Assessment of 2D and 3D Ultrasound Volume Measurements and Cardiac Function

Introduction

Ultrasonography is a widely used diagnostic technique that allows physicians to visualize internal body structures in real-time[1]. This non-invasive, painless, and affordable imaging modality is an important tool for diagnosing and monitoring a wide range of conditions, including cardiovascular disease, cancer, and pregnancy. B-mode ultrasound machines work by emitting high-frequency sound waves into the body and detecting the reflected waves to create a 2D image of internal structures [2]. B-mode ultrasound is a specific type of ultrasound that produces 2D images of internal body structures using reflected sound waves [3]. Despite its many advantages, there are limitations to 2D ultrasound, such as the inability to accurately determine the depth of a field and the difficulty in visualizing complex structures [4]. This has led to the development of 3D ultrasound technology, which involves the use of additional transducers and advanced imaging algorithms and enables the generation of volumetric images that can provide more detailed information about internal body structures [5].

The study will involve a comparison of 2D and 3D ultrasound volume measurements in a sample of patients. The primary goal is to determine the accuracy and reliability of 3D ultrasound measurements in comparison to 2D ultrasound, and to assess the feasibility of using 3D ultrasound in clinical practice.

The development of 3D ultrasound technology has the potential to improve diagnostic accuracy and patient outcomes, but it is important to evaluate its clinical effectiveness in comparison to traditional 2D ultrasound. The results of this study could contribute to ongoing efforts to improve medical imaging technology.

Methods

2D ultrasound measurement of balloon

First, fill a balloon phantom with 390 ml volume of water and put it under water. Then put ultrasound transducer under water to find the balloon. Adjust the transducer until a clear outline of the balloon appears on the screen then quickly freeze this picture. Choose the longest distance and the shortest distance on this frozen image. They are major axis L and minor axis D1 respectively. The converter is then rotated 90 degrees to measure the third-dimension minor axis D2 of the balloon. Also freeze the image and select two points on it to get D2.

3D ultrasound measurement of balloon

Use the same balloon for 2D ultrasound measurement. Then put the ultrasound transducer underwater and adjust the orientation. Freeze the best pictures in three dimensions. Manually use a left ventricle model to fit the edge of balloon in the pictures and the machine can tell the volume it calculated.

2-D transthoracic echocardiography

First let the patient laying on the exam table. Then, put electrodes on the patient to track the heart rate. The first two leads are set at upper right and left shoulders. The third lead goes on the lower left belly. Attach them separately with white, black and red leaves.
After setting the electrodes, let the patient turn to the left lateral position, with the left arm behind the head. To begin scanning, we need ultrasound gel to prevent any attenuation of the sound waves with the air. Then use the probe to investigate the Papillary, Mitral, Apex positions. Record the data shown on ultrasound machine.

The videos are also collected and be analyzed on MATLAB to get their long axis and short axis distances. Then a MATLAB script is established to help the physician

Results

According to table 1, the three axis distances is detected by 2D ultrasound. Applying the formula $V_{2d} = \frac{4}{3}\pi \times \frac{L}{2} \times \frac{D_1}{2} \times \frac{D_2}{2}$, the volume measured by 2D ultrasound is 335.9 ml. The one measured by 3d ultrasound is 230 ml. The difference between 2D measurement and actual balloon volume is 54 ml. Actual balloon volume differs by 160 ml from 3D measurement.

Table 2 shows the echocardiography data of a healthy volunteer's heart. The Ventricular cavity volume is calculated by the formula: $V = \frac{\pi}{6} {D_{endo}}^2 L_{endo}$. The two ventricular cavity volume at end-diastole (EDV) and end-systole (ESV) of papillary muscle are 84.84 cm^3 and 27.02 cm^3. The stroke volume (SV) is 57.82 cm^3, and ejection fraction (EF) is 68%. Cardiac output is calculated by SV times heart rate (4625.77 ml/min). By using doppler measurements (CO=VTI*HR*($\pi D_{AO}^2/4$)), the cardiac output is 5551.52 ml/min.

As shown in table 3, the distance in long axis and short axis are manually collected in MATLAB (Appendix). We assume that papillary, mitral and apex are circles to calculate their areas. By following the modified Simpson's rule formula ($V = (A_1 + A_2)h + \frac{A_3 h}{2} + \frac{\pi h^3}{6}$), the two volumes at end-diastole and end-systole are 80.38 cm^3 and 47.73 cm^3. The stroke volume is 32.65 cm^3 and the ejection fraction is 41%. The cardiac output here is 2611.86 ml/min calculated by SV times heart rate.

