Rapid freehand scanning three-dimensional echocardiography : Accurate measurement of left ventricular volumes and ejection fraction compared with quantitative gated scintigraphy

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博　士　論　文

Rapid Freehand Scanning Three-Dimensional Echocardiography:
Accurate Measurement of Left Ventricular Volumes and Ejection Fraction Compared With Quantitative Gated Scintigraphy

(和訳)

フリーハンド・スキャン３次元心エコー法による左室容量および駆出率計測の精度の検討：心電図同期心筋 SPECT (QGS) との比較検討 に関する研究

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神戸大学大学院医学系研究科保健学専攻

川井　順一

Rapid Freehand Scanning Three-Dimensional Echocardiography: Accurate Measurement of Left Ventricular Volumes and Ejection Fraction Compared With Quantitative Gated Scintigraphy

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This study was performed to assess clinical feasibility of rapid freehand scanning 3-dimensional echocardiography (3DE) for measuring left ventricular (LV) end-diastolic and -systolic volumes and ejection fraction using quantitative gated myocardial perfusion single photon emission computed tomography as the reference standard. We performed transthoracic 2-dimensional echocardiography and magnetic freehand 3DE using a harmonic imaging system in 15 patients. Data sets (3DE) were collected by slowly tilting the probe (fan-like scanning) in the apical position. The 3DE data were recorded in 10 to 20 seconds, and the analysis was performed within 2 minutes after transferring the raw digital ultrasound data from the scanner. For LV end-diastolic and -systolic volume measurements, there was a high correlation and good agreement (LV end-diastolic volume, r = 0.94, P < .0001, standard error of the estimates = 21.6 mL, bias = 6.7 mL; LV end-systolic volume, r = 0.96, P < .0001, standard error of the estimates = 14.8 mL, bias = 3.9 mL) between gated single photon emission computed tomography and 3DE. There was an overall underestimation of volumes with greater limits of agreement by 2-dimensional echocardiography. For LV ejection fraction, regression and agreement analysis also demonstrated high precision and accuracy (y = 0.82x + 5.1, r = 0.93, P < .001, standard error of the estimates = 7.6%, bias = 4.0%) by 3DE compared with 2-dimensional echocardiography. Rapid 3DE using a magnetic-field system provides precise and accurate measurements of LV volumes and ejection fraction in human beings (J Am Soc Echocardiogr 2003;16:110-5.)

Three-dimensional (3D) echocardiography (3DE) has demonstrated superior accuracy and reproducibility over conventional 2-dimensional (2D) echocardiography (2DE) for measuring left ventricular (LV) volume, because no geometric assumptions are necessary about LV shape.[1-3] There are several methods for registering multiple 2DE images in 3D space. However, only magnetic-field systems are able to track the position and orientation of a transthoracic scan head during freehand scanning, allowing acquisition of images from randomly oriented image planes.[4] The ultrasound probe is coupled to a sensor that registers the spatial coordinates inside a magnetic field. The introduction of a method for freehand dynamic echocardiographic acquisition and reconstruction using raw digital ultrasound data provides an alternative to preserve high-temporal resolution in the 3D reconstruction.[5]

The purpose of this study was to assess clinical feasibility and the precision and accuracy of this system for measuring LV volumes. Quantitative gated myocardial perfusion single photon emission computed tomography (SPECT) was used as the reference standard.[6,7]

METHODS

Study Participants

We performed a freehand 3DE scanning in patients for whom a standard transthoracic echocardiographic examination and rest technetium-99m methoxy isobutyl isonitile SPECT were clinically indicated. Patients with a variety of LV shapes were considered in an attempt to cover a large range of LV volumes. Exclusion criteria were cardiac arrhythmias, including patients with pacemaker and implantable cardioverter defibrillators. A total of 15 patients (8 men; mean age, 65.2 years [range: 39 to 78

