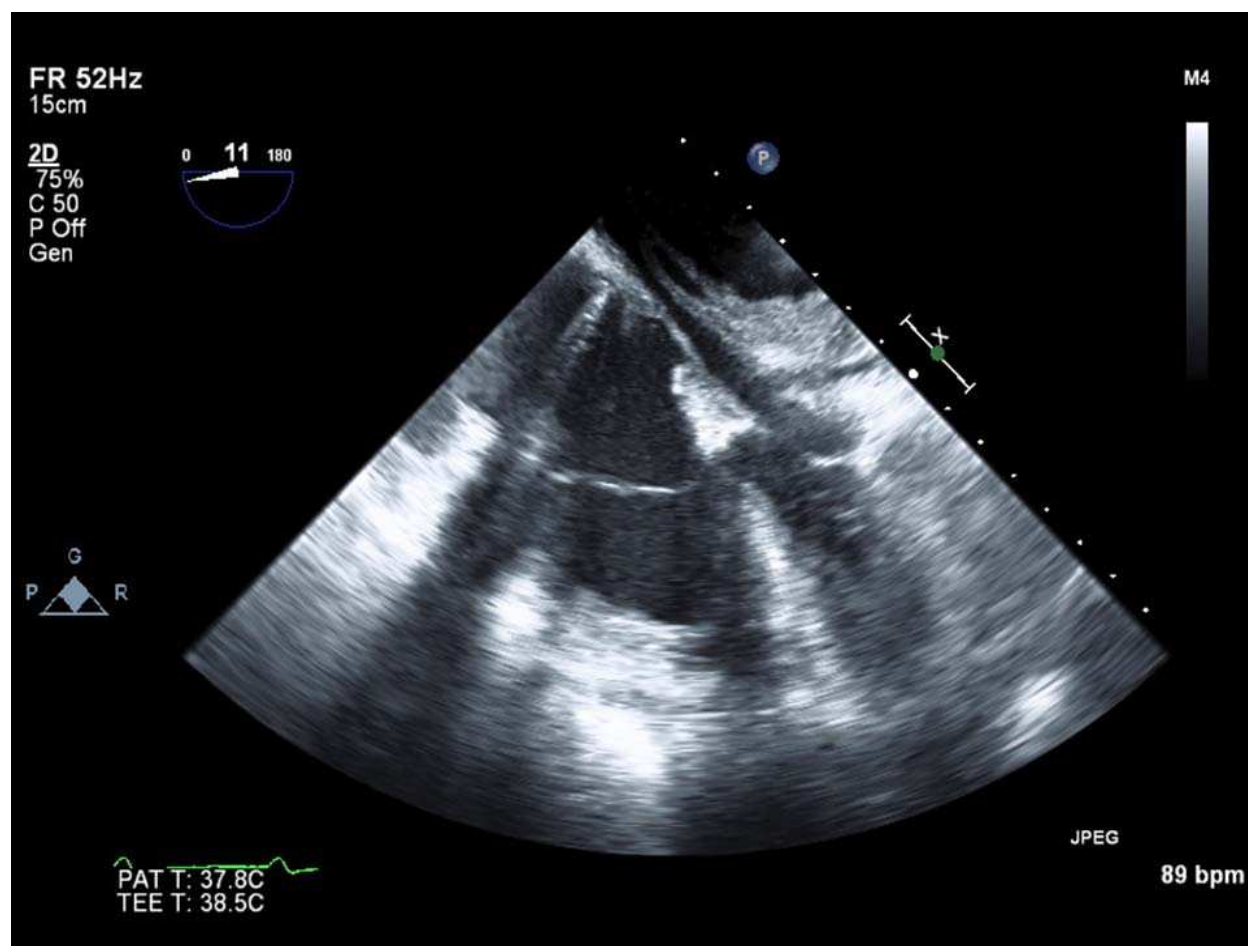


Fig. 6. Left heart compression from a large pericardial haematoma

a pericardial collection may be difficult to assess, especially if it is localised. Additionally, small volume collections can have significant consequences if they are in a critical location, such as around the atria which may limit flow into a VAD cannula. Classic echocardiographic features of tamponade may be absent in patients supported by a VAD. Clues to tamponade include haemodynamic instability (especially early post operatively) with chamber compression or compression limiting flow around a cannula. Diffuse bleeding may result in a generalised mediastinal haematoma which can also result in significant cardiac compression. Due to these often being more anterior in location, these can be difficult to diagnose on transoesophageal echocardiography and a TTE may be helpful in this circumstance.

