Left Ventricular Volumes from Three-Dimensional Echocardiography by Rapid Freehand Scanning using Digital Scan Line Data

Stig A. Slørdahl, MD, PhD, Sevald Berg, MSc, Asbjørn Støylen*, MD, Stein Samstad, MD, PhD and Hans Torp, PhD

Department of Physiology and Biomedical Engineering, Norwegian University of Science and Technology, Trondheim, Norway

**Department of Cardiology, University Hospital of Trondheim, Norwegian University of Science and Technology, Trondheim, Norway*

SUMMARY

We present a new rapid method using digital scan line data for 3D cardiac reconstruction. The ultrasound scanner was equipped with a magnetic position locating device and the digital data were transferred before scan conversion. The probe position data were captured continuously while freely tilting the probe from an apical position in held end-expiration. The left ventricle was reconstructed from the digital data. The volumes were estimated from short axis images using long axis images as guidance for border detection. The accuracy of the method was tested in phantoms. Stroke volumes estimated from 3D data were compared with stroke volumes estimated from LV outflow tract Doppler velocity time integral and area, and stroke volumes from a modified biplane Simpson's method in 7 normal subjects. The estimated phantom volumes (range 161.2- 601.4 ml) were close to true volumes with a mean difference ± SD of -2.5 ± 5.0 ml (n=24). The mean difference between the estimated 3D stroke volumes and stroke volumes from LV outflow tract was -10.7 ± 12.6 ml. The mean difference between the estimated 3D stroke volume and a biplane Simpson's method was -13.1 ± 11.8 ml.

Address for correspondence:

Stig A. Slørdahl, Department of Physiology and Biomedical Engineering, NTNU, 7005 Trondheim, Norway

Phone: -47 73 59 86 18 Fax: -47 73 59 86 13 Email: stig.slordahl@medisin.ntnu.no

Previous investigations have demonstrated that three-dimensional echocardiography improves the accuracy and reproducibility of estimates of left ventricular volume and mass (1-3). However, three-dimensional cardiac reconstructions have been limited by such factors as using video quality images, lengthy image acquisition times, limited acoustic windows, respiratory gating, and assumptions of left ventricular shape. The purpose of this study was to estimate left ventricular volumes from a new freehand scanning method using digital scan line data obtained with a frame rate of 50-100 frames per second and to validate the method in phantoms. Left ventricular stroke volumes were estimated in 7 healthy subjects and compared with two different echocardiographic methods.

METHODS

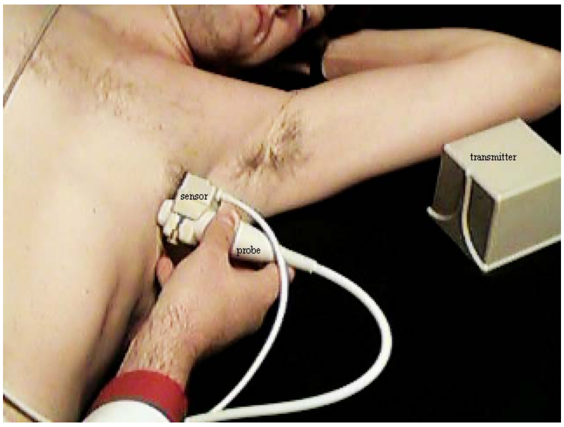

Figure 1 The photo shows the ultrasound probe with the magnetic position locating device. The sensor is mounted on the probe while the transmitter is placed 25-60 cm from the sensor.

