Review Article

Transesophageal echocardiography: Instrumentation and system controls

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ABSTRACT

Transesophageal echocardiography (TEE) is a semi-invasive, monitoring and diagnostic tool, which is used in the perioperative management of cardiac surgical and hemodynamically unstable patients. The low degree of invasiveness and the capacity to visualize and assimilate dynamic information that can change the course of the patient management is an important advantage of TEE. Although TEE is reliable, comprehensive, credible, and cost-effective, it must be performed by a trained echocardiographer who understands the indications and the potential complications of the procedure, and has the ability to achieve proper acquisition and interpretation of the echocardiographic data. Adequate knowledge of the physics of ultrasound and the TEE machine controls is imperative to optimize image quality, reduce artifacts, and prevent misinterpretation of diagnosis. Two-dimensional (2D) and Motion (M) mode imaging are used for obtaining anatomical information, while Doppler and Color Flow imaging are used for information on blood flow. 3D technology enables us to view the cardiac structures from different perspectives. Despite the recent advances of 3D TEE, a sharp, optimized 2D image is pivotal for the reconstruction. This article describes the relevant underlying physical principles of ultrasound and focuses on a systematic approach to instrumentation and use of controls in the practical use of transesophageal echocardiography.

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Transesophageal Echocardiography (TEE) has rapidly become a powerful monitoring technique and diagnostic tool for the perioperative management of cardiac surgical and hemodynamically unstable patients. It is a semi-invasive procedure that should be performed by a trained echocardiographer, who understands the indications and the potential complications of the procedure.[1] TEE is used to visualize the anatomy of the heart and thoracic aorta, assess global and regional cardiac function and detect the presence of intracardiac air during cardiac surgery.[2] Adequate knowledge of the physics of ultrasound and TEE machine controls is imperative to optimize the image quality, reduce artefacts, and prevent misinterpretation of the diagnosis. The aim of this article is to explain the underlying physical principles and focus on the instrumentation and use of controls in the practical use of transesophageal echocardiography.

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PRINCIPLES OF ULTRASOUND

Echocardiography uses ultrasound (US) to create real-time images of the cardiovascular system in action.[3] Two-dimensional (2D) and Motion (M) mode imaging are used for obtaining the anatomical information, while Doppler and Color Flow imaging are used for information on the blood flow.

Sound is a mechanical energy transmitted in the form of pressure waves causing alternate rarefaction and compression through the medium.[4] Piezoelectric elements emit ultrasonic waves that are partially reflected back from layers of different tissue densities. These vibrations are transformed back into the electrical pulses, which are converted by the scanner into a digital image. Distance is measured by computing the time taken for the reflected US beam to return to the transducer. The scanner lights up the appropriate pixels

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on the screen, based on the measured distance, with a brightness scale proportional to the strength of the echo. When all the echoes are recorded on the screen, a grayscale image is obtained. These images are produced continuously in 'real time' by the computer.[5]

An ultrasound should be used prudently using the, 'as low as reasonably achievable' (ALARA) principle, in order to minimize the bioeffects.[6] This can be done by limiting exposure time and using the lowest output intensity needed to attain good image quality. The bioeffects include thermal and mechanical effects. The thermal bioeffects are the result of a rise in focal temperature caused by the absorption and scattering of US by a biological tissue.[7] The mechanical effects include a movement of cells in a liquid, electrical changes in cell membranes, and shrinking and expansion of bubbles in a liquid (cavitation).[8,9]

CARDIAC ULTRASOUND

The cardiac ultrasound machine comprises of three components: The transducer, the display and recording unit, and the echocardiography unit.

Transesophageal echocardiography transducer

The multiplane TEE probe is essentially a modified gastroscope with a motor-controlled ultrasonic transducer at its tip [Figure 1a].

The main component consists of a phased array of piezoelectric crystals (up to 128 for a 2D probe and 2500 for a 3D probe), which function both as the transmitter and receiver of ultrasonic waves[5] [Figure 2]. The commonly used transducer material is ceramic lead zirconate titanate. The piezoelectric crystal oscillates at a specified resonant frequency in response to an electric field and emits ultrasonic waves. Conversely the crystal converts the reflected ultrasonic waves into electric pulses. Pulse repetition frequency is the number of pulses per unit time. The electrodes conduct electrical energy to the crystals and also record the voltage from the returning echoes. Backing or damping materials help to dampen the extraneous vibrations of the piezoelectric elements.[5,10]

The standard connector is plugged and locked into the machine slot. The handle contains two control wheels and array rotation buttons [Figure 1b]. It is crucial that the tip of the probe should be aligned in the neutral position during movement, to prevent tissue damage. The body of the tube includes an articulating section,