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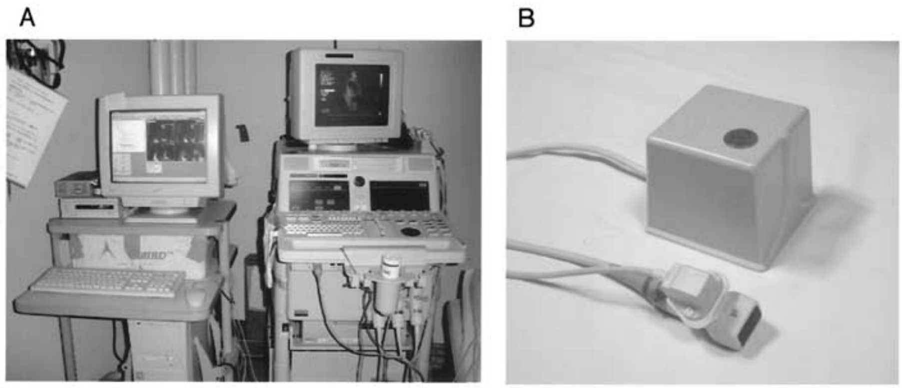

Figure 1 A, Data were acquired using digital ultrasound scanner (*right*). For 3D data processing, personal computer-based 3D freehand system was used (*left*). **B**, Magnetic-field transmitter (*above*) and receiver. Receiver is mounted directly on scan head.

years]) entered the study. Of these, 10 had previous myocardial infarction, 2 had severe mitral regurgitation, 2 had dilated cardiomyopathy, and 1 had hypertrophic cardiomyopathy. All echocardiographic examinations were performed within 24 hours before or after SPECT study and no changes in clinical status occurred during that period. Informed consent was obtained before the study from all patients.

2DE Study

All patients had a complete 2DE and Doppler study. LV end-diastolic volume (EDV) and end-systolic volume (ESV) were measured by using the modified biplane Simpson's rule with the apical 4- and 2-chamber views.[8] The QRS wave from the electrocardiogram (ECG) was used to select the largest volume (ie, LVEDV), and the T wave was used to select smallest volume (ie, LVESV). An experienced sonographer, blinded to clinical and gated SPECT data, measured 2D volumes. The total stroke volume of the LV was calculated as the difference between these volumes. The derived LV ejection fraction (EF) was calculated directly as the ratio of stroke volume to EDV.

3DE Study

The data were acquired using a digital ultrasound scanner (Sonos 5500, Philips, Andover, Mass). For 3D data processing, a personal computer-based 3D freehand system (3D Echotech, Munich, Germany) was used (Figure 1, *A*). The system uses an electromagnetic sensor device. The sensor device consists of an electromagnetic-field transmitter and a field receiver (Figure 1, *B*). The electromagnetic receiver (position sensor) was attached directly to the standard ultrasound probe with the frequency of 1.8/3.6 MHz in harmonic mode. The field transmitter generates an alternating spheric electromagnetic field in a strength of up to 5 times the earth magnetic field depending on the distance between transmitter and receiver. For 3D data acquisition, the ultrasound probe with the attached position sensor can be moved freely in a hemisphere of 60 cm around the transmitter. During data acquisition the electromagnetic sensor device generates, with a frequency of about 100 Hz, a set of 3 translation and 3 angulation values. These values describe the position of the ultrasound probe in space. Simultaneous to the calculation of the position, the images of the ultrasound system are digitized and stored. The acquired ultrasound images are transformed into an isotropic rectangular (Cartesian) coordinate system with the help of the corresponding set of translation and angulation values. All other relevant scanner parameters, including the ECG signal from the patient, were recorded simultaneously. The precision of the system for locating a point target from any direction was tested using a calibration phantom consisting of nylon strings (calibration-operating instructions, 3D Echotech, March 1997).