Imaging technique

An ultrasound scanner (System Five, GE Vingmed Ultrasound, Horten, Norway) with a 2.5 MHz phased array transducer and equipped with a magnetic position locating device (Ascension Technology Flock of Birds, USA) was used for all ultrasound imaging. The magnetic position locating device consisted of a transmitter which generated a magnetic field and this device was placed 25-60 cm from the sensor which was mounted directly on the ultrasound probe (Fig 1). The position of the sensor was recorded by the control unit and the spatial position of each recorded frame was stored in the digital replay memory of the scanner together with the corresponding frame. The sensor position coordinates, the digital ultrasound images and the ECG signal were captured continuously while freely tilting the probe from an apical position in held end-expiration (Fig 2). The accuracy of the Bird position sensor system is earlier found to be around 1 mm (1), so the reconstruction errors were smaller than the ultrasound beam resolution. The digital scan line data were transferred to an external computer from the scanner before scan conversion. The 2D scan plane resolution was up to 512 samples for each beam and there was up to 128 beams. The total number of frames depended on the frame rate and the total acquisition time. Typically 15-20 heart cycles were recorded covering almost completely the left ventricle. All the 2D echocardiograms were done in the second harmonic mode.

a

b

c

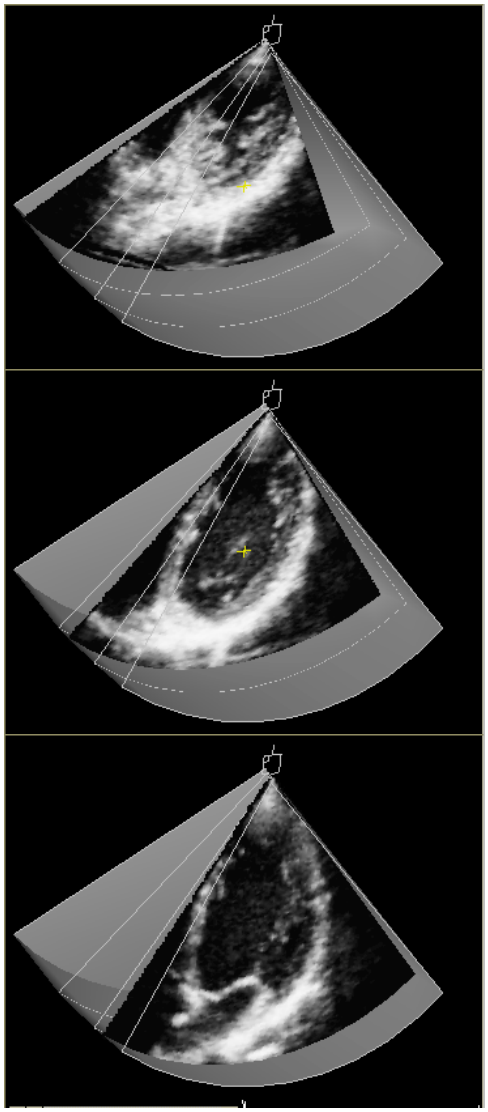

Figure 2 These three ultrasound images demonstrates the tilting procedure starting in the wall of one side of the ventricle (a) and slowly tilting the probe towards the other side (b-c).

Volume reconstruction
The data were reorganized and scan converted into regular geometries and visualized using a modified version of the EchoPAC-3D software (GE Vingmed Ultrasound, Horten, Norway) . The R wave in the QRS complex from ECG was the trigger point for determining the position of the frames in the heart cycle. The individual frames were reorganized so that each frame located at the same position relative to the trigger point was combined into one unit. Since the duration of each cardiac cycle was not constant, the number of 3D volumes depended on the length of the minimal cardiac cycle and recorded frames outside this range were disregarded. The starting point for a cardiac cycle was defined right before the P wave of the ECG. The probe was tilted in a fan-like manner during the examination, and the pace of this motion and the heart rate decided the sampling density for each volume. Then all the beam samples were scan converted into a grid of voxels for conversion of each volume into a regular geometry. Interpolations were done in areas of no data. After volume reconstruction one could interactively browse the ultrasound volumes by selecting individual frames and time positions and display cineloops through the heart cycle.

