Advanced echocardiographic techniques

Abstract

Echocardiography has advanced significantly since its first clinical use. The move towards more accurate imaging and quantification has driven this advancement. In this review, we will briefly focus on three distinct but important recent advances, three-dimensional (3D) echocardiography, contrast echocardiography and myocardial tissue imaging. The basic principles of these techniques will be discussed as well as current and future clinical applications.

Keywords: contrast imaging, echocardiography, myocardial tissue imaging, ventricular assessment.

Rebecca Perry
BSc, DMU (cardiac) AMS

Majo Joseph
MBBS FRACP

Flinders Clinical Research
South Australian Health
and Medical Research
Institute
Adelaide
South Australia
Australia

Department of
Cardiovascular Medicine
Flinders Medical Centre
Bedford Park
South Australia
Australia

Discipline of Medicine
Flinders University
Bedford Park
South Australia
Australia

Correspondence to email
majo.joseph@health.
sa.gov.au

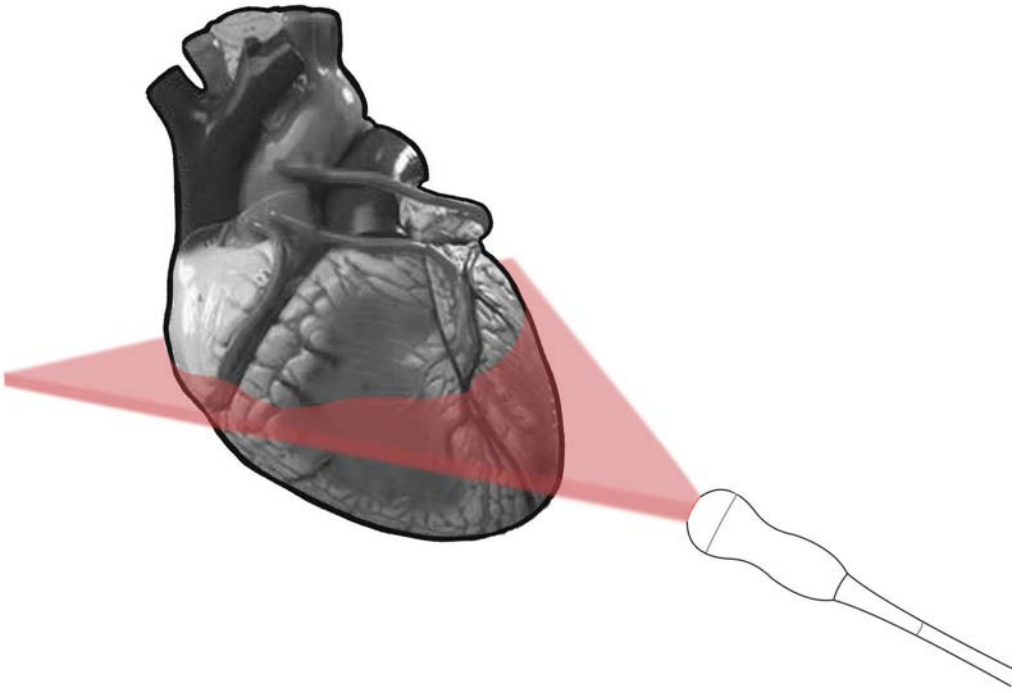

Figure 1: The imaging plane from a standard 2D probe demonstrating foreshortening with the LV apex being missed from the acquisition.

3D echocardiography

The heart is a complex, moving, 3D shape and for many years operators of ultrasound have had to build up an image of the heart in their mind using a series of two-dimensional (2D) "cuts". Live 3D echocardiography is a novel technique for evaluation of cardiac abnormalities without any of the assumptions made in 2D imaging. Recent guidelines on the acquisition and display of 3D datasets have been published to attempt to standardise the clinical application of this advanced echocardiographic modality.[1]

A 2D phased array transducer provides only one plane of imaging at a time whereas a 3D matrix array transducer functions in a similar way to a shower head, giving a 3D "shower" of ultrasound in both the lateral and elevation planes. The 2D imaging plane within the 3D dataset may therefore be "foreshortened" as the LV apex is captured within the data set. Post processing adjustments can then be made to obtain the true apex (Figures 1 and 2) allowing for more accurate assessment of LV volumes and ejection fraction.

There are two types of 3D imaging;

i) live 3D where a single beat volume can be acquired
ii) multi-beat 3D; where the 3D dataset is acquired over multiple beats (usually from 2 to 7 beats).

The advantage of a live 3D volume is that there is no "stitching" of beats together which may cause artifacts and misalignment of structures. In addition, single beat volume can be used in

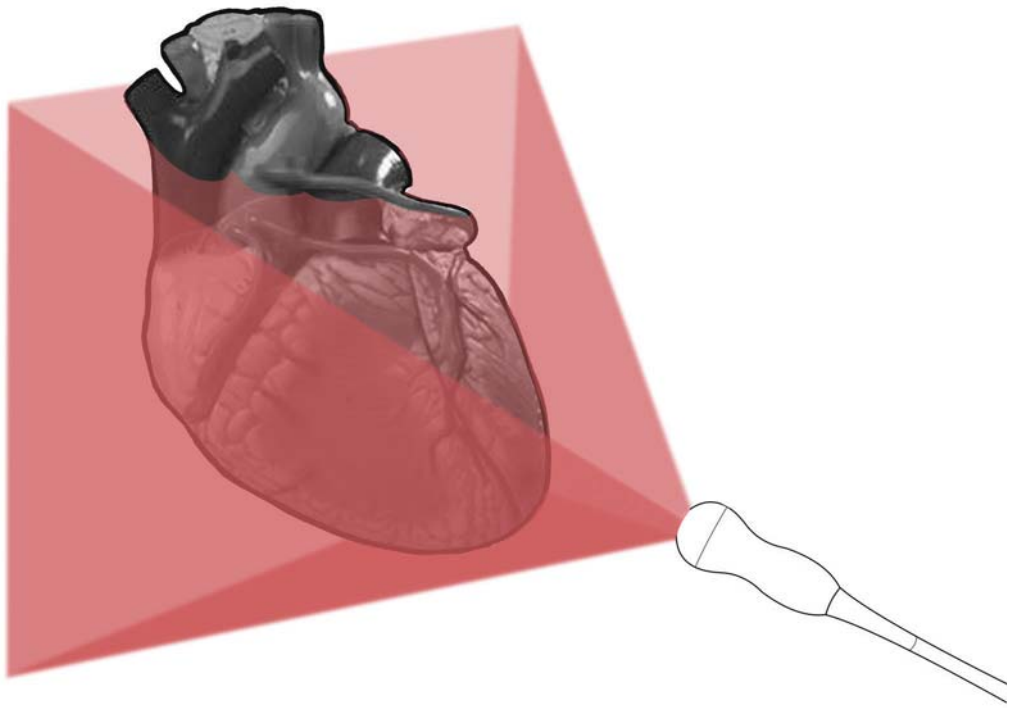

Figure 2: The probe is in the same position as in Figure 1, however because it is a 3D imaging transducer the apex is now within the image acquisition.

the presence of arrhythmias such as atrial fibrillation which are common in the cardiac patient population. The downside is that the spatial and temporal resolution is compromised and can reduce accuracy in quantification. A multi-beat acquisition gives a much higher frame rate and is often the only type of 3D dataset that can be analysed in dedicated 3D quantification software packages. Despite these limitations, 3D echocardiography has significant advantages over cardiac magnetic resonance imaging (MRI) and computed tomography (CT) in that it is relatively inexpensive, portable and can be used for patients with metal implants and claustrophobia.

Left ventricular assessment

Left ventricular mass, volumes and ejection fraction (EF) are important prognostic parameters[2–6] that are used for serial follow up of patients in various conditions including congestive cardiac failure, ischaemic heart disease, and valvular disease and for monitoring chemotherapy cardiac toxicity. Unfortunately, 2D echocardiography has limited test-retest reliability with regards to measuring LV parameters and has been reported to give a variation in EF between operators of as much as 11%.[7,8] Cardiac MRI is considered the gold standard as it overcomes the geometrical assumptions made in 2D echocardiography; however the cost and availability of MRI makes it more difficult in a clinical setting. 3D echocardiography has a lower cost than MRI and has been found to have a high reproducibility in regards to LV volumes, EF and mass and is comparable to MRI.[9–25] There is a high test-retest reliability of 3D LV volume and EF measurements[26] making it ideal for serial EF follow up, particularly when using a semi-automated border detection software which does not rely on geometric assumptions of a "normal" LV.[14,16,27,28] It also improves the detection of regional wall motion abnormalities compared with 2D imaging.[29] Contrast imaging (discussed later) can also be used with 3D echocardiography to improve image quality and assist in assessment of EF and regional wall motion abnormalities.[30]

Recently, 3D echocardiography has been used to determine LV dyssynchrony.[31–35] It has been found that a 3D derived dyssynchrony index can determine which chronic heart failure patients are more likely to respond to cardiac resynchronisation therapy.[36] Contraction wave mapping is also thought to assist in determining the area of latest activation and therefore the optimal position for lead placement.[37,38]

3D echocardiography may also be used in the assessment of right ventricular[39–43] and left atrial[44–49] volumes and function but is beyond the scope of this review.

