CHAPTER 2

ECHOCARDIOGRAPHY

2.1 INTRODUCTION

The use of ultrasound in the diagnosis of cardiac disease has been available for more than four decades with the diagnostic potential of this modality first recognized in 1954 when the first continuous recordings of the heart walls were recorded. The term “Echocardiography” was adopted to describe the utility of sound in cardiology in which returning echoes are reflected from the boundaries of the cardiac structures.

Echocardiography has emerged as the primary tool for assessment of the cardiovascular system because of the following advantages: it is noninvasive, safe, no known risk to the patients or technicians, hemodynamic and diagnostic data can be provided. The basic principles of echocardiography, including the mechanical features of echocardiographic equipment are no different from diagnostic ultrasound in general. Nevertheless, there are aspects of echocardiography that set it apart from general echocardiography. Because the heart is a moving organ, and because echocardiography must additionally capture that movement, an understanding of echocardiography requires the knowledge of both cardiac anatomy and physiology.

This technique has become widely employed as a common cardiac investigative tool. It has revolutionized the investigation of gross cardiac pathology and has become an integral component in the routine clinical assessment of the cardiac patient. In fact echocardiography is the most frequently used imaging procedure in the diagnosis of heart disease and rivals the more traditional techniques such as chest radiography and electrocardiography (ECG) [Feigenbaum, 1993].

Echocardiography is used to evaluate cardiac chamber size, wall thickness, wall motion, valvular anatomy, valve motion, the proximal great vessels and the pericardium. Anatomic relationships can be determined and cardiac function can be assessed. This technique is a
sensitive tool for detecting pericardial and pleural fluid, identifying mass lesions within and adjacent to the heart, characterizing congenital cardiac defects and diagnosing valvular and myocardial pathology.

2.2 PRINCIPLES OF ULTRASOUND

By definition, ultrasound is sound having a frequency greater than 20,000 Hz, that is, the sound is above the audible range. Ultrasound waves share the same characteristics of all sound waves. When discussing any type of sound, one must understand the following terms: cycle, wavelength (\(\lambda\)), velocity (\(v\)), and frequency as shown in Figure 2.1. The frequency (\(f\)) is the number of cycles in a given time. In other words, the velocity

\[ v = f \times \lambda \]  

(2.1)

Thus, frequency and wavelength are inversely proportional; higher the frequency, the shorter the wavelength. This means ultrasound can travel faster in a solid dense medium rather than a less dense medium like water. The velocity of sound is fairly constant for human soft tissue (\(\approx 1540 \text{ m/sec}\)). The difference in velocity is significant if it passes through a solid structure such as bone [Feigenbaum, 1993].

The major advantages of ultrasound as a diagnostic tool are (1) ultrasound scan be directed in a beam (2) it obeys the laws of reflection and refraction (3) it is reflected by objects of small size. The disadvantage of ultrasound is that it propagates poorly through a gaseous medium. The amount of ultrasound reflected depends on the acoustic mismatch. Thus, when the beam travels through tissue containing gases and solids, almost all of the sound is reflected and penetration is poor. A dense substance, such as bone, calcium, or metal, will also reflect almost all the energy. Thus, lungs, ribs, and prosthetic material offer distinct challenges for the echocardiographic examination. As a result, the ultrasound producing element or transducer must have airless contact with the body of the patient. Sound travelling through a medium is frequently referred to as the acoustic impedance of that medium. The interaction of ultrasound waves with organs and tissues encountered, along the ultrasound beam, can be described in terms of (1) attenuation (2) absorption (3) reflection (4) scattering (5) refraction, and (6) diffraction as shown in Figure 2.2.
The intensity of the ultrasound beam decreases as it travels away from the transducer because of the above factors. The largest ultrasound reflection depends upon the acoustic mismatch between the two media. When the ultrasound beam is perpendicular to the imaged structure it creates a strong reflection or *echo*. The amount of reflection and transmission can be calculated if the impedance of the two media is known with the formula of (2) and (3) [Solomon, 2006]

\[
\text{percentage reflected}(\%) = \frac{Z_2 - Z_1}{Z_2 + Z_1} \times 100 \quad (2.2)
\]

\[
\text{percentage transmitted}(\%) = \frac{4Z_1 Z_2}{(Z_2 + Z_1)^2} \times 100 \quad (2.3)
\]

Large differences in acoustic impedance are found at bone/soft tissue interfaces and boundaries. For example, the percentage transmitted in soft tissues/bones is 57% and percentage reflected is 43%.
2.3 TRANSDUCERS AND PRODUCTION OF ULTRASOUND BEAMS

Ultrasound results from the property of certain crystals to transform electrical oscillations into mechanical oscillations such as sound. This is called the piezoelectric effect as shown in Figure 2.3. The same crystals can also act as ultrasound receivers since they can affect the transformation in the opposite direction i.e. mechanical to electrical. The repetition rate is 1000/second. Each transmitting and receiving period lasts for 1 ms. Transmission accounts for 1 µs of this time. The remaining time is spent in ‘receiving’ mode. At the core of any echo machine is this piezoelectric crystal transducer. When varying voltages are applied to the crystal, it vibrates and transmits ultrasound. When the crystal is in receiving mode, if it is struck by ultrasound waves, it is distorted. This generates an electrical signal which is analyzed by the echo machine.