VAD associated thrombosis is another serious complication with significant morbidity and mortality. Thrombus formation may occur within the cardiac chambers themselves, within the cannulae or actually within the pump chamber. As for bleeding, the incidence of thrombus formation can vary. In patients with a left atrial cannula, left ventricular thrombus is more likely to occur due to a relative 'bypassing' of the left ventricle in the circuit (41). Bleeding has also been found to be a predictor of thrombus formation (41). Transoesophageal echocardiography usually enables detection of cardiac chamber thrombus formation. It can also detect thrombus around the tips or just within the cannulae. Echocardiography does not directly visualise intra-cannulae or intra-device thrombus formation, but will provide information to help diagnose this condition. Figure 8 shows a

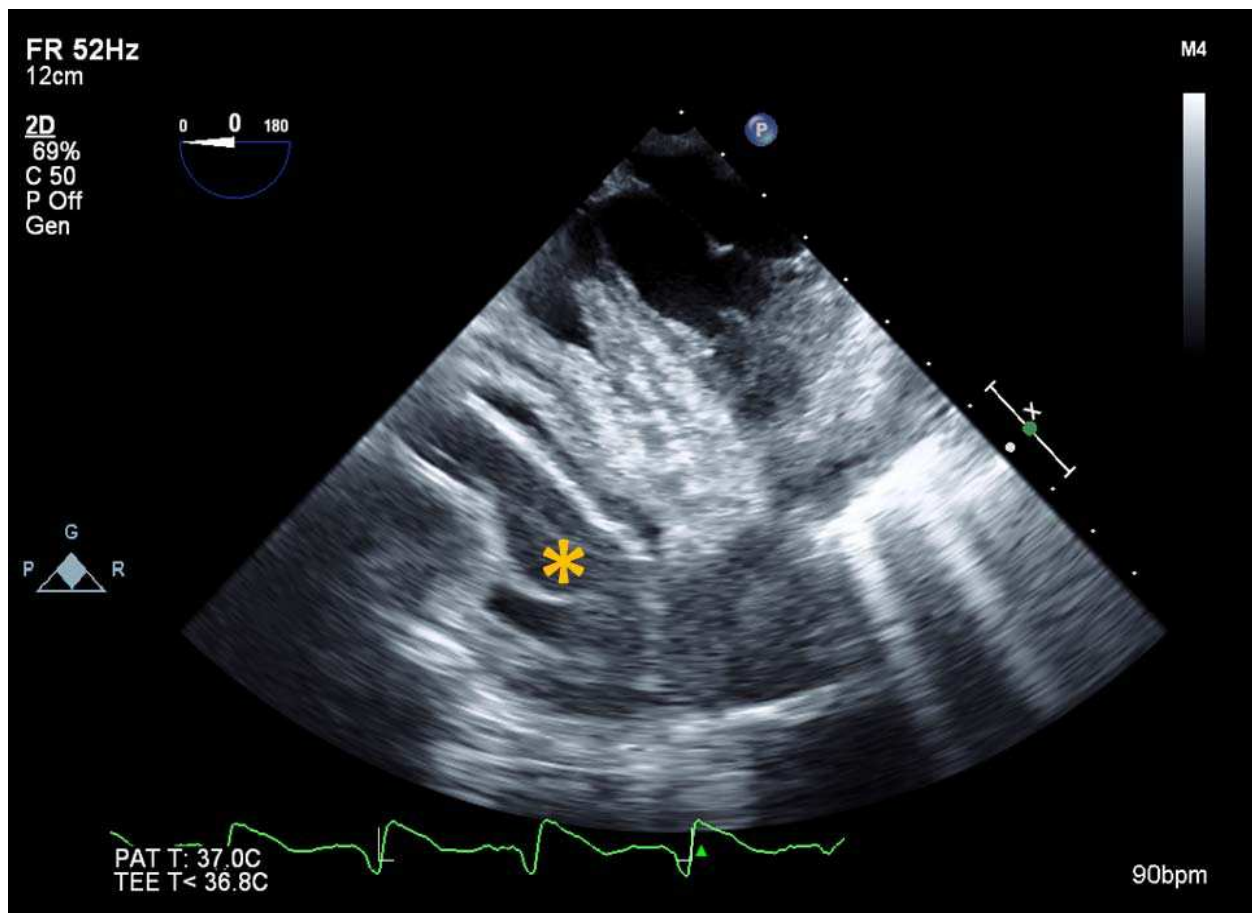


Fig. 7. Right heart compression from a large anterior mediastinal haematoma (marked with a *)

thrombus found within a VAD cannulae following an alarm for low VAD flows. Figure 9 shows a 3D TOE of an apical LV thrombus prior to LVAD insertion. However, intracavity thrombi may be hard to detect with echocardiography, particularly laminar thrombi at the apex of the left ventricle or smaller thrombi around the cardiac insertion points of a cannula. Mobility of a thrombus increases the likelihood of detection using echocardiography when the thrombus is small. Compounding this limitation is the fact that a thrombus does not have to be particularly large to have a significant impact following systemic embolisation. Contrast enhance echocardiography has a role in improving the diagnostic yield of intra-ventricular thrombus detection.

Patients supported by a VAD are at increased risk of infection, including infective endocarditis. The presence of extensive prosthetic material within the mediastinum and heart, along with external drive lines and associated medical issues put these patients at risk of endocarditis. VAD associated infection results in significant morbidity and mortality and poses complex questions regarding appropriate management (42). Due to its greater spatial resolution, transoesophageal echocardiography is usually required to investigate these patients. There are several