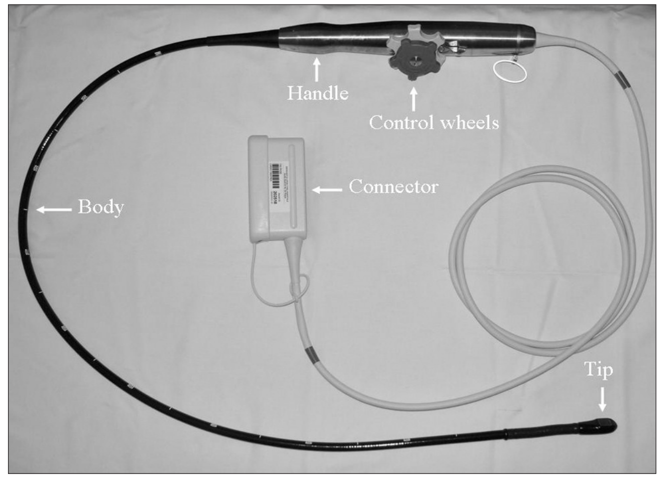

Figure 1a: Photo of a transducer

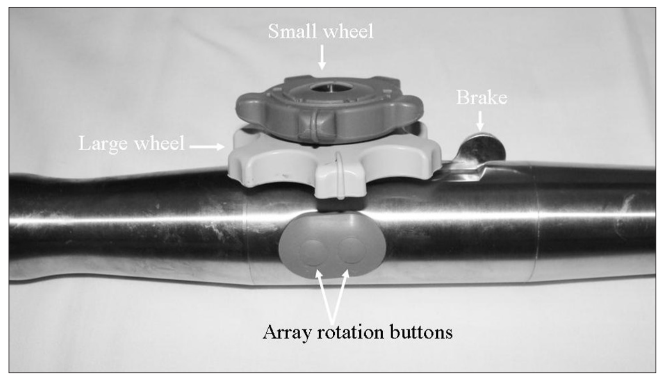

Figure 1b: Close up of the body of a transducer

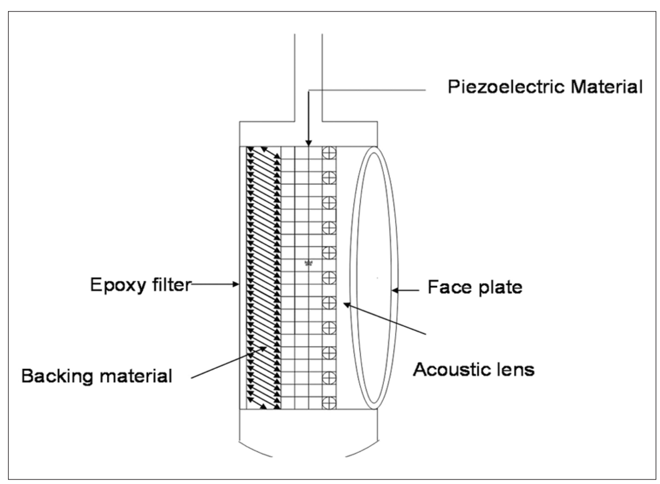

Figure 2: Components of an ultrasound transducer

which can be controlled by the large and small control wheels. Each wheel has friction brakes that hold the tip position without locking it.

The probe position and orientation can be changed by maneuvring the probe using the two control wheels. The large wheel flexes the tip of the probe anteriorly (anteflexion) and posteriorly (retroflexion).

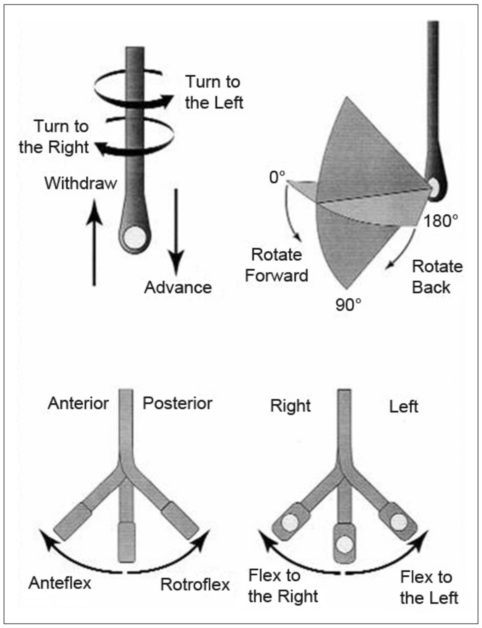

Figure 3: Terminology used to describe the manipulation of the probe and transducer during image acquisition. Reproduced with permission from Shanewise, Cheung, Aronson *et al*. ASE/SCA Guidelines for Performing a Comprehensive Intraoperative Multiplane Transesophageal Echocardiography Examination. J Am Soc Echocardiogr 1999;12:884-900

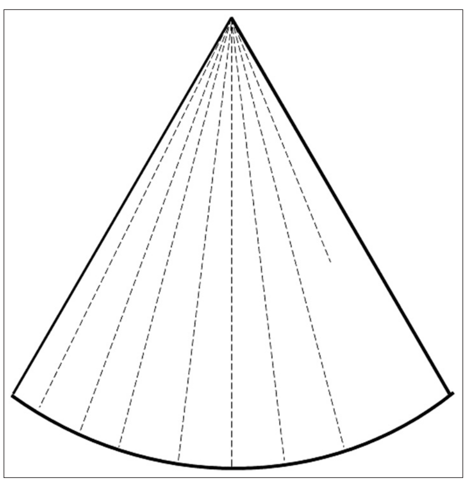

Figure 5: Diagram of a sector showing progression of scan lines

The small wheel allows for lateral flexion or side-to-side movement of the tip. In addition, the probe can be advanced or withdrawn in a vertical fashion into the esophagus and stomach or manually turned to the left or right with respect to the esophagus[11] [Figure 3]. The array rotation buttons turn the mutiplane angle from 0 to 180°. The piezoelectric elements can be electronically rotated either clockwise or anticlockwise using the multiplane angle control, to enable viewing of the heart in any desired plane. The newer probes are enabled to suppress the electrocautery artifacts. Paediatric probes are of smaller diameter (5-7mm) and higher frequency (5-10MHz) with greater flexibility.

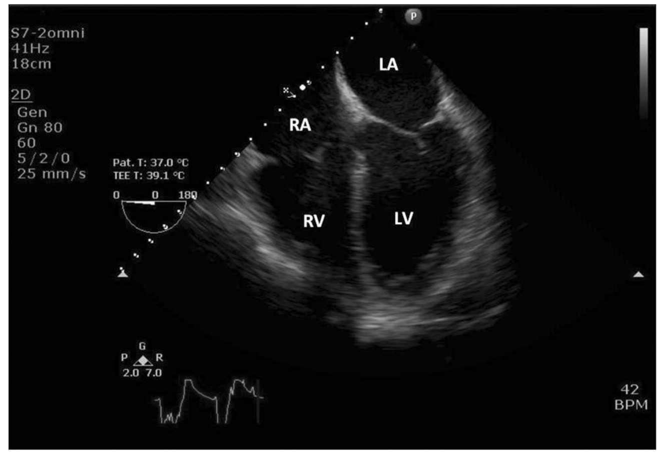

Figure 4: Mid-esophageal four-chamber view at 0° multiplane angle displaying the sector with a frame rate of 41 Hz, depth of 18 cm, 2D gain at 80, and focus set at the level of the atria. LA - Left atrium; RA - Right atrium; RV - Right ventricle; and LV - Left ventricle

Miniaturized multiplane micro probes are equipped with most of the features of adult TEE probes with a frequency of 4.2-7.4MHz.

