Rapid Three-Dimensional Echocardiography
Clinically Feasible Alternative for Precise and Accurate Measurement of Left Ventricular Volumes

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Background—Clinical applicability of conventional ultrasonographic systems using mechanical adapters for 3D echocardiographic imaging has been limited by long acquisition and processing times. We developed a rapid (6-s) acquisition technique that collects apical tomograms using a continuously internally rotating transthoracic transducer. This study was performed to examine the clinical feasibility of rapid-acquisition 3D echocardiography to estimate left ventricular end-diastolic and end-systolic volumes using electron-beam computed tomography as the reference standard.

Methods and Results—We collected a series of 6 to 11 apical echocardiographic tomograms, depending on heart rate, in 11 patients. There was good correlation, low variability, and low bias between rapid 3D echocardiography and electron-beam computed tomography for measuring left ventricular end-diastolic volume ($r=0.96$; standard error of the estimate, 21.34 mL; bias, $-4.93$ mL) and left ventricular end-systolic volume ($r=0.96$; standard error of the estimate, 14.78 mL; bias, $-6.97$ mL).

Conclusions—The rapid-acquisition 3D echocardiography extends the use of a multiplane, internally rotating handheld transducer so that it becomes a precise and clinically feasible tool for assessing left ventricular volumes and function. A rapid-image acquisition time of 6 s would allow repeated image collection during the course of a clinical echocardiographic examination. Additional work must address rapid and automated data processing.

Key Words: echocardiography ■ ventricles ■ tomography

Three-dimensional echocardiography has demonstrated superior accuracy and reproducibility over conventional 2D echocardiography for measuring left ventricular (LV) volume, because no geometric assumptions are necessary about LV shape.1 Real-time volumetric 3D echocardiography2 with a very fast, internally rotating crystal array for real-time 3D imaging,3 various mechanical adapters for rotation or translation with conventional transthoracic echocardiography transducers,4 or free-hand 3D image acquisition with magnetic5 or spark-gap6 spatial positioning systems were investigated in an effort to use the 3D approach in a clinical setting. However, the clinical application of these techniques is not widespread because of compromised image quality, challenging technical design, or slow acquisition times. The initial experience with a prototype handheld transducer with an internally rotating crystal array for multiplane image acquisition was reported recently.7 The transthoracic echocardiography transducer is comparable in size to conventional probes and is stable during multilumigraphic data acquisition, because the rotating crystal array is not in direct contact with the body surface.

Using the 180° continuous-rotation mode of the multiplane transducer, we developed a rapid 3D image-acquisition technique that addresses the issue of clinical practicality of 3D echocardiography.

The purpose of this study was to assess the clinical feasibility and the precision and accuracy of the new rapid, 3D echocardiographic acquisition technique for measuring LV end-diastolic (LVEDV) and end-systolic (LVESV) volumes. Electron-beam computed tomography (EBCT) was used as the reference standard.

Study Population
We performed a rapid 3D apical scan in patients for whom a standard transthoracic echocardiographic examination was clinically indicated. Patients with a variety of cardiac pathologies were considered in an attempt to cover a large range of LV volumes. Exclusion criteria were cardiac arrhythmias, sinus bradycardia, and any clinical condition preventing 6 s of suspended respiration. Thirteen patients entered the study; echocardiographic data from 2 patients were excluded because the image quality from remote myocardial regions was not adequate for determining the endocardial border. In the other
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11 patients (8 men; mean age, 54 years; range, 36 to 68 years), the
clinical transthoracic echocardiographic study was requested for
ischemic heart disease (n=2), mitral regurgitation (n=2), aortic
regurgitation (n=2), cardiac amyloidosis (n=1), constrictive peri-
carditis (n=1), pulmonary fibrosis (n=1), and pulmonary hyperten-
sion (n=1). In the final patient, LV function was evaluated before
liver transplantation. The study protocol was approved by the
Institutional Review Board of the Mayo Foundation. Informed
consent was obtained before the study from all patients.

3D Echocardiographic Study

We used a HP 2500 system (Hewlett-Packard) fitted with a prototype
5-MHz multiplane transthoracic transducer. An internal crystal array
continuously rotates and collects images over 180° about its imaging
axis. The desired diastolic and systolic tomograms are selected
during subsequent off-line data processing on the basis of a synchrono-
ously acquired electrocardiographic signal. The number of tomo-
grams obtained from the 6-s 180° rotation cycle depends on the
patient’s heart rate. For example, with a rate of 80 beats/min, 8
tomograms are obtained. The end-diastolic (temporally related to the
R wave on the ECG) and end-systolic (smallest chamber volume
during the cardiac cycle) phases were identified at each cardiac
cycle. Images were digitized, and LV endocardial borders were
traced manually, including the LV outflow tract up to the aortic
valve. The mitral valve plane was traced as the straight line between
the boundaries of the mitral annulus. Two independent observers
(K.T. and D.J.), who were blinded to the LV volumes obtained with
the reference EBCT measurements, performed endocardial diastolic
and systolic tracings, which took about 20 minutes per left ventricle.
The LVEDV and LVESV were measured from computer-generated
LV cavity casts, which were reconstructed from the interactive
tracings using the Sun SPARC station 20 and a custom software
algorithm; this took another 15 minutes.