Valvular assessment:

As a 3D dataset can be cropped and displayed in any orientation, direct visualisation or "enface" views can be obtained (depending on image quality) of all four valves. The development of 3D transoesphageal echocardiography (TOE) has made 3D valvular assessment easier with superior resolution of images, particularly in mitral valve disease. The ability to display the mitral valve enface and in a surgical view (displayed as the surgeon would see the valve after opening up the left atrium) allows easier communication between cardiology and surgical teams (Figures 3 and 4). Note the resolution differences between the transthoracic (TTE) and TOE images.

Both 3D TOE and TTE have been shown to improve the detection of mitral valve disease, particularly where complex pathology such as a cleft or prolapse at the commissural level

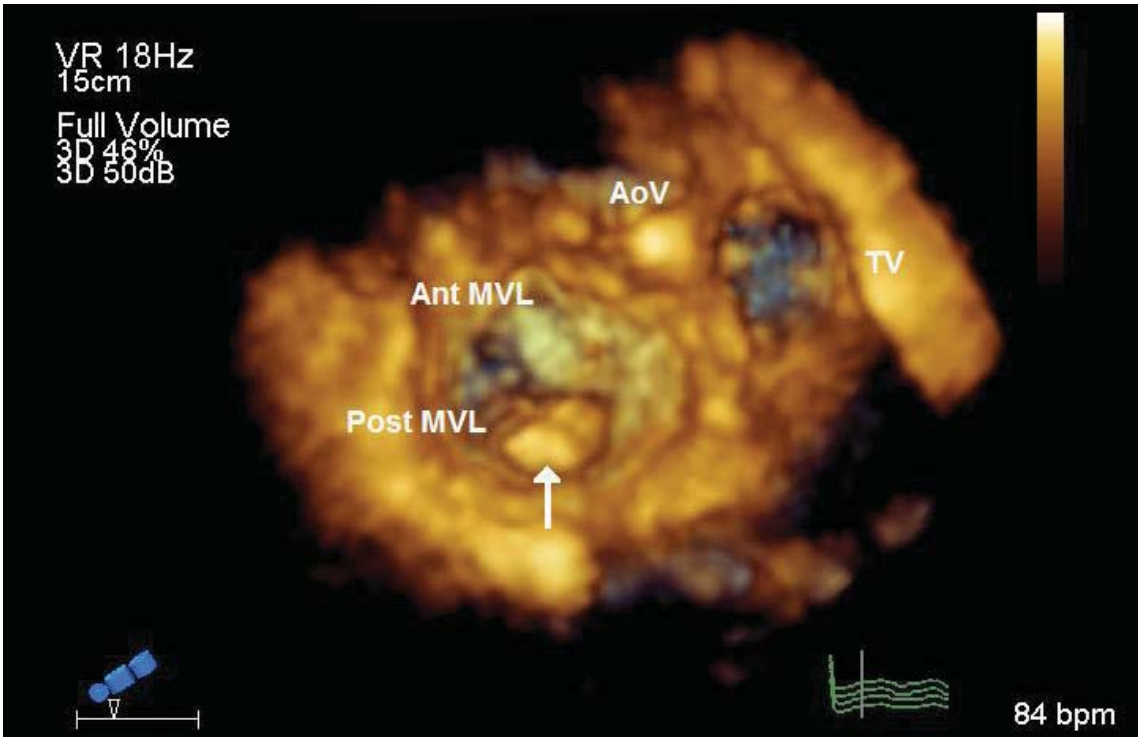

Figure 3: A 3D transthoracic image of the mitral valve enface in a surgical view demonstrating a large mid posterior (P2) segment prolapse (arrow). AoV – aortic valve, Ant MVL – anterior mitral valve leaflet, Post MVL – posterior mitral valve leaflet, TV – tricuspid valve.

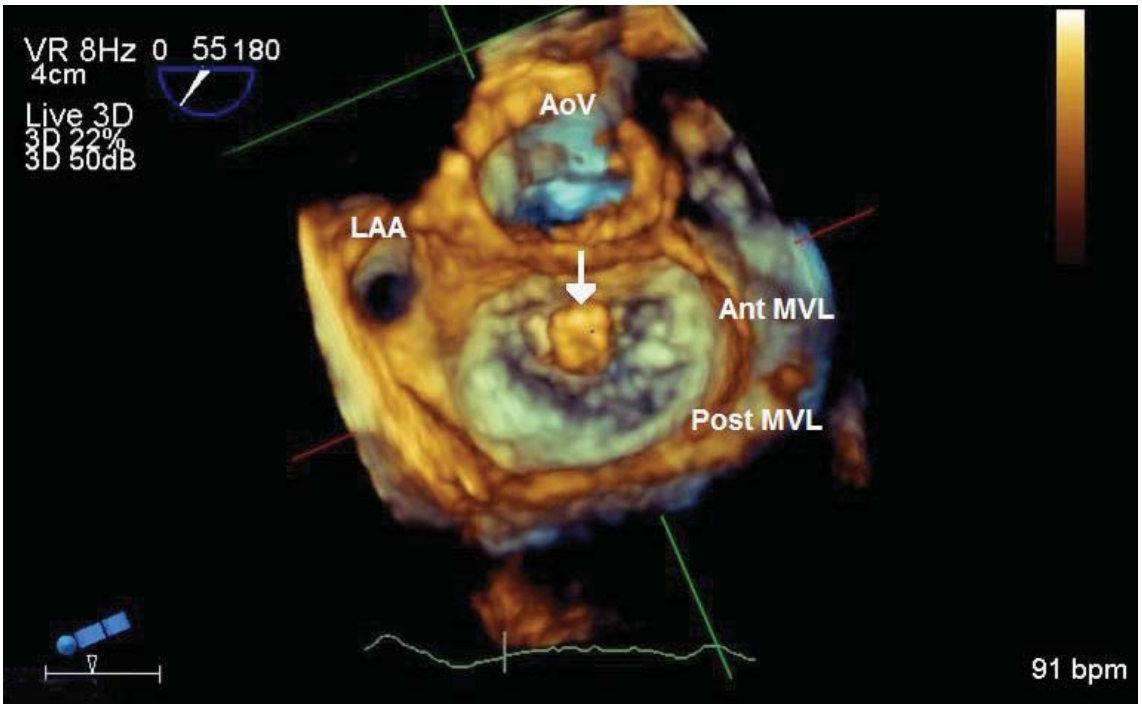

Figure 4: A 3D transoesophageal image of the mitral valve enface in a surgical view demonstrating a mid anterior (A2) segment prolapse (arrow). AoV – aortic valve, Ant MVL – anterior mitral valve leaflet, Post MVL – posterior mitral valve leaflet, LAA – left atrial appendage.

exists.[50–54] The measurement of mitral valve area in mitral stenosis from 3D planimetry has a better correlation with invasively derived results than 2D alone[55–62] (Figure 5).

Other cardiac valves can also be visualised and assessed using both 3D TTE and TOE. Estimation of aortic valve area in aortic stenosis via direct planimetry[63–66] and continuity equation[67,68] can be performed using 3D and has been shown to be superior to 2D assessment alone.

