Real-Time Three-Dimensional Echocardiographic Study of Left Ventricular Function After Infarct Exclusion Surgery for Ischemic Cardiomyopathy

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Background—Infarct exclusion (IE) surgery, a technique of left ventricular (LV) reconstruction for dyskinetic or akinetic LV segments in patients with ischemic cardiomyopathy, requires accurate volume quantification to determine the impact of surgery due to complicated geometric changes.

Methods and Results—Thirty patients who underwent IE (mean age 61±8 years, 73% men) had epicardial real-time 3-dimensional echocardiographic (RT3DE) studies performed before and after IE. RT3DE follow-up was performed transthoracically 42±67 days after surgery in 22 patients. Repeated measures ANOVA was used to compare the values before and after IE surgery and at follow-up. Significant decreases in LV end-diastolic (EDVI) and end-systolic (ESVI) volume indices were apparent immediately after IE and in follow-up (EDVI 99±40, 67±26, and 71±31 mL/m², respectively; ESVI 72±37, 40±21, and 42±22 mL/m², respectively; P<0.05). LV ejection fraction increased significantly and remained higher (0.29±0.11, 0.43±0.13, and 0.42±0.09, respectively, P<0.05). Forward stroke volume in 16 patients with preoperative mitral regurgitation significantly improved after IE and in follow-up (22±12, 53±24, and 58±21 mL, respectively, P<0.005). New York Heart Association functional class at an average 285±144 days of clinical follow-up significantly improved from 3.0±0.8 to 1.8±0.8 (P<0.0001). Smaller end-diastolic and end-systolic volumes measured with RT3DE immediately after IE were closely related to improvement in New York Heart Association functional class at clinical follow-up (Spearman's ρ=0.58 and 0.60, respectively).

Conclusions—RT3DE can be used to quantitatively assess changes in LV volume and function after complicated LV reconstruction. Decreased LV volume and increased ejection fraction imply a reduction in LV wall stress after IE surgery and are predictive of symptomatic improvement. (Circulation. 2000;102[suppl III]:III-101-III-106.)

Key Words: ventricles • aneurysm • cardiomyopathy • echocardiography

For >40 years, cardiac surgeons have proposed the resection of left ventricular (LV) aneurysms as a method of improving LV performance; however, clinical and physiological improvements in function are difficult to predict. Previous studies have demonstrated improvements in LV function after aneurysmectomy with cine left ventriculography and echocardiography. However, because LV geometry changes significantly after myocardial infarction and after cardiac surgery, the accuracy of LV volume measurements based on geometric assumptions with 2-dimensional (2D) methods is limited. A variety of 3-dimensional (3D) echocardiographic (3DE) systems have been developed during the past decade, including reconstruction of a series of 2D echocardiographic (2DE) images and real-time acquisition of 3D image data sets. A primary goal of these systems is to overcome the limitations of 2D methods due to geometric assumptions. Buck et al demonstrated the accuracy of 3DE for the determination of LV volumes and function in patients with chronic LV aneurysms. Their results showed excellent correlation and agreement of LV volume measurements between 3DE and MRI, whereas conventional 2D methods underestimated MRI data. Our previous studies showed that real-time 3DE (RT3DE), a recently developed imaging technique, has the ability to acquire RT3DE images and to accurately assess LV function during cardiac surgery.

Infarct exclusion (IE) surgery is a technique of LV reconstruction for dyskinetic or akinetic LV segments in patients with ischemic cardiomyopathy. In patients undergoing IE surgery, accurate quantitative examinations are necessary to determine the impact of surgery because of complicated postoperative LV geometric changes. Unlike most prior aneurysm operations, this reconstruction more effectively

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TABLE 1. Patient Characteristics

<table>
<thead>
<tr>
<th>Age, y</th>
<th>61±8</th>
</tr>
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<tbody>
<tr>
<td>Sex (male/female), n</td>
<td>22/8</td>
</tr>
<tr>
<td>NYHA functional class, n (%)</td>
<td>9 (30)</td>
</tr>
<tr>
<td>II</td>
<td>13 (43)</td>
</tr>
<tr>
<td>IV</td>
<td>8 (27)</td>
</tr>
<tr>
<td>EF</td>
<td>0.26±0.09</td>
</tr>
<tr>
<td>MR, n (%)</td>
<td>16 (53)</td>
</tr>
<tr>
<td>Urgent and emergent, n (%)</td>
<td>14 (47)</td>
</tr>
</tbody>
</table>

The purpose of the present study was to use RT3DE imaging techniques to investigate LV function in patients with ischemic cardiomyopathy immediately before and after IE surgery and in short-term follow-up.