![Image](image_url)

**Fig. 2.3** Piezoelectric effect

The crystal can receive as long as it is not transmitting at that time. This fixes the function of the crystal – it emits a pulse and then listens for a reflection. When ultrasound propagates in a uniform medium, it maintains its initial direction and is progressively absorbed or scattered. If it meets a discontinuity such as the interface of 2 parts of the medium having different densities, some of the ultrasound is reflected back. Ultrasound meets many tissue interfaces and echo reflections occur from different depths. Some interfaces or tissues are more echo-reflective than others (e.g. bone or calcium are more reflective than blood) and these appear as echo-bright reflections.

Two quantities are measured in an echo:

1. The time delay between transmission of the pulse and reception of the reflected echo
2. The intensity of the reflected signal, indicating the echo-reflectivity of that tissue or tissue–tissue interface.
CHAPTER 2: ECHOCARDIOGRAPHY

The signals that return to the transducer therefore give evidence of depth and intensity of reflection. These are transformed electronically into grayscale images on a TV screen or printed on paper – high echo reflection is white, less reflection is grey and no reflection is black.

Fig. 2.4  Philips Ultrasound Machine used for the research (a) Philips Envisor C HD11 (b) Philips S4-2 Adult Probe.

In this research work, the Philips Envisor C ultrasound machine and the S4-2 adult probe were used throughout to acquire patient images as shown in Figure 2.4. This probe has the following features:

- 4 to 2 MHz extended frequency range
- Steerable CW Doppler, PW Doppler, High PRF Doppler, Color Doppler, Color Power Angio, Tissue Doppler Imaging, XRES, and Harmonic Imaging
- Adult cardiac, deep abdominal, obstetrical and gynecological applications
- Supports reusable plastic bracket with disposable biopsy guides
- Transcranial Doppler
- Explora connector with new cable technology that is extremely flexible and lightweight

Three echo methods are in common clinical usage:

- Two-dimensional (2D) or cross-sectional
• Motion or M-mode
• Doppler – continuous wave, pulsed wave and color flow

As stated earlier, for the current research work the analysis is restricted to only 2D and Doppler color flow imaging techniques. All images have been taken from the adults i.e. 20 – 70 years of age consisting of both male and female with the assistance of expert sonographers at Sri Jayadeva Institute of Cardiovascular Sciences and Research Hospital, Bangalore. The transducer usually has a line or dot to help rotate it into the correct position to give different echo views.

Fig. 2.5 Three types of artifacts in a PSAX view echo image

The subject usually lies in the left lateral position and ultrasound jelly is placed on the transducer to ensure good images. Continuous electrocardiograph (ECG) recording is performed and phonocardiography may be used to time cardiac events. The frequency or wavelength of the ultrasound beam is one of the important determinants in two dimensional echocardiography.

The complexity of image creation using phased array technology is evident. Therefore, it should not be surprising that a variety of artifacts can occur that have significant impact on image quality and diagnostic potential. Side lobes, reverberations, shadowing, and near field clutter are some of the source of artifacts in 2D echo imaging. Figure 2.5 shows some of the artifacts such as reverberation, shadowing, and drop outs in LV area of a PSAX 2D echo image in apical region [Solomon, 2006].

2.4 PRINCIPLES OF DOPPLER ECHOCARDIOGRAPHY

Doppler echocardiography is an integral part of almost every ultrasonic examination of the heart. Thus knowledge of Doppler principles is essential for anyone involved with
echocardiography. It is primarily a technique for recording the manner in which blood moves within the cardiovascular system.

The Doppler examination is based on the Doppler effect first described by Christian Johann Doppler in 1842 [Solomon, 2006]. The Doppler principle states that the frequency of a sound wave will shift (higher or lower) when it is emitted from, or reflected off, a moving object. This occurs because sound waves emitted from a moving source (or reflected off a moving source) are either compressed or expanded depending on the direction of the movement.

This is the same principle responsible for the changing frequency of an ambulance siren as it travels toward or away from an observer as shown in Figure 2.6. In diagnostic echocardiography, waves are emitted from the transducer at a particular frequency and reflected off moving red blood cells within the heart or blood vessels. If the flow of blood is moving towards the transducer, the sound waves will be compressed as the frequency of the reflected ultrasound will be greater than the frequency of the emitted ultrasound. The opposite is true for moving away from the transducer. The difference between the emitted frequency and the returning frequency is called the Doppler shift. This difference in frequency is directly related to the velocity of the structures reflecting the sound (the red blood cells) and, therefore, is related to the velocity of blood flow. This relationship is described by the following equation [Feigenbaum, 1993] [Solomon, 2006]:

\[
v = \frac{c(F_r - F_i)}{2F_i(Cos\theta)}
\]  

(2.4)
where \( c = \) velocity of sound, \( F_r = \) frequency of the returning ultrasound, \( F_t = \) frequency of the transmitted ultrasound, and \( \theta = \) angle of incidence between the ultrasound beam and the blood flow.

### 2.4.1 PULSED AND CONTINUOUS WAVE DOPPLER

Two modes of Doppler ultrasound are typically employed in standard diagnostic echocardiography: Pulsed Wave (PW) Doppler and Continuous Wave (CW) Doppler are as shown in Figure 2.7(a) and 2.7(b) respectively.

![Fig. 2.7 Two types of Doppler echo images (a) PW Doppler (b) CW Doppler](image)

PW requires individual pulses of ultrasound to be emitted and returned to the transducer. In CW Doppler imaging, a continuous tone is emitted from the transducer [Solomon, 2006].