EBCT Study

Each EBCT (Imatron C-100) study was performed within 48 hours
of the echocardiographic examination. Each subject was positioned
in the scanner to obtain parallel tomographic images in the short axis
(transverse cardiac) from the LV apex to the base of the right
ventricular outflow tract. During imaging, an intravenous infusion of
nonionic contrast medium was delivered at 3 mL/s for 20 s. Eight to
12 parallel tomographic scans were obtained from the LV apex
through the base, depending on the overall long-axis dimensions of
the ventricle. The endocardial borders were traced manually, and the
LVEDV and LVESV were obtained using a disk summation method.

Statistical Evaluation

To assess precision, LV volumes estimated from rapid 3D echocar-
diography by 2 independent observers were averaged and compared
with those measured with EBCT 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<0.05. The
accuracy of the rapid 3D echocardiography with respect to the EBCT
measurements was examined by a limits-of-agreement analysis. 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.

Results

The mean±SD of the testing 3D echocardiographic reference
and EBCT measurements were 165.1±68.0 mL and 160.2±67.6 mL,
respectively, for LVEDV and 70.4±47.9 mL and 63.5±54.0 mL for LVESV. A regression analysis
and a Bland and Altman plot for LVEDV measurements are shown in Figures 1A and 1B, respectively. Linear regression
indicated a high correlation (r=0.96; P<0.0001) between the
reference and the testing methods, with a standard error of
estimate of 21.34 mL. The limits-of-agreement analysis demonstrated a minimal mean difference (bias, −4.93±20.44
mL). The t test indicated no significant mean differences
between the 2 methods. The results of LVESV regression and
agreement analysis, which are shown in Figures 1C and 1D,
also demonstrated high precision and accuracy (r=0.96;
P<0.001; standard error of estimate, 14.78 mL; bias,
−6.97±16.22 mL) and no significant mean differences be-
tween the 2 methods. Systolic volumes were not distributed
as proportionally along the correlation line as the diastolic
volumes, and the results were influenced by a large LVESV
in one patient with ischemic heart disease.

The linear regression and agreement plots of corresponding
LVEDV and LVESV values estimated from the 3D echocar-
diographic data by 2 independent observers are shown in
Figure 2. These results showed excellent correlation and only
a small bias. In the estimation of the LVEDV and LVESV
values, interobserver variability was 6.11% and 9.14%,
respectively.

Discussion

We report a new rapid (6-s) 3D echocardiographic image
acquisition method that uses a prototype handheld transducer
with an internally rotating crystal array. This approach
represents a practical solution to a clinically feasible acquisition of 3D data and provides precise and accurate diastolic and systolic volumes for a functional assessment of the left ventricle. In the present implementation, diastolic and systolic frames, which are required for 3D reconstruction of volumetric data, are selected a posteriori during off-line processing, although on-line processing is conceivable.

Advantages of Rapid 3D Echocardiography

The technique allows the rapid collection of data during 6 s of suspended respiration, which makes the technique feasible in most clinical scenarios. The prototype transducer is capable of all current Doppler and harmonic imaging modalities. Rotational geometry has been applied successfully to 3D reconstruction, and the approach discussed herein represents a practical extension of these efforts. An important characteristic of this geometry is that the images are equispaced and particularly useful for reconstructing the whole left ventricle. In addition, this system could sample sufficient 4D data for a dynamic analysis of LV function and shape.

Limitations

The manual delineation and off-line data processing were time-consuming; however, this was not an issue from the viewpoint of our experimental objectives and did not prolong the time needed to examine a patient. The present implementation of the method is limited to patients with a heart rate \( \geq 60 \) beats/min to collect a minimum of 6 tomograms. Multiplane transducers equipped with an adjustable rate of rotation would overcome this limitation.

The 5-MHz frequency of the transducer was not optimal for adult echocardiography but was dictated by the initial prototype design using transesophageal transducer mechanics. Consequently, limited signal penetration led to the exclusion of 2 patient data sets from analysis. A production system would certainly use a rotating transducer with lower frequency for transthoracic clinical applications.

Conclusions

Rapidly acquired 3D data sets of 6 to 11 sequential tomograms provide precise and accurate measurements of LV volumes and ejection fractions in humans. Because of the short duration of acquisition (6 s), the technique is clinically feasible, and it allows, if necessary, repeated collection of 3D data during the course of a clinical examination, further enhancing the results. Additional work must concentrate on rapid and automated data processing before this technique can be used widely.

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References

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