Volume estimation
Using manual segmentation in consecutive, parallel cross-sectional slices, a volume was built up by a triangulation process (4). The contours defining the margins of the left ventricular wall were drawn in the images perpendicular to the long axis images (short axis). Eight to ten short axis images were used to calculate the volumes, beginning at the level of the mitral valve and the last level was at apex. There was no predetermined distance between the levels, but the levels were approximately equally distributed. Figure 3 demonstrates how the margins of the left ventricle were defined in end diastole and end systole. First we traced some long axis views as a guidance to define apex and the length of the left ventricle (red color). These contours were also shown in the short axis images which were traced (green color) for volume estimation.

Phantoms
Six water-filled balloons with different volumes (161.2- 601.4 ml) were immersed in a water tank kept at 33 degrees Celsius and adjustments were made to allow for ultrasound velocity in water at this temperature. The traces were outlined in the center of the balloon edge. The shape of the balloons was different in each case. Two investigators estimated the volumes twice in order to assess inter-observer and intra-observer variability. The range of volume estimates from these four calculations were used in the comparison with the measured volumes.

Study subjects
Seven healthy and physically active male volunteers (mean body surface area 1.96 m^2) without any evidence of cardiac disorders were studied. All volunteers were in normal sinus rhythm and gave informed consent to participate in the study.

2D volumes
Stroke volumes estimated from 3D data were compared with two different echocardiographic methods. In the first method the stroke volume was estimated from Doppler flow velocity time integral in the left ventricular outflow tract and the subvalvular diameter assuming a circular outflow tract (5). In the second method the stroke volume was estimated from a modified biplane Simpson's method using an apical four chamber view and an apical long axis view(6). It was not the same ultrasound images that were used in estimating the volumes from the 3D data and from the biplane Simpson's method. A cardiologist blinded for the 3D results did the 2D measurements.

Statistics
All mean values are given ± the standard deviation. In order to compare the different methods in estimating volumes the lack of agreement was summarized by calculating the bias estimated by the mean difference and the standard deviation of the differences. Inter-observer and intra-observer variability is reported similarly as mean difference and the standard deviation of the differences between two observers and between two estimations of the same observers.

RESULTS

Phantoms
There was an excellent agreement between measured phantom volumes and estimated volumes from the three-dimensional reconstruction (Tab 1). The mean difference between the estimated volumes and the true volumes was –2.5 ± 5.0 ml (n=24), while mean percentage error was -0.9 ± 1.6 %. The root mean square percent error was 1.8%. The mean difference between two observers was -

1.1 ± 7.3 ml (inter-observer variability) and the mean difference between two estimations by the same observer was -2.0 ± 7.2 ml (intra-observer variability).

Table 1 The true phantom volumes and the range estimated from the new three-dimensional echocardiographic method (n=4) with the percentage error of the estimates.

True volume ml	Estimated ml range	% error range
161.2	155.9- 164.2	-3.3- 1.8
239.8	225.4- 239.1	-6.0- -0.3
414.9	414.2- 417.2	-0.2- 0.5
257.0	253- 255.2	-1.6- -0.7
372.0	365.2- 373	-1.8- 0.3
601.4	583.6- 603.5	-3.0- 0.3

Stroke volumes

The mean end-diastolic volume of the left ventricle in the healthy subjects was 120.7 ± 16.4 ml and the mean end-systolic volume was 59.7 ± 9.6 ml estimated from the three-dimensional reconstructions (Tab 2). The mean end-diastolic volume calculated from The Simpson's method was 148.4 ± 17.4 ml , and the mean end-systolic volume was 74.3 ± 10.8 ml . The mean difference between estimated three-dimensional stroke volumes and stroke volumes from left ventricular outflow tract was -10.7 ± 12.6 ml. The mean difference between the estimated three-dimensional stroke volume and a biplane Simpson's method was -13.1 ± 11.8 ml.

Table 2 The left ventricular stroke volumes (end distolic volume/ end systolic volume) estimated from the three different methods in the seven study subjects.All measurements in ml.