Colour Doppler is also available using 3D;[69,70] however single beat acquisition is not available in this mode due to poor temporal and spatial resolution. A 4 to 7 beat acquisition is required to obtain a 3D colour dataset and care must be taken to avoid "stitching" artifact. Quantification of both the vena contracta and the proximal isovelocity surface area (PISA) in mitral regurgitation has been shown to be more accurate and reproducible using 3D compared to 2D.[71–74] The vena contracta in the assessment of aortic regurgitation can also be more accurately assessed with 3D echocardiography.[75,76]

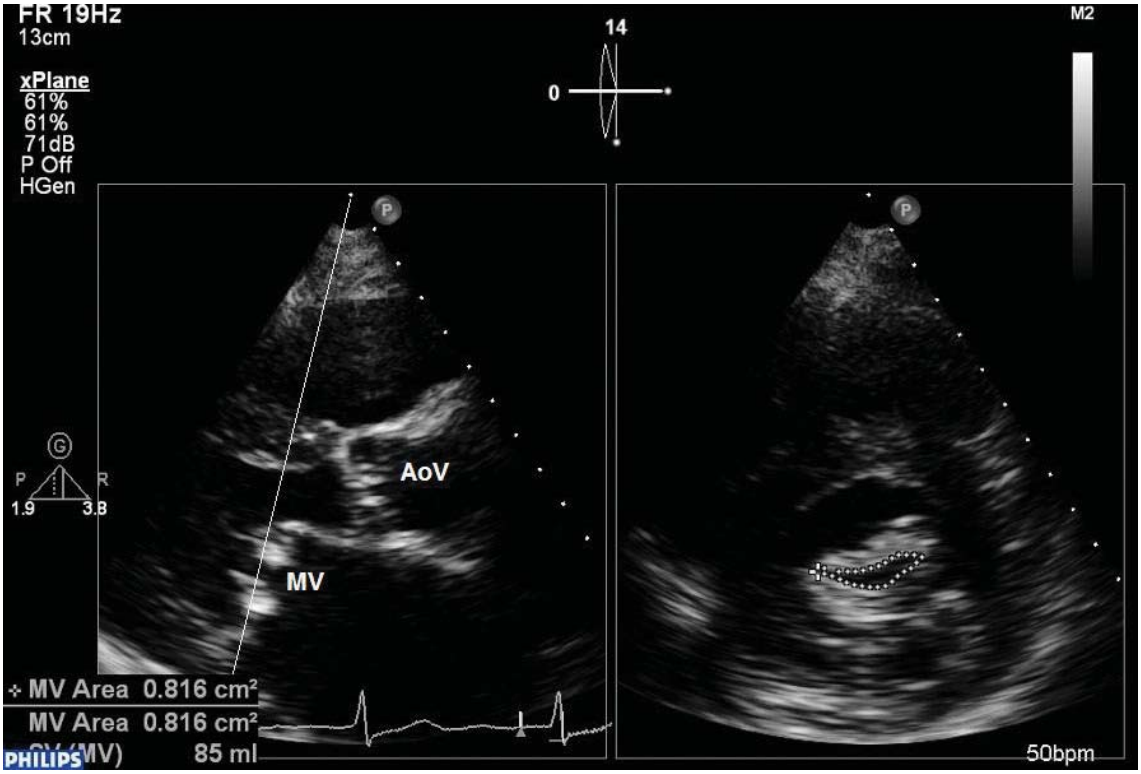

Figure 5: A 3D biplane transthoracic image of mitral valve stenosis demonstrating the line of measurement through the mitral valve on the parasternal long axis view (left pane) with the measurement of the mitral valve area on the right pane. AoV – aortic valve, MV – mitral valve.

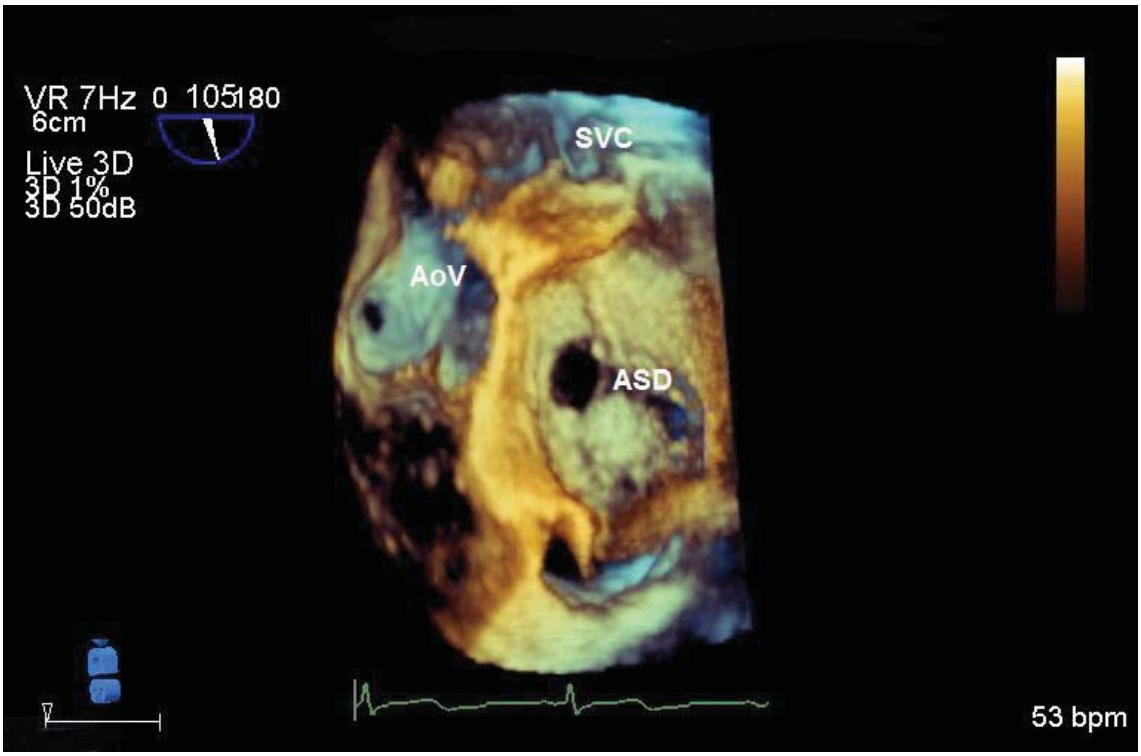

Figure 6: A 3D transoesophageal image of an atrial septal defect viewed from the left atrial aspect. ASD – atrial septal defect, AoV – aortic valve, SVC – superior vena cava.

Other 3D uses

The same measurement package used for calculation of mitral valve area may also be used to size atrial septal defects prior to device closure and has been shown to be superior to 2D assessment alone[77] (Figure 6).

Another less heralded but very clinically useful feature of 3D technology is multi–plane imaging which allows a structure to be displayed in simultaneous orthogonal views. Not only does this make interrogation of structures such as mitral valve and left atrial appendage quicker and more accurate, it plays an important role in guiding interventions such as septal punctures (Figure 7), septal defect closure devices (Figure 8),[78–80] percutaneous

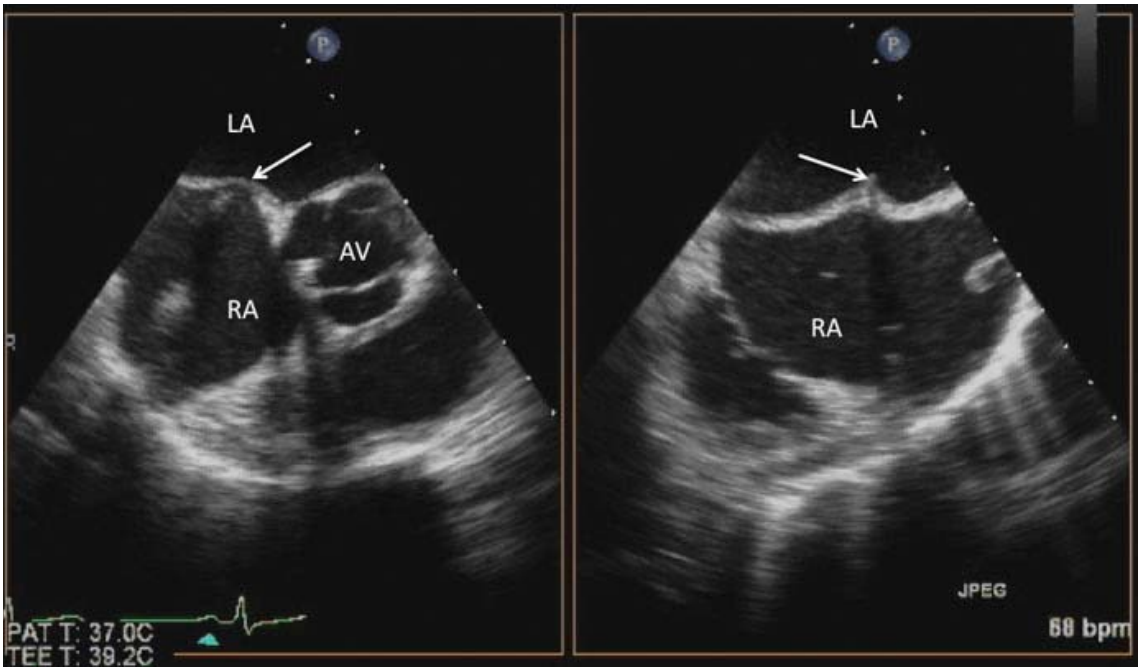

Figure 7: A 3D biplane transesophageal image of the interatrial septum demonstrating a needle tenting the septum pre septal puncture. The biplane image ensures that the septal puncture will occur in the mid septum. AV – aortic valve, LA – left atrium, RA – right atrium.

