Comparing Volume Measurements in Cardiology using 2D and 3D Ultrasound Techniques

1st Nikhil Kumar Kuppa
Dept of Biomedical Engineering
Columbia University in the City of New York
New York City, USA
nkk2126@columbia.edu
Collaborators: Anurag Sharma, Pankaj Pradeep, Rebecca Maria, Vignesh Ramanathan, Emanuel Cordina, Fenisha Shah

***Abstract*— Clinical examinations must consider various factors such as size, shape, material, motion, and sometimes the presence of internal soft tissues and structures. To facilitate this, diagnostic ultrasound imaging is necessary, as it is a convenient, portable, and non-invasive imaging technique. This study aims to compare the accuracy of volume measurements in cardiology using 2D and 3D ultrasound techniques. The study hypothesizes that 3D ultrasound will provide more accurate volume measurements due to its ability to visualize the heart in three dimensions. The results of this study will provide valuable insights into the most effective ultrasound techniques for accurately measuring volume in cardiology, which could ultimately improve diagnosis and treatment planning for patients with cardiovascular diseases.**

Keywords—Volume measurements, Cardiology, 2D ultrasound, 3D ultrasound, Echocardiography, Ultrasound

I. Introduction

Ultrasonography is a valuable and non-invasive technique for determining the volume of an organ and has numerous applications in the fields of cardiology, nephrology/urology, gynecology, and gastroenterology. It enables interactive visualizations to be conducted on online images, video tapes, or digitized ultrasonograms. This study aims to compare and contrast two approaches to ultrasonography: 2D and 3D, and examine their respective applications.

Two-dimensional echocardiography has several benefits, including the ability to evaluate wall motion, valve pathology, and cardiac hemodynamics, as well as being portable, non-invasive, and cost-effective. However, limitations such as the subjective nature of visual assessments, assumptions regarding geometric shapes, and incorrect image positioning restrict its standard techniques. Despite the convenience of using 2D measurements for cardiac evaluations, their accuracy is compromised by errors associated with the process, such as image positioning, geometric assumptions, and boundary tracing. As a result, the accuracy of left ventricular volumes and ejection fraction is limited by errors in the two-dimensional echocardiogram.

To overcome these limitations, three-dimensional echocardiographic methods were developed. Creating images in the 3D method comprises 5 different steps to achieve precision and accuracy while calculating the volume of an organ. These steps are identified as follows: data acquisition, data digitization, data storage, data processing and, data display. The main advantages of 3D ultrasound measurements over 2D are that it is superior in terms of accuracy and precision. [1]

This research paper employs both 2D and 3D measurement techniques to evaluate the cardiac function of a healthy volunteer. To verify the precision of the ultrasound system, a phantom with a known volume of water is utilized to confirm the accuracy of volume measurement. The primary aim of this study is to use a MATLAB routine to select the end-diastole and end-systole frames from the four heart views, measure the diameters of the valves, muscles, and left ventricular cavity, and calculate the Stroke Volume (SV), End-Diastolic Volume (EDV), End-Systolic Volume (ESV), Cardiac Output (CO), and Ejection Fraction (EF) of the observed subject.

II. Materials

A. Materials Used

a. *Phantom Measurement*

   i. Balloon filled with a known volume of water.

   ii. Box filled with water to place the balloon in.

b. *2D and 3D Ultrasound Measurement*

   i. A healthy volunteer, whose cardiac output is measured.

   ii. Ultrasound Machine.

The same probe and machine are used for both the phantom and volunteer measurements in order to maintain consistency.

III. Methods

A. Phantom Measurement

In order to evaluate the quality of the ultrasound equipment being used for measurements, a water-filled balloon of a predetermined volume (390 mL in this study) is employed. The balloon is inserted into a plastic container filled with water and secured in place at the base of the container with tape. The container is then covered with two layers of plastic sheets, simulating the skin and muscle layers of the human body.

1) 2D Measurement

The geometry of the balloon is assumed to be that of an ellipsoid, which requires three main measurements to calculate its volume: the major axis dimension and the two minor axes dimensions, which are perpendicular to each other. To obtain these measurements, the ultrasound probe is placed at the surface of the water and the depth of the balloon is observed. The measurement along the longest dimension of the balloon, which is the major axis (L), is then recorded.

