Evaluation of Cardiac Function: A Comparison Study

George Saab
Columbia University, gs3159@columbia.edu

***Abstract* - Evaluation of the left ventricular cavity volume at end diastole and systole is commonly performed when conducting evaluation metrics of cardiac function. As there are many metrics that can be used to determine cardiac health, it is often cumbersome and unnecessary to explore all possible evaluations and instead focus on ones that are considered easy to determine; stroke volume, ejection fraction, and cardiac output. Estimation of the left ventricular cavity was explored using a phantom balloon model and compared to the true value. Furthermore, a MatLab analysis was performed to compare analytically determined metrics via MatLab to ones determined by a sonographer.**

***Index Terms* - MatLab, Echocardiogram, Ultrasound, Cardiac Evaluation, End Systolic Volume, End Diastolic Volume, Stroke Volume, Cardiac Output, Ejection Fraction**

I. Introduction

In order to determine the health and function of the heart muscle, physicians will often examine the left ventricular cavity due to its importance in supplying oxygenated blood throughout the body. Simple modalities, such as electrocardiograms (ECGs), are commonly used due to their ease of implementation and effectiveness in determining general cardiac function. However, it is not sufficient in determining the volume of blood flow throughout the cardiac muscle as it lacks spatial information. Because of this, cardiac ultrasonography, also known as echocardiography, is typically employed alongside ECG monitoring as it is both non-invasive and sufficient for determining both tissue functionality and volumetric output.

As discussed throughout the BMEN 6003 course, there are numerous metrics that can be utilized to evaluate cardiac function. While a holistic approach of measuring and calculating every cardiac function is optimal, it is often time consuming and typically unnecessary. Because of this, there exist three metrics that can be generalized to determine overall cardiac function and health; stroke volume (SV), ejection fraction (EF), and cardiac output (CO). Due to the ability for these metrics to all be calculated during an echocardiogram, they are convenient for sonographers in quickly evaluating the health of the patient during examination.

II. Materials and Methods

The approaches for measuring an estimation for cardiac volume in both systole and diastole occurred in three sessions. The first method involved filling a balloon phantom with a fixed amount of water, replicating the filling of the left ventricular cavity, and conducting a mock echocardiography examination to measure the end diastolic volume. Second, a cardiac ultrasound was performed and recorded, examining the results obtained by the echocardiographer. Third, echocardiogram videos were processed in MatLab where manual selection and measurement of the end systolic and diastolic moments were used to determine the cardiac evaluation metrics. A rough calibration of the video size was performed to convert measured distances to centimeters. In all tests, the heart rate was fixed at 60 beats per minute (bpm) to maintain uniformity. The equations found in equation 1 represent the formulas used to calculate the stroke volume (SV), ejection fraction (EF), and cardiac output (CO) using the end diastolic (EDV) and end systolic volumes (ESV), and the heart rate (HR) in beats per minute.

$$SV = EDV - ESV$$

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

$$CO = SV \times HR$$

Equation 1: List of equations used to calculate the stroke volume (SV), ejection fraction (EF), and cardiac output (CO). The end diastolic and end systolic volumes are denoted EDV and ESV, respectively, and the heart rate (HR) is in beats per minute.

A. *Balloon*

A predetermined volume of water was inserted into a balloon and tied off to prevent leakage. A water basin was constructed and filled partially with water to prevent attenuation. The balloon was then inserted into the basin prior to examination.

With the assumption that the balloon can be represented as having an ellipsoidal geometry, the volume can be determined by the general formula:

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

Equation 2: General formula for determining volume of an ellipsoid. L denotes the major axis length, D_1 denotes the first orthogonal minor axis, and D_2 denotes the second orthogonal minor axis.

Where L denotes the major axis dimension, D_1 denotes the first orthogonal minor axis, and D_2 denotes the second orthogonal minor axis.

A terason t3000 ultrasound device was used to conduct a 2-D ultrasound examination on the balloon. The major axis and minor axes were evaluated and measured to obtain the necessary values for determining the volume. The examination required two users, one to place and hold the transducer on the balloon, and the other for freezing the frame where the end diastolic volume could be measured (which was determined simply by indicating where along the transducer placement the diameter of the long axis was greatest.) Similarly, a Philips IE33 ultrasound machine was used to perform a 3-D ultrasound examination on the balloon.The measurements to produce the axes required for volume determination were extracted from the same method for the 2-D balloon, and all measured units were in centimeters. After collecting measurements from both methods, the estimated volume of the balloon was computed and compared with the actual value, and an error was determined.

B. *Echocardiogram Recording*

A clinical demonstration of conducting an echocardiogram on a patient was performed and recorded to explain the steps necessary for determining cardiac function and health. The physician demonstrated a common method for determining left ventricular diameter; freezing a frame in which the cavity volume was greatest and measuring the long axis using the ultrasound machine software, an example of which can be seen in figures 1-2. The physician then verbally stated each of the measurements determined, along with the heart rate of the patient. The cardiac metric equations can be found in equation 3 and were calculated using the measured values.