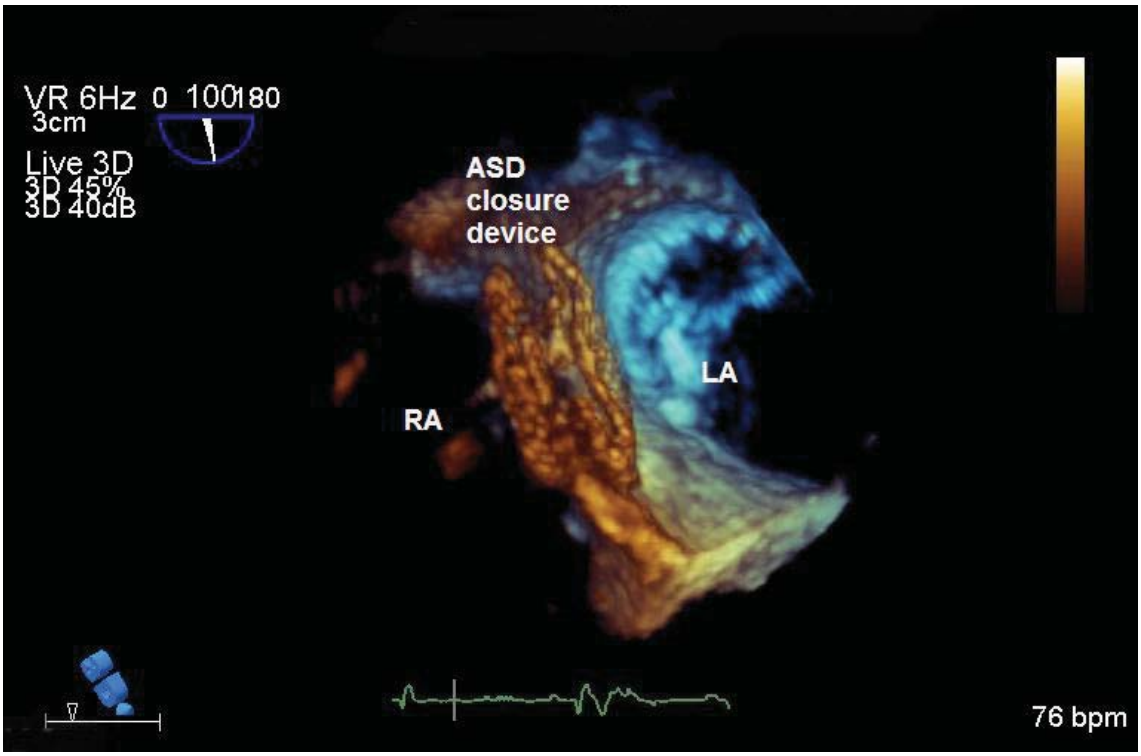

Figure 8: A 3D transesophageal image of an atrial septal defect closure device. ASD – atrial septal defect, LA – left atrium, RA – right atrium.

valve repairs,[81] percutaneous repair of prosthetic mitral valve paravalvular regurgitation,[82–85] balloon valvuloplasty[81] and placement of left atrial appendage occluder devices.[86]

Contrast echocardiography

Contrast echocardiography is an important arsenal in any echo laboratory in improving image quality. Its uptake into the Australian setting has been slow but has gained momentum since the introduction of second generation contrast agents. This technique has special relevance in Australia with increasing obesity and co-morbidities such as airway diseases making optimal imaging difficult in up to 10–15% of patients.[87]

Contrast echo relies on different ultrasound properties exhibited by the contrast agents and human tissue enabling better delineation of the endocardium. Agitated saline injected into peripheral veins has long been used as a simple and readily available contrast agent to opacify right heart structures as well as identify intracardiac shunts and improve Doppler signals (i.e. tricuspid regurgitation). However, left heart contrast agents require that the microbubbles are small (4–5 μm) and

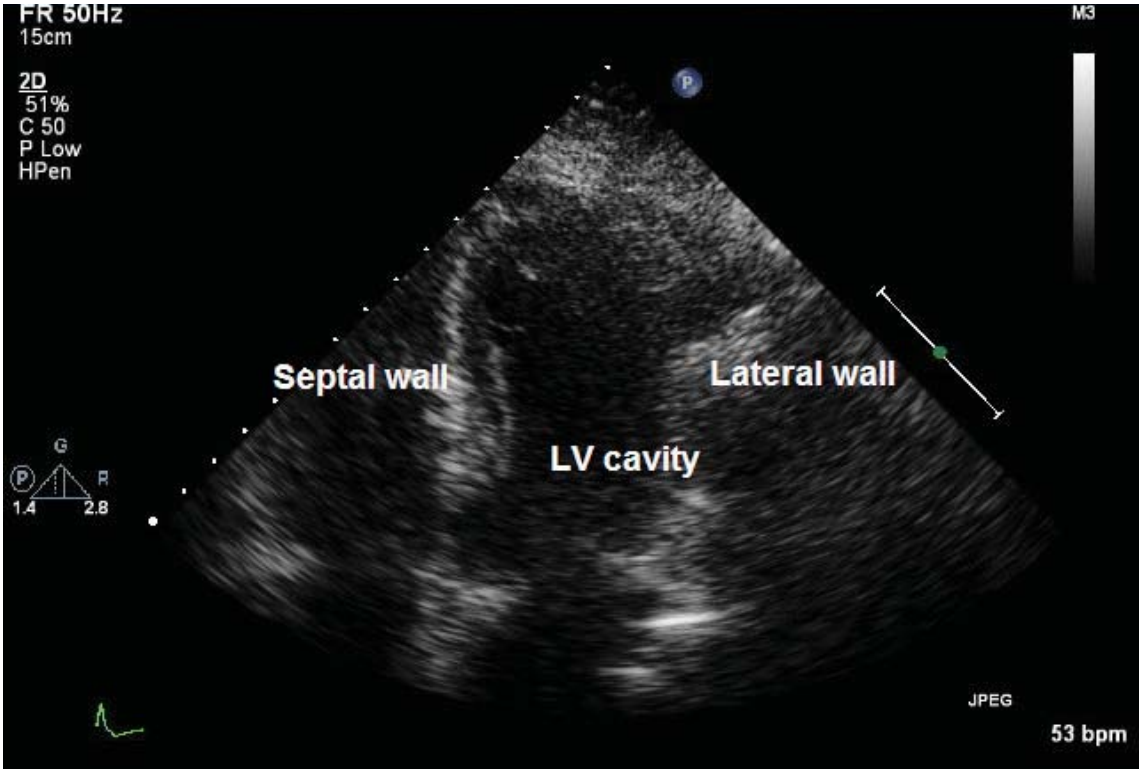

Figure 9: An apical 4 chamber view of the left ventricle without contrast – note that the lateral wall is poorly visualised. LV – left ventricle.

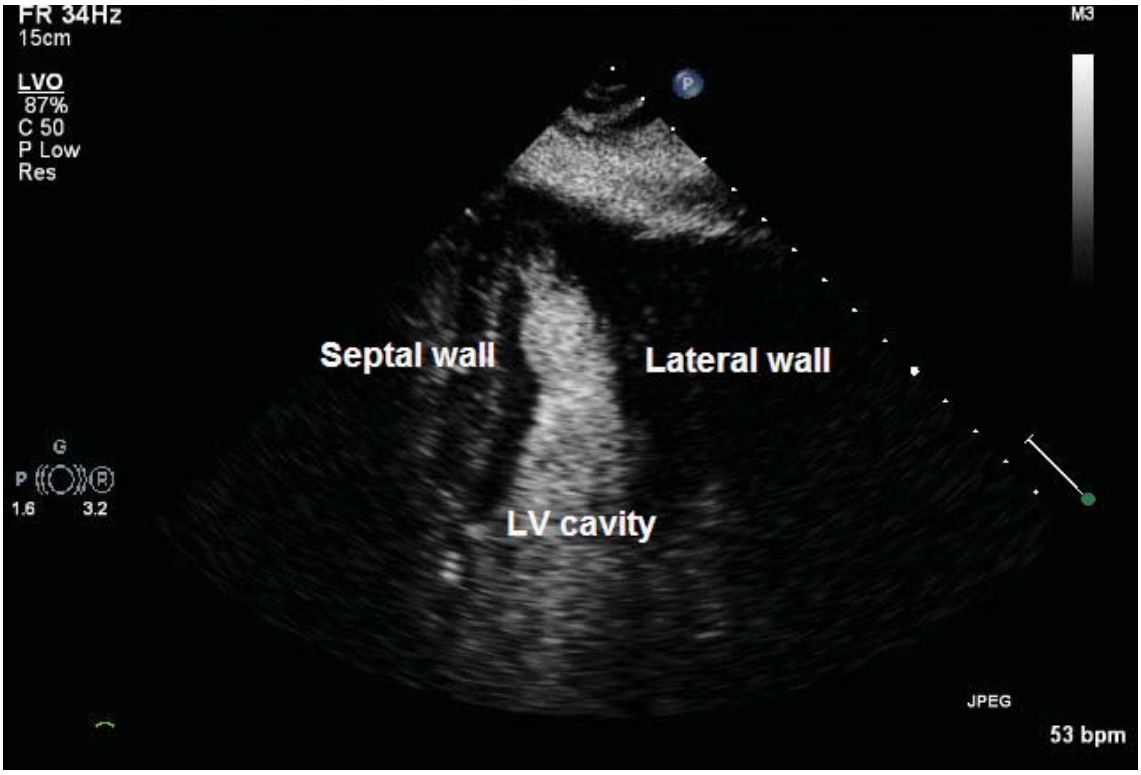

Figure 10: The same image as Figure 8 with the addition of contrast – note the improvement of lateral wall endocardial/ cavity border definition. LV – left ventricle.