The breadth of the balloon along one of the minor axes is also measured and noted as D1.

The position of the probe is then changed by 90º to obtain the measurement of the other minor axis, which is perpendicular to the first one, and this is noted as D2. Using the assumption that the balloon is an ellipsoid, its volume can be calculated using the formula provided below:

$$\mathbf{V = 4/3 \times \pi \times L/2 \times D_1/2 \times D_2/2 \text{ --- } (1)}$$

In the above formula, the variables are:
L – Major axis dimension
D_1 – Orthogonal Minor axis dimension
D_2 – Orthogonal Minor axis dimension

2) 3D Measurement

To obtain a 3-dimensional view of the image, we adjust the ultrasound settings by pressing the 3-D button. We then position the pointers around the balloon and calculate its volume based on its geometry, as illustrated in the figure below. The ultrasound machine will then automatically provide us with the volume of the balloon, denoted as V_{3D}, which will be displayed in the right column.

B. Ultrasound Measurements

Before taking measurements of the volunteer's heart, the EKG and ultrasound imaging equipment are prepared. Three electrodes are attached to the patient, with two below the right and left shoulders, and a third one below the rib cage on the left side. This allows for visualization of the EKG signal and recording of the patient's heart rate, which was found to be 80 beats per minute.

To obtain volume measurements of the heart, we require four different views to capture specific dimensions of the valve diameters and the length of the left ventricular cavity. To obtain the parasternal long axis image of the heart, we position the ultrasound probe on the patient's right side of the chest in the fifth intercostal position. From the four videos of the patient's heart, we obtain measurements of the same variables at two points - the end-diastole and end-systole. Specifically, we measure the diameter of the mitral valve, apex, and papillary muscle at these two points in the cardiac cycle. These measurements are taken from the following views:

- Mitral valve view
- Apical view
- Papillary muscle view
- Four chamber view

We utilize MATLAB programming to perform the computations. From the videos, we calculate the following values:

- Mitral Valve Area (A1)
- Papilary Muscle Area (A2)
- Apex short axis Area (A3)

By positioning the ultrasound probe in the aforementioned manner, we can obtain the mitral valve, apex, and papillary muscle views of the heart. To acquire the apical four-chamber view, the transducer should be positioned in the fourth or fifth intercostal space, with the orientation marker towards the patient's left shoulder.

In this study, the Modified Simpsons' formula is used to calculate the volume measurements of the volunteer's heart. We calculate the End Diastole Volume (EDV) and the End Systolic Volume (ESV) by calculating the lengths at the diastolic and systolic points.

Modified Simpson’s formula is given by:

$$\mathbf{V = (A1 + A2)h + (A3) \times h/2 + (\pi \times h^3 /6) \text{ --- } (2)}$$

where:

- h = L/3
- A1 = Mitral Valve short Axis area
- A2 = Papilary Muscle area
- A3 = Apex short axis area

We can compute the stroke volume (SV) from EDV and ESV as follows:

$$\mathbf{SV = EDV - ESV \text{ --- } (3)}$$

We can also compute the ejection fraction (EF) as follows:

$$\mathbf{EF = SV / EDV \text{ --- } (4)}$$

Using the patient’s Average Heart Rate (HR), we can calculate the Cardiac Output (CO) of the heart using the formula as follows:

$$\mathbf{CO = SV \times HR \text{ --- } (5)}$$

If we assume that the left ventricular cavity has an ellipsoid geometry and is approximately 3/4 of an asymmetric ellipsoid, with L_{endo} as the major axis dimension and D_{endo} as the papillary muscle short axis diameter, we can use the following formula to calculate the volume of blood that passes through the left ventricular cavity [2]:

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

Additionally, the estimated cardiac output considering the same ellipsoid geometry can be computed as follows:

$$\mathbf{CO_{est} = VTI \times HR \times \frac{\pi}{4} \times (D_{AO})^2 \text{ --- } (7)}$$

where:
VTI – Velocity Time Integral
HR – Heart Rate
D_{AO} – Aortic root Diameter