sites where infection may be present in a patient supported on a VAD (43). Infective material may be visualised around the tip of a cannula, on the native cardiac valves, around the insertion point of the cannulae or focal infective collections around the heart or within the mediastinum. Patients with VADs may also get infections around the drivelines, within the pump pocket or inside the actual pump chamber (44).



Fig. 8. Thrombus found within a VAD cannulae following an alarm for low VAD flows

The presence of air within a VAD circuit can have significant adverse consequences. Air bubbles can usually be clearly visualised within the circulation using echocardiography. Exclusion of air from the circulation and VAD circuit is an important process during VAD insertion. This is important during VAD cannula anastomosis and removal from cardiopulmonary bypass. Close attention needs to be paid to anastomotic sites for the entry of air. Visualisation of outflow cannula will aid in the detection of any air that has entered the VAD circuit. A confluence of bubbles within a cardiac chamber has the echocardiographic appearance of an echo-dense region, which may initially cause diagnostic confusion unless the operator is aware of this complication and its appearance.

Air embolism is a known risk with VAD use, due to potential anatomic (connection of the circulation to the atmosphere via VAD cannulae or occasionally an open chest) and mechanical (device malfunction) entry points for air entry. However, it is a very rare complication, with only three case reports in the literature of air embolism associated with LVAD use, due to either device malfunction (45), entry of air into the systemic circulation during a pump exchange (46) or systemic air embolization through the left atrial wall cannula site, from an intermittent pleural air leak (47). Figure 10 demonstrates air in the left atrium and left ventricle, after entering around the LA cannula cuff.

Aortic dissection is a recognised but rare complication of VAD insertion (48-50). It usually arises due to the associated shear forces imparted on the ascending aortic wall from a high velocity jet being ejected from an LVAD outflow cannula. Transoesophageal echocardiography is the imaging modality of choice to detect a dissection flap in the