Methods

Population
The study group consisted of 30 patients with ischemic cardiomyopathy (average age 61±8 years, 22 men). Each patient had characteristic clinical symptoms of ischemic cardiomyopathy, such as syncope, angina, orthopnea, or dyspnea of at least New York Heart Association (NYHA) functional class II. Thirteen patients were in NYHA functional class III, and 8 were in class IV. Routine preoperative right- and left-side heart catheterization with coronary angiography was performed to evaluate the extent of the underlying coronary disease and the potential need for surgical IE and coronary revascularization. In addition, preoperative routine transesophageal echocardiography demonstrated moderate to severe mitral regurgitation in 16 of the 30 patients (53%) and severe LV dysfunction with a mean LV ejection fraction (EF) of 0.26±0.09 (Table 1).

RT3DE Images
All intraoperative RT3DE images were acquired epicardially with a real-time 3DE system (Volumetrics Medical Imaging Inc) with a 2.5-MHz phased-array hand-held transducer (14-mm diameter) covered by 2 sterile ultrasound scanhead sheathes. Imaging was performed after routine median sternotomy, pericardiotomy, and great vessel cannulation. Modified parasternal views were used to obtain a series of 22 vol/s at a depth of 12 cm or, when necessary in patients with aortic valve. Modified apical views were obtained by placing the 3D probe on the base of the right ventricle, directed toward the LV apex. All images included the LV apex, the mitral valve, and the aortic valve. Modified parasternal views were used to obtain a series of RT3DE images of the LV from the right ventricle (Figure 1). A pyramidal tissue volume that measured 60×60° was imaged at a rate of 22 vol/s at a depth of 12 cm or, when necessary in patients with a large ventricle, at 17.1 vol/s at a depth of 16 cm. After the highest-quality image was obtained, the digital LV volumetric data set was stored on an optical disk for off-line analysis. Care was taken to include the entire LV cavity in the real-time pyramidal volumetric data set during the entire cardiac cycle. After IE surgery, epicardial 3DE images were acquired again after complete weaning from cardiopulmonary bypass before the chest was closed.

For the 3DE follow-up study, RT3DE image data set acquisition was performed with the same 3DE system with images obtained transthoracically in the outpatient echocardiography laboratory. All images were obtained from an apical view with the patient in a left decubital supine position for imaging of the entire LV cavity.

Quantitative Analysis of LV Function by RT3DE
The LV volumes were calculated according to the 3D Simpson method, a 3D modification of the conventional 2D method.19 The cavity of the LV in each parallel slice was manually traced, and the cavity area was calculated with software equipped with the RT3DE system. After multiplication of each cavity area by the slice thickness (8 to 10 mm), these segmental volumes were consecutively added to obtain an entire LV cavity volume. The QRS wave from the simultaneously recorded ECG was used to select the largest LV volume (ie, end-diastolic volume [EDV]), and the T wave was used to select the smallest LV volume (ie, end-systolic volume [ESV]). The total LV stroke volume (SV), which included LV forward SV and mitral regurgitant (MR) volume when associated with MR, was calculated as the EDV minus the ESV. LVEF was calculated as SV divided by EDV. LV end-diastolic volume index (EDVI), LV end-systolic volume index (ESVI), and SV index (SVI) were obtained through normalization of the LV EDV, LV ESV, and SV by body surface area. LV EDVI, LV ESVI, SVI, and EF were determined before and after surgery and at follow-up in all patients. For both diastolic and systolic measurements, LV trabeculations and papillary muscles were carefully excluded from the LV cavity contour.

Transesophageal Echocardiography
Conventional multiplane transesophageal echocardiography (TEE) imaging was performed with HP 1500 or 2500 echocardiographs with 5-MHz transducers (Hewlett-Packard) before and after IE surgery to evaluate the extent of MR. MR volume (VMR) was determined according to the flow convergence method as

\[ V_{MR} = \frac{\pi r^2 v_N \times \text{VTI}_{MR}}{v_{max}} \]

where \( r \) is the radius to the aliasing contour, \( v_N \) is the Nyquist or aliasing velocity, and \( \text{VTI}_{MR} \) and \( v_{max} \) are the velocity-time integral and peak velocity of the regurgitant jet, respectively.20 Forward SV was calculated as the total LV SV minus the MR volume.