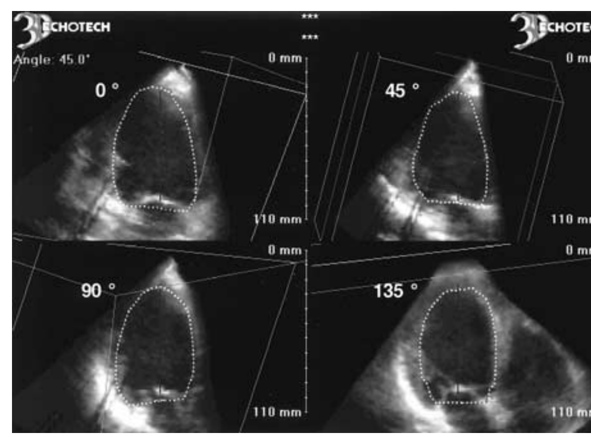

Figure 2 Left-ventricular volume measurement using equally spaced apical 4-plane images (ie, 45-degree increments).

For the data acquisition, the probe was placed apically between 2 ribs and then tilted slowly, covering the whole LV. The pace of this motion and the patient heart rate decided the sampling density for each volume (ie, the distance between the 2D frames). The total recording was done with normal respiration, and typically lasted for 10

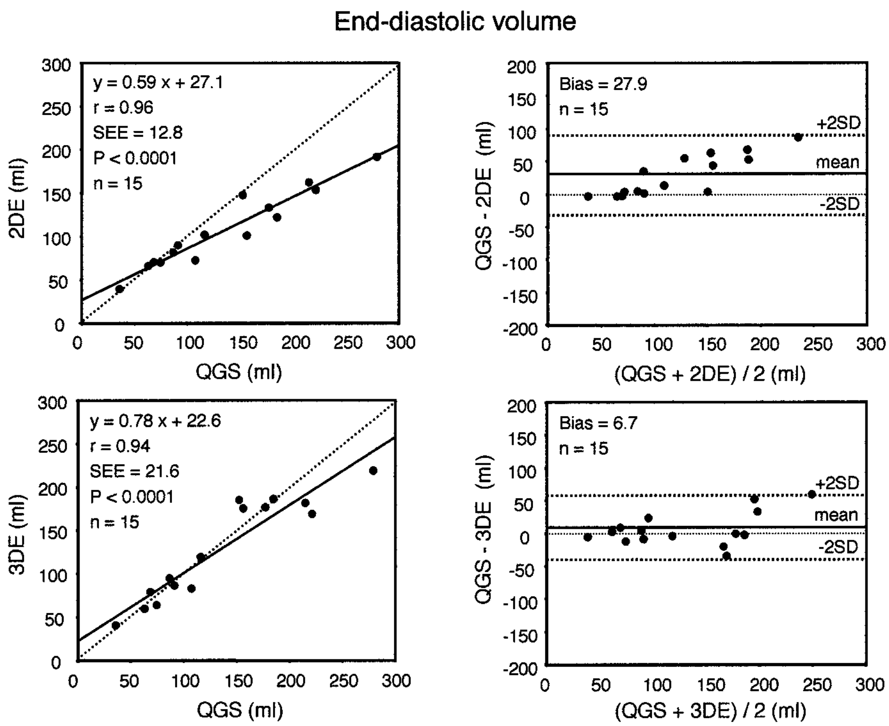

Figure 3 Linear regression analysis (*left*) and limits of agreement analysis (*right*) for left-ventricular end-diastolic volume measurements by 2-dimensional echocardiography (*2DE*) (*upper*) and 3-dimensional echocardiography (*3DE*) (*lower*) compared with gated single photon emission computed tomography (*QGS*). *SEE*, standard error of the estimates.

to 20 cardiac cycles. The data were sampled continuously all the time, so the operator did not have to interact to start a recording. Acquisition was repeated 2 to 3 times to optimize image quality.