2-D measurements	
Major axis L	9.06 cm
Minor axis D1	8.91 cm
Minor axis D2	7.95 cm
$V_{2d} = \frac{4}{3}\pi \times \frac{L}{2} \times \frac{D_1}{2} \times \frac{D_2}{2} = 336\ ml$	
3-D measurements	
$V_{3d} = 230\ ml$	

Table 1. Comparison of 2-D and 3-D ultrasound volume measurement techniques

Heart Rate	80 bpm					
Aorta Diameter D_{AO}	2.00 cm					
2D echocardiography	End-diastole			End-systole		
Long axis L_{endo}	7.53 cm			5.27cm		
Short axis D_{endo}	Papillary 4.64 cm	Mitral 4.75 cm	Apex 2.52 cm	Papillary 3.13 cm	Mitral 3.71 cm	Apex 1.47 cm
Ventricular cavity volume	84.84 cm^3			27.02 cm^3		
Stroke volume	57.82 cm^3					
Ejection fraction	68%					
Cardiac output	4625.77 ml/min					
Doppler measurements						
Velocity time integral (VTI)	22.1 cm					
Cardiac output	5551.52 ml/min					

Table 2. 2-D transthoracic echocardiography data of a healthy volunteer's heart

2D echocardiography	End-diastole			End-systole		
Long axis L_{endo}	6.51 cm			5.10cm		
Short axis D_{endo}	Papillary 4.30 cm	Mitral 4.63 cm	Apex 2.87 cm	Papillary 3.95 cm	Mitral 3.90 cm	Apex 2.46 cm
Area	A2: 14.51	A1: 16.83	A3: 6.47	12.25	11.94	4.76
Volume	80.38 cm^3			47.73 cm^3		
Stroke volume	32.65 cm^3					
Ejection fraction	41%					
Cardiac output	2611.86 ml/min					

Table 3. Echocardiography data collected in MATLAB

Discussion

For the first experiment, errors in 2d measurements can be attributed to the fact that people have a lot of subjectivity in choosing the axis. Additionally, 3D ultrasound obtains less close volumetric measurements than 2D. This could probably because the model chosen for balloon is not suitable. The left ventricle model oval or egg-shaped, but the balloon is more circular. This leads to larger errors in 3D measurements compared with 2D measurement.

For the second experiment, we have different results with regard to different approaches we use. The CO is 4625.77 ml/min from echocardiography, and CO is 5551.52 ml/min. The reason why the results from these two methods are different is because they measure cardiac output based on different variables. Whereas Doppler measurements base their CO calculations on the velocity and cross-sectional area of blood flow in a particular region of the heart, echocardiography bases its calculations on the volume of blood the heart expels with each contraction.

The two methods have their own strengths. They can both assess cardiac function in real time and provide information on both systolic and diastolic function. Echocardiography also helps to visualization of cardiac structures and abnormalities, allowing for diagnosis and monitoring of various cardiac conditions. Doppler measurement Can provide information on blood flow velocity and direction, which can be useful in diagnosing and monitoring certain cardiac conditions.

In the end, I obtained the corresponding coordinate axis length by extracting the frame of the video in MATLAB. But this result is very different from that presented in Echocardiography. The main difference exists at the measurement of the long axis and apex short axis. This is probably because the frame chosen is different throughout the cardiac cycle. The distances could fluctuate due to variations in measurement precision.

The two volumes here are also using different method to calculate. The papillary volume is typically measured by tracing the region around the papillary muscles, while modified Simpson's rule formula involves measuring volumes of the mitral valve and apex regions as well. This result in different SV, EF, and CO values. In the future, Different volume formulas can also be used to detect the differences they make.