### 2.4.2 BLOOD FLOW PROFILES IN THE HEART

Blood flowing through the heart and blood vessels can be either laminar or turbulent. Laminar flow occurs when the majority of flow is moving in the same direction and at similar velocities. Turbulent flow occurs when flow is disturbed, by a stenosis or regurgitation as shown in Figure 2.8. The type of flow can be discerned from the PW Doppler waveform. With laminar flow, the waveform will appear *hollow* because the majority of blood cells will be moving at the same velocities [Solomon, 2006]. With the turbulent flow, the velocities will cover a wider spectrum, with some blood cells moving very rapidly and some moving very quickly. Thus, the waveform will appear *filled*.

Examples of Doppler assessments that are typically made with PW Doppler include assessing the LV outflow tract velocity, assessment of mitral inflow velocities, and assessment of pulmonary venous velocities. These are all relatively low velocity flows within the heart.
These are not discussed further as both PW and CW are not being analyzed in this research work.

Fig. 2.8 (a) PW Doppler flow (A) Laminar flow (B) Turbulent flow (C) Flow away from the transducer (b) Color Doppler scale depicting flow direction and relative velocities (c) Short form

Conventional PW Doppler is able to locate abnormal flows in space precisely, but suffers because true velocity recordings are not possible due to aliasing. Conventional CW Doppler is able to record very high velocities, but suffers because it is not possible to exactly locate the jet in space. However, the Color Flow Doppler is makes the Doppler data more readily understandable because of the avoidance of complex spectral velocity displays.

2.4.3 COLOR FLOW DOPPLER

Color flow Doppler imaging uses the same general technology as PW Doppler imaging.

Fig. 2.9 Color flow direction during early systole

However, color flow Doppler samples multiple locations along a scan line simultaneously and determines the velocity of individual locations [Joseph, 2011]. These velocities are then
color encoded utilizing a color map in which particular colors are used to represent particular velocities as shown in Figure 2.8(b). By convention, flow that is moving away from the transducer is encoded in blue and flow that is moving toward the transducer is encoded in red (that is, BART – Blue Away Red Toward) as shown in Figure 2.8(c) and Figure 2.9.

2.5 THE ECHOCARDIOGRAPHIC EXAMINATION

The ability to obtain a high-quality echocardiographic recording is probably the most important factor in determining how useful an echocardiographic examination will be. It is not possible to obtain adequate information from the image unless the tracing is perfect. It is also not so easy to trace, even with the expertise of the operator. Unfortunately, the machine settings are not common for all patients. It must be customized for each patient separately. Thus, the echocardiographic examination has become a highly sophisticated technique that requires skill, experience, domain knowledge, etc.

2.5.1 ANATOMY AND PHYSIOLOGY OF HEART

The heart is a muscular cone-shaped organ about the size of a clenched fist of the same person. It is located in the upper body i.e. chest area between the lungs, and with its pointed end called the apex downwards, forwards, and pointing towards the left. The main purpose of the heart is to pump blood around the body. The basic structure of the heart as illustrated in Figure 2.10 may be described as follows:

The Heart is divided into separate right and left sections by the interventricular septum or "septum" when the context is clearly that of the heart. Each of these (right and left) sections is also divided into upper and lower compartments known as atria and ventricles, respectively.

The four main chambers of the heart are therefore: Right Atrium (RA), Right Ventricle (RV), Left Atrium (LA), and Left Ventricle (LV). According to the Cleveland Clinic, the heart will beat approximately 2.5 billion times during one's lifetime. That said, on any given day, the heart will beat up to 100,000 times. The Texas Heart Institute suggests that most hearts can pump up to 2,000 gallons of blood during each twenty-four hour period.

Cardiac Cycle

The cardiac cycle is a term referring to all or any of the events related to the flow or blood pressure that occurs from the beginning of one heartbeat to the beginning of the next. The
frequency of the cardiac cycle is described by the heart rate. Each beat of the heart involves five major stages. The first two stages, often considered together as the "ventricular filling" stage, involve the movement of blood from atria into ventricles. The next three stages involve the movement of blood from the ventricles to the pulmonary artery, in the case of the right ventricle) and the aorta, in the case of the left ventricle.

- **Systole**

  During this cardiac cycle, the aortic and pulmonary valves open and blood is forcibly ejected from the ventricles, while the mitral and tricuspid valves close to prevent backflow. At the same time, the atria start to fill with blood again. In an electrocardiogram (ECG), electrical systole of the ventricles begins at the beginning of the QRS complex as shown in Figure 2.11.

- **Diastole**

  After a while, the ventricles relax, the aortic and pulmonary valves close, and the mitral and tricuspid valves open and the ventricles start to fill with blood again.
For the purpose of this research work the echo images were acquired with ECG gating so that the ED and ES images frames can be identified easily from the video.

2.5.2 TWO-DIMENSIONAL EXAMINATION

Two-dimensional (2D) echocardiography is the backbone of cardiac ultrasound. Almost all studies are done with reference to the two-dimensional image. Doppler and M-mode studies are obtained after first having a reference from the 2D echo image study. Figure 2.12 illustrates the three basic orthogonal views used for 2D imaging.