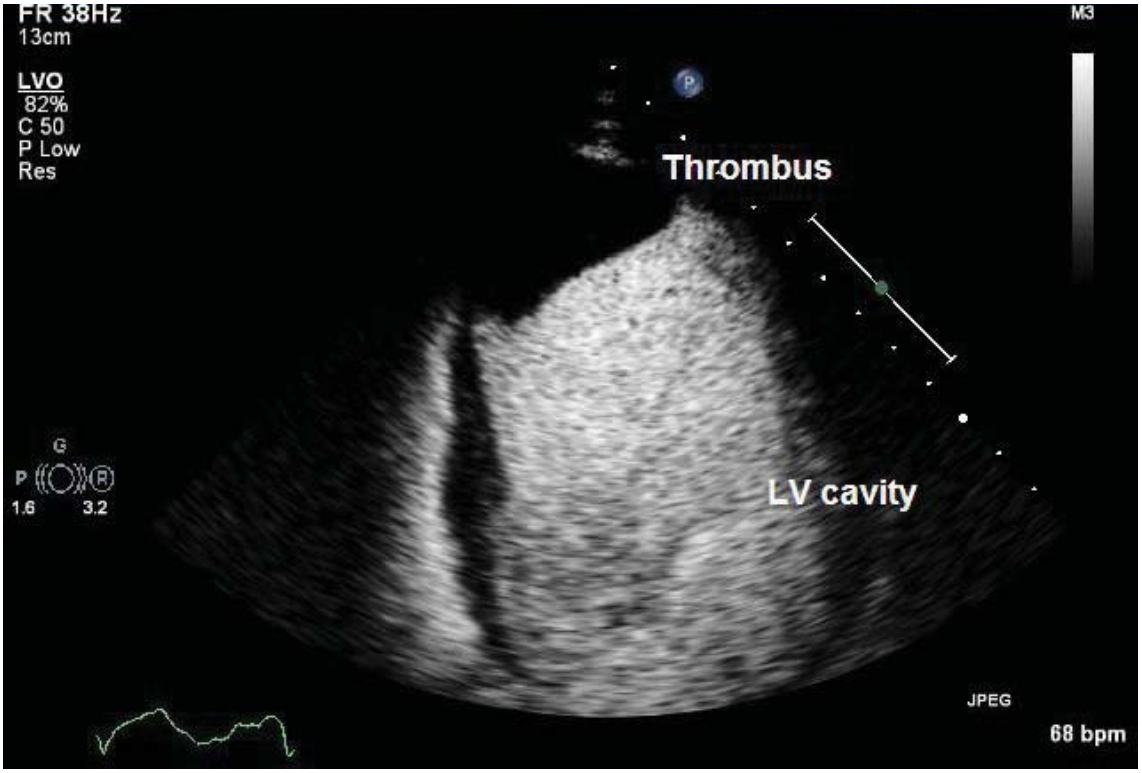

Figure 11: A contrast image demonstrating an apical thrombus (seen as black against the white contrast). LV – left ventricle.

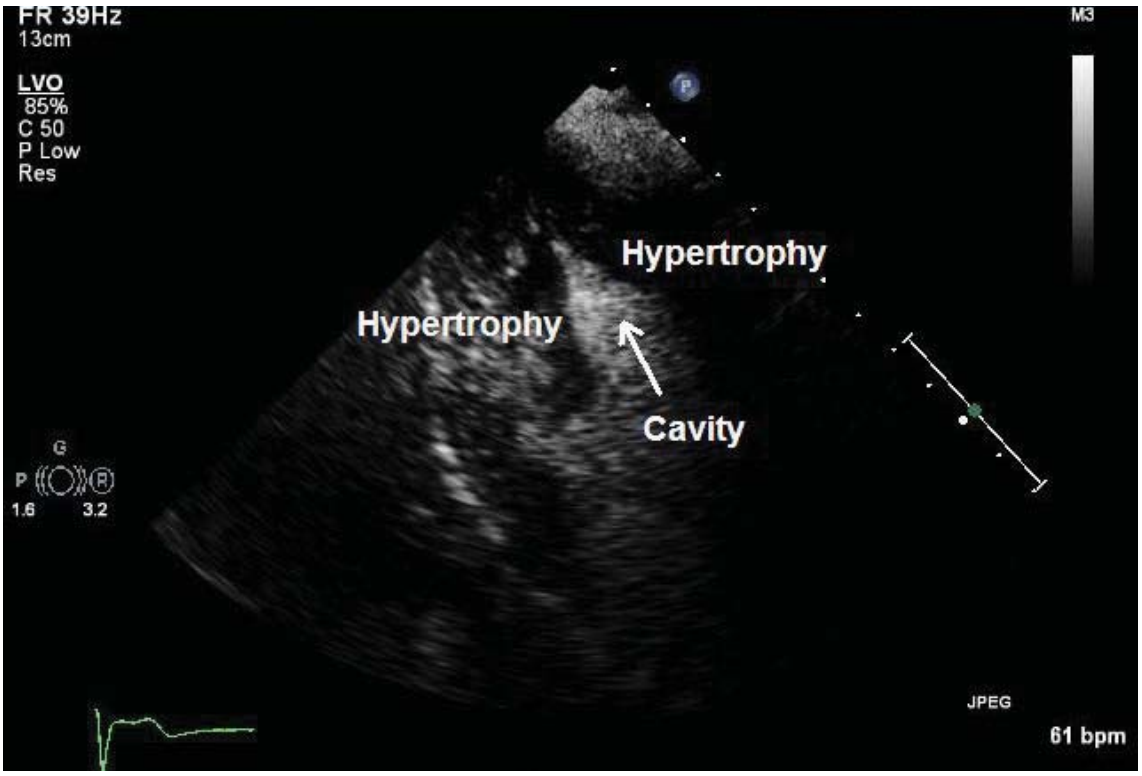

Figure 12: A contrast image demonstrating apical hypertrophy – note the degree of left ventricular cavity obliteration (arrow).

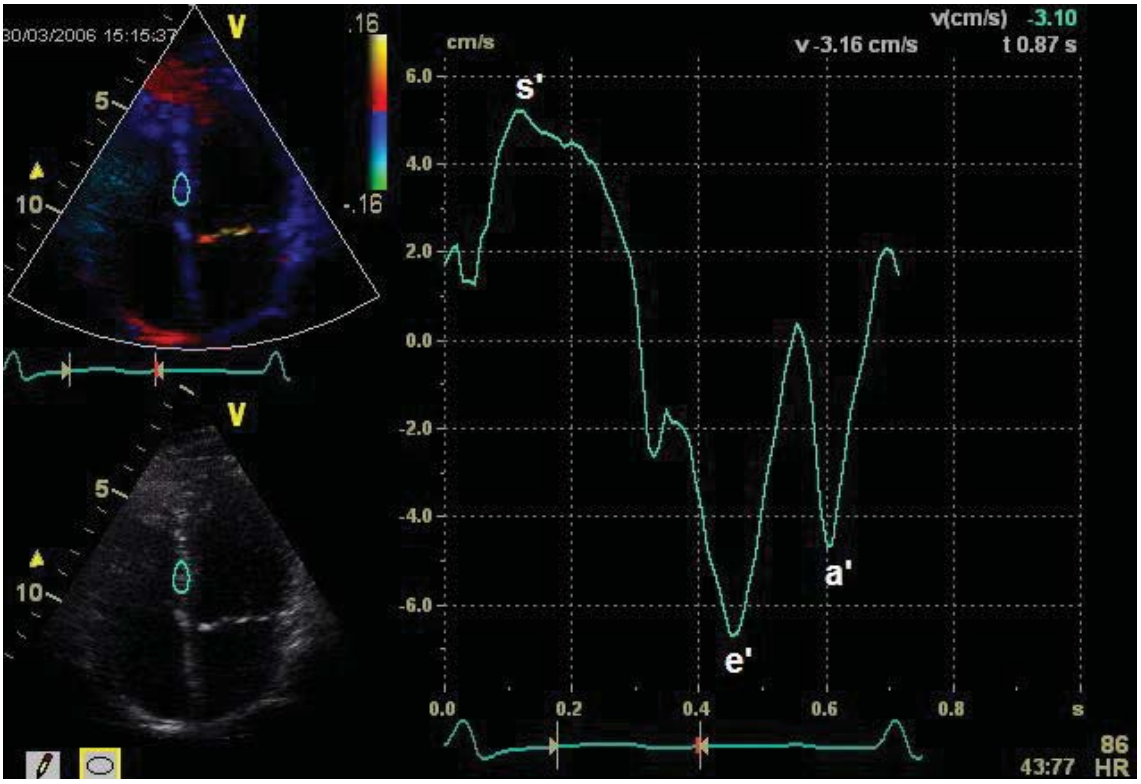

Figure 13: Tissue Doppler imaging demonstrating velocity curves. The peak systolic velocity is labeled as s', the peak early diastolic velocity is labeled as e' and the atrial kick diastolic velocity is labeled as a'.

