Left Ventricular Function using 2D Ultrasonography

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***Abstract*—This report discusses the importance of cardiac imaging techniques in diagnosing and managing heart conditions. Among these techniques, echocardiography is the most commonly used non-invasive, portable and inexpensive method. However, there are some limitations in measuring left ventricular function using two-dimensional echocardiography. Three-dimensional ultrasound is being developed to overcome these limitations. The objective of this study is to gain exposure to the clinical use of ultrasound in cardiology and to experience the use of several modern ultrasound devices and techniques for evaluating cardiovascular function. The study involves a comparison of 2D and 3D ultrasound volume measurement techniques, cardiac function evaluation using clinical ultrasound, and the development of a MATLAB routine to evaluate cardiac function. The results obtained from these experiments are discussed.**

Keywords— healthcare, cardiac imaging, heart conditions, echocardiogram, diagnostic ultrasound, 2D ultrasound, 3D ultrasound, volume measurement, clinical ultrasound, cardiac function, MATLAB, end-diastolic volume, end-systolic volume, stroke volume, ejection fraction, cardiac output, Simpson's rule

I. INTRODUCTION

Healthcare providers use cardiac imaging techniques to take pictures of the heart, blood vessels and surrounding anatomy. These techniques can help them diagnose and manage heart conditions by evaluating cardiac performance factors. They can also screen for heart conditions to detect problems early and identify the cause of a heart condition like chest pains and shortness of breath and evaluate the extent of the damage. These imagine techniques can also help to determine if the recommended course of treatment is working for the patient.

There exist various methods for viewing the heart and its structures including echocardiogram, cardiac computed tomography, nuclear cardiac stress tests, single photon emission computed tomography, cardiac positron emission tomography, coronary angiogram or left heart catheterization, cardiac MRI and multigated acquisition.

Among these, the most commonly used technique is the non-invasive, portable and inexpensive, diagnostic ultrasound or echocardiography. The hypothesis of an echocardiogram is that when sound waves are transmitted into the body, they bounce off structures within the body and return to the transducer, creating echoes that can be detected and used to generate an image of the internal structures. This principle is used in medical ultrasound imaging to visualize internal organs, tissues, and structures. By analysing the echoes produced by the sound waves, it is possible to create detailed images of the body without using ionizing radiation or invasive procedures.

The drawbacks of using two-dimensional echocardiography, particularly in terms of measuring the left ventricle, are that some of the equations used to calculate the left ventricular ejection fraction and volume are based on assumptions that may not be valid in cases of dilated or failing ventricles that become more spherical as the disease progresses. There also exists differences in how individual observers perceive and interpolate data between two-dimensional images. This gives rise to interobserver variability in these interpretations. Three-dimensional ultrasound is being developed to overcome these limitations.

The objective is to gain exposure to the clinical use of ultrasound in cardiology and to experience the use of several modern ultrasound devices and techniques for evaluating cardiovascular function.

II. MATERIALS AND METHODS

A. *Comparison of 2D and 3D ultrasound volume measurement techniques*

The materials used for this experiment consists of a balloon filled with a known amount of water and a modern ultrasound scanner - Acuson Sequoia.

The ultrasound machine was used to find out the two-dimensional measurements of the balloon. This included the major axis, L1 and the minor axes D1 and D2.

Assuming the balloon has ellipsoid geometry, its volume can be calculated using the formula,

$$V = \frac{4}{3}\pi \times \frac{L}{2} \times \frac{D_1}{2} \times \frac{D_2}{2}$$

Where L is the major axis dimension, and D1 and D2 are orthogonal minor axis dimensions obtained by 2D ultrasound imaging. This equation is used to compute the volume of the balloon from the standard 2D echo.

The three-dimensional features of the ultrasound were then used to find the volume of the balloon.

The actual volume was known by the volume of water filled in the balloon.

B. *Cardiac Function using clinical ultrasound*

In this study, a two-dimensional transthoracic echocardiography was performed to view the heart of a healthy volunteer using the modern ultrasound scanner. Assuming that the ventricular cavity is approximately three-fourths of an axisymmetric ellipsoid with a long axis, L_{endo} and short axis, D_{endo}, the volume of the cavity at end-diastole (EDV) and end-systole (ESV) was calculated using the formula given below,

$$V = \frac{\pi}{6} \times (D_{endo})^2 \times L_{endo}$$

The D_{endo} is taken to be the papillary short axis diameter. The stroke volume is the difference between the end-diastolic and end-systolic volume. It can be given by the equation,

$$SV = EDV - ESV$$

The ejection fraction (EF) refers to the fraction or proportion of blood that the heart's left ventricle pumps out with each contraction. The EF can be calculated as the ratio between the stroke volume (SV) and the end-diastolic volume (EDV).

$$EF = \frac{SV}{EDV}$$

The cardiac output (CO) refers to the amount of blood pumped by the heart per unit of time, usually measured in litres per minute (L/min). It is calculated by multiplying the stroke volume by the heart rate.

$$CO = SV \times HR$$

Additionally, the cardiac output is also estimated using the formula,

$$CO = VTI \times HR \times \pi \frac{D_{AO}{}^{2}}{4}$$

Where VTI is the velocity time-integral at the aortic outflow tract and D_{AO} is the diameter of the aorta.