Analysis was performed by 2 independent observers. After 3D data sets were transferred to the computer system, the computer displayed rotating radial LV images around a center axis as apical bi-, 4-, 6-, and 9-plane images, respectively. The true long axis was defined in the reconstructed cross-section showing the maximal distance from mitral annulus to apex. Using equally spaced apical 4-plane images (ie, 45-degree increments), LV endocardial borders were manually traced, including the LV outflow tract up to the aortic valve (Figure 2). The mitral valve plane was traced as the straight line between the boundaries of the mitral annulus. The LV volume was calculated using the multiplanar Simpson's method. The QRS wave from the ECG was used to select the largest volume (ie, LVEDV), and the T wave was used to select smallest volume (ie, LVESV), from which EF was calculated.

Gated SPECT Study

A single dose of technetium-99m methoxy isobutyl isonitile (600 MBq) was administered intravenously at rest. ECG gated myocardial SPECT was initiated 60 minutes after tracer injection. Data acquisition was performed with a 2-headed SPECT system (GE Medical Systems, Haifa, Israel) with a low-energy high-resolution collimator. Acquisition was performed using a total of 60 projections of 40 heart beats duration at 3-degree steps. LV volumes were calculated from the gated SPECT images using previously validated and commercially available automated software (Quantitative gated SPECT, QGS, Cedars-Sinai Medical Center, Los Angeles, Calif).[6]

Statistical Analysis

All values of the LV and EF measurements were expressed as mean ± SD. To assess precision, LV volumes estimated from 3DE by 2 independent observers (J.K., K.T.) were averaged and compared with those measured with gated SPECT by linear regression. Interobserver variability was expressed as the coefficient of variation between the 2 observers. To determine whether the difference in the values between the 2 methods was statistically significant, a paired *t* test was performed; the level of significance was set to $P < .05$. The bias was expressed as the mean difference between the 2 methods, and the limits of agreement as 2 SDs of the difference of the 2 methods.[9]

RESULTS

LV volumes and EF determined with gated SPECT were as follows: EDV ranged from 35.8 to 279.0 mL (135.1 ± 69.8 mL), ESV ranged from 3.8 to 236.0 mL (80.1 ± 67.6 mL), and EF ranged from 15.4 to 89.4% (49.5 ± 22.1%).