![Diagram demonstrating the three orthogonal planes for 2D Echo imaging](image)

The long-axis plane runs parallel to the heart or left ventricle. The short-axis plane is perpendicular to the long-axis. The four-chamber plane is perpendicular to the other two and somewhat represents a frontal plane. The five standard acoustic windows are the left parasternal long-axis and short-axis, apical four chamber, suprasternal, subcostal and right-parasternal views. The suprasternal, subcostal and right-parasternal views are less commonly used in echo examination.

2.5.3 THE PARASTERNAL LONG AXIS VIEW (PLAX)

The patient should be placed in a left lateral decubitus position with the left arm elevated supporting the head. Optimal patient positioning will help to separate the ribs, thus opening up the intercostals spaces. This position will allow for improved quality acoustic windows and views. Images are obtained from the left parasternal position with the transducer in the second, third or fourth inter costal space close to the sternum.
Fig. 2.13 Parasternal Long Axis View (PLAX) during End-Diastole (ED)

The transducer is held with its reference index pointing towards the patients’ right shoulder.

2.5.4 THE PARASTERNAL SHORT AXIS VIEW (PSAX)

Short axis views are obtained optimally with the patient in the same position as for the parasternal long axis view. The transducer is rotated 90 degrees clockwise from the long axis position. The transducer reference index will now point towards the patients’ left shoulder. Figure 2.14 illustrates the echo image in PSAX view at Mitral Valve (MV) level.

Fig. 2.14 PSAX view at Mitral Valve (MV) level

The short axis plane allows mainly for three different views by angulating the transducer from the level of the aortic and pulmonary valves to the left ventricular apex. Starting at a superior medial and tilting to an inferior lateral position, thus tilting the transducer towards the apex.

2.5.5 APICAL FOUR CHAMBER VIEW

Imaging of the heart in the apical region is performed with the patient rotated between 60 and 90 degrees to the left with the transducer applied inferiorly and lateral to the point of
CHAPTER 2 - ECHOCARDIOGRAPHY

cardiac impulse. The reference index of the transducer is pointed towards the left side of the patient. Figure 2.15 demonstrates the apical four chamber view at End-Systole (ES).

![Figure 2.15 Apical four chamber view at ES](image)

The right chambers are on the left of the screen/image:

- **RV (Right Ventricle):** In apical 4 chamber view, the RV should not be larger than 2/3 of the LV width. One can estimate the RV function by looking at the vertical motion of the lateral tricuspid annulus. The contraction of the RV is mainly longitudinal.
- **RA (Right Atrium):** The area of the RA for a normal patient must be in the range of 8.3 to 19.5 cm$^2$.
- **TV (Tricuspid Valve):** Should be a few millimeters more apical than the mitral valve. One can assess a tricuspid regurgitation with color Doppler.
- **LV (Left Ventricle):** It is possible to assess the overall function of the left ventricle and the contractility of the inter-ventricular septum, apex, and lateral wall.
- **LA (Left Atrium):** In this view measuring the long and short axis of LA and its area and volume is possible.
- **MV (Mitral Valve):** The anterior leaflet is close to the inter-atrial septum, the posterior leaflet is lateral. Apical four chamber is a good view to assess the direction of a regurgitant jet and to quantify mitral stenosis.

A mentioned in Chapter 1, majority of the analysis of echo images are based on apical four chamber view. Few data have been calculated from PSAX view at MV level images

### 2.5.6 Doppler Echocardiography

There are many important differences between the Doppler echocardiographic examination and M-mode and 2D techniques. The Doppler examination is frequently done with a lower frequency transducers; whereas the other two use higher frequency transducers. Another
difference is the orientation of the ultrasound beam. Since M-mode, PW, and CW Doppler imaging are not considered for this research work, further discussion is omitted. However, Doppler flow imaging is discussed in greater detail in the next section due to its application in detecting valvular regurgitation.

2.5.7 Doppler Flow Imaging

As described in the previous section, Doppler flow imaging is fairly a complex technology, which can be influenced by many technical factors. Perhaps the most useful application of color flow imaging is in the detection of valvular regurgitation. Many of the patients examined in echocardiography laboratories dealing primarily with adult populations undergo Doppler examination for the presence and relative severity of valvular insufficiency. Color flow techniques avoid time-consuming PW Doppler examination mapping techniques and thus reduce patient examinations and interpretation times.

Mitral Regurgitation (MR)

Mitral regurgitation is a condition in which disease or injury has caused the heart's mitral valve to become leaky. This is one of the most common acquired valvular heart diseases in the adult echocardiography practice.

Fig. 2.16 Mitral Regurgitation Images (a) Low/Moderate Mitral Regurgitation in 4-chamber view (b) Severe MR in apical 4 chamber view

Normal diastolic flow through the mitral valve is very low velocity and rarely exceeds 1.5 m/s. Aliasing is, therefore, seldom seen during diastole when using a 2.5 MHz transducer. Figure 2.16(a) shows the low/moderate mitral regurgitation of a patient in 4-chamber view. We can also notice the following abnormalities: left atrium is dilated as compared to aorta, left ventricle is dilated as the dots on the left side are in centimeters, moderate posterior directed
mitral regurgitation jet seen. Similarly, Figure 2.16(b) shows severe MR in a four chamber view with the turbulence at LA (see the white arrow) and the mosaic color is seen full area of LA.