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

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

Equation 3: Alternative equation to Simpson's rule to calculate the volume of the left ventricular cavity. It is assumed that the cavity is approximated to be ¾ of and axisymmetric ellipsoid with the long axis denoted by L_{endo} and short axis denoted by D_{endo}. D_{AO} denoted the aortic diameter and VTI denotes the velocity time integral.

C. *MatLab*

A set of four videos were recorded of a previously conducted echocardiogram evaluation. Figures 1-2 are examples of the resulting frames regarding the aforementioned method of distance measurement.

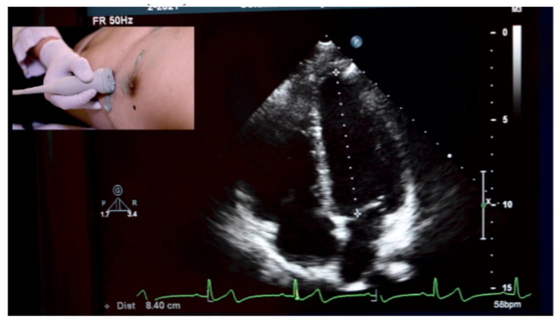

Fig 1: Physician produced example of ventricular long-axis at end diastole. The following image was produced from the apical four channel view of the echocardiographic examination.

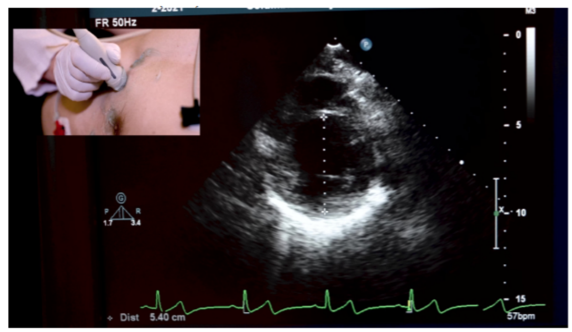

Fig 2: Physician produced example of short-axis at end diastole. The following image was produced from the mitral valve view of the echocardiographic examination

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A separate, uncorrelated echocardiogram recording was obtained which was separated into four videos: a recording of the mitral valve, papillary muscle, cardiac apex, and apical four channel views. Since only one full cardiac cycle is required to determine all of the relevant measurements, the videos were cropped to two second snippets as makes loading and examining the images on MatLab less computationally expensive and time consuming. A handout was provided by the instructor that contains a modified version of Simpson's formula which will be used to the determine the volume of the left ventricular cavity and can be seen as:

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

Equation 4: Modified Simpson's rule formula for determining ventricular volume. The major axis is derived from the ventricular long-axis. A_1 denotes the mitral short-axis area, A_2 is the papillary muscle area, A_3 is the apex short-axis area, and h is one-third the long-axis length.

where A_1 is the mitral valve short-axis area, A_2 is the papillary muscle area, A_3 is the apex short-axis area, and h is one-third of the long-axis length of the left ventricular cavity. These measurements must be determined twice, during end diastole and end systole as necessary in calculating the various cardiac metrics needed for evaluation.

The videos were read into MatLab at a framerate of 30 frames per second. Prior to measurement determinations, the distance was calibrated by measuring the distance along the y axis of the scale bar in the images. Since the value on the scale is known, the conversion from pixel distance to centimeter can be easily determined by calculating the Euclidean distance between the points, as shown in figure 4.

$$d(x,\ y)\ =\sqrt{\sum_{i=1}^{n}(y_i - x_i)^2}$$

Equation 5: Formula to determine the Euclidean distance between two points. In a two-dimensional space, n = 2 and x and y denote the array positions along the x and y axes, respectively.

The video frames were displayed to show three frames at a time, as shown in figure 3, and incremented by one to display the central frame in reference to the frame before and after it.

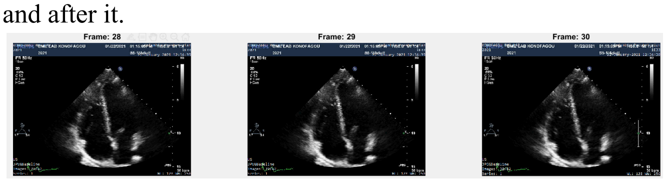

Fig 3: Display of frames 28, 29, and 30 for the apical four channel view.. The images are all incremented by one, with the focus being on the middle frame (ie. the left frame goes from frame 28 to 29, middle frame goes from 29 to 30, and the right frame goes from 30 to 31.)

After all of the frames were displayed, a prompt questions which frame indicates the end diastolic and systolic frames among the set of images. After selection, the respective frame was re-introduced, allowing for measurement of the axis as shown in figure 4. This process was repeated for each video; apical four chamber, mitral valve, apex, and papillary muscle. The resulting measurements were converted into centimeters using the calibration conversion determined previously. The values were then used to calculate the end systolic and end diastolic volumes, and further used to determine the stroke volume, ejection fraction, and cardiac output metrics.