Surgical Technique
Techniques of IE have been described by others in detail previously.5,6,21,22 Briefly, the procedure was performed with the use of cardiopulmonary bypass with both antegrade and retrograde cold blood cardioplegia for myocardial protection. Coronary revascularization, when needed, was performed first with internal mammary artery and saphenous vein grafting. The left atrium was then opened in the intra-atrial groove, and the mitral valve (MV) was repaired with an annuloplasty ring if there was significant MR. After revascularization and MV surgery, the cross-clamp was removed, and IE was performed on the beating heart in sinus rhythm. The LV was opened through the apical scar. Palpation and RT3DE assessment of regional akinesia or dyskinesia were used to define the border zone between infarcted and normal myocardium. A purse-string polypropylene suture was placed and tied through this border zone to create a neck. Additional sutures and an occasional endoven-
CABG. Twelve patients required urgent procedures (same closure). Five of the 30 patients had a history of prior mitral valve surgery with calcified aneurysms that required reduced tension on the mitral leaflet approximation (“Alfieri stitches”), as previously described by Fucci et al.²³ to treat MR. Fifteen patients had both Alfieri stitches and mitral ring annuloplasties performed. No other mitral reconstructive techniques were used to eliminate MR. An endoventricular patch was used with IE in 5 patients (one patient with severe mitral regurgitation, the other 4 patients with intermediate degree of MR, 0.11 ≤ PSV ≤ 0.43). An associated ventricular septal defect repair was performed in 2 patients. All patients were successfully weaned from cardiopulmonary bypass. Minimal inotropic (either dobutamine or milrinone) support was required in 13 patients. None of the patients required postoperative LV assist devices or intra-aortic balloon pumps or were listed for heart transplantation.

RT3DE Results
The real-time 3D system provided unique 3D information about the LV aneurysm location and size that were used to plan the operation. The imaging time required to obtain each intraoperative epicardial and transthoracic 3D data set was 3.4 ± 2.8 minutes, and there were no associated complications. Off-line measurement of LV volumes by RT3DE required 3.7 ± 1.6 minutes. The average LV EDV, LV ESV, SV, and EF values before IE, after IE, and at follow-up are shown in Table 2.

LV Volume Indices Before and After IE Surgery
The LV cavity was extremely dilated before surgery in most patients. The average LV EDVI was 99 ± 40 mL/m² (range 45 to 213 mL/m²), and the average LV ESVI was 72 ± 37 mL/m² (range 30 to 174 mL/m²). After the IE surgery, LV volumes dramatically decreased by 32 ± 16% for LV EDVI and by 43 ± 20% for LV ESVI (both \( p < 0.05 \), before versus after IE; Figure 3). Follow-up RT3DE, performed on average 42 ± 67 days after surgery in 22 patients, demonstrated that LV volumes were similar to the intraoperative post-IE volumes (\( p = 0.09 \) for LV EDVI and \( p = 0.3 \) for LV ESVI) and as such were also significantly decreased from the preoperative volumes (\( p < 0.05 \) for both LV EDVI and LV ESVI), before surgery versus follow-up; both \( p < 0.01 \) by repeated measures.
Follow-up was not performed in 8 patients due to death (n=2) or traveling difficulties (n=6).

LV Stroke Volume Indices Before and After IE
Despite significant reductions in LV EDVI and LV ESVI, there was no significant change in total LV SVI when the post-IE and follow-up values were compared with preoperative total LV SVI in all patients (P>0.50 by ANOVA) (Table 2 and Figure 3). However, in 16 patients with significant preoperative MR who also underwent valve repair, the LV forward SV significantly increased from 22±12 to 53±24 mL after IE and 58±21 mL for follow-up (P<0.005 for both by ANOVA and for after IE and follow-up versus baseline) due to a significant reduction in, or elimination of, MR (preoperative regurgitant volume 31±9 mL/beat, Figure 4). In all patients, no significant MR was detected after surgery.

