Semi-automated Assessment of Left Ventricular Volume through 2D Echocardiographic Images using a Tissue-mimicking Phantom

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Abstract

Left ventricular (LV) volume is an important index for a wide range of cardiovascular diseases. In clinical assessment, echocardiography is one of the most frequently used imaging modalities. The aim of this study was to investigate the accuracy of the LV volume quantification through echo images based on a laboratory phantom with known volume.

A tissue-mimicking phantom with the same ultrasound property as human blood and soft tissue was developed. It is considered to be a good reference for evaluating the accuracy of a semi-automated technique for LV volume measurement through 2D echo images. The volume measured by the semi-automated technique was compared with the theoretical volume and manual measured volume.

The results showed a significant underestimation of the phantom volume when compared with the known volume: bias with known volume: -2.77ml (P=0.03); bias with manual measurement: -2.87ml (P=0.03).

1. Introduction

Accurate quantification of left ventricular (LV) volumes and function is an important issue for clinical assessment and therapy selection of patients with cardiovascular diseases [1, 2]. Echocardiography is the most widely used imaging modality in the clinical diagnosis of LV function abnormalities. A lot of effort has been invested into developing efficient and accurate semi-automated or automated imaging analysis techniques for LV volume quantification through 2D or 3D echo images [3-5].

To investigate the accuracy of the LV volume measurement in echo images, laboratory phantoms with known dimension and volumes are frequently used as references, such as a water-filled latex balloon [6, 7]. However, the ultrasound propagation speed in these laboratory phantoms varies due to the different materials used. They are normally different from the default ultrasound speed in clinical echocardiography of 1540 m/s, which is the average ultrasound speed in the human soft tissue and blood, resulting in the difficulties of technique assessment and comparison.

In this study, we aimed to assess the accuracy of a semi-automated volume quantification technique through 2D echocardiographic images using a tissue-mimicking phantom, produced with a special-made material which provided the same ultrasound property as human blood and soft tissue.

2. Methods

2.1. Phantom production

The detailed method and procedure of production of tissue-mimicking material with the ultrasound speed of 1540m/s was described in a paper published by Madsen et al [8]. The finial phantom is shown in Figure 1. It was designed to have a semiellipsoidal shape, which is a simplification of human heart left ventricle.

The phantom is hollow (Figure 1, down). The volume of the phantom chamber is 33.58ml. The equatorial radius are both 20 mm (along the x and y axes), and the polar radius is 40 mm (along the z axis). Since the mould (Figure 1, up) was produced by a CNC (computer numerical control) lathe system, the geometry and the volume of the phantom was very accurately controlled.

2.2. Imaging acquisition

The phantom was submerged into the saline water in a tank. The salt concentration of the saline water was 48 g/l. With this concentration, the speed of ultrasound in the saline water is 1540m/s at room temperature, which is the same as human blood.

Six short axis 2D echo images were then acquired by a conventional real time 2D echocardiography. The transducer was positioned at 2.5mm, 7.5mm, 12.5mm, 17.5mm, 22.5mm and 27.5mm along the z axis of the phantom from its apex to base (Figure 2). The slice thickness is 5mm.

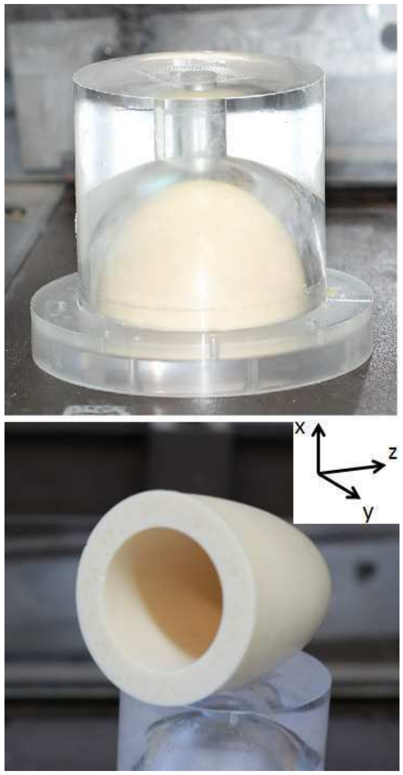

Figure 1. Pictures of the tissue-mimicking phantom with semiellipsoidal shape, which is a simplification of the human heart left ventricle.

Because it was very difficult to position the transducer at the exactly precise height of the z-axis, the manual volume measurement was used as a confirmation. For each captured 2D image, the phantom inner wall border was delineated manually by the implemented software of the echocardiography. Then, the phantom chamber volume of each slice was calculated by this delineation.