![Image of severe MR in apical 4 chamber view (End Systole frame)](image)

**Fig. 2.17 Severe MR in apical 4 chamber view (End Systole frame)**

Quantifying the severity of valvular regurgitation is based approximately on the size and configuration of the regurgitant jet. Very small jets, localized just to the proximal side of the regurgitant valve, usually signify trivial valvular insufficiency. Large jets that fill the receiving chamber usually indicate significant valvular insufficiency as shown in Figure 2.17.

**Aortic Regurgitation (AR)**

AR occurs when a fraction of the blood ejected from the LV into the aorta during systole flows back into LV during diastole. This backflow of blood results in both volume and pressure overload of the LV leading to increased work of LV. The echocardiographic assessment of patients with AR involves the following:

- valve morphology
- aortic root
- degree of AR regurgitation
- ventricular size and function

Almost all of the previous comments of MR also apply to the detection and approximate quantification of aortic insufficiency. Aortic regurgitant jets may be small and narrow. When they are, location and mapping by convention PW techniques may be very time-consuming. Color flow approaches can readily identify these abnormalities, as seen in Figure 2.18 shown in four chamber view.

Color flow Doppler imaging provides a semiquantitative method to evaluate the severity of aortic regurgitation. Measurement of the vena contracta – the regurgitant jet as it traverses the
aortic orifice or the effective regurgitant area – can also be used to estimate AR severity. Figure 2.19 shows the method to calculate this width.

![Fig. 2.18 AR shown in apical four chamber view](image)

![Fig. 2.19 Semi-quantitative method to calculate AR severity with vena-contracta width](image)

A vena contracta width of less than 0.3 cm correlates with a mild AR. When this width is 0.3-0.6 it indicates moderate AR whereas above 0.6 cm is severe AR.

**Mitral Stenosis (MS)**

MS is a narrowing of MV orifice area to less than 2.5 cm$^2$ and thus resulting in an obstruction to the flow of blood from LA to LV. One of the first applications for the diagnostic use of echocardiography was for the detection and assessment of MS.

![Fig. 2.20 Mitral Stenosis (Apical four chamber view)](image)
Mitral Stenosis is the leading cause of congestive heart failure in developing countries. Mitral stenotic jets are characterized by a bright burst of color from the mitral valve orifice in very early diastole as shown in Figure 2.20. The apical views are clearly the best for recording this characteristic appearance, as the interrogating beam is nearly parallel to flow and the best mean velocity estimates are possible.

**Aortic valve Stenosis (AS)**

Aortic valve stenosis (AS) is a type of valvular heart disease characterized by an abnormal narrowing of the aortic valve opening. It mediates the flow of blood from the left ventricle to the aorta and the rest of the body during ventricular systole. When the aortic valve becomes progressively stenotic, a pressure gradient is created between the left ventricle (LV) and the aorta since blood cannot be adequately pumped through a narrow orifice as shown in Figure 2.21.

![Fig. 2.21 Aortic Stenosis in apical four chamber view](image)

Acquired degenerative valvular calcification is by far the most frequent cause of aortic stenosis. It is frequent in older patients and results from progressive calcification and restriction of the aortic cusps.

### 2.6 ECHOCARDIOGRAPHIC EVALUATION OF CARDIAC CHAMBERS

This section describes methods to calculate various parameters of cardiac chambers. The assessment of LV is an essential component of the evaluation of any patient with known or suspected heart disease. Today with the echo image views, it is possible to obtain a fairly comprehensive evaluation of the left ventricle. Therefore, most of the research work is directed
towards the study of left ventricle. Quantification details of normal and abnormal patients are also discussed in the later part of this section.

2.6.1 TWO-DIMENSIONAL ECHOCARDIOGRAPHIC MEASUREMENTS AND CALCULATIONS

Quantification of cardiac chamber size, ventricular mass, and function ranks among the most clinically important and most frequently requested tasks of echocardiography. Over the last decades, echocardiographic methods and techniques have improved and expanded dramatically, due to the introduction of higher frequency transducers, harmonic imaging, fully digital machines, left-sided contrast agents, and other technological advancements. Therefore, the American Society of Echocardiography (ASE), working together with the European Association of Echocardiography, a branch of the European Society of Cardiology, has critically reviewed the literature and updated the recommendations for quantifying cardiac chambers using echocardiography. These standards have been followed throughout the present work.

2.6.2 QUANTIFICATIONS OF LV

Left ventricular dimensions, volumes and wall thicknesses are echocardiographic measurements widely used in clinical practice and research. During measurements of LV dimensions, end-diastole and end-systole frames are to be obtained very carefully. End-diastole can be defined at the onset of the QRS, but is preferably defined as the frame following mitral valve closure or the frame in the cardiac cycle in which the cardiac dimension is largest. End-systole is best defined as the frame preceding mitral valve opening or the time in the cardiac cycle in which the cardiac dimension is smallest in a normal heart. Most of these measurements are made with apical four chamber view.

(1) LV Volume

The most commonly used 2-D measurement for volume measurements is the biplane method of discs (modified Simpson’s rule) and is the currently recommended method of choice by consensus of ASE as shown in Figure 2.22 (a) [Anderson, 2007]. The length \( L \) is normally calculated from four chamber view. The primary advantage of this method is that it treats the ventricle as a series of discs and therefore it is independent of the geometrical shape of the
ventricle. The LV volume, therefore, can be calculated using the following equation [Lang, 2005] [Anderson, 2007]:

\[
Volume = \frac{\pi}{4} \sum_{i=1}^{20} a_ib_i \frac{L}{20}
\]  

(2.5)

where, \(a_i\) – diameter in plane 1 (cm), \(b_i\) – diameter in plane 2, and \(L\) – Length.