LVEF Before and After IE
In conjunction with the decreases in LV EDVI after IE, LVEF improved significantly after surgery. Preoperative LVEF was 0.29±0.11 (range 0.12 to 0.47). Twenty patients had an LVEF of <0.30. RT3DE demonstrated a significant immediate improvement after the surgery (LVEF 0.43±0.13, P<0.0001). This improvement in EF persisted to follow-up (LVEF 0.42±0.09, P<0.01 by ANOVA, P=0.002 versus before surgery, P=0.9 versus after surgery; Table 2).

Clinical Follow-Up Results
The clinical follow-up was performed for all patients at a mean of 285±144 days after surgery (range 11 to 638 days). Only 3 patients had a clinical follow-up duration of <3 months. During clinical follow-up, NYHA functional class was worse in 2 patients, unchanged in 4 patients, and improved in 22 patients (73%, or 22 of 30). NYHA functional class improved significantly from 3.0±0.8 to 1.8±0.8 (P<0.0001, Figure 5). The overall survival rate was 93% (28 of 30). Of the 2 deaths, 1 occurred in a patient who had severe congestive heart failure and underwent emergency surgery (preoperative EF of 0.12). The other death occurred in a patient with extensive polymorphic ventricular tachycardia who required emergency surgery (preoperative EF of 0.299). The preoperative NYHA functional class was IV for each. The cause of death in both cases was severe sepsis with multiorgan failure, and neither patient was considered a candidate for a transplant or ventricular assist device.

The close relationship between post-IE RT3DE LV volumes and NYHA functional class at clinical follow-up was determined with the Spearman rank order test. A lower LV EDV (<150 mL) and LV ESV (<100 mL) correctly predicted better outcome in patients at 285±144 days after IE surgery (ρ=0.58 and 0.60, respectively; Figure 6).

Discussion
The development of an LV aneurysm after a myocardial infarction has been shown to be an independent factor that negatively influences outcome.24 It has been assumed, on the basis of the law of LaPlace, that an LV aneurysm produces a greater volume of stress and oxygen demand on the contractile myocardium; therefore, improved LV function after aneurysmectomy and coronary revascularization is hypothesized. However, early reports of aneurysmectomy with a linear suture technique showed no reduction in LV EDV. These findings were thought to be a result of incomplete surgery; the infarcted scarred septum was not resected and may have accounted for continued dilation.25 Subsequently, the surgical outcome was significantly improved with the use of endoventricular circular patch plasty repair techniques, which are presumed to better restore a normal ventricular geometry.4,5 As we have demonstrated with both RT3DE and clinical follow-up, patients with a large akinetic or dyskinetic scar and severe LV dysfunction benefit from this relatively simple surgical procedure. The combination of infarcted scar resection, endoventricular circular patch plasty, mitral valve repair, and coronary revascularization in the present study dramatically decreased LV EDVI; increased coronary blood flow; and improved LVEF.
Supplemental supply, forward SV, and contractility; and improved clinical status. Our results showed that NYHA functional class improved in 73% of patients with an average of 285±144 days of postoperative follow-up.

Surgical Results Evaluated With RT3DE
The location and size of the LV aneurysm observed with RT3DE preoperatively assisted surgeons in deciding whether surgery was indicated and how to plan the operation. For example, an IE procedure was chosen for 1 of our patients who had been listed elsewhere for heart transplantation because of RT3DE findings thought to be favorable for reconstruction.

Dor et al. reported that the outcome of IE surgery was excellent in both akinetic and dyskinetic LV patients, as was observed in the present study. In the studies of Dor et al., LV volumes were measured with cineangiography. As discussed earlier, 2D techniques may produce overestimations or underestimations of LV volumes, especially for the asymmetrical LVs that are often encountered in this patient population. To our knowledge, the present study is the first to present the outcome of IE surgery as correlated with RT3DE. We demonstrated with RT3DE that LV volumes (both LV EDV1 and LV ESV1) significantly decreased and that LVEF significantly increased after IE surgery. Furthermore, and as important, the improvement in LV function persisted during follow-up. The reduction in wall tension and oxygen demand, due to the marked decrease in LV volumes and the elimination of MR, combined with the increase in oxygen supply, due to revascularization, may account for the improvement in and maintenance of LV function, but further studies are required to quantify these assumptions. More importantly, smaller LV ESV and LV EDV values measured with RT3DE immediately after IE correlated significantly with improved functional class during our clinical follow-up study.