IV. Results

A. Phantom Results

Table I
2D Ultrasound Measurements of Phantom

Major Axis L (cm)	9.325
Minor Axis D_1 (cm)	8.5
Minor Axis D_2 (cm)	7.23

We calculate the volume using equation (1)

Table II
Volume Measurements of Phantom

Ultrasound Volume Measurements		True volume of the balloon
2D	300.05 mL	390 mL
3D	225.03 mL	390 mL

B. *Cardiac Ultrasound Results*

Table III
Evaluation of Cardiac Function using Ultrasound

Heart Rate (HR)	80 bpm					
Aortic root diameter D_{AO} (cm)	2.00					
2D Echocardiography	**End-diastole**			**End-systole**		
Long Axis L_{endo} (cm)	7.53			5.27		
Short Axis D_{endo} (cm)	papillary	mitral	apex	papillary	mitral	apex
	4.64	4.75	2.52	3.13	3.71	1.47
Doppler Measurement						
Velocity Time Integral (VTI) (cm)	22.1					

Assuming that all the chambers are perfectly circular, we use the formula for the area of a circle (πr^2) to calculate the required areas. The EDV and ESV of the volunteer are determined by utilizing the corresponding values of D_{endo} associated with the papillary short axis diameter. Equations (6) and (7) are then utilized to estimate the cardiac output of the volunteer. Finally, the results are organized into the following table:

Table IV
Volume Measurements assuming Ellipsoid Geometry of Heart

End-Diastolic Volume	97.982 mL
End-Systolic Volume	55.673 mL
Estimated Cardiac Output	5554.33 mLpm

After this, the Modified Simpson's formula is used to calculate the EDV, ESV, SV, EF, and CO. A MATLAB routine is developed based on the methodology explained in section III B, and the calculated values obtained from the MATLAB routine and the Clinical Demo of Week 2 are arranged in a table for comparison.

Table V
Computed volume measurements from Clinical Demo and MATLAB

Parameter	**Clinical Demo**	**MATLAB routine**
EDV	97.982 mL	96.235 mL
ESV	55.673 mL	20.473 mL
SV	42.309 mL	75.762 mL
EF	0.43	0.78
CO	3384 mLpm	6061 mLpm

V. Discussion

The 2-D measurements obtained from Week 3 calculations are compared with the results obtained in the lab, and it is observed that there are differences between the two. However, we conclude that the Week 3 computations are accurate and reliable because it is possible to select the frame as needed and the only assumption required is that the ventricles are perfectly circular in shape.

Although, in the first experiment, the volume of a balloon is calculated by assuming it has an ellipsoid shape, and both 2D and 3D measurements are taken to compare against the known volume of the balloon – where it is found that the 2D measurements are more accurate due to several factors. They include the possibility that waves reflected from the balloon were not all incident back on the transducer during 3D measurements, and the possibility of improper probe positioning by an inexperienced handler. The presence of air bubbles may also have contributed to measurement errors.

During the phantom experiment, the plastic layers covering the box caused air to be trapped and made it difficult to view the balloon on the ultrasound screen. To resolve this issue, the layers were removed and the probe was placed directly on the surface of the water.

In the measurements taken from the volunteer, EDV, ESV, and SV are compared between formula (6) and a MATLAB routine that uses the Modified Simpson's rule. Formula (6) only considers the papillary muscle short axis diameter, which may not be the most accurate estimate of blood volume in the left ventricle due to the differing diameters of the mitral valve and the apex of the heart. However, in the MATLAB routine we assume perfectly circular valves and compute their areas using equation of the area of a circle.

References

[1] O. H. Gilja, T. Hausken, A. Berstad, and S. Ødegaard, “Measurements of organ volume by ultrasonography,” *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, vol. 213, no. 3, pp. 247–259, Mar. 1999, doi: https://doi.org/10.1243/0954411991534951.

[2] M. R. Zile, R. Tanaka, J. R. Lindroth, F. Spinale, B. A. Carabello, and I. Mirsky, “Left ventricular volume determined echocardiographically by assuming a constant left ventricular epicardial long-axis/ short-axis dimension ratio throughout the cardiac cycle,” Journal of the American College of Cardiology, vol. 20, no. 4, pp. 986–993, Oct. 1992, doi: https://doi.org/10.1016/0735-1097(92)90202-x.