Image display

Conventionally, the transducer is located at the apex of the triangular field of display. In the mid-esophageal position, at 0°, the patient's right side is depicted on the left side of the display and vice versa [Figure 4]. Upon rotation of multiplane angle to 90°, the anterior and posterior structures are depicted on the right and left side of the display respectively.

Field of view

The field of view (FOV) is the plane or area scanned by the ultrasound transducer.

Sector

The sector is a fan-shaped image with the narrow end displaying objects closer to the transducer and the wider section showing the more distant structures**.** The region of interest (ROI) should be kept as close as possible to the TEE probe. 2-D imaging is displayed on a gray scale, with the high amplitude signals being ascribed a white color and low amplitude a black color. The shades of gray form a picture of the heart in a sector.

Scan lines

Each piezoelectric element of the transducer transmits a US pulse along a line. All echoes from the structures along this line are received, thus producing a scan line whose length is the image depth.[12] The ultrasound beam then moves on to the next scan line position where the process is repeated [Figure 5]. Increased scan lines improve the resolution of the image.

Frame

Each frame represents a total sweep of the US beam and is made up of a complete set of scan lines depending on the number of individual piezoelectric elements in the transducer.[12]

Frame rate

The frame rate (number of images recorded every second, i.e., Hertz) provides a seamless, continuous, moving 'real time' display.[13] The highest frame rate possible should be sought as a lower frame rate lends a 'swimmy' quality to the moving image. In order to maintain a higher frame rate, the smallest FOV that allows the display of the region of interest, should be employed.[14]

Depth

This control alters the vertical FOV of the image, and is used to get the ROI into view. Increasing the depth increases the time taken for the signal to return back to the transducer, thereby decreasing the frame rate, and vice versa.

Zoom

Zoom is used to magnify and improve the resolution of the selected ROI, by decreasing the sector size and increasing line density. The entire FOV is used to display the enlarged ROI image. This function is invaluable in the investigation of valvular morphology, pathology, and relatively small pathological masses, such as, vegetations. It can also be employed to improve measurement accuracy, when measuring smaller structures.[14]

Most ultrasound scanners feature one or more zoom modes. In a receive zoom mode, the ROI is selected via trackball control and then magnified. Receive zoom is a post-processing function that simply enlarges the pixels within a selected ROI, without improving the fundamental resolution, akin to a magnifying glass.[15] An acoustic or transmit zoom is a pre-processing function that digitizes the image data in the selected region at a higher density, by increasing the data bandwidths, to provide a higher resolution zoom image.[16]

Freeze

The freeze button freezes the real-time display and retains it in the digital memory, in a sequence of the immediately preceding frames. Scrolling the frames will allow selection of the appropriate image for study, annotation, and archiving.[15] Freezing the image also stops the transmission of the ultrasound and prevents the probe from overheating and possible tissue damage.

Trackball

This control is a stationary pointing device that contains a movable ball rotated with the fingers or palm, similar to using a mouse on the PC. It is used for moving Doppler boxes to the desired location and for measuring and annotating.

Image acquisition, storage, and archiving

Quantitative assessment of the chamber dimensions, valve area, regurgitant orifice area, peak velocity, and area under the curve of the Doppler trace, provides useful, objective information for echocardiographic evaluation.

Callipers

The buttons for callipers and the trackball measure the distance between two points. This can be used for measuring chamber dimensions, diameter of the aorta, valve annulus, left ventricular outflow tract, and so on.

Trace

This function is used to trace the object of interest and quantify the delineated area.

Recording unit

Recorded echocardiographic images can be used for storing, manipulation, and comparison. The recording can be done on paper, tape, and optical or hard disks. The digital frame grabbing system obtains continuous, high quality, cine-loop recording.[17] The images can be digitally transferred to a central server for storage via a network connection. The DICOM (Digital Imaging and Communications in Medicine) format is a standard for handling, storing, printing, and transmitting information in medical imaging.[18] This enables comprehensive archiving, comparisons, including off-site access, and requisite security.

Echocardiography unit

Before starting the TEE examination, the preliminary checks include electrocardiography monitoring, entering patient verifiable data for easy identification and archiving, connecting and selecting the appropriate transducer probe, and finally choosing an appropriate TEE preset.[16] Timing of the cardiac cycle from the ECG can be critical in making the proper interpretation of an echocardiogram, especially with spectral Doppler displays.

The echocardiography unit combines two component technologies: Imaging (Two-dimensional imaging and M-mode) and Doppler (continuous wave, pulse wave, and color-flow Doppler mapping). The individual components that execute the different modes of imaging are a video display unit and a power source.[19]

System controls

Power is the rate of energy delivered in a sound wave. Intensity is the concentration of power within the cross-sectional area of the US beam.[20] There are several system controls that can be used to obtain a good image by using minimal acoustic intensity. These controls can be divided into three categories:

Direct controls

The Power control has a direct impact on acoustic intensity and is used to select the minimal intensity levels required to produce an optimal image.

Indirect controls

The controls of imaging mode, pulse repetition frequency (PRF), focus depth and frequency have an indirect effect on acoustic intensity. 2D imaging mode disperses energy over the entire scanned area but Doppler concentrates energy in a particular area. Increasing the rate and time of the ultrasound signals increases the time-averaged intensity value.

Receiver controls

Receiver controls such as gain, dynamic range and image processing influence ultrasound without affecting the intensity output. Hence they should be optimized first before increasing the power.

Another classification of these controls can be based on the time of modification of the signal. Preprocessing controls modify the analog and digital signal prior to storage in the computer memory whereas postprocessing controls manipulate the image after its entry into memory.[21]

Two-dimensional imaging

2D imaging helps to image the heart motion in real-time enabling detailed morphological and functional assessment [Figure 6]. It also helps quantitative assessment of cardiac dimensions and provides the framework for M-mode and Doppler imaging.[22] The various control buttons used to get an optimal image are described in Table 1.