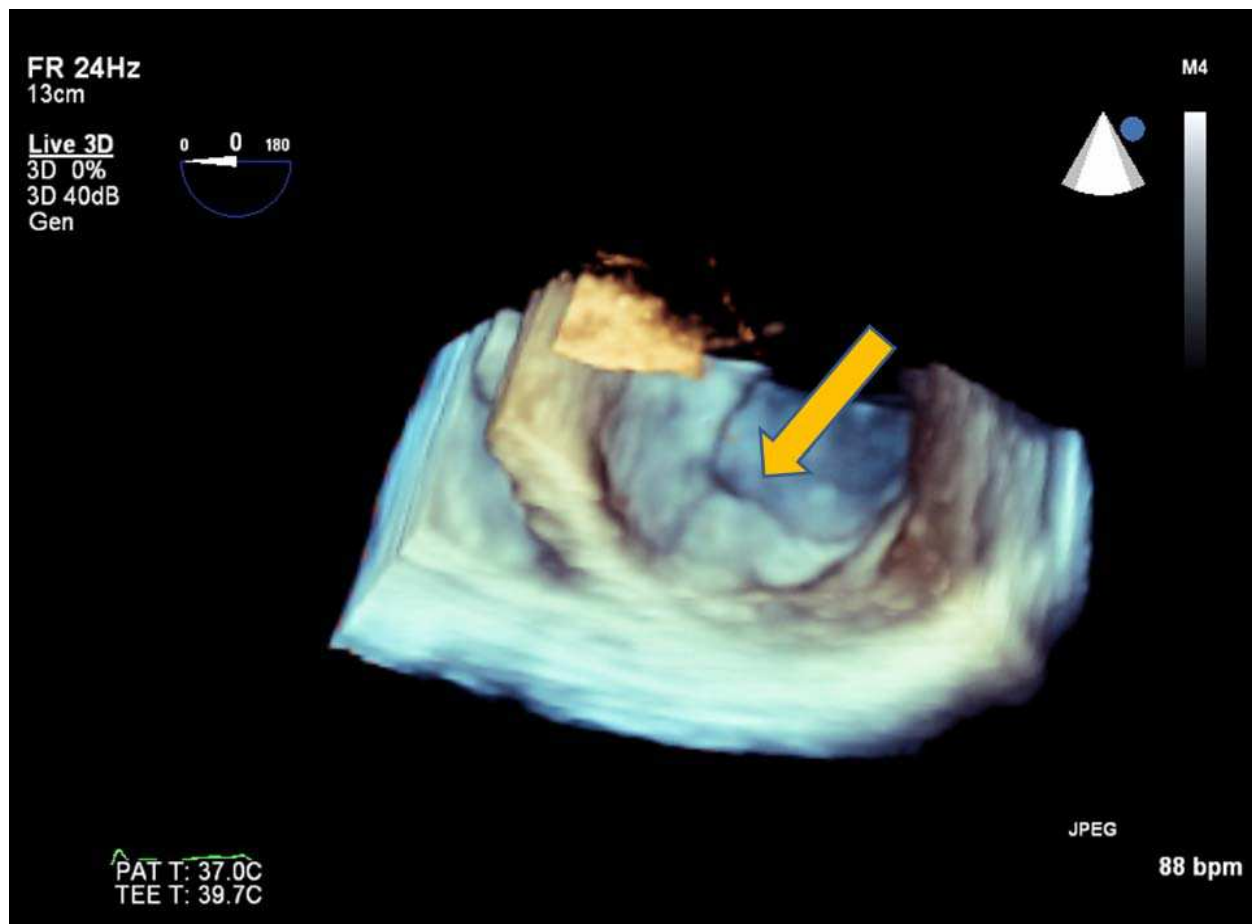


Fig. 9. Real time 3D transoesophageal echocardiogram of a left ventricular apical thrombus (arrow)

ascending aorta in this group of patients. It enables the visualisation of the typical features of aortic dissection, including an intimal flap or tear, identification of the true and false lumen and associated complications.

VAD Weaning and Explantation

VAD explantation may occur following satisfactory recovery of native cardiac function or if cardiac transplantation occurs. Echocardiography is fundamental in the assessment of native cardiac function when determining if there has been any recovery and can the VAD be explanted. However, the decision making process is a complex one and does not get rely on one set of parameters. There is not a consensus as to the best way to assess cardiac recovery during weaning and it is likely multiple parameters from multiple investigative procedures are likely to be required to assess for recovery. There is even less work evaluating weaning of an RVAD and assessing right ventricular recovery following RVAD support.