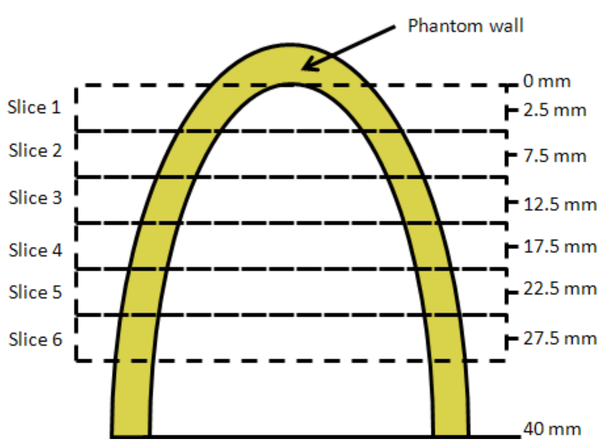

Figure 2. Illustration of the transducer positions to acquire different echo images. Six short axis slices were acquired at 2.5mm, 7.5mm, 12.5mm, 17.5mm, 22.5mm and 27.5mm along the z axis of the phantom from its apex to base by the echo transducer. Slice thickness: 5mm.

Since the phantom geometry was well controlled, the theoretical volume of each slice was known. Therefore, the position of the transducer can be confirmed by comparing the manually measured volumes with the theoretical volumes.

Table 1 shows the theoretical volume and manually measured volume of each slice. Since their differences at all the slices are very small, it confirms that the transducer was positioned correctly.

Table 1. The theoretical volume and manually measured volume of each acquired slice.

		Volume (ml)		
Slice	Height(mm)	Theoretical	Manual	Bias
1	2.50	0.76	0.77	0.01
2	7.50	2.14	2.13	-0.01
3	12.50	3.31	3.34	0.03
4	17.50	4.30	4.29	-0.01
5	22.50	5.08	5.12	0.04
6	27.50	5.67	5.71	0.04

2.3. Semi-automated imaging analysis

A semi-automated analysis was performed on the six short axis slices. To trace the phantom inner wall border automatically, three slices (slice at 2.5mm, 12.5mm and 27.5mm along the z axis) were selected for initialization. One point inside the phantom chamber and one point inside the phantom wall were selected for each of them, so that the region of interest (ROI) was established automatically in all slices.

A 5×5 first order derivative Macleod operator was applied to each slice, and original intensity images were transferred to edge enhanced gradient images. After that, a threshold was used to eliminate the small edges caused by noise.

A border detection technique was employed to trace the phantom inner wall borders in each slice. It sought intensity changes in the gradient images along 120 radial lines from a point inside the chamber towards the phantom wall with three degree intervals. For each radial line, it considered the steepest edge in the gradient image, as the phantom inner wall border.

After the delineation of the wall borders of a 2D slice, the area of the phantom chamber in the slice was calculated by counting the number of pixels inside the chamber. Then the volume = area×wall thickness (5mm).

The measured slice volumes of the semi-automated technique were compared with the phantom theoretical slice volumes and manually measured slice volumes. The paired Student t test was used to investigate whether the differences were significant.

3. Results

Figure 3 shows the volume of every slice given by theoretical calculation, manual measurement and semi-automated measurement respectively. Since the manual measurement was used as a confirmation for mechanically positioning the echo transducer, the curves of the theoretical and manual almost overlapped. However, there was a systematic volume underestimation from the semi-automated measurement.

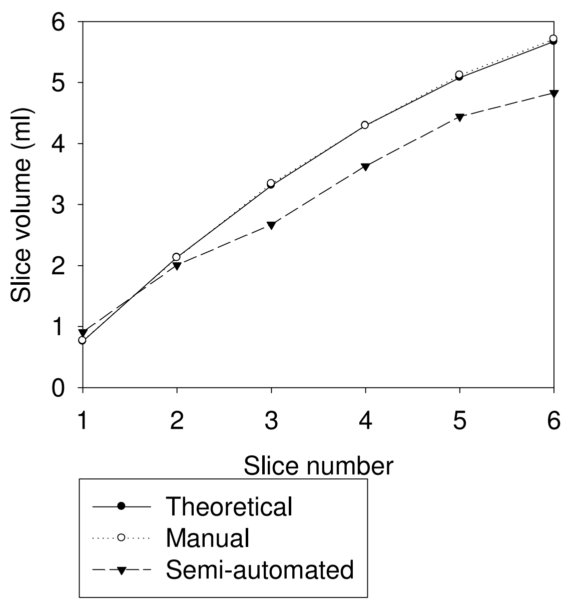

Figure 3. Comparison of the theoretical slice volumes, manually measured slice volumes and the semi-automated measured slice volumes. The theoretical and manual volumes overlap.