3 D method	Doppler method	Simpson's method
58.4 (100.4/42.0)	68.6	67.4 (135.5/68.1)
61.8 (120.7/58.9)	70.8	86.9 (155.3/68.4)
82.3 (150.9/68.6)	67.7	75.0 (152.9/77.9)
57.1 (116.0/58.9)	66.8	63.1 (141.0/77.9)
52.2 (106.1/53.9)	67.2	70.3 (135.3/65.0)
60.9 (128.6/67.7)	82.7	87.4 (183.1/95.7)
54.3 (122.0/67.7)	78.0	68.8 (135.7/66.9)

DISCUSSION

This study demonstrates that left ventricular volumes can be calculated from three-dimensional echocardiography using a new rapid freehand scanning method and that the method is reliable in phantoms. Although the three-dimensional method gave similar volume results as the routine two-dimensional method, the three-dimensional assessment has several advantages. The method reduces the possibility of errors due to regional dysfunction or asymmetry of the left ventricle. The method also makes it possible to optimize the acoustic window and reduce the possibility of dropouts when using two standardized views. As expected, the advantages of the method will be of less importance in healthy young subjects with symmetrical ventricles. Since the method is using digital scan line data, the temporal resolution in the 3D data is equal to the resolution in the original 2D data. This reduces the reconstruction error due to the lack of synchronization between the ECG and the scanner frame sampling. Therefore, the method is superior to systems using video quality images. The high spatial and temporal resolution of the images of this system will be even more important in studying structures like the heart valves and flow.

This new method has several advantages compared with other 3D methods. The position sensor is attached to the probe and 3D acquisition is obtained without any further interaction. This enables the use of an optimal acoustic window during acquisition since the probe can be moved freely. It takes less than one minute to reconstruct all volumes and start analysis when the data has been transferred to the computer. The image acquisition time is only seconds since a complete scan of the left ventricle is obtained by 15-20 cardiac cycles, while the acquisition using a probe with a rotating stepper motor takes more than three minutes. Image acquisition time and the volume reconstruction time is also shorter than two other freehand three-dimensional methods published recently (3,7). Currently, the time consuming part of this system besides tracing the margins of the left ventricle, is the data transfer from the ultrasound scanner to the computer which takes 3-5 minutes.

The difficult part in estimating volumes is often to define the margins of the left ventricle in the echocardiographic images. We have earlier shown that by using a biplane method in calculating ventricular volumes by magnetic resonance imaging, it was easier to define the margins when the contour in the long axis image was also plotted automatically in the short axis images where it intersected these, and vice versa (8). Similarly, we were in this study defining the margins in the short axis images, but we used the long axis images to define the length of the left ventricle. The contours in the long-axis images could also be seen in the short axis images (Fig 3). Tracing the margins of the left ventricle is a time consuming procedure of about ten minutes, but better image quality by using digital scan line data makes it easier.

A problem in validating the accuracy in estimated ventricular volumes in humans, is the lack of a gold standard. Magnetic resonance imaging is one of the reference standards for end-systolic and end-diastolic volumes and could have been a better validation of our ventricular volume estimates in the healthy subjects. However, we chose to compare our stroke volumes with two other echocardiographic methods which are used by several groups and which is easier accessible than magnetic resonance imaging . A biplane Simpson's method is in principle a three-dimensional method which one would expect could give similar results as the new three-dimensional method. On the other hand, the echocardiographic method using Doppler recordings is based completely on another approach using velocity and area as input in the calculation. Even though the Doppler method is an acceptable reference standard for stroke volumes, the method can not be said to constitute a validation of the three-dimensional method, but the results show that the methods are comparable as shown by the results. The good agreement between the three methods in the study subjects therefore indicates that the new three-dimensional method is feasible for estimating ventricular volumes.

SUMMARY

A new rapid freehand method using digital scan line data from three-dimensional echocardiography was validated in phantoms and left ventricular stroke volumes were estimated in normal subjects and compared with two standard echocardiographic methods. The results showed that the method was very accurate in estimating the volumes in the phantoms and that the agreement between the three methods in the study subjects were acceptable.