resilient enough to pass through the pulmonary circulation.[87] Commercially available contrast agents are small microbubbles consisting of an inert gas encapsulated by a surface shell, often a lipid or polymer coat. When subjugated to ultrasound waves they oscillate (normal tissues don't), creating multiple frequencies that can create a stronger signal intensity in comparison to tissue which causes the blood pool to opacify hence improving endocardial definition. Furthermore, current ultrasound machines use various processes to suppress tissue signals while enhancing the signal from the contrast agents.[87]

Contrast safety

The Food and Drug Administration (FDA) and European licensing authority in the recent past have raised safety concerns based on a higher than usual incidence of deaths in critically ill patients who have undergone contrast echo.[88] However, subsequent studies using a larger numbers of patients have demonstrated conclusively that contrast is very safe.[87–89] The half life of contrast echo is short and it is excreted from the body through the lungs within a few minutes. Unlike other contrast agents used in imaging, echo contrast does not affect the kidneys and has a very low incidence of allergic reactions. The most common side-effects that patient may experience are minor and include flushing headache, nausea, chest or back pain. The only absolute contra-indication to contrast would include previous allergy to the agent and known intra-cardiac shunting.[87]

Administration of contrast

All major ultrasound companies have a contrast package that can be purchased as an option. The mechanical index (the power of the ultrasound beam) needs to be reduced to avoid destroying the microbubbles and the focal zone should be lowered to the base of the heart (around the mitral valve level). The near field gain needs to be reduced as the contrast is particularly bright in the LV apex. The contrast agent is injected into a peripheral vein very slowly along with a saline flush or for sustained imaging. An infusion pump may be used.[87] Any remaining contrast is discarded. The agents have a six-month shelf life and needs to be refrigerated. The current American Society of Echocardiography (ASE) and European Association of Echocardiography (EAE) guidelines suggest that the use of contrast agents are indicated when greater than two of the 17 LV wall segments are poorly visualised[87] (Figures 9 and 10). Currently there are no specific Australian guidelines available on the use of contrast agents in echocardiography.

If there is not enough contrast in the LV (noted as contrast "swirling" in the LV) you can either inject more contrast or reduce the mechanical index. If attenuation of the beam occurs you usually have to wait for some of the contrast to leave the LV or increase your mechanical index.[87]

Clinical indications

The most common use of contrast is to better assess LV function in patients whose images are suboptimal with normal harmonic imaging, known as LV opacification (LVO).[90–94] It can also be used for stress and dobutamine echocardiography[95–98] to increase the number of wall segments visualised enabling greater accuracy in diagnosing coronary artery disease. It is also particularly useful in assessing for apical thrombus[99] which appears black in comparison to the white blood pool (Figure 11). Rare conditions such as apical hypertrophy[100] can be distinguished from foreshortening using contrast (Figure 12). Non-compaction cardiomyopathy which is characterised by deep recesses within the endocardium can also be highlighted

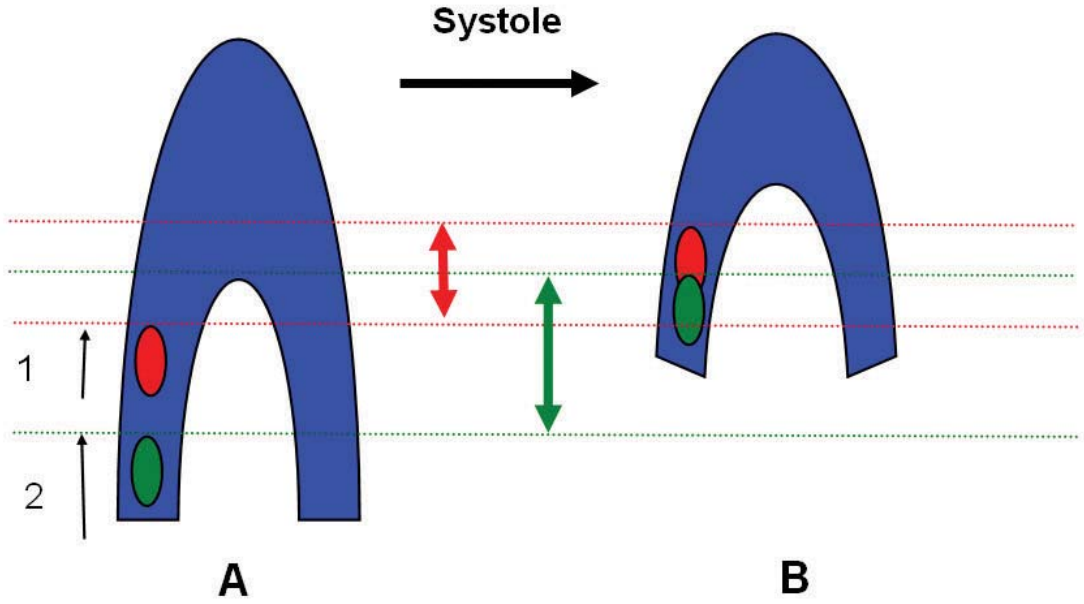

Figure 14: A schematic representation of tissue Doppler theory in a normal heart showing an apical 4 chamber view with the left ventricular apex at the top of the image with diastole in A and systole in B. See text for details.

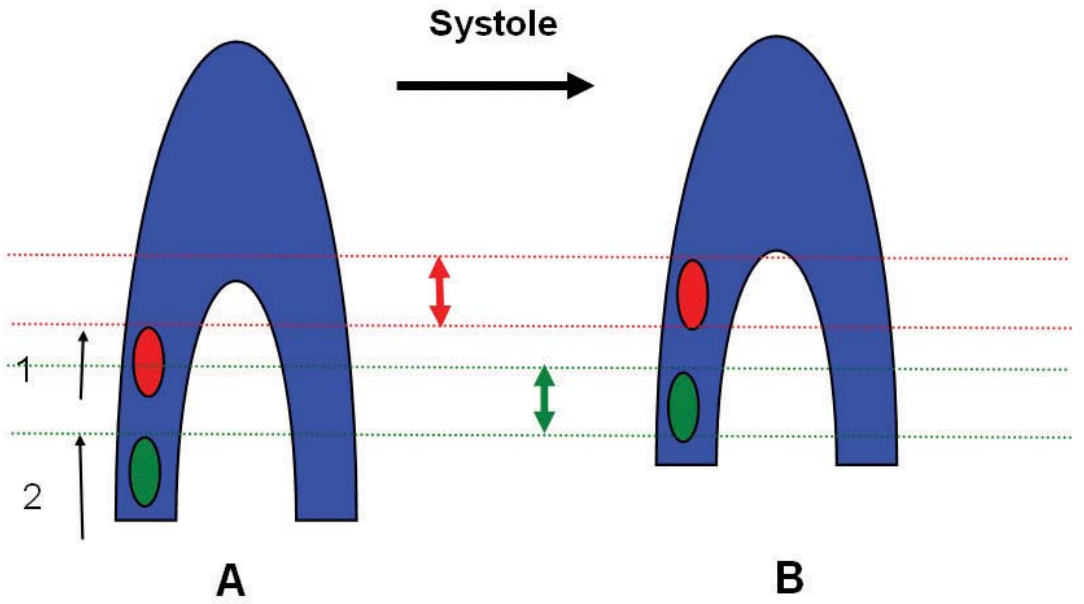

Figure 15: A schematic representation of tissue Doppler theory in an abnormal heart showing an apical 4 chamber view with the left ventricular apex at the top of the image with diastole in A and systole in B. See text for details.

by contrast echo.[101] Contrast can also be used to enhance the quality of Doppler signals and is particularly useful in difficult aortic stenosis cases.[102,103] Assessment of myocardial perfusion can also be performed but its use for this purpose has not yet been approved by the FDA and therefore is still in the research and development phase.[104,105]