Transmit power

Most machines describe power in terms of decibels (dB). An increase of 3 dB increases power or intensity by twice the original and a decrease of 3 dB will halve the power- the 3 dB rule.[23] Minimum power which is consistent with good image quality should be used.

Thermal Index (TI) is an estimate of risk from thermal effects of US and is defined as the ratio of total acoustic power to that required to raize the temperature by 1°C under defined assumptions.[9]

Mechanical Index (MI) is an estimate of risk from the non-thermal effects and is the amount of negative acoustic pressure within an ultrasonic field. It is defined as the peak negative pressure divided by the square root of the ultrasound frequency. Values of indices less than 1 are generally considered safe and though a high index reading is not proportional to a bioeffect, every effort must be made to reduce the chances of a high index.[5]

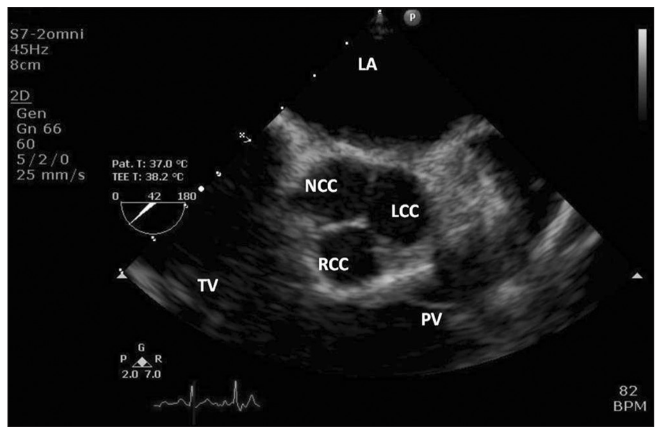

Figure 6: Mid-esophageal AV short axis view. LA - Left atrium; NCC - Non-coronary cusp; LCC - Left coronary cusp; RCC - Right coronary cusp; TV - Tricuspid valve; PV - Pulmonary valve

Table 1: Commonly used echocardiography controls

2D imaging	Pulse wave Doppler	Continuous wave Doppler	Color Doppler
Power	Sample volume size and placement	Beam axis placement	Color box size and placement
Frequency	Trackball	Trackball	Trackball
Depth	Scale	Scale	Color scale
Focus	Baseline	Baseline	Color map
Gain	Gain	Gain	Color gain
TGC	Sweep speed	Sweep speed	Baseline
LGC	Depth	Depth	Filter
Sector size	Frequency	Frequency	Measurement and trace
Zoom	Measurement and trace	Measurement and trace	
Compression	Reject	Reject	
Reject	Invert	Invert	
Persistence	Filter	Filter	
Freeze	Angle correction	Angle correction	
Measurement and trace			
Annotation			

Frequency

The frequency of most TEE probes is between 3.5-7.5 MHz. A higher transducer frequency improves resolution but lacks depth penetration whilst a lower frequency diminishes resolution and improves penetration.[17] The highest possible frequency that allows adequate penetration upto the ROI should be used in two-dimensional (2-D) imaging.[14]

Focus

Focusing the US beam by mechanical or electrical means helps to optimize resolution. The area of interest should be in the "near field" between the transducer and the focal length as the resolution is highest in this region. Therefore repositioning of the focal zone is particularly important when performing 2D measurements and examination of specific regions of interest.[14]

Gain

Gain is the degree of amplification of the returning US signal.[20] The gain button alters the "brightness" of the whole image by adjusting the amplification of all returning echo signals. Minimal gain should be used to provide an optimal image with good quality without dropout or blooming of signals[14] [Figure 7]. As a rule of thumb, fluid and blood should appear black, myocardium a medium grey and the pericardium and calcification, a bright white color on the grey scale.

Time gain compensation (TGC)

As the US beam passes deeper through tissue, there is a steady loss of transmitted intensity caused by attenuation of ultrasound. TGC toggles amplify the weak returning signal proportionately to the time delay and increase the gain for that particular depth [Figure 8]. Near field gain is usually set low and the farfield gain is set high to compensate for the energy loss. Therefore the primary function of TGC is to ensure signals of similar magnitude at different depth are displayed at same amplification.[20]

Lateral gain compensation (LGC)

LGC is similar to TGC except they alter image gain at specific angle sectors in a direction perpendicular to TGC. It is useful to image hypoechoic images caused by suboptimal positioning [Figure 9].

Compression

This control determines the spread of weaker echoes relative to stronger echoes within the grey scale range of the system.[15] Dynamic range is the term used to describe the ratio of the largest to the smallest signals measured at the point of input to the display.[20]

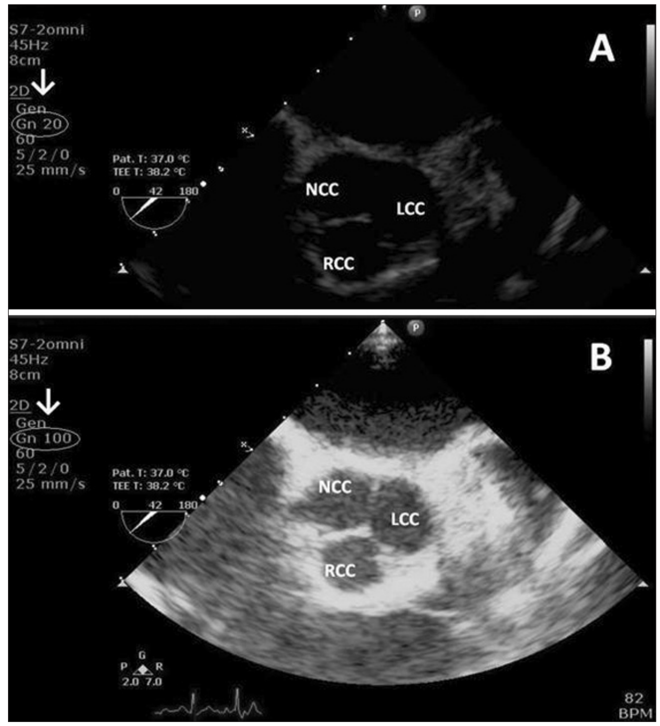

Figure 7: Mid-esophageal AV short axis view. In the image the a arrow highlights a low gain setting of 20; and the coaptation line between NCC and LCC is not visualized. In image b, the gain is set too high at 100. LCC - Left coronary cusp; NCC - Non coronary cusp; RCC - Right coronary cusp