References

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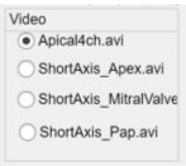
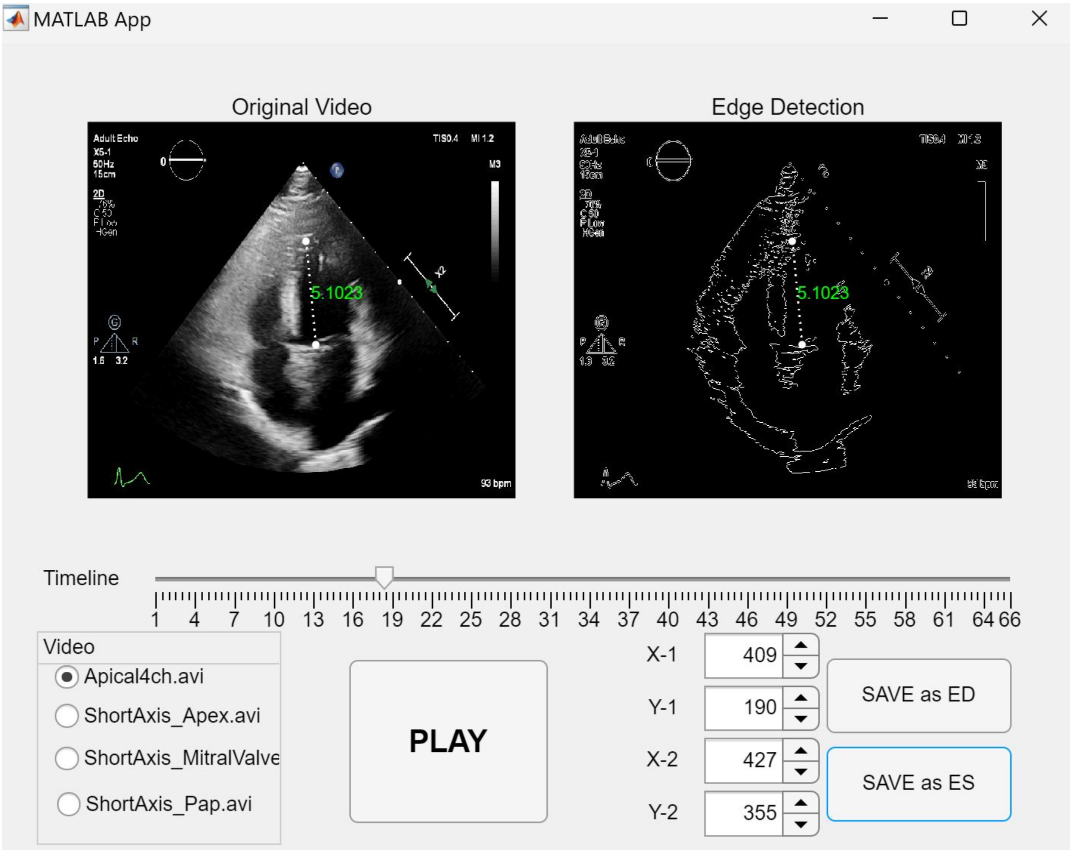
Appendix

MATLAB command:

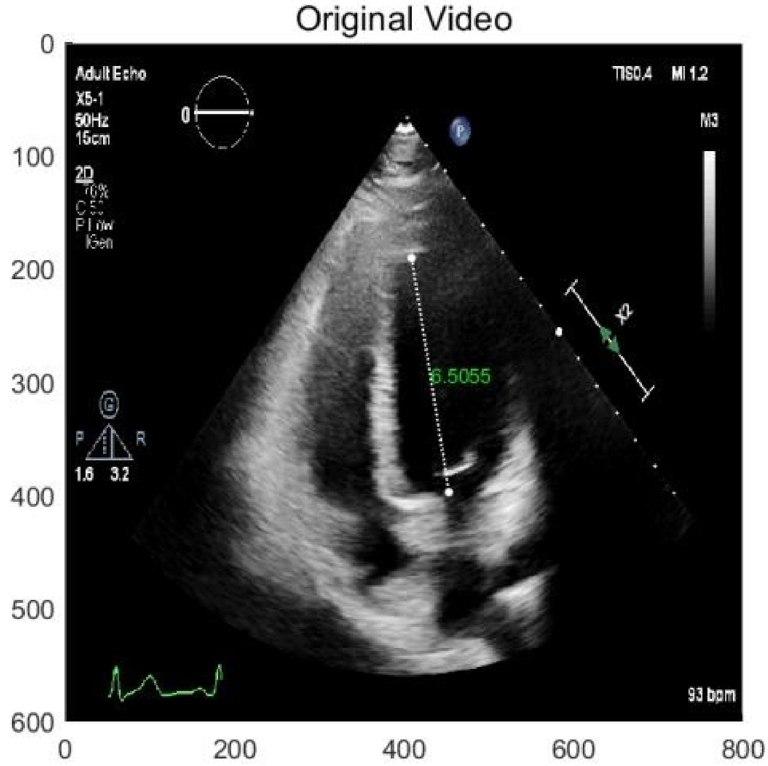
- First, put the HW_1.mlapp under this folder with 4 videos.
- Choose the video you are interested in