Myocardial tissue Imaging

One of the newer and exciting advances in echocardiography is the ability to use imaging techniques which are based on tissue Doppler or myocardial speckles to directly assess LV function and mechanics. These techniques unlike EF and visual estimation of LV function, which look at volume displacement, directly assess the mechanics of the myocardial tissue. They can measure the velocity of myocardial motion or the deformation (also known as strain). This technique is more commonly used to assess mitral annular velocities to assist in the determination of diastolic function. Tissue Doppler imaging (TDI) uses the same principle as pulsed wave Doppler except that it detects myocardial motion in relationship to the transducer rather than blood flow (Figure 13). The best profile is obtained when the motion of the tissue is directly aligned to the ultrasound beam. Hence TDI is best suited for myocardial motion in the longitudinal plane using an apical window. This angle dependency of TDI is this techniques' greatest limitation. Strain or myocardial deformation differs from myocardial velocity in that it is not affected by tethering, i.e. being pulled along or affected by other myocardial segments (discussed later). Strain using TDI is more accurate in assessing regional wall motion than myocardial velocity alone.[106,107]

TDI velocity data has been used extensively for the detection of mechanical dyssynchrony with excellent results in predicting response to cardiac resynchronisation therapy in single centres with proficiency in this technique[108–112]; however a recent multicentre trial (PROSPECT) using TDI dyssynchrony analysis has disappointing results indicating that this technique was subjective and needed expertise in image analysis.[113] Speckle tracking strain

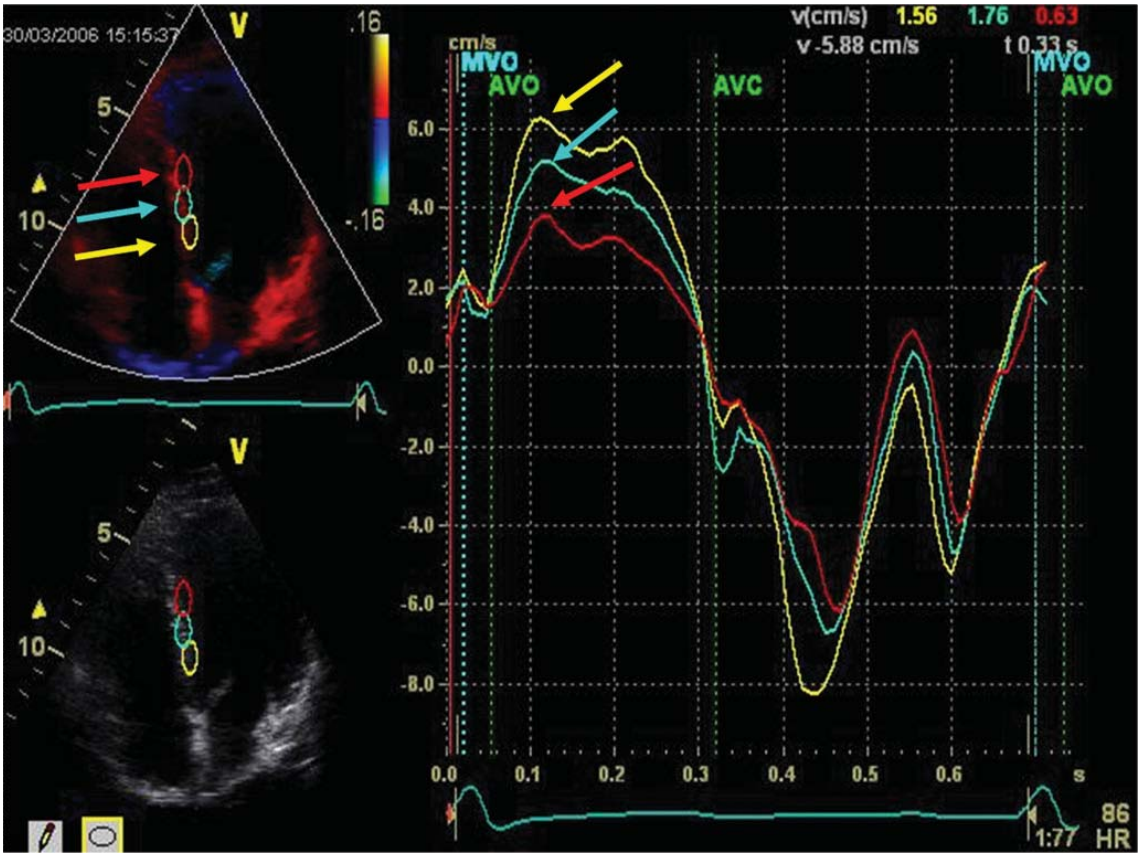

Figure 16: A tissue Doppler graph with 3 myocardial sample volumes on the septal wall. The yellow sample volume is the most basal point with the red sample volume the most apical point. The corresponding graphs demonstrate a higher velocity in systole of the more basal myocardial point (yellow arrow) than the more apical point (red arrow).

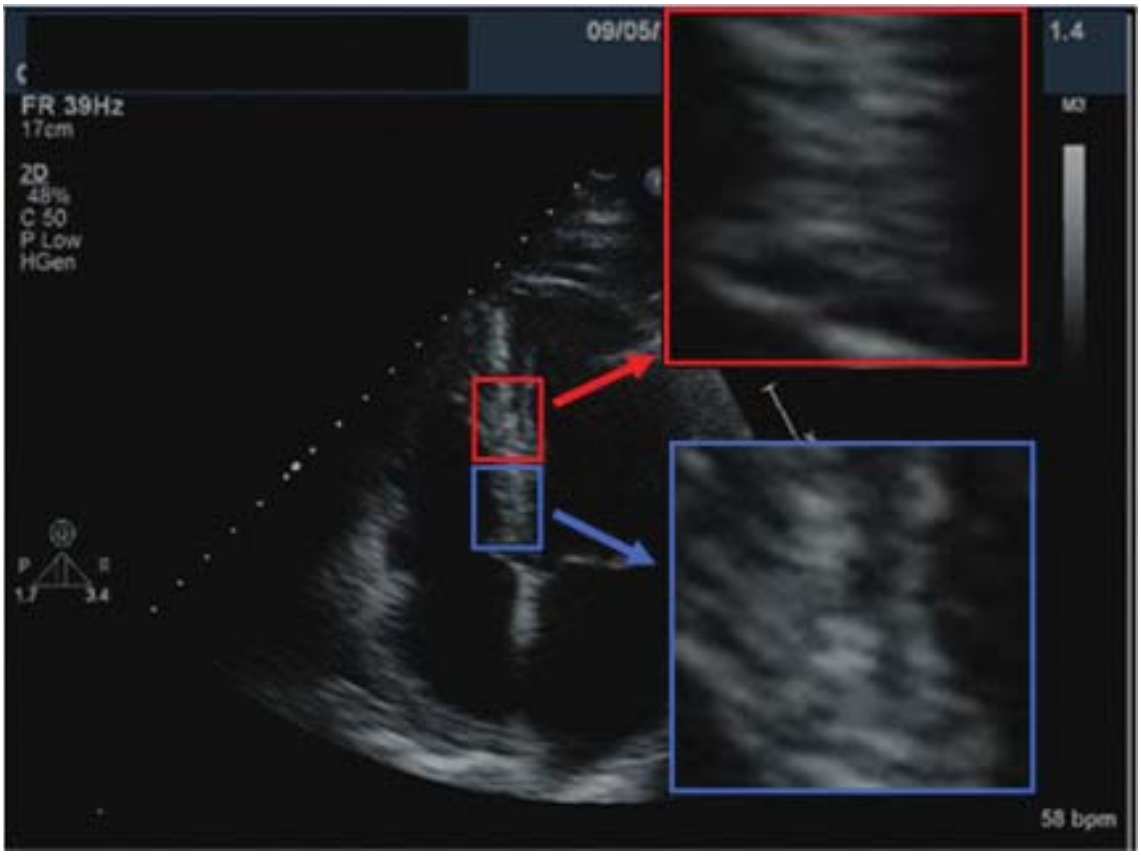

Figure 17: An apical 4ch view with 2 myocardial points highlighted and enlarged to demonstrate the unique speckle "fingerprint" at each point.