All 2D echocardiographic techniques require an accurate measurement of chamber length. Apical views are absolutely essential when LV volume is calculated. Another problem with LV volume calculation is that the approach requires identification of endocardium border in apical view.

![Fig. 2.22 2D measurements for LV Volume calculations (a) Modified Simpson’s rule method (b) Area-Length method](image)

Figure 2.23 shows an example echo image traced manually by the technician to calculate the LV dimensions. An alternative method to calculate LV volumes when apical endocardial definition precludes accurate tracing is the area-Length method where the LV is assumed to be bullet-shaped or ellipsoid (Figure 2.22(b)) [Anderson, 2007].

![Fig. 2.23 LV quantification using modified Simpson’s rule method – LV is traced manually during ED](image)
This method is used when only one apical view is able to be assessed and it is expressed by the following equation:

\[ Volume = 0.85 \frac{A^2}{L} \]  

(2.6)

where, \( A \) – Area of the LV in four chamber view in cm\(^2\), \( L \) – Length of LV in cm.

(2) Ejection Fraction

Ejection Fraction (EF) is the fraction of blood pumped out of the left ventricles with each heart beat. Similarly, the volume of blood left in a ventricle at the end of contraction is end-systolic volume. The difference between end-diastolic and end-systolic volumes is the stroke volume (SV). Hence, the EF can be calculated using the following equation:

\[ SV = EDV - ESV \]  

(2.7)

\[ EF(\%) = \frac{EDV - ESV}{EDV} \times 100 \]  

(2.8)

(3) Fractional Shortening (FS)

Fractional Shortening (FS) is the percentage of change in the left ventricular cavity dimension with systole. The standard measurements of the left ventricle required for this calculation include the left ventricular end-diastolic diameter (LVEDD) and left ventricular end-systolic diameter (LVESD). The percentage fractional shortening (FS\%) is calculated from the following equation:

\[ FS(\%) = \frac{LVEDD - LVESD}{LVEDD} \times 100 \]  

(2.9)

(4) Reference values for LV measurements

According to ASE, the reference values to be followed for 2D LV measurements are summarized in Table 2.1 [Lang, 2005] [Lang, 2006].
Table 2.1 Reference limits for LV

<table>
<thead>
<tr>
<th>LV dimension</th>
<th>Women</th>
<th>Men</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference range</td>
<td>Mildly abnormal</td>
</tr>
<tr>
<td>LV diastolic diameter</td>
<td>3.9–5.3</td>
<td>5.4–5.7</td>
</tr>
<tr>
<td>LV diastolic diameter/BSA, cm²/m²</td>
<td>2.4–3.2</td>
<td>3.2–3.4</td>
</tr>
<tr>
<td>LV diastolic diameter/height, cm/m</td>
<td>2.5–3.2</td>
<td>3.3–3.4</td>
</tr>
<tr>
<td>LV diastolic volume, ml</td>
<td>35–75</td>
<td>76–86</td>
</tr>
<tr>
<td>LV systolic volume, ml</td>
<td>19–49</td>
<td>50–59</td>
</tr>
</tbody>
</table>

BSA, body surface area; LV, left ventricular.
Bold italic values: Recommended and best validated.

Quantification of the RV

The normal right ventricle (RV) is a complex crescent-shaped structure wrapped around the left ventricle and is incompletely visualized in any single 2-D echocardiographic view.

Table 2.2 Reference limits for RV measured in Apical four chamber view

<table>
<thead>
<tr>
<th>Reference range</th>
<th>Mildly abnormal</th>
<th>Moderately abnormal</th>
<th>Severely abnormal</th>
</tr>
</thead>
<tbody>
<tr>
<td>RV diastolic area, cm²</td>
<td>11–28</td>
<td>29–32</td>
<td>33–37</td>
</tr>
<tr>
<td>RV systolic area, cm²</td>
<td>7.5–16</td>
<td>17–19</td>
<td>20–22</td>
</tr>
<tr>
<td>RV fractional area change, %</td>
<td>32–60</td>
<td>25–31</td>
<td>18–24</td>
</tr>
</tbody>
</table>

Compared with the LV, the RV is a thin-walled structure under normal conditions and as recommended by ASE, the reference limits for RV measurements is given in Table 2.2 [Lang, 2005][Lang, 2006].
Figure 2.24 shows the measurements performed by an expert operator to trace the RV and the calculations are same as the measurements done for LV.

### 2.6.3 Quantification of Left Atrium (LA)

When LA size is measured in clinical practice, volume determinations are preferred over linear dimensions because they allow accurate assessment of the asymmetric remodeling of the LA chamber.

One technique that is proposed for calculating LA volume is to measure the area and length in apical four and two chamber views. The formula is given below [Feigenbaum, 1993] [Lang, 2006]: 

```latex
\text{Volume (LA)} = \text{Area} \times \text{Length}
```
CHAPTER 2: ECHOCARDIOGRAPHY

\[
LA \text{ Volume} = \frac{8}{3\pi} \left[ \frac{A_1A_2}{L} \right]
\]

(2.10)

where, \( L \) is the shortest of four and two chamber views, \( A_1 \) and \( A_2 \) are the areas of four chamber and two chamber views respectively.