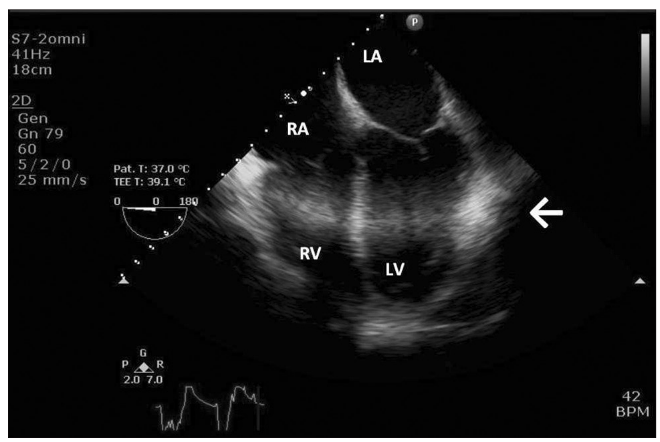

Figure 8: In this mid-esophageal four-chamber view, the TGC toggles at the level of the ventricles have been manipulated to illustrate the high gain at that particular depth (arrow)

Compression alters the difference between the highest and lowest echo amplitudes by compressing the wide spectrum of amplitudes and fitting them in a grey-scale range. Increasing compression provides a smoother image with more shades of grey but may increase unwanted signals i.e. "noize"[Figure 10]. A mid-level compression is usually adequate for optimal imaging.

Reject

The reject control is an adjustable control that eliminates low-level interference caused by refracted aberrant

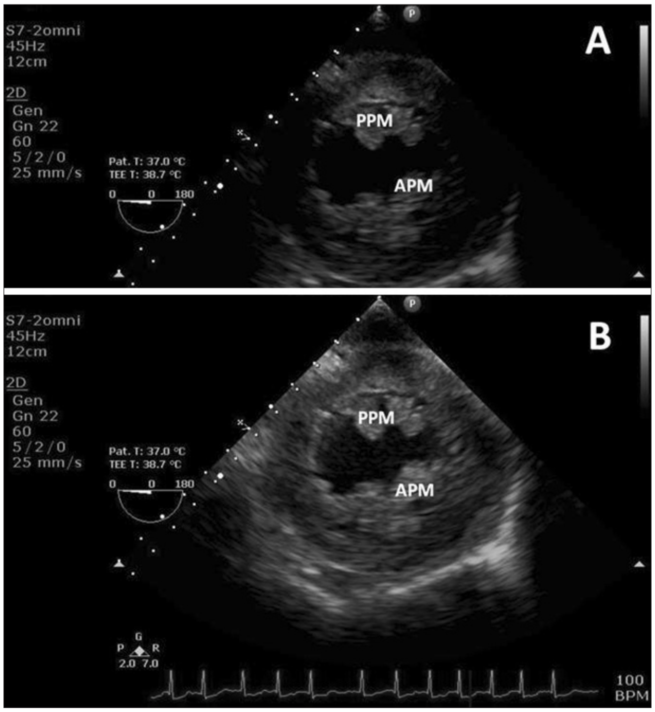

Figure 9: Transgastric mid-papillary short axis view. In panel A the septal and lateral wall areas are poorly defined. In panel B both wall regions are adequately imaged by increasing the lateral gain. PPM - Posteromedial papillary muscle and APM - Anterolateral papillary muscle

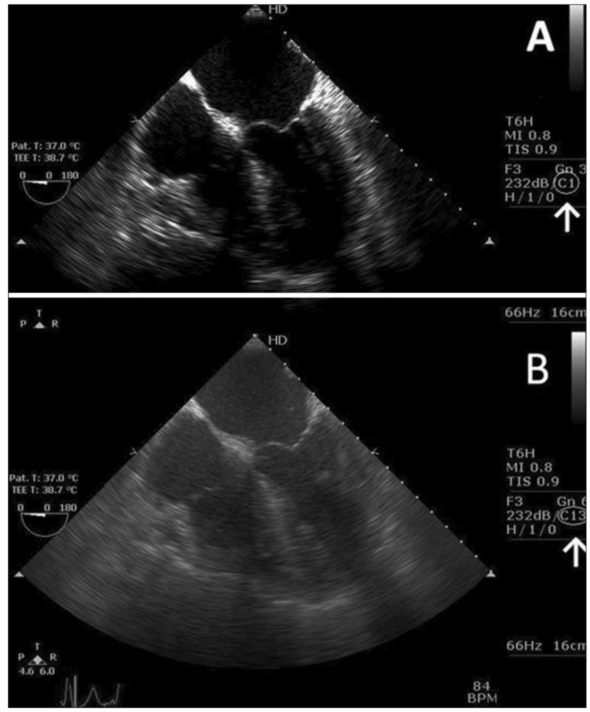

Figure 10: The arrows highlight the compression setting. With low compression, Panel A displays a grainy image with stark contrast. With high compression Panel B provides a smoother image with more shades of gray, but increased unwanted signals. A mid-level compression is usually appropriate