Multiple clinical, haemodynamic and echocardiographic variables are analysed in an attempt to determine whether recovery has occurred. The likelihood and degree of recovery can also be related to the aetiology and chronicity of the underlying disease process. Due to the left ventricle being in an unloaded state when supported by a VAD, it is usually not possible to accurately assess underlying function unless a challenge/wean of VAD support is attempted. Numerous protocols are in place during echocardiographic assessment during VAD weaning and these tend to vary between institutions (51-60).

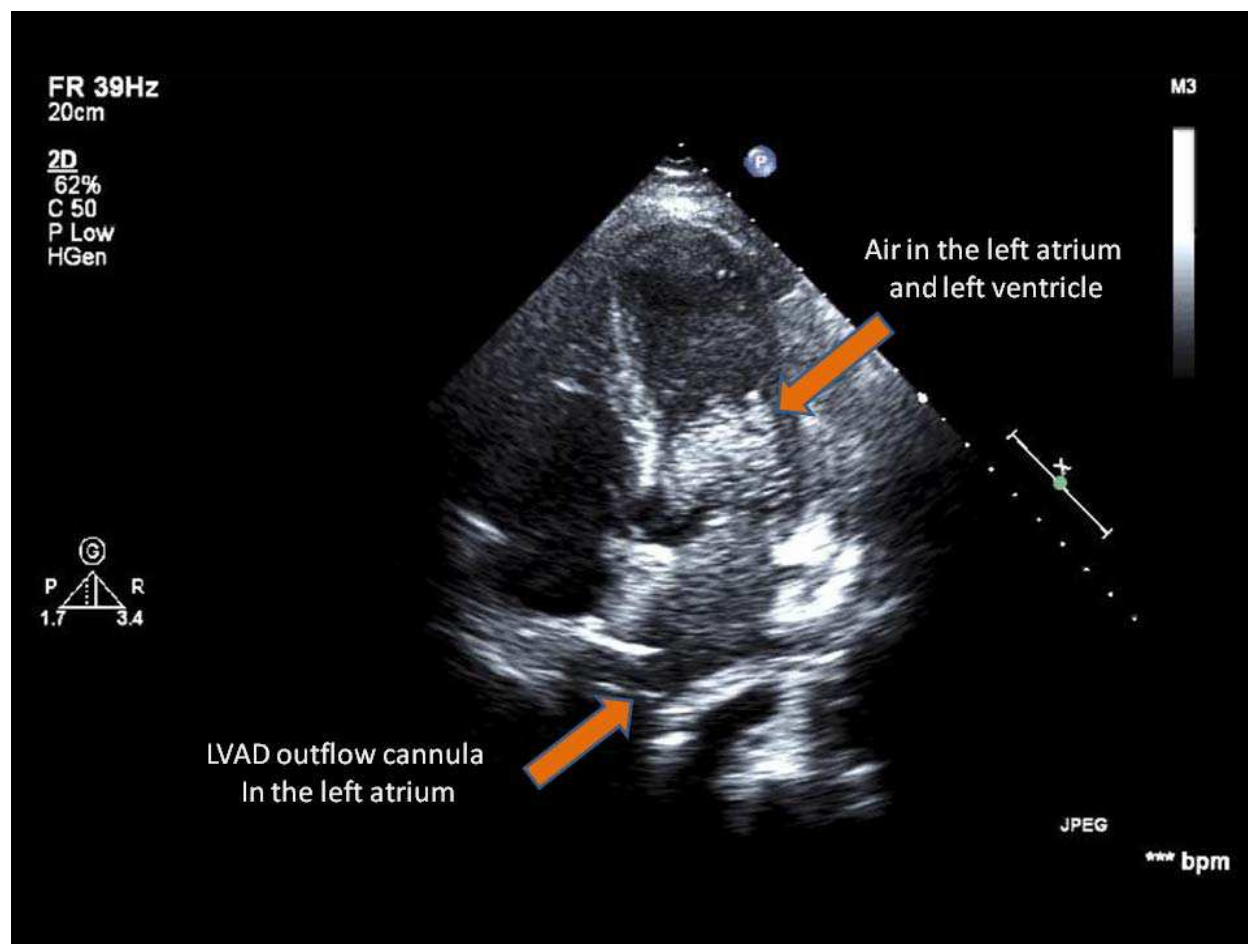


Fig. 10. Air bubbles in the left atrium and left ventricle, after entering around the LA cannula cuff, originating from a pleural tear.