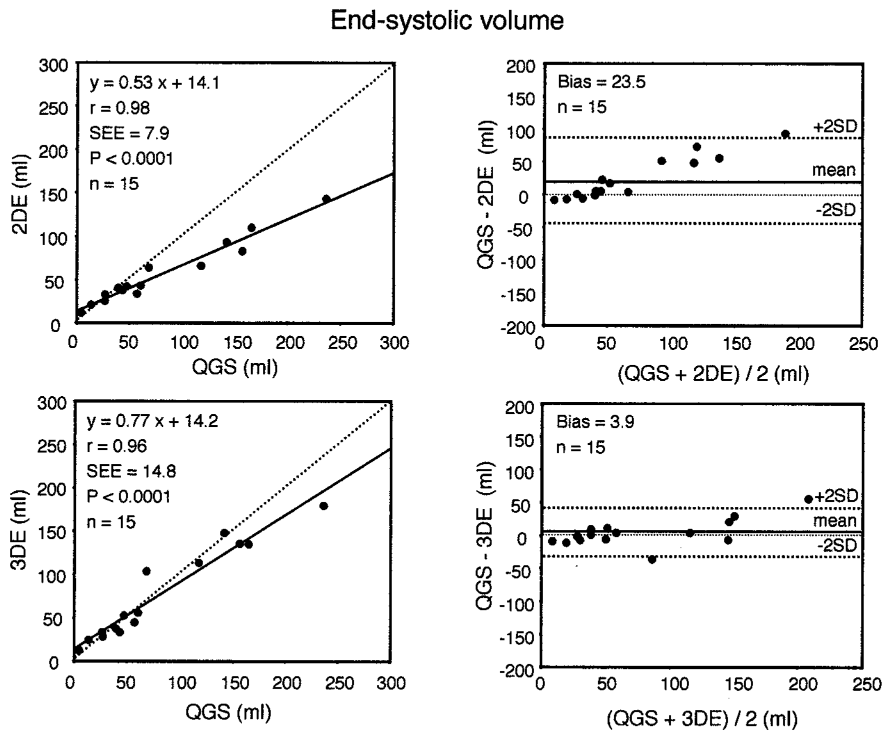

Figure 4 Linear regression analysis (*left*) and limits of agreement analysis (*right*) for left-ventricular end-systolic volume measurements by 2-dimensional echocardiography (*2DE*) (*upper*) and 3-dimensional echocardiography (*3DE*) (*lower*) compared with gated single photon emission computed tomography (*QGS*). *SEE*, standard error of the estimates.

The 3D data were recorded in 10 to 20 seconds, and the analysis was performed within 2 minutes after transferring the raw digital ultrasound data from the scanner. In the estimation of the LVEDV and LVESV values by 3D method, interobserver variability was 7.4% and 5.6%, respectively. Regression analysis and Bland-Altman plots for LVEDV and LVESV measurements are shown in Figures 3 and 4. Linear regression indicated a high correlation (r = 0.94, $P < .0001$ for LVEDV; and r = 0.96, $P < .0001$ for LVESV) between gated SPECT and 3D method, with standard error of estimates (SEE) of 21.6 mL for LVEDV and 14.8 mL for LVESV. The limits of agreement analysis demonstrated minimal mean differences (bias, 6.7 mL for LVEDV and 3.9 mL for LVESV). The 2D method also showed similar correlations with gated SPECT for LVEDV and LVESV (r = 0.96 and 0.98, respectively) with a SEE of 12.8 and 7.9 mL, respectively. There was an overall underestimation of volumes with greater limits of agreement by 2D method.

The results of LVEF regression and agreement analysis, which are shown in Figure 5, demonstrated high precision and accuracy (y = 0.82x + 5.1, r = 0.93, $P < .001$, SEE 7.6%, bias, 4.0%) and no significant mean differences between gated SPECT and 3D method. Because the degree of underestimation was same for LVEDV and LVESV by 2D method, overall agreement was good (r = 0.95, $P < .001$, SEE 4.5%, bias −1.8%). However, the regression line of 2D method for LVEF was significantly different from the line of identity (y = 0.59x + 22.2).

DISCUSSION

Three-dimensional reconstructions of LV volumes with the use of either freehand scanning techniques[10,11] or rotational data acquisition[12-14] have previously been reported. More recently, real-time acquisition of LV volume data has been introduced.[15] However, the clinical application of these techniques is not widespread because of compromised image quality, challenging technical design, and prolonged acquisition or processing times. We demonstrated that, with a magnetic position sensor integrated with the harmonic imaging system, 3D acquisition and reconstruction can be performed in a considerably shorter time than previously described. The clinical value depends on the amount of quantitative information that can be extracted from the data and the quality of the tissue rendering. Compared with video-based systems, both these factors were improved using raw digital tissue data.[5] In addition, tissue harmonic imaging has been intro-