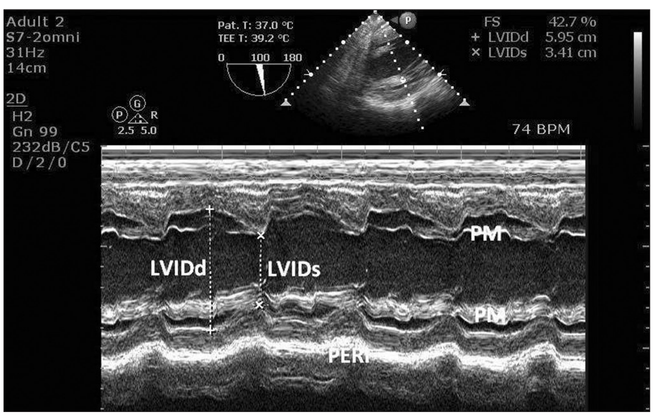

Figure 11: M mode applied to a transgastric long axis view to quantify chamber size. LVIDd - Left ventricular diameter in diastole; LVIDs - Left ventricular diameter in systole; PM - Papillary muscles; PERI - Pericardium

ultrasound and electronic "noize". Care must be taken not to eliminate low-intensity echoes from fresh intracardiac thrombi by setting the reject threshold too high.[24]

Persistence

Persistence was the phenomenon of superimposition of new images on the old fading images in the cathode ray tubes of earlier ultrasound machines.[25] Nowadays it is a postprocessing control that averages and merges the frames thereby producing a smooth moving image of the heart. Persistence should be set low to retain temporal resolution and a real-time appearance.[24]

Brightness, contrast, colorisation, grey scale

These postprocessing controls are all designed to enhance contrast resolution to produce the most pleasing and diagnostically useful image.[15]

M-mode imaging

Motion mode imaging is one of the basic forms of imaging. One scan line provides a single dimensional "ice-pick" view of the heart and the signal is plotted as brightness mode against time on the X-axis. The amplitude of movement of an object and its distance from the transducer is displayed on the Y-axis[26] [Figure 11].

The short sampling time ensures a higher sampling frequency and frame rate, which allows for extremely accurate measurement and timing of events. M-mode is typically used for measurements of the aortic and mitral valve, ventricle cavity size and thickness during systole and diastole and timing of flow patterns in combination with color flow mapping.[17,27]

DOPPLER IMAGING

The Doppler shift is defined as the change in frequency of sound reflected by a moving object and is determined by the Doppler equation[28] [Figure 12]. Doppler shift caused by red blood cells reflecting ultrasound can be

Doppler frequency(f_d)= $\dfrac{2.\, f_t.V.\text{Cos}\theta}{c}$

f_d = doppler shift
f_t = transmitted beam
c = speed of sound in tissue
V = velocity of blood flow
θ = angle of incidence between the ultrasound beam and the direction of flow.

Figure 12: The Doppler frequency shift (f_d) depends on the transmitted frequency (f_t) and the velocity (V) of the moving blood and the angle (θ) between the ultrasound beam and the direction of blood flow. c = speed of sound in the tissue

used to assess the trajectory and speed of normal and abnormal blood flow by determining flow velocity, direction and turbulence. The two main types of Doppler imaging techniques are pulsed wave Doppler (PWD) and continuous wave doppler (CWD) [Table 1].

Pulse wave Doppler

PWD measures low-velocity flows at a specific point along the beam axis. The beam axis should be parallel to the blood flow to maintain accuracy. For practical purposes, if the angle between the US beam and the blood flow is greater than 20°, there is an unacceptable degree of error in estimating the velocity. PWD is used to diagnose diastolic dysfunction from mitral valve and pulmonary vein inflow patterns, estimate aortic valve area and calculate stroke volume.[27]

Sampling

PWD uses a single piezoelectric crystal which acts both as a transmitter and receiver to measure blood velocity intermittently at a particular area called as sample volume. Adjusting the gate control can increase or decrease the size of the sample volume. The trackball is used to place the sample volume at the area of interest.

Depth

The ROI should be as near the transducer as possible. This is because as imaging depth increases, there is a decrease in the pulse repetition frequency.

Gain

Gain is used to amplify the returning Doppler signals. The audio volume can be used to hear the Doppler shift to optimize the spectral waveform.

Display

The velocity is displayed as a spectral waveform on the vertical axis with time displayed on the horizontal axis [Figure 13]. By convention, blood flowing towards the probe is displayed above the baseline and blood flowing away from the probe is displayed below the baseline. The baseline should be adjusted to accommodate the complete waveform.

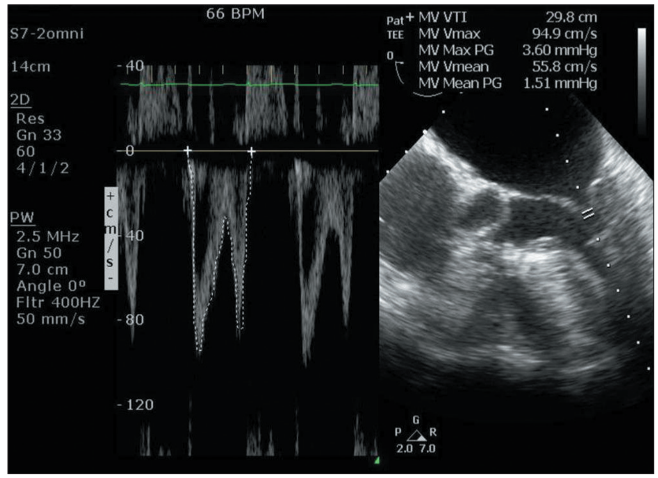

Figure 13: PWD applied across the mitral valve inflow. Tracing the typical hollow velocity envelope is used to calculate Velocity Time Integral, peak, and mean gradient

Aliasing

The major limitation of PWD is the maximum velocity (2 m/sec) that can be measured. A velocity higher than half of pulse repetition frequency (Nyquist limit) will appear as an ambiguous signal on the other side of the baseline. This is known as aliasing.[28] High PRF Doppler imaging is a technique that combines features of both PWD and CWD imaging which can be used to prevent aliasing.[20]

Frequency

Since Doppler shift is proportional to ultrasound frequency, lower frequency transducers are more useful as there is less chance of reaching the Nyquist limit.

Reject

Reject function is used to eliminate low-velocity signals near the baseline by filtering the lower frequencies and trace a sleek waveform.

Invert

The invert button is used to reverse the direction of the signal display above or below the baseline irrespective of the direction of flow.