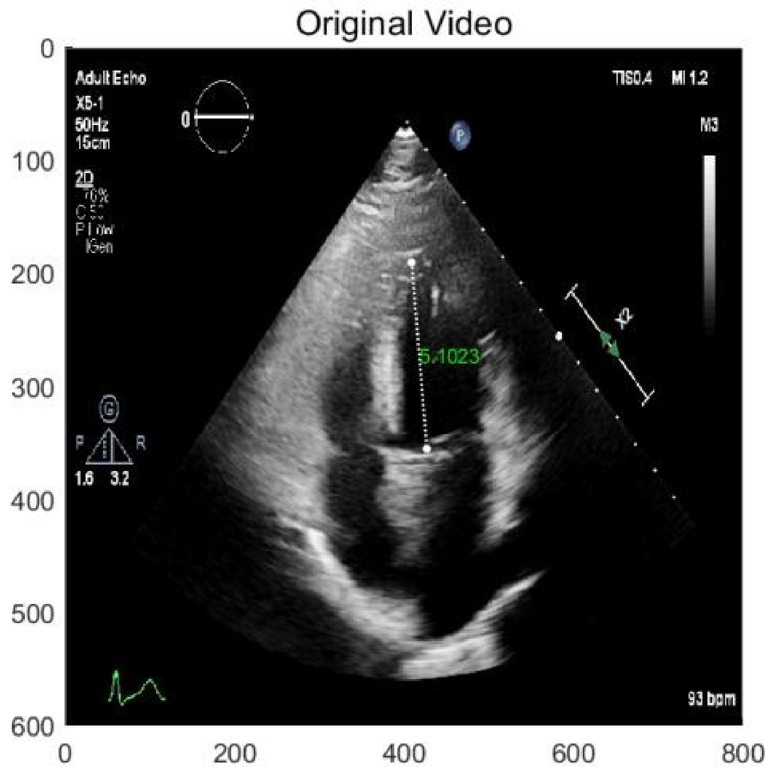
- Click PLAY to have a look of the whole video.
- Drag the progress bar to select the ED frame
- Adjust the two points (X-1, Y-1) and (X-2, Y2), you can get the distance between them (The edge detection here is just to help you know the edge)
- Click "SAVE as ED", if you want to save