During attempted weaning from a VAD, echocardiographic parameters that can be evaluated to help predict recovery include left ventricular systolic function and ejection fraction, left ventricular end diastolic dimension, left ventricular stroke volume, left ventricular fractional area change, degree of mitral regurgitation and right ventricular size and systolic function. Additionally, dynamic manoeuvres may be applied to elucidate recovery. Kahn et al evaluated the role of using dobutamine stress echocardiography to assess for recovery (56). In this study, 19 patients on VAD support had a dobutamine stress echocardiogram (with a dose increasing from 5 to 40 mcg/kg/min). Echocardiographic parameters assessed included left ventricular end diastolic dimension, left ventricular ejection fraction, along with other invasively derived haemodynamic parameters. Patients had a favourable response to dobutamine stress if the LVEF increased and the LVEDD decreased. 9 patients had a favourable response and underwent explantation with 6 surviving beyond 12 months. Of the 7 unfavourable responders, 2 died and 5 required cardiac transplantation.

Further research is required to ascertain which echocardiographic variables and weaning protocols should be used to determine myocardial recovery during VAD weaning. Additionally, these echocardiographic variables need to be integrated with other clinical and haemodynamic parameters to arrive at a clinically useful paradigm in assessing VAD weaning and cardiac recovery.

Echocardiography and Extra-Corporeal Membranous Oxygenation

Extra-Corporeal Membranous Oxygenation (ECMO) is an increasingly utilised form of short term cardiopulmonary support for either severe pulmonary or cardiac failure. There are two types of ECMO support: VV ECMO - veno-venous for isolated respiratory support and VA ECMO - veno-arterial for haemodynamic support (61). There are also two types of ECMO cannulation, peripheral cannulation and central/surgical cannulation. First successful use of ECMO was in 1971 and it has been more widely available since the 1990s. However, improvements in device design, cannulae, oxygenators and medical management has extended duration of ECMO support from days to several weeks.

VV ECMO is used for respiratory failure. Blood is drained from the venous system, oxygenated and then returned to the venous system. Cannulae are typically placed in the venae cavae and right atrium. They are usually introduced percutaneously via the femoral &/or jugular veins. VV ECMO relies on adequate native cardiac output to maintain circulation. VV ECMO is used for severe acute respiratory failure where typical support measures have been inadequate & adequate cardiac function is anticipated for the duration of therapy. VA ECMO is used to support cardio-respiratory failure (CO up to 5.0L/min) Blood is drained from the venous system, oxygenated and returned to the arterial system. As such, it can provide complete or partial haemodynamic support as well as maintaining oxygenation. Support with VA ECMO can be provided by either central or peripheral cannulation. VA ECMO is indicated for potentially reversible, life-threatening forms of cardiac failure which are unresponsive to conventional therapy and use of a VAD is deemed inappropriate.

Due to the patient population and nature of the therapy, ECMO does have significant complications. However, with increasing experience and technological advances, along with formation of specialist ECMO centres, these are likely to become less common. Common complications include bleeding/coagulopathy, limb ischaemia, sepsis, haemolysis and mechanical failure (oxygenator or cannula/device thrombosis). Echo has a fundamental role in managing patients supported with ECMO. It provides information that determines appropriate patient selection, guides insertion of cannulae, monitors progress, detects complications and helps in determining recovery/weaning of support. Insertion and commencement of ECMO is done with transoesophageal echocardiographic guidance. TOE is indicated at ECMO insertion to exclude new reversible pathology such as pericardial effusion, exclude aortic valve and aortic pathology, help position the cannulae, ensure the heart is adequately decompressed and ensure there is no intra-cardiac thrombus or stasis. Figure 11 demonstrates a 3D transoesophageal colour Doppler image of oxygenated blood being returned to the right atrium. Note also the flow out of the side holes of the return cannula.