The corresponding echo image views of both four and two chamber views are shown side-by-side in Figure 2.25. To estimate the LA minor-axis dimension of the ellipsoid more reliably, the long-axis LA areas can be traced and a composite dimension derived. This dimension takes into account the entire LA border, rather than a single linear measurement. When long-axis area is substituted for minor-axis dimension, the biplane area-length formula is used: \( 8 \frac{(A_1)}{(A_2)} \frac{3\pi}{L} \), where \( A_1 \) and \( A_2 \) represent the maximal planimetered LA area acquired from the apical 4 and 2-chamber views, respectively, and \( L \) is length. The length remains the LA long-axis length determined as the distance of the perpendicular line measured from the middle of the plane of the mitral annulus to the superior aspect of the LA as shown in Figure 2.25. In the area-length formula the length is measured in both the 4- and 2-chamber views and the shortest of these 2 length measurements is used in the formula [Lang, 2006].

Table 2.3 Reference limits for LA

<table>
<thead>
<tr>
<th></th>
<th>Women</th>
<th></th>
<th>Men</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference range</td>
<td>Mildly abnormal</td>
<td>Moderately abnormal</td>
<td>Severely abnormal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>atrial dimensions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LA diameter, cm</td>
<td>2.7–3.8</td>
<td>3.9–4.2</td>
<td>4.3–4.6</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>1.5–2.3</td>
<td>2.4–2.6</td>
<td>2.7–2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>LA diameter/BSA, cm²</td>
<td>2.9–4.5</td>
<td>4.6–4.9</td>
<td>5.0–5.4</td>
<td>5.5</td>
</tr>
<tr>
<td>RA minor-axis length</td>
<td>1.7–2.5</td>
<td>2.6–2.8</td>
<td>2.9–3.1</td>
<td>3.2</td>
</tr>
<tr>
<td>RA minor axis length/BSA, cm²</td>
<td>1.7–2.5</td>
<td>2.6–2.8</td>
<td>2.9–3.1</td>
<td>3.2</td>
</tr>
<tr>
<td>atrial area, cm³</td>
<td>≤20</td>
<td>20–30</td>
<td>30–40</td>
<td>&gt;40</td>
</tr>
<tr>
<td>atrial volumes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LA volume, mL</td>
<td>22–52</td>
<td>53–62</td>
<td>63–72</td>
<td>≥73</td>
</tr>
<tr>
<td></td>
<td>18–58</td>
<td>59–68</td>
<td>69–78</td>
<td>≥79</td>
</tr>
<tr>
<td>LA volume/BSA, mL/m²</td>
<td>22 ± 6</td>
<td>29–33</td>
<td>34–39</td>
<td>≥40</td>
</tr>
<tr>
<td></td>
<td>22 ± 6</td>
<td>29–33</td>
<td>34–39</td>
<td>≥40</td>
</tr>
</tbody>
</table>

However, this method makes geometric assumptions that may be inaccurate. Table 2.3 shows the normal values of LA measurements.

2.6.4 QUANTIFICATION OF RIGHT ATRIUM (RA)

Clinical data right atrial (RA) size is not widely available. However, limited data on small number of normal subjects revealed that RA volumes are similar to LA normal values in men (21 ml/m²) but appear to be slightly smaller in women. Although the RA can be assessed from
many different views, quantification of RA size is most commonly performed from the apical 4-chamber view. The reference limits of RA dimensions are shown in Table 2.3.

Consolidated Normal Values for Two-Dimensional Echocardiographic Measurements

Based on the discussions of the previous sections and recommendations by ASE and details provided in Fiegenbaum, a consolidated list of normal values for length, diameter, area, volume, EF, stroke volume, FS, and many more measurements for LV, LA, RV, RA are given in Table 2.4 [Feigenbaum, 1993] [Lang, 2005] [Anderson, 2007] [Lang, 2006].

To assess the severity of the disease these values can be used as reference limits and it is mandatory that the computer assisted programs must also refer to these values.

2.7 HEART DISEASES

In general, there are three major types of heart diseases as follows:

- **Rheumatics** – due to acquired of infection
- **Ischaemic** – due to aging
- **Congenital** – by birth

This section talks about these diseases in the view of echocardiographic images and how one can analyze to find out the severity with 2D and color Doppler flow imaging techniques.

| Table 2.4 Normal Values, Two-Dimensional Echocardiography – Apical four-chamber view (50 subjects, Age 19-63 Years, Mean 31.2 ± 10.0) |
|---|---|---|
| | Range | Remarks |
| LV Diameter | Diastole 3.6-5.2 cm Systole 2.3-3.9 cm | |
| LV Length | 7.2-10.3 cm | |
| LV Area | Diastole 17.7-47.3 cm² Systole 7.0-31.5 cm² | |
| LV Volume | 95.5 ml | 38.6 ml |
| Fractional Shortening (FS) | | 27-50% 0.18-0.42 |
| Stroke Volume (SV) | 42-70 ml | Biplane |
| Ejection Fraction (EF) | Diastole 54-66% | ≥55% |
| LA Diameter | 1.5-2.3 cm | |
| LA Length | 4.2-6.1* | |
| LA Area | 0 cm² | BSA |
| LA Volume | 16-28 ml | BSA |
| RV Diameter | 2.2-3.3 cm | |
| RV Length | 6.3-7.3 cm | |
| RV Area | Diastole 10.7-25.5 cm² Systole 7.5-16.0 cm² | |
| RV Volume | 2.7-36.5 ml | |
| RA Diameter | 2.6-5.0 cm | |
| RA Length | 3.4-5.7 cm | |
| RA Area | Diastole 6.9-22.3 cm² Systole 8.3-19.5 cm² | |
| RA Volume | 20-34 ml | |
2.7.1 Rheumatics Heart Disease