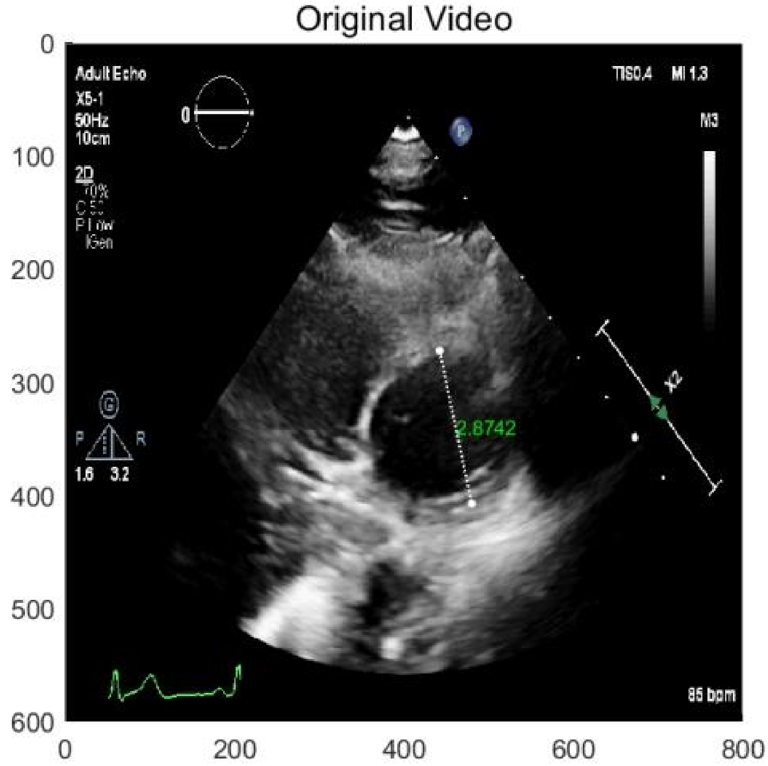
Apical4ch_ED



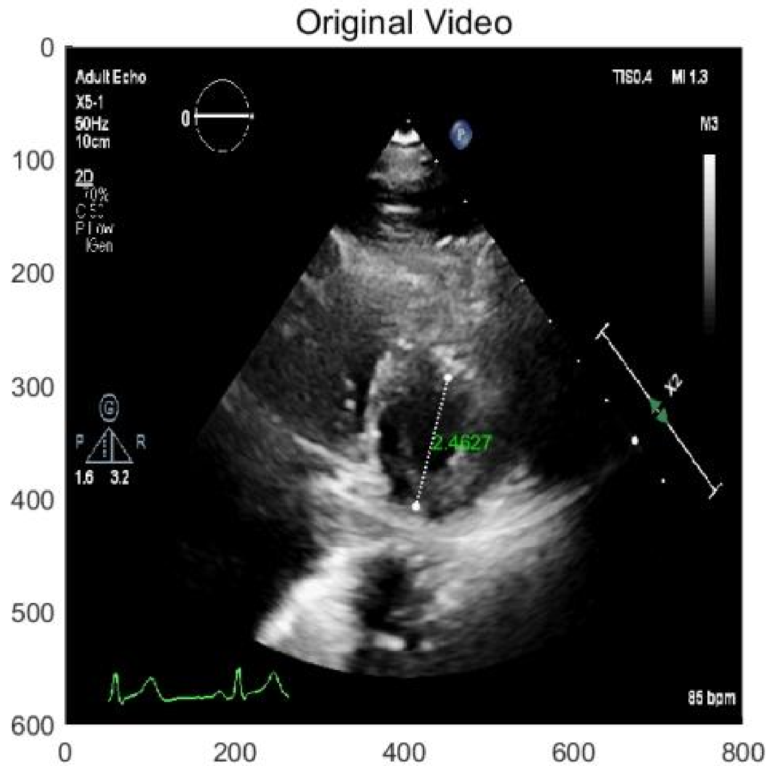
Apical4ch_ES



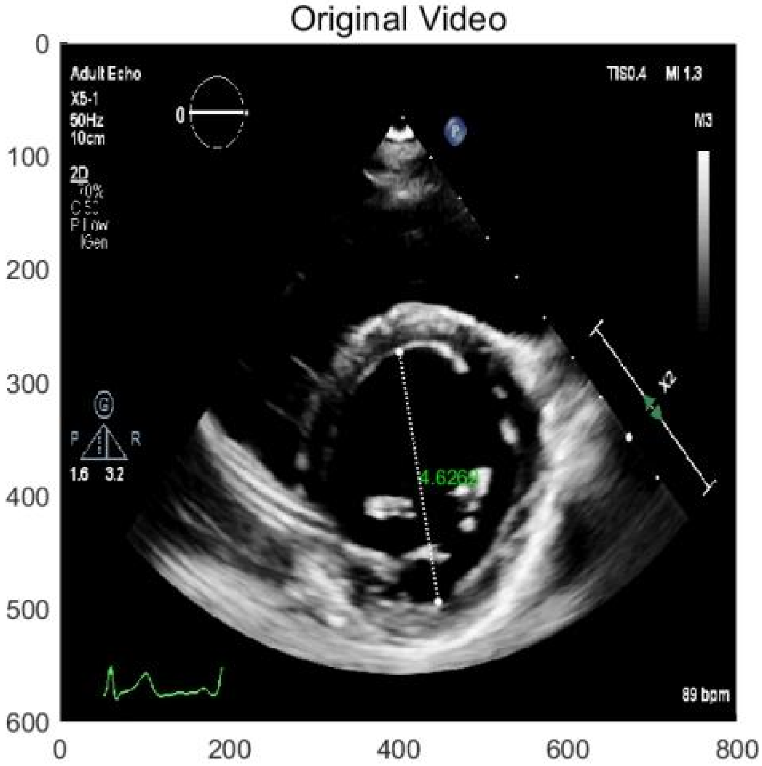
ShortAxis_Apex_ED