Continuous wave Doppler

Continuous wave Doppler (CWD) can accurately measure high-velocity flows (<9 m/second) along the beam axis, provided it is parallel to the blood flow. It is used to calculate the grade of stenotic valve lesions and estimates pulmonary artery pressure.[27]

Sampling

The CWD uses two separate piezoelectric crystals to transmit and receive signals in order to measure all

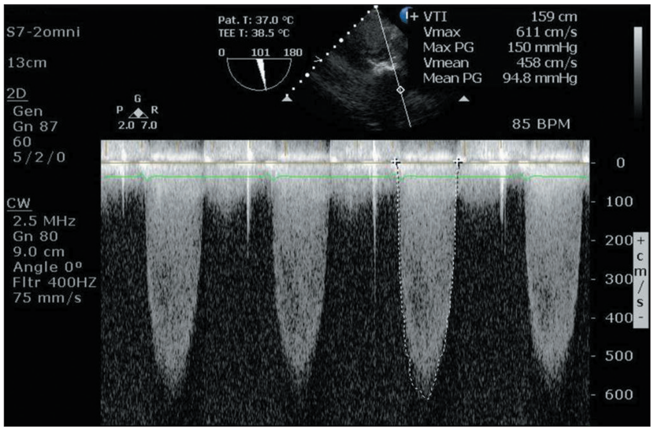

Figure 14: The transgastric long axis view and the CW Doppler applied through the stenosed calcific aortic valve displays a typical 'filled-in' velocity envelope. By tracing the velocity signal the VTI, peak, and mean gradient are calculated

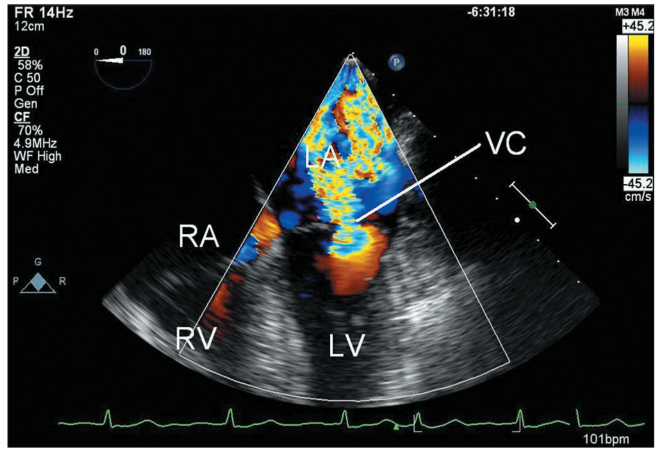

Figure 15: A mid esophageal, four-chamber view superimposed with color flow doppler showing mitral regurgitation. The vena contracta (VC) depicts the regurgitant orifice. LA - Left atrium; RA - Right atrium; RV - Right ventricle; LV - Left ventricle

the different blood velocities along the beam axis, continuously. This makes it difficult to accurately know the depth of the reflected signal. The main disadvantage of CWD is its lack of depth discrimination (Range ambiguity).

Display

The CWD is displayed as a waveform with a filled-in spectrum caused by the different velocities being measured along the scan line [Figure 14]. A turbulent flow, caused by obstruction, results in spectral broadening and increased velocities.

Scale factor

The scale control adjusts the range of velocity that can be displayed, and should be set so that the highest velocity spectral trace can be displayed without cutting off the peak of the trace.

Sweep speed

This control indicates how fast the spectral waveform can sweep across the screen. Increasing the sweep speed decreases the number of cycles and increases the width of the waveform. A low sweep speed shows more waveforms on the screen and is useful to demonstrate waveform variations caused by respiration and arrhythmias.

Wall filters

All Doppler systems have a variable wall filter control that sets a threshold beyond which frequency signals can be removed from the display.

Angle correction

This control changes the angle calculation in the Doppler equation by adjusting the beam axis to the direction of assumed flow, thereby minimizing the error. This does not actually change the direction of the Doppler beam nor does it alter the quality of the spectral recording. It is preferable to adjust the transducer to position the beam axis parallel to the blood flow rather than count on angle correction.

Compression, and the Reject and Invert buttons can be used as for the pulse wave Doppler.

Color flow Doppler

The Color Flow Doppler (CFD) provides a striking display of both blood flow and the cardiac anatomy by superimposing the PWD flow data on 2D images[29] [Figure 15]. It is useful in diagnosing the abnormal flow as well as confirming the normal structures.

Color maps

The PWD used for color mapping, records the mean velocity data from multiple sample volumes – color packets along each scan line. This velocity data is then color-coded; blue indicates flow away from the transducer and red is the flow toward the transducer. The color bar on the screen provides a reference frame for interpreting the colors. The color flow maps are then integrated with 2-D imaging to provide a real-time display.

Sampling and depth — Color sector size and placement

The size, position, and trackball controls are used to change the width, length, and position of the color box. The color box, while enclosing the ROI, should be narrow and as close to the transducer as possible. This prevents aliasing, lower frame rates, and 'swimmy images' caused by the longer time taken to interrogate pulses that are far away from the transducer.[19]

Gain

Excessive 2-D gain before superimposing the CFD should be avoided, as it may obscure the flow. Optimal adjustment of the color gain setting is essential, as too much gain will result in noise and impair the image quality and interpretation. A low gain setting will attenuate sensitivity and make the image appear smaller than the flow jet.

Velocity scale

The adjustable velocity scale is calculated by the machine depending on the depth of the image. When the blood-flow velocity exceeds the velocity scale of the color legend, the machine will continue to represent the velocity of the blood flow, but in the opposite direction. This means that once the velocity of blood flow in one direction exceeds the brightest red, the color will instantaneously change to the brightest blue, then gradually darken.[19] The velocity scale must be set to around 50 – 60 cm/second usually. Lower scales increase sensitivity, but promote aliasing. When the flow is turbulent, some of the velocities will be depicted as a multicolored mosaic signal.

Baseline

The baseline button helps to shift the zero baseline of the velocity scale.

Smoothing

Smoothing determines the grade at which the color packets merge into the adjacent packets. A low smoothing setting will create a speckled flow pattern and a high setting will blend the color packets together.