C. *Cardiac Function using MATLAB*

A routine is created on MATLAB to find the end-diastolic volume, end-systolic volume, stroke volume, ejection fraction and cardiac output.

Four videos are acquired from a volunteer's heart including the four-chamber view and the short-axis views at the mitral valve (MV), papillary muscle (PM) and apex (APEX) levels. The movie files are loaded onto MATLAB and the end-diastolic and end-systolic frames are extracted and saved.

A MATLAB routine is developed which can be used to manually measure the diameter of the left-ventricular cavity on the images. The points are indicated on the image. The distance between the points is found and scaled using the scale shown in the selected frame.

The routine then uses the modified Simpson's rule on each of the end-diastolic and end-systolic frames to calculate the ventricular cavity volumes. The modified Simpson's rule formula is as shown below,

$$V = (A_1 + A_2) \times h + (A_3 \times \frac{h}{2}) + (\frac{\pi \times h^3}{6})$$

Where, h=L/3 and L is calculated on the four-chamber view, A_1 is the mitral valve short axis area, A_2 is the papillary muscle level area and A_3 is the apex short axis area.

The stroke volume, ejection fraction and cardiac output is then calculated from the end-systolic and end-diastolic volumes found using the modified Simpson's rule formula.

III. Results

A. *Comparison of 2D and 3D ultrasound volume measurement techniques*

The ultrasound machine was used to find out the two-dimensional measurements of the balloon. This included the major axis, L1 and the minor axes D1 and D2. The results are tabulated below.

TABLE I. 2D Measurements

Axis	Measurements
Major L	9.5 cm
Minor D1	8.75 cm
Minor D2	7.23 cm

The volume of the balloon is calculated using the formula for an ellipsoid.

$$V = \frac{4}{3}\pi \times \frac{L}{2} \times \frac{D_1}{2} \times \frac{D_2}{2}$$

Where L is the major axis dimension, and D1 and D2 are orthogonal minor axis dimensions obtained by two-dimensional ultrasound imaging. This equation is used to compute the volume of the balloon from the standard two-dimensional echo.

Plugging the obtained values into the ellipsoid formula we get,

$$V = \frac{4}{3}\pi \times \frac{9.5}{2} \times \frac{8.75}{2} \times \frac{7.23}{2}$$
$$V = 314.68\ ml$$

The volume of the balloon was found to be 314.68 ml using the two-dimensional estimation technique. The actual volume is 390 ml. The error is 19%.

The ultrasound was then used to find out the three-dimensional measurements using the 3D features. The results were as obtained below.

TABLE II. 3D Measurements

Volume	Measurements
V_{3D}	225.03 ml

The volume of the balloon was found to be 225 ml using the three-dimensional feature of the ultrasound. The actual volume is 390 ml. The error is 42%.

B. *Cardiac Function using clinical ultrasound*

The two-dimensional transthoracic echocardiography was performed to view the heart of a healthy volunteer using the modern ultrasound scanner. The following results were obtained,

TABLE III. Cardiac Function Measurements

Parameter	Measurement
Heart Rate	80 bpm
Aorta Diameter (D_{AO})	2 cm

TABLE IV. Two-Dimensional Echocardiography

End-diastole	Measurement
Long Axis L_{endo}	7.53 cm
Short Axis D_{endo}	
Papillary	4.64 cm
Mitral Valve	4.75 cm
Apex	2.52 cm

End-diastole	Measurement
End-systole	**Measurement**
Long Axis L_{endo}	5.27 cm
Short Axis D_{endo}	
Papillary	3.13 cm
Mitral Valve	3.71 cm
Apex	1.47 cm

TABLE V. DOPPLER MEASUREMENTS

Velocity Time Integral (VTI)	22.1 cm

The volume of the cavity at end-diastole (EDV) and end-systole (ESV) was calculated using the formula given below,

$$V = \frac{\pi}{6} \times (D_{endo})^2 \times L_{endo}$$

The D_{endo} is taken to be the papillary short axis diameter. Using the above formula, the end-diastolic volume (EDV) was found to be,

$$EDV = \frac{\pi}{6} \times (4.64)^2 \times 7.53 = 84.88\ ml$$

Using the above formula, the end-systolic volume (ESV) was found to be,

$$ESV = \frac{\pi}{6} \times (3.13)^2 \times 5.27 = 27.03\ ml$$

The stroke volume is the difference between the end-diastolic and end-systolic volume. It can be given by the equation,

$$SV = EDV - ESV = 57.85$$

The ejection fraction (EF) refers to the fraction or proportion of blood that the heart's left ventricle pumps out with each contraction. The EF can be calculated as the ratio between the stroke volume (SV) and the end-diastolic volume (EDV).

$$EF = \frac{SV}{EDV} = 68\%$$

The cardiac output (CO) refers to the amount of blood pumped by the heart per unit of time, usually measured in litres per minute (L/min). It is calculated by multiplying the stroke volume by the heart rate.

$$CO = SV \times HR = 4628\ ml$$

The cardiac output was evaluated as 4.63 litres. Additionally, the cardiac output is also estimated using the formula,

$$CO = VTI \times HR \times \pi \frac{{D_{AO}}^2}{4}$$

Where VTI is the velocity time-integral at the aortic outflow tract and D_{AO} is the diameter of the aorta. The cardiac output is therefore, 5.55 litres using this formula.