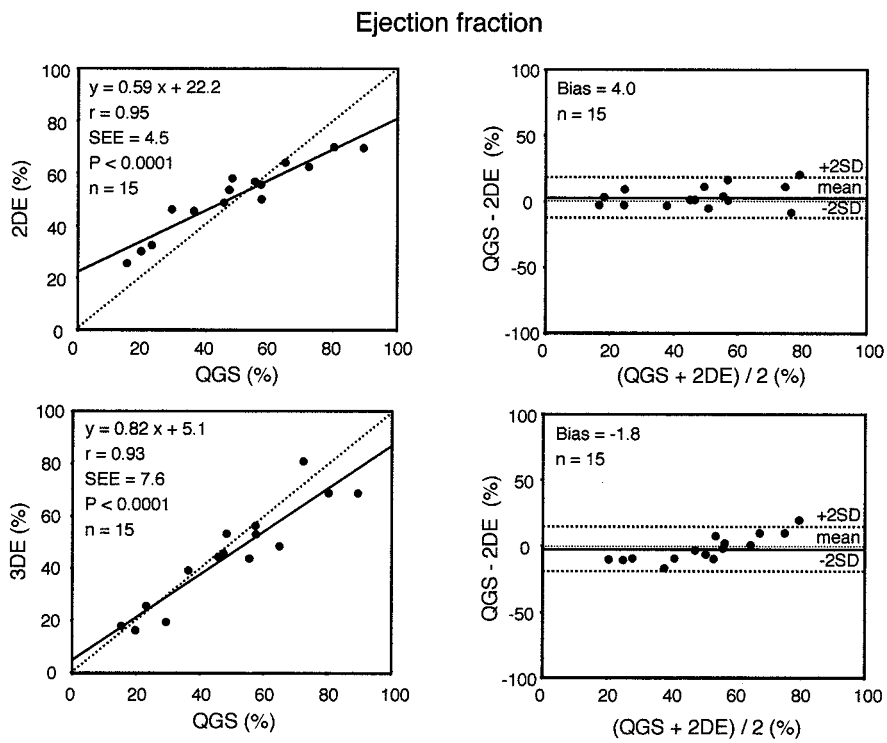

Figure 5 Linear regression analysis (*left*) and limits of agreement analysis (*right*) for left-ventricular ejection fraction measurements by 2-dimensional echocardiography (*2DE*) (*upper*) and 3-dimensional echocardiography (*3DE*) (*lower*) compared with gated single photon emission computed tomography (*QGS*). *SEE*, standard error of the estimates.

duced and overall image quality is improved with particular enhancement of endocardial borders.[16,17] Thus, the time and subjectivity involved in manual identification of the LV endocardial borders are minimal.

Freehand scanning techniques are conceptually biased because the image planes are not uniformly arranged. Thus, we collected a series of 10 to 20 apical tomograms using fanlike scanning. Because the probe movement was measured continuously, geometrical distortion was minimized. An important characteristic of apical geometry is that the slice resolution is unchanged along the imaging axis at the same radial distances and is particularly useful for reconstructing the whole LV. In addition, this system could sample sufficient 4-dimensional data for a dynamic analysis of LV function.

The M-mode and 2DE methods of estimating LV volumes have 2 major limitations, image position errors and use of geometric assumptions. Erbel et al[18] has shown, in a large percentage of patients, that in the apical view the LV is foreshortened as a result of anterior displacement of the imaging transducer by rib interference, thus, potentially leading to underestimation of LV volumes. The accurate assessment of LV remodeling is integral to the clinical evaluation of patients with LV overload or dysfunction. In normal ventricles, assessment of LV size and function using M-mode echocardiography is adequate.[19] Therefore, 3DE assessment is not necessary in all patients undergoing echocardiography. It is an important addition for the appropriate measurement of LV volumes in patients in whom LV dilation or remodeling is suspected, such as patients with cardiomyopathy, previous myocardial infarction, or valvular heart disease.

Limitations

For patients with severe arrythmias, the method described will result in reconstruction errors. Nonrepresentative cardiac cycles need to be eliminated during acquisition. The accuracy of the magnetic-field system diminishes if the receiver is >60 cm from the transmitter. The calibration procedure can be time consuming. However, if the sensor is firmly attached to the ultrasound scan head, the calibration need be done only once.

CONCLUSIONS

Rapidly acquired 3D data sets of apical tomograms using a magnetic-field system provide precise and accurate measurements of LV volumes and EF in human beings. Because of the short duration of

acquisition and processing time, this technique is clinically feasible, and it allows repeated collection of 3D data during the course of a routine clinical examination, further enhancing the results.

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