Rheumatic heart disease was formerly one of the most serious forms of heart disease of childhood and adolescence. Rheumatic heart disease involves damage to the entire heart and its membranes. Rheumatic heart disease is a complication of rheumatic fever and is common worldwide and responsible for many cases of damaged heart valves. However, the incidence of rheumatic heart disease has been greatly reduced by use of antibiotics effective against the streptococcal bacterium that causes rheumatic fever.

Mitral valve disease is the most common cardiac problem seen in rheumatic heart disease. In rheumatic heart disease, the mitral valve becomes laden with heavy deposits of calcium, which disrupt the normal function of the valve. Because of these heavy calcium deposits, the valve often fails to open completely (a condition called mitral stenosis as discussed in previous sections). The same calcium deposits can also prevent the valve from closing completely, leading to mitral regurgitation called a "leaky" valve. So, people with rheumatic mitral valves often have both mitral stenosis and mitral regurgitation.

Aortic valve disease is also common in rheumatic heart disease. Aortic valve damage is also caused by calcium deposits that disrupt normal valve function. And as with rheumatic mitral valves, rheumatic aortic valves can develop either stenosis or regurgitation, or both. Therefore, color Doppler flow imaging would give a clear analysis of diagnosing this type of disease. Additional details can be obtained with the following ways:

(1) Mitral Stenosis

PLAX View
- 2D Echo Imaging
  1. Increased thickness of Mitral Valve
  2. Reduced opening (intercuspid distance)
- Color Doppler flow Imaging
  1. Mosaic color
  2. Reduced color jet width

PSAX View at MV level during ED
- Reduced orifice Area
- Indirect Evidences
  1. LA & RA Enlargement
  2. Pulmonary Artery (PA) Enlargement
3. RV Hypertrophy

(2) Aortic Stenosis

**PLAX View (ES)**
- 2D Echo Imaging
  1. Increased leaflet thickness
  2. Reduced cusps separation
- Color Doppler flow Imaging
  1. Turbulence at the valve and Aort

**PSAX View at AV level during ED**
- Leaflet thickness
- No. of cusps
- AV orifice reduced
- Indirect Evidences
  1. LV hypertrophy

(3) Mitral Regurgitation

**PLAX View (ES)**
- 2D Echo Imaging
  1. Increased leaflet thickness
- Color Doppler flow Imaging
  1. Turbulence at LA
- Indirect Evidences
  1. LV increase in size
  2. LA increase in size
  3. PA increase in size

2.7.2 **Ischaemic Heart Disease**

Ischaemic Heart Disease (IHD), otherwise known as Coronary Artery Disease (CAD), is a condition that affects the supply of blood to the heart. As the heart is the pump that supplies oxygenated blood to the various vital organs, any defect in the heart immediately affects the supply of oxygen to organs like brain, kidney, etc. IHD is the most common cause of death in several countries around the world.

The potential value of echocardiography is ischemic heart disease lies in two areas: assessment of left ventricular function and diagnosis of complications that arise as sequelae of infarction. Unfortunately, many patients with ischemic heart disease are overweight or heavy
smokers, and have large ‘barrel’ chests with hyperinflated lungs. These factors make complete echocardiographic visualization of the left ventricle difficult. Two-dimensional echocardiography is usually superior for this purpose because its wider field of view provides the ability to locate and determine the extent of the infarcted myocardium. Thus, echocardiography is now growing in use for the exercise evaluation of patients with suspected coronary artery disease.

### 2.7.3 Congenital Heart Disease

A Congenital Heart Disease (CHD) is a condition existing at birth and often before birth, or that develops during the first month of life, regardless of causation. In the Unites States, there are currently more than 5 lakh patients over the age of 21 years with congenital heart diseases. A congenital disorder may be the result of genetic abnormalities, the intrauterine (uterus) environment, errors of morphogenesis, infection, or a chromosomal abnormality. Combinations of both 2D echo and color Doppler is more than sufficient to for the diagnosis of most congenital heart disease and has been used effectively for young patients.

The techniques and the corresponding algorithms developed out of this research are particularly applicable for rheumatic heart diseases only. Hence, we will not discuss details of echocardiographic study for the ischaemic and congenital heart diseases.

### 2.8 SUMMARY

Echocardiography has emerged as the primary tool for assessment of the cardiovascular system because of the following advantages: it is noninvasive, safe, no known risk to the patients or technicians, etc. To investigate the patient for heart abnormalities four image modalities are used: 2D, Color Doppler, M-Mode, and conventional Doppler. 2D echo images provide quantitative details of the cardiac chambers whereas CDF images offer details about regurgitation and stenosis. The image analysis is done on various views of images: PSAX, PLAX, apical 4-chamber. American Society of Echocardiography gives the benchmark for the dimensions of the various heart chambers. Some of the other important parameters are EF, FS, SV, etc.