REFERENCES

1. Leotta DF, Munt B, Bolson EL, Kraft C, Martin RW, Otto CM, Sheehan FH. Quantitative three-dimensional echocardiography by rapid imaging from multiple transthoracic windows: in vitro validation and in vivo studies. J Am Soc Echocardiogr 1997;10:830-39.
2. Kupferwasser I, Mohr-Kahaly S, Stähr P, Rupprecht H-J, Nixdorff U, Fenster M, Voigtländer T, Erbel R, Meyer J. Transthoracic three-dimensional echocardiographic volumetry of distorted left ventricles using rotational scanning. J Am Soc Echocardiogr 1997;10:840-52.
3. Gopal AS, Schnellbaecher MJ, Shen Z, Boxt LM, Katz J, King DL. Freehand three-dimensional echocardiography for determination of left ventricular volume and mass in patients with abnormal ventricles: comparison with magnetic resonance imaging. J Am Soc Echocardiogr 1997;10:853-61.
4. Thune N, Gilja OH, Hausken T, Matre K. A practical method for estimating enclosed volumes using 3D ultrasound. European J of Ultrasound 1996;3:83-92
5. Skjaerpe T, Hegrenaes L, Ihlen H. Cardiac output In: Hatle L, Angelsen B, eds. Doppler ultrasound in cardiology. 2nd ed. Philadelphia: Lea and Febiger, 1985: 306-320.
6. Feigenbaum H. Echocardiographic evaluation of cardiac chambers. In Echocardiography. 5th ed. Philadelphia: Lea and Febiger, 1994: 134- 180.
7. Barry CD, Allott CP, John NW, Mellor PM, Arundel PA, Thomson DS, Waterton JC. Three-dimensional freehand ultrasound: image reconstruction and volume analysis. Ultrasound Med Biol 1997;23:1209-1224.
8. Slørdahl SA, Myrheim J, Kværness J, Piene H, Rinck PA. Left and right ventricular volumes by magnetic resonance imaging from a new biplane method. Cardiovasc Imag 1994;6:123-128.