Advantage of Real-Time 3D Method
Due to the geometric changes in LV shape after myocardial infarction or IE surgery, conventional 2D methods are not ideal for accurate quantification of LV volumes. Biplane cineventriculography has been shown to overestimate LV EDV, whereas monoplane or biplane 2DE methods have been shown to underestimate LV EDV. In our previous studies, we demonstrated that conventional transthoracic 2DE underestimated LV volumes measured with MRI in patients with aneurysmal LVs, probably due to the difficulty of obtaining true apical LV views. Compared with the reconstruction techniques of previously described 3DE methods, RT3DE has retained many of the clinical advantages of 2DE. On-line adjustment of conventional echocardiographic planes can be performed to ensure adequate-quality 3D data sets. Compared with 3D reconstruction techniques applied to 2DE, the imaging time is dramatically reduced, because all planes are imaged simultaneously. In addition, because the 3DE hand-held probe is similar to that of a conventional transthoracic 2DE probe, sonographers do not need additional training to acquire 3DE data sets, a major advantage over the previously reported reconstruction methods of 3DE, which require complex imaging probes. Another advantage of RT3DE imaging is the elimination of the need for ECG and respiratory gating. These factors are particularly important for the study of critically ill patients, particularly when epicardial 3DE images are acquired in the operating room and when patients with arrhythmias are imaged.

In our initial studies, we demonstrated the role of RT3DE in the accurate quantification of LV volumes in the imaging of critically ill patients and intraoperatively, particularly patients with LV aneurysms and abnormal LV geometries. For patients with aneurysmal LVs, excellent correlation and agreement between RT3DE and MRI were found, hence demonstrating similar diagnostic yield but increased versatility of RT3DE compared with MRI.

Although MRI might provide high-resolution images of the heart and accurate measurements of the LV volumes and function, currently available MRI systems require prolonged imaging time, high equipment costs, and special facilities. Immobility of the MRI system also limits clinical use in the operating room and in critically ill patients when continuous physiological monitoring and hemodynamic support are required. In addition, the metallic composition of advanced medical devices (eg, implantable defibrillators, ventricular assist devices, pacemakers) that are occasionally used in patients with end-stage heart disease would preclude the application of MRI. RT3DE overcomes these limitations because of the elimination of geometric assumptions for volume measurement combined with a lower cost, increased mobility and general patient access, and no radiation exposure. These benefits are all of particular importance in patients with end-stage heart disease in whom multiple follow-up evaluations are necessary to not only monitor clinical progress but also evaluate the response to different treatment strategies.

Study Limitations
Minimal inotropic agents infused after the surgery resulted in enhanced myocardial contractility in 13 patients. Thus, RT3DE immediately after surgery might overestimate LV function. However, 3-month follow-up confirmed the improvement of the LV function after IE procedure.

The number of the patients in this study was not large enough to analyze the surgical outcome in various patient subgroups such as those with akinetic versus dyskinetic aneurysms, those with versus without preoperative mitral regurgitation, or those with an LVEF of <0.30 versus >0.30. The RT3DE follow-up date was relatively short (average 42 days), and long-term follow-up with a larger study population is necessary to further demonstrate the durability of the clinical benefits of IE surgery. Long-term follow-up data, both clinical and RT3DE, are being accumulated.

One major limitation of the current RT3DE system is limited image resolution due to 16:1 parallel processing. In patients with dilated hearts, the 60°×60° pyramidal angle often limits the ability to image the entire ventricle, although this was not a problem in the presents study. The maximal achievable frame rate is only 22 frames/s at an image depth of 12 cm. Low frame rates may be problematic to capture precise end-diastolic and end-systolic frames, especially in the presence of tachycardia. These limitations in image...
acquisition technology may be the major reasons for RT3DE underestimation of LV volumes. However, improvement of the imaging resolution with higher-frequency transducers, wider sector angles, and higher frame rates could progressively resolve these problems in the next generation of RT3DE technology.

Conclusions
RT3DE was used to quantitatively assess changes in LV volumes and function after complicated LV postinfarct re- construction. Functional class significantly improved during clinical follow-up and correlated with RT3DE postoperative volumes. Decreased LV volume and increased EF imply a reduction in LV wall stress after IE surgery.

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