Table 2. The volume of each slice measured by the semi-automated algorithm, and the slice volume difference between semi-automated measurement and theoretical calculation or manual measurement respectively

	Volume (ml)		
Slice	Semi auto	Semi auto - Theoretical	Semi auto - Manual
1	0.91	0.15	0.14
2	2.01	-0.13	-0.12
3	2.67	-0.64	-0.67
4	3.63	-0.66	-0.66
5	4.44	-0.64	-0.68
6	4.83	-0.84	-0.88
summation	18.49	-2.77	-2.87

The slice volumes measured by the semi-automated technique are listed in Table 2. When compared with the theoretical and manually measured slice volumes, the volume from the semi-automated technique was significantly underestimated by 2.77ml and 2.87ml respectively (both P=0.03)

Figure 4 and Figure 5 show the slice volume difference between semi-automated measurement and theoretical calculation, and the difference between semi-automated and manual measurement. As the transducer moves from phantom apex to base (from slice 1 to 6), with bigger slice volume, the underestimation of the volume from the semi-automated technique increased.

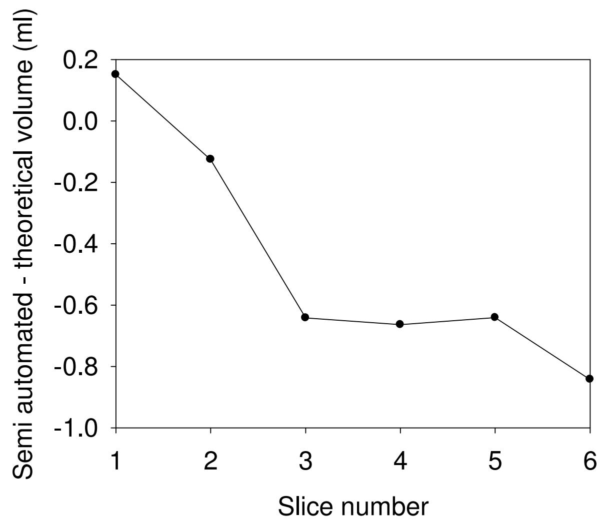

Figure 4. The slice volume differences between semi-automated measurement and theoretical calculation.

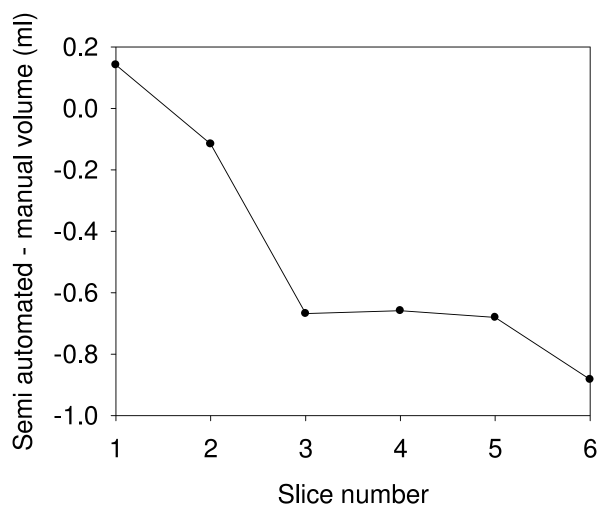

Figure 5. The slice volume difference between semi-automated measurement and manual measurement.

4. Discussion and conclusion

A laboratory phantom can provide a well controlled reference for volume quantification. However, many of the phantom studies for echocardiographic imaging quantification have not considered the difference of the ultrasound property, especially the ultrasound speed, in different materials.

Using the default setting for clinical echocardiography measurement to scan such phantoms, the echo images would present geometry distortion. This normally leads to a systematic bias of the compassion between measured volume and known phantom volume.

In this study, the phantom material was specially made from ingredients in a published study, which provided the ultrasound propagation speed as 1540 m/s [8]. Besides that, the phantom was filled with saline water with controlled concentration, so that the ultrasound speed in it was also 1540 m/s. Besides that, the mould for producing the phantom was cut by a CNC lathe system, thus the dimension and geometry of the phantom was very precisely controlled. All these efforts were to make sure that the reference was good and accurate enough for a comparison of phantom volume quantification through echocardiographic images.

One of the limitations of this study is the imaging acquisition. Practically, it is very difficult to put the echo transducer at the correct height next to the phantom (2.5mm, 7.5mm…along the z-axis of the phantom from the apex to base). However, in this study, the position of the transducer was confirmed by additional manual measurements. In the future, a precise mechanical system needs to be designed, which can hold the transducer horizontally, and move it vertically with accurate control.

The final results showed a significant underestimation of the phantom volume from semi-automated measurement, which may be caused by the imaging quality and the drawbacks of the semi-automated imaging analysis technique.

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