The ICU setting frequently limits satisfactory transthoracic imaging and contrast echocardiography has been shown to improve image quality. However, there is little published work on the role of echocardiographic contrast agent use in those patients supported with non pulsatile ventricular assist devices or ECMO(62). In patients supported by an ECMO circuit who have non diagnostic transthoracic echocardiographic images, the addition of a microsphere contrast agent can result in obtaining diagnostic images, despite passage of the agent through a mechanical circuit. Figure 12 demonstrate pre and post TTE contrast enhanced images of a ventilated patient in ICU on VA ECMO. The recently published CESAR trial (63) may result in an increased number of patients in ICU supported by ECMO, where contrast enhancement may need to be considered. As such, this technique could be utilized to assess these patients prior to proceeding to more invasive diagnostic strategies.

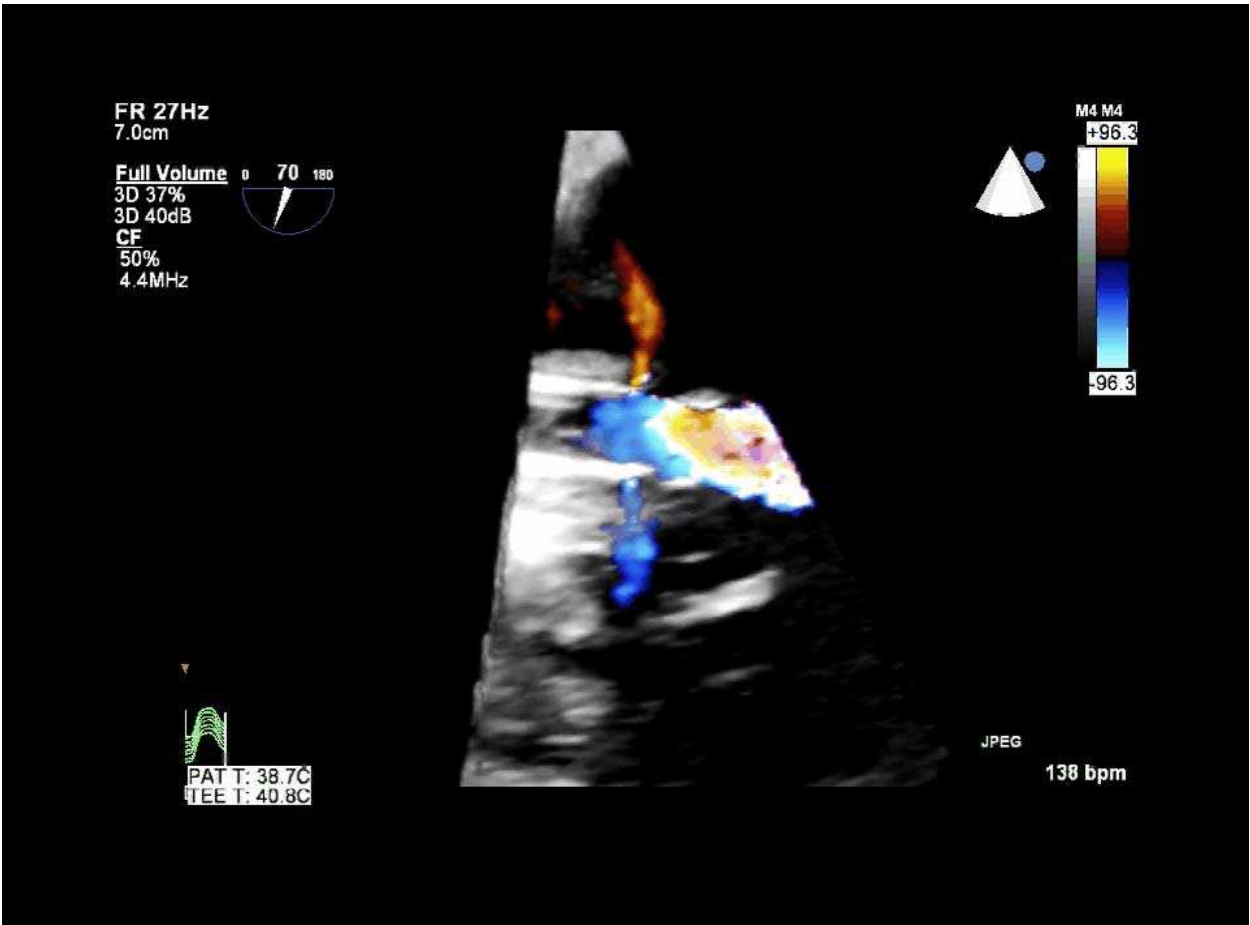


Fig. 11. 3D transoesophageal colour Doppler image of oxygenated blood being returned to the right atrium.

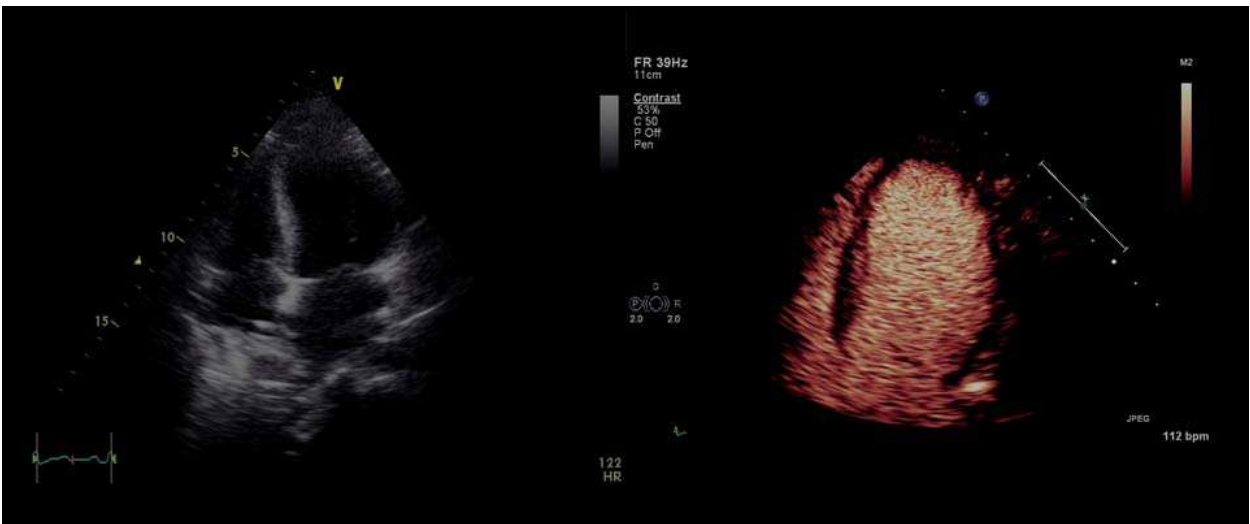


Fig. 12. Pre (left) and post TTE (right) contrast enhanced images of a ventilated patient in ICU on VA ECMO

5. References

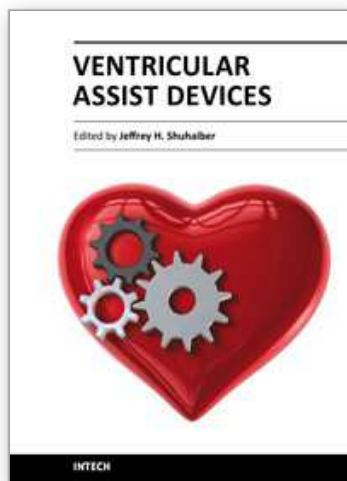
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The assist devices will continue adding a large number of years of life to humans globally and empower the medical society to optimize heart failure therapy. While expensive and cumbersome task, the foundation provided in this book reflects a contemporary product of original research from a multitude of different experts in the field. We hope this cumulative international effort provides the necessary tools for both the novice as well as the active practitioner aiming to change the outcome of these complex patients.

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