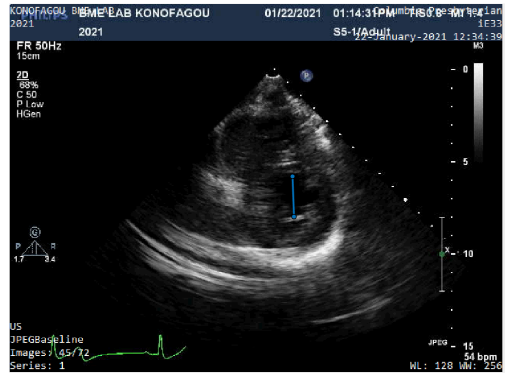

Fig 4: Frame of the end systolic apex short axis. Measurement is manually inserted and can be seen by the blue line. Output of measurement is displayed in the MatLab command line during processing.

III. Results

The known balloon volumetric measurement was obtained to be 330 ml. Using the measurements found in the phantom balloon ultrasound examination, the major axis was found to be 9.34 cm, and the minor axes were found to be 7.55 cm and 7.41 cm, respectively. Using the ellipsoid equation found in equation 2, the final volume was calculated to be 273.5966 ml. The relative error between the true and estimated values is 17.09%.

The measurements obtained from the echocardiographer during examinations were orally presented and are relative to a heart rate of 60 beats per minute. The left ventricular long axis was found to be 8.40 cm at diastole and 7.14 cm at systole. The papillary muscle short-axis was found to be 5.40 cm at diastole and 3.61 cm at systole. The left ventricular outflow tract (LVOT) diameter was found to be 2.00 cm. The pulse and continuous doppler velocity time integrals (VTIs) were 19.0 and 23.8 cm, respectively. Using equations 1 & 3, the end diastolic volume (EDV) was calculated to be 128.25 cm and end systolic volume (ESV) as 48.72 cm. The stroke volume (SV) is 79.53 cm with an ejection fraction (EF) of 0.62 and cardiac output (CO) of 3.581 L/min with pulse doppler and 4.486 L/min with continuous doppler.

For the analysis in Matlab, the EDV was calculated to be 99.157 cm and ESV as 17.984 cm. The SV was 81.173 cm, EF as 0.819, and CO as 4.87 L/min. In comparison to the sonographer's measurements, the EDV relative error is 22.7%, ESV error is 63.09%, SV error is 2.07%, EF error is 32.10%, and CO error is 8.56%.

IV. Discussion

Examining the computed volumetric measurement error of 17% for the balloon estimate volume and true value can be attributed to the error in deformation of the balloon upon filling. As the estimated volume assumes ellipsoidal geometry, it does not account for the compression of the balloon with the surface of the basin. This compressive force lessens the minor axis distances and therefore lowers the overall estimated volume. Furthermore, this error in assumption can also be applied to estimations of left ventricular volume; the generality of assumptions used to conduct estimations of cavity volumes is susceptible to numerous sources of error as the geometry of the ventricle ridges does not form a uniform ellipsoidal surface.

For the purpose of comparison, it is assumed that the sonographer's determined values are reasonably measured and thus represent the true value of the patient's heart measurements. The ESV relative error was the highest at 63.09%, indicating most likely that the measurements obtained in MatLab were underestimated relative to the sonographer. As the error is significant, it can be attributed to the error in manually measuring the distance during the end systole portion of the cardiac cycle. As the raw value of the ESV from MatLab was calculated to be 17.9 cm, it is far under the 48.72 cm obtained from the sonographer. Since the error for the EDV value is 22.7%, far under the ESV error, it is suggested that the calibration error regarding distance measurement in MatLab is not the significant error factor and instead may be attributed to the manual measurement error. In both cases, however, the analytical calculation of distance in MatLab was under the values found by the sonographer.

The relative error for SV is 2.07%. As this number is relative to the difference between the end systole and diastole moments, it is actually a plausible metric for determining the overall accuracy and plausibility of the MatLab distance calculation. Under the assumption that cardiac transitions between systolic and diastolic moments of healthy individuals carry a uniform percent constriction, having a low SV error indicates that the MatLab method of measurement extraction is relatively decent in approximating cardiac metrics. Similarly, the low error for CO at 8.6%, accommodating for the basis that they were calculated using different equations, indicates that the frame analysis and measurement yielded sufficient results for general determination of cardiac health and function.

The comparison of various methods of determining cardiac function continuously proves to be a difficult task in terms of accuracy and easability. Simple ellipsoidal models of the left ventricular cavity, such as the balloon, imply that there are significant differences. While it does allow for easy modeling of the cavity, it sacrifices a great deal of accuracy that must be accounted for when using such an assumption during cardiac evaluation calculations. Alternatively, using a more complex set of equations, such as Simpson's rule, while more accurate in determining cardiac metrics, is more cumbersome and difficult to obtain. Furthermore, incorrect measurements of the required parameters can yield intensively inaccurate volumetric results, so it is important to check the measurements to patients of similar size and stature. Despite this, the evaluation of cardiac metrics using MatLab did prove to result in a sufficient method for determining the values. Due to the adaptability of code and script writing, having the ability to delve and expand upon other cardiac functions can be explored in future studies as well as determination of other model equation assumptions.

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