C. *Cardiac Function using MATLAB*

A routine is created on MATLAB to find the end-diastolic volume, end-systolic volume, stroke volume, ejection fraction and cardiac output. A MATLAB routine is developed which can be used to manually measure the diameter of the left-ventricular cavity on the images. The routine then uses the modified Simpson's rule on each of the end-diastolic and end-systolic frames to calculate the ventricular cavity volumes. The modified Simpson's rule formula is as shown below,

$$V = (A_1 + A_2) \times h + (A_3 \times \frac{h}{2}) + (\frac{\pi \times h^3}{6})$$

Where, h=L/3 and L is calculated on the four-chamber view, A_1 is the mitral valve short axis area, A_2 is the papillary muscle level area and A_3 is the apex short axis area.

The stroke volume, ejection fraction and cardiac output is then calculated from the end-systolic and end-diastolic volumes found using the modified Simpson's rule formula.

The calculations have been done for a heart rate of 60 bpm as shown in the clinicians videos.

Three iterations were done and average was found. The results are tabulated below,

TABLE VI. MATLAB RESULTS

Iteration	EDV	ESV	SV	EF	CO
1	133 ml	82 ml	51 ml	38 %	3 lts
2	130 ml	75 ml	55 ml	42 %	3.3 lts
3	140 ml	73 ml	67 ml	48 %	4 lts
Average	134 ml	76.67 ml	57.33 ml	43 %	3.4 lts

The study conducted three iterations of 2-D transthoracic echocardiography to image the heart of a healthy volunteer. The end-diastolic volume (EDV), end-systolic volume (ESV), stroke volume (SV), ejection fraction (EF), and cardiac output (CO) were calculated for each iteration. The average results across the three iterations were as follows: EDV of 134 ml, ESV of 76.67 ml, SV of 57.33 ml, EF of 43%, and CO of 3.4 litres. These results provide valuable information about the function of the healthy heart, and may serve as a baseline for comparison with patients who have cardiac abnormalities.

IV. DISCUSSION

The results of the balloon experiment show that the two-dimensional estimation technique using the ellipsoid formula produced a volume measurement of 314.68 ml for the balloon, which is 19% lower than the actual volume of 390 ml. The three-dimensional measurement technique, which used the 3D features of the ultrasound machine, produced a volume measurement of 225.03 ml for the balloon, which is 42% lower than the actual volume of 390 ml. This indicates that the three-dimensional method may have limitations in accurately measuring the volume of irregularly shaped objects such as balloons.

It is important to note that the accuracy of ultrasound measurements may depend on several factors such as the skill of the operator, the quality of the ultrasound machine, and the characteristics of the object being measured.

It's important to note that both 2D and 3D ultrasound imaging have their own advantages and limitations. That being said, there are certain situations where 2D ultrasound may provide better results than 3D ultrasound. One advantage of 2D ultrasound is that it provides real-time imaging, allowing the clinician to visualize the heart in motion and to capture images at specific phases of the cardiac cycle. This can be particularly useful in assessing the function of the heart valves, detecting abnormalities in the heart muscle, and evaluating the flow of blood through the heart. Another advantage of 2D ultrasound is its ability to provide high spatial and temporal resolution, which can be particularly useful for detecting small or subtle changes in the heart's structure and function. In addition, 2D ultrasound is widely available, cost-effective, and can be performed relatively quickly and noninvasively.

On the other hand, 3D ultrasound can provide a more comprehensive and detailed view of the heart's structure and function, allowing for better visualization of complex anatomy and more accurate measurements of cardiac volumes and ejection fraction. 3D ultrasound may be particularly useful in preoperative planning, assessing congenital heart disease, and evaluating complex valvular abnormalities. In summary, both 2D and 3D ultrasound have their own unique advantages and limitations, and the choice of imaging technique depends on the specific clinical question and the expertise of the operator.

As per an article by Robin Houck, the benefits of three-dimensional echocardiography, particularly for volume measurements, septal defects visualization, and whole-valve evaluation, makes it clear that 3D echocardiography is becoming a routine part of cardiac ultrasound examinations. This trend is expected to continue as more vendors, such as GE Healthcare and Siemens Medical Solutions, develop real-time 3D echocardiography, which will likely be available on most cardiac ultrasound systems. Based on these developments, it can be concluded that 3D echocardiography will eventually replace 2D echocardiography, similar to the transition from M-mode to 2D echocardiography that occurred in the past.

Further studies may be required to determine the most accurate method for measuring the volume of irregularly shaped objects using ultrasound technology.

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