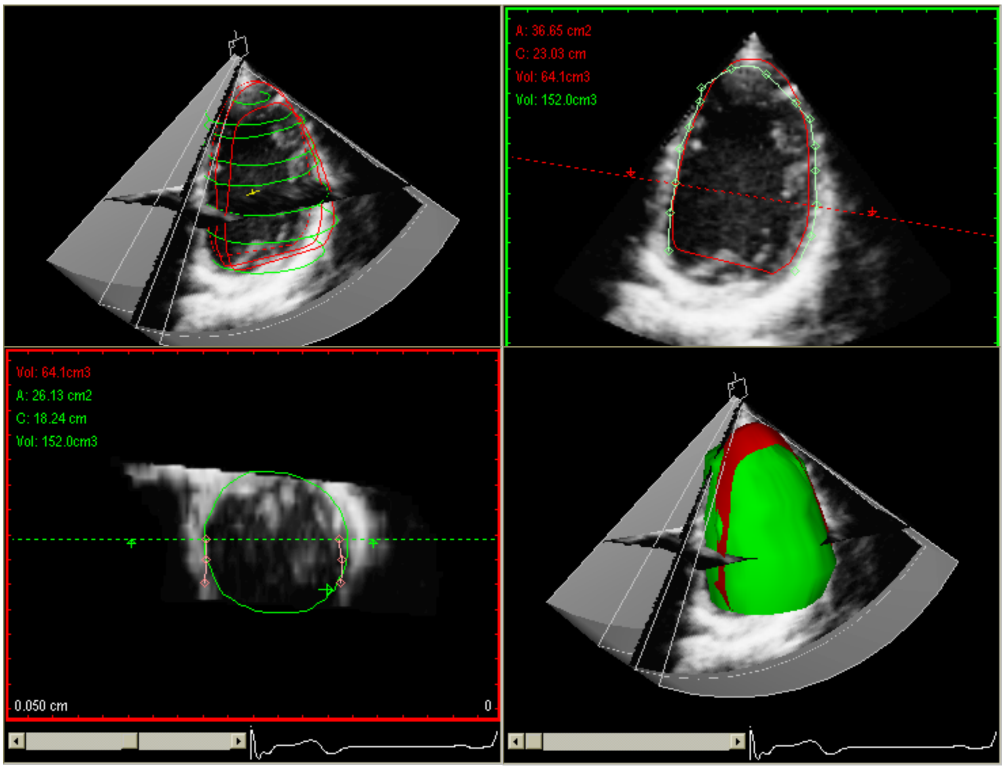

Figure 3 a These four images demonstrates the defining of the margins of the left ventricle in end diastole. First we traced some long axis views seen in red as a guidance to define apex and the length of the ventricle, but the volumes were estimated from the short axis views seen in green.

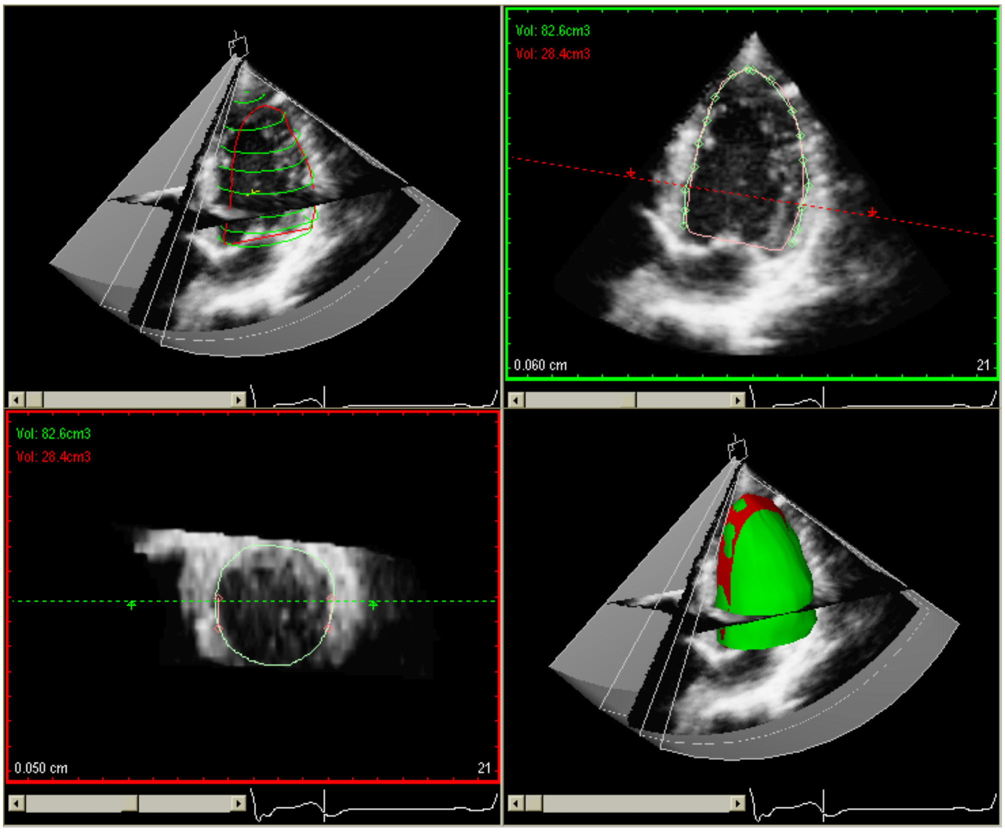

Figure 3b These four images demonstrates the defining of the margins of the left ventricle in end systole. The same procedure was done in end systole as in end diastole (3a)