Tissue Doppler echocardiography

Tissue doppler echocardiography (TDE) uses the Doppler frequency shift to calculate low myocardial velocity, to objectively quantify regional myocardial motion[30] [Figure 16].

Pulsed TDE is similar to PWD, while the color-coded TDE display is based on assigning colors to different velocities. Lower velocity colors tend to be darker colors, while higher velocities are represented by brighter colors. This modality has been applied in the assessment of regional and global left ventricular systolic and diastolic function. TDE is limited by its reliance on the angle of interrogation. This problem can be solved by 2D Speckle Tracking Echocardiography which tracks tissue movement by offline analysis of acquired ECG triggered image loops. Speckles are small areas of different brightness and shape contained within the 2D gray-scale. By tracking the velocity, direction of movement and spatial relationship of speckle clusters during a cardiac cycle, strain and strain rate can be measured to quantify myocardial wall deformation.

Three-dimensional (3D) echocardiography

The 3D technology enables us to view the cardiac structures from different perspectives. Real-time (RT) 3D TEE, using a matrix array probe, interrogates a volume of tissue and produces pyramidal-shaped ultrasound datasets.[31] The 3D image quality depends on the quality and number of 2D images used, limiting motion artifacts and achieving adequate ECG, and respiratory gating.[32]

Three-dimensional live mode

This displays a live narrow angle RT 3D volume of the selected 2D view for single or multiple heart beats with a frame rate of 20 – 30 Hz. The maximum sector dimensions are 60°×30° in the lateral and elevational planes, respectively, which can be changed using trackball controls. Using physical movements of the probe, this mode can be used to rapidly scan the heart and guide RT interventional procedures.[33]

Three-dimensional zoom mode

This provides a magnified RT 3D image, with sector dimensions of 90° × 90° and a lower frame rate of 10 – 15 Hz. Selecting a 3D zoom displays two orthogonal 2D images, which can be modified in the lateral and elevational planes, to accommodate the ROI within the box. The acquired dataset can then be cropped and orientated to provide excellent spatial resolution for structures such as mitral valves, intraoperatively [Figure 17].

Three-dimensional full-volume mode

Although this mode is not an RT imaging modality, it provides a large volume image, with sector dimensions of 75°×75°. Selecting 'Full volume' displays two orthogonal 2D images that can be modified in the lateral and elevational planes, to accommodate the ROI. Small sub-volumes are acquired over four to seven cardiac cycles, synchronized, and then 'stitched' together to display the 'blob view'. The frame rate varies between 20 and 50 Hz, depending on the number of cardiac cycles. The dataset can then be cropped and orientated. The 3D color flow Doppler can be superimposed on a 3D full volume, using seven cardiac cycles, but it reduces the frame rate to <10 Hz.

Arrhythmias, electrocautery artifacts, and probe movements cause a demarcation line, termed as a

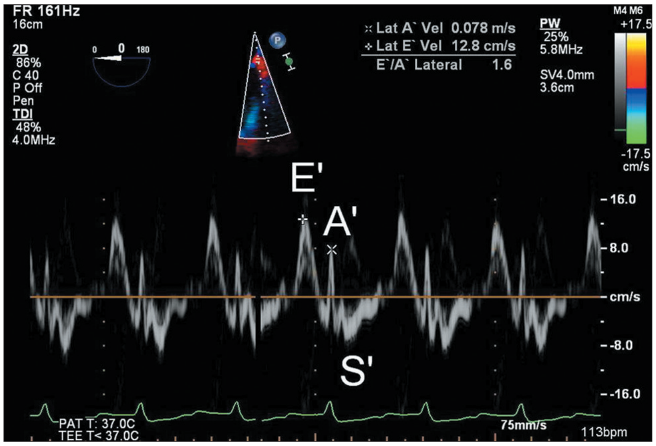

Figure 16: Tissue Doppler image of the lateral mitral annular motion showing early diastolic filling E', atrial contraction A', and movement in systole S'

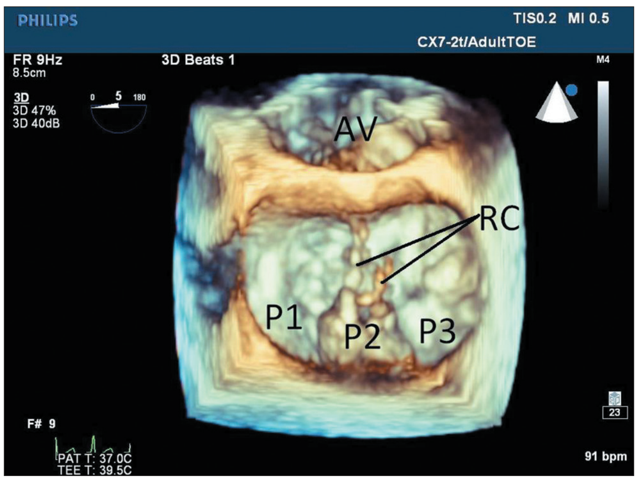

Figure 17: A 3D zoom mode image rotated to display the surgeons view from the left atrium onto the mitral valve, with a P2 prolapse and ruptured chordae tendinae (RC). (AV) aortic valve, (P1,P2,P3) posterior mitral leaflet scallops according to Carpentier's nomenclature

stitch artifact, which is seen between the sub-volumes, distorting the anatomy.[34] Offline analysis of digitally recorded cine loops using specialist software allows manipulation, rotation and cropping of an image to display details in a surgical orientation including measurements of distance, area and volume.

CONCLUSION

Echocardiography is an important technology, widely used for the evaluation of cardiac anatomy and physiology. Despite the recent advances of 3D TEE, a sharp, optimized 2D image is pivotal for the reconstruction. The low degree of invasiveness and the capacity to visualize and assimilate dynamic information that can change the course of the surgery is an important advantage of TEE. An understanding of the fundamental principles of cardiac ultrasound and knowledge of ultrasound instrumentation and settings is necessary for the proper acquisition and interpretation of the echocardiographic data.

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