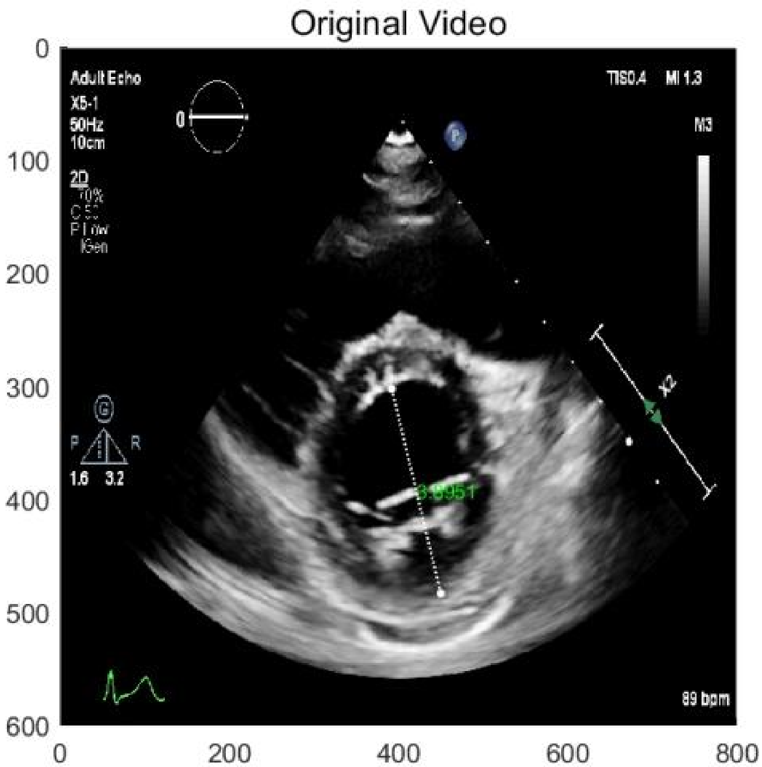
ShortAxis_Apex_ES



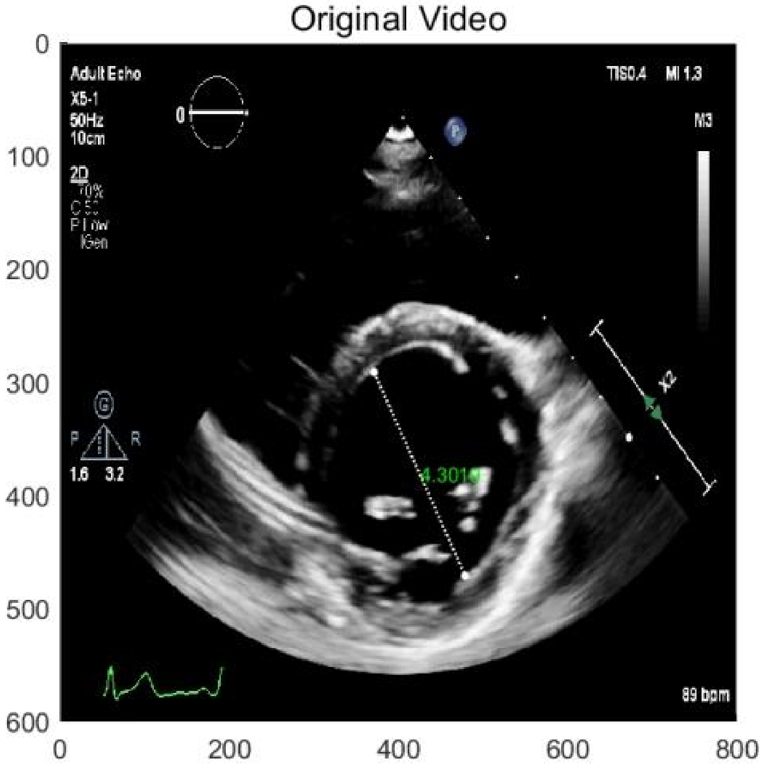
ShortAxis_MitralValve_ED



ShortAxis_MitralValve_ES



ShortAxis_Pap_ED



ShortAxis_Pap_ES