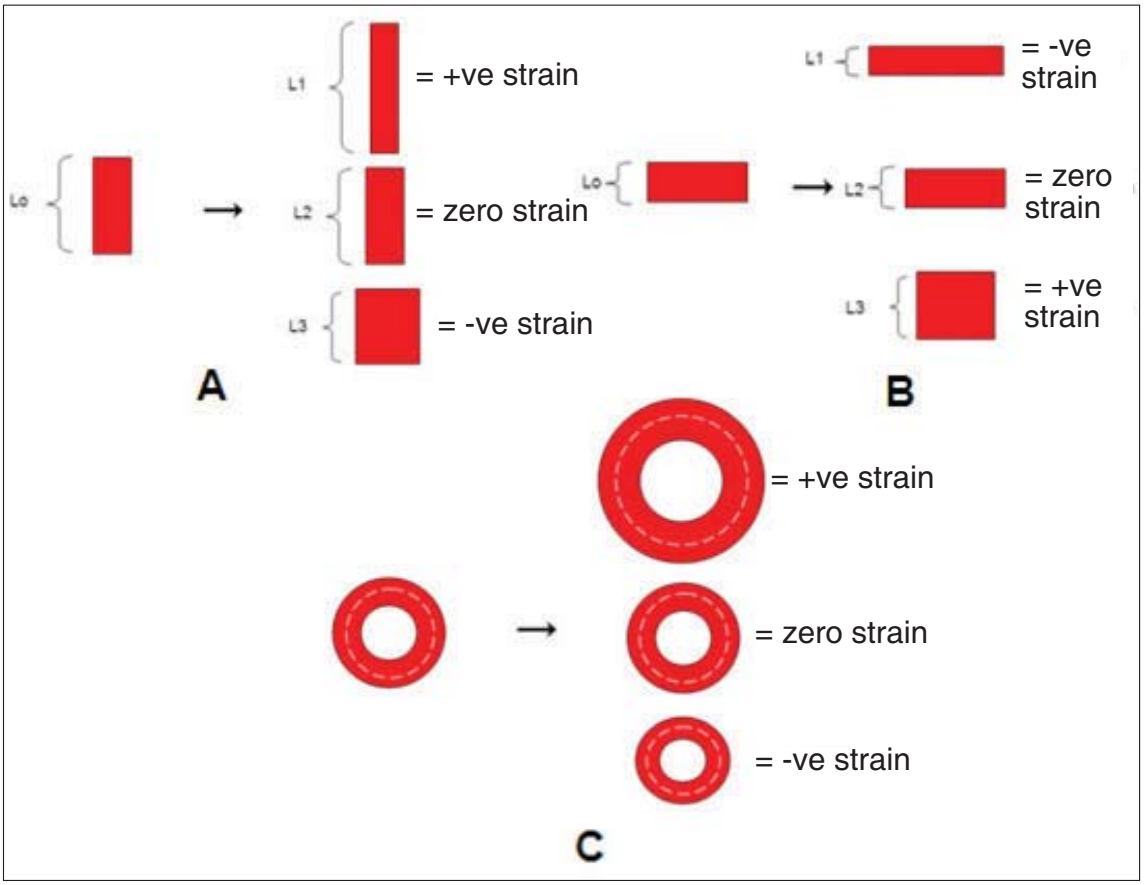

Figure 18: The three directions of myocardial strain as measured by echocardiography. Panel A shows longitudinal strain, with positive strain as a lengthening of the myocardium (L1), zero strain as no change (L2) and negative strain as a shortening of the myocardium (L3). Panel B shows radial strain, with negative strain as a thinning of the myocardium (L1), zero strain as no change (L2) and positive strain as a thickening of the myocardium (L3). Panel C shows circumferential strain, with positive strain as a lengthening of the myocardial circle, zero strain as no change and negative strain as a shortening of the myocardial circle.

detection of dyssynchrony may overcome some of these reliability issues but this is yet to be verified on a larger scale.[114–117]

The key differences between tissue velocity, strain and strain rate are illustrated in Figure 14. There are two myocardial "muscle bundles" shown in red (1) and green (2). In a normal heart the base of the heart descends to the apex during systole. The more basal muscle bundle (green) is pulled along by the more apical myocardium and therefore has a velocity even without contracting; however this green muscle bundle also has its own intrinsic contraction.

Because of this intrinsic contraction the velocity of the green muscle bundle is higher than that of the more apical red muscle bundle. To further illustrate this Figure 15 shows a heart with myocardial damage in the green muscle bundle. You can see that this damaged muscle bundle still has a velocity (this movement is known as tethering) however it is the same as the more apical red muscle bundle – indicating that there is no intrinsic contraction.

This velocity gradient from the base to the apex is how strain and strain rate are calculated from TDI data (Figure 16). Strain is calculated from the TDI data by comparing the velocity of two myocardial points and normalising this to the distance between these two points. Strain rate is simply the rate at which these two points move towards or away from each other.[118]

Speckle tracking like tissue Doppler techniques also assess myocardial velocities and strain. This technique relies on tracking unique speckles found within the ultrasound image accentuated by harmonic imaging. These speckles are like unique fingerprints that can be tracked using complex algorithms to determine myocardial velocities or strain[119–122] (Figure 17). However unlike Doppler techniques, they are angle independent and hence are not restricted to assess longitudinal function but can also assess circumferential and radial motion as well as rotation and twist of the myocardium (Figure 18). Speckle tracking requires high quality imaging with good spatial resolution so that the speckles are able to be tracked. The deformation (or strain) within the speckle fingerprint can be assessed directly rather than be converted from velocity information as the TDI technique does.[119–122]

Strain imaging using both TDI and speckle tracking has been shown to be of benefit in patients with ischaemic heart disease for detection of regional wall motion abnormalities[123–127] and in the detection of myocardial viability.[128,129] Strain imaging has been shown to detect subclinical changes in patients with hypertrophic cardiomyopathy,[130–134] amyloid heart disease,[135–138] chemotherapy cardiac toxicity[139] and may also assist in timing of surgery in valvular heart disease by detecting subtle changes prior to any decrease in ejection fraction (Figure 19).[140–146]

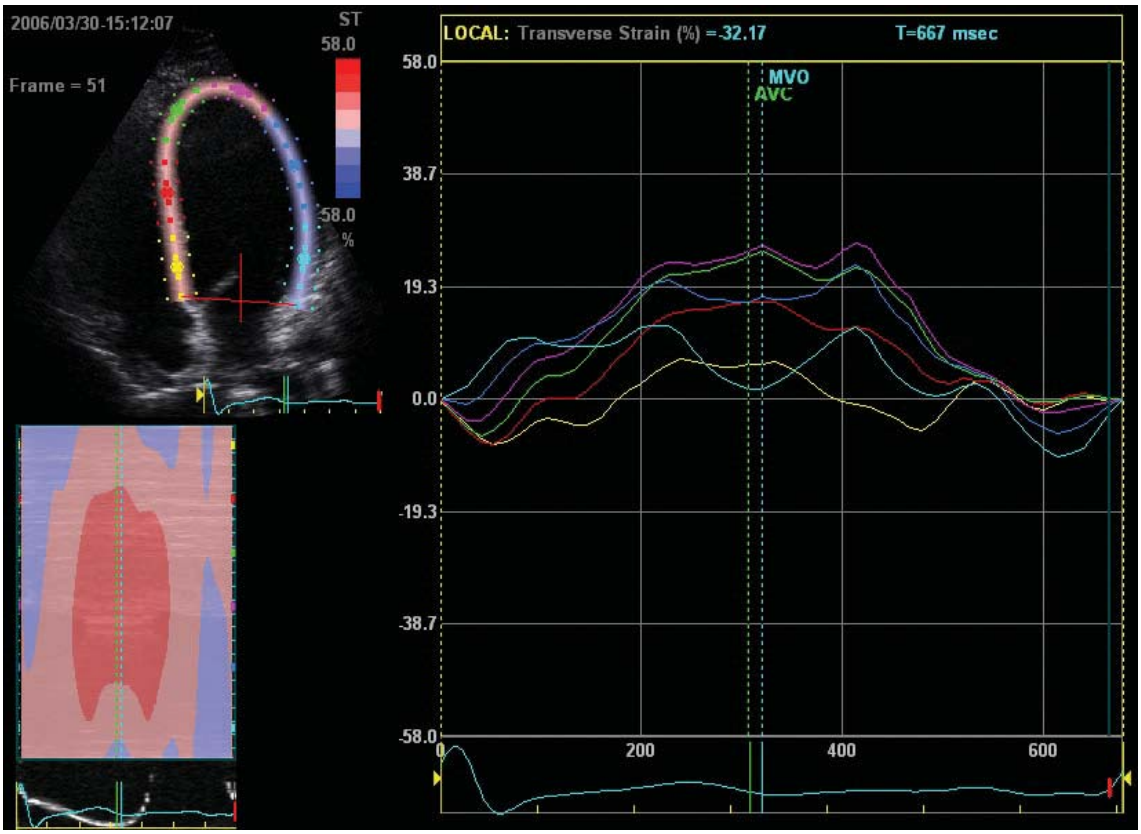

Figure 19: A speckle tracking image demonstrating apical transverse (radial) strain profiles.

Conclusions

Though these new and evolving techniques are very different, they have a common purpose which is to improve the diagnostic, prognostic and therapeutic utility of echo in patients with cardiac disease. While competing imaging modalities such as cardiac MRI and CT have made rapid progress, echocardiography particularly with these new techniques still remains the primary imaging modality in cardiology. 3D imaging for LV volumes and EF and contrast imaging in difficult patients have become standard practice in many echocardiography labs and continue to assist in daily clinical practice. Myocardial image with strain and strain rate however still remains within the realm of research at this stage but holds significant future promise.

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