Quantitative two-dimensional echocardiographic analysis of motion and thickening of the interventricular septum after cardiac surgery

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ABSTRACT Septal and lateral wall motion and septal thickening were evaluated with quantitative two-dimensional echocardiography in 20 patients who underwent cardiac surgery without complications. Postoperative mean ejection fraction (48 ± 10%) measured by radionuclide ventriculography was unchanged from the preoperative value (45 ± 8%). Mean postoperative systolic thickening of the septum (33 ± 15%) was also unchanged from the preoperative value (26 ± 10%). However, septal endocardial motion as measured by an external frame-of-reference (fixed-axis) system fell from a 22 ± 10% mean percent shortening (MPS) of septal radii to a postoperative value of ~8 ± 15% (p < .001). Fixed-axis analysis also led to an increase in MPS of lateral radii: preoperative 16 ± 5%; postoperative 28 ± 9% (p < .001). With an internal frame-of-reference (floating-axis) system, which compensates for the effects of translation and rotation on wall motion, postoperative MPS of septal radii (22 ± 10%) was unchanged from preoperative MPS (25 ± 8%; p = NS). Similarly, MPS of lateral wall radii was unchanged (preoperative, 15 ± 5%; postoperative, 12 ± 5%; p = NS). Thus systolic translation of the ventricle accounts for abnormal postoperative septal motion seen in a fixed-axis system and can be corrected by a floating-axis system. These data have important implications for the noninvasive evaluation of regional wall motion after cardiac surgery. Systems using a fixed external frame of reference such as radionuclide ventriculography are prone to systematic error. A combination of systolic thickening analysis by two-dimensional echocardiography and analysis of endocardial motion by the floating-axis system is a more appropriate method for evaluating the effects of cardiac surgery on regional left ventricular function.


THE EFFECT of coronary artery bypass grafting (CABG) on left ventricular regional wall motion has been extensively investigated with cardiac catheterization and contrast ventriculography. More recently studies have used noninvasive techniques to evaluate regional left ventricular function before and after CABG.1-4 Some have attempted to identify wall motion abnormalities that may be improved by CABG. These studies have been hampered by the difficulty in assessing the postoperative motion of the interventricular septum (IVS), which has almost always been found to be abnormal and even frankly paradoxical when assessed by M mode echocardiography.5-7 qualitative two-dimensional echocardiography,4 and radionuclide ventriculography.1-3, 5, 6, 8, 9 These difficulties have led investigators to exclude the IVS from their analysis of postoperative regional wall motion.1,2 Although the cause of this abnormal IVS motion remains debatable,4, 10, 11 recent work has suggested that ischemic damage to the septum is an unlikely explanation.12,13 These authors suggest that anterior motion of the entire heart accounts for their findings; however, in all of the studies done to date, septal function has only been assessed by M mode–determined septal thickening.

Therefore, we undertook this study with quantitative two-dimensional echocardiography to evaluate whether systolic anterior motion of the heart could by itself account for the apparent deterioration in postoperative IVS motion, and to use this information to examine alternative methods for analyzing postoper-
tive left ventricular regional function, which would permit analysis of the function of the IVS.

Methods

Patient selection. We studied 30 male patients who underwent open heart surgery at the West Roxbury Veterans Administration Hospital during a 4 month period. All patients with electrocardiographic (ECG) or echocardiographic evidence of a prior anterior, septal, or lateral wall infarction were excluded.

Patients were selected for the study on the basis of an adequate preoperative two-dimensional echocardiogram in four standard views, i.e., parasternal long- and short-axis views and apical four-chamber and apical long-axis views. We further selected only those patients who had normal motion of the IVS and lateral wall of the left ventricle on quantitative analysis (see below) by the apical four-chamber view. We have previously defined a range of normal from studies of 10 normal volunteers.14 The ages of the patients studied ranged from 42 to 66 years (mean 59).

All patients were also studied within 6 weeks before surgery by cardiac catheterization and selective coronary angiography.

Surgical technique. All patients underwent cardiopulmonary bypass at a systemic temperature of 25°C. Left ventricular venting was performed through the right superior pulmonary vein. Distal bypass graft anastomoses were performed through one period of aortic cross-clamping. Myocardial preservation was achieved with cold (4°C) potassium crystalloid cardioplegia administered through the aortic root and through the free ends of the grafts immediately after the distal anastomoses were performed. Myocardial temperature, maintained below 15°C throughout the period of aortic cross-clamping, was continuously monitored in the IVS anteriorly and sometimes in the posterior or lateral wall of the left ventricle. The proximal anastomoses were performed with partial aortic cross-clamping while the patient was being rewarmed. In all our patients reverse saphenous vein was used exclusively, and all grafts were constructed to single coronary arteries. In the majority of patients topical hypothermia was also maintained with ice slush. The pericardium was left open after surgery in each case.

Two-dimensional echocardiographic studies

Image acquisition techniques. Two-dimensional echocardiographic studies were performed with a commercially available Hewlett Packard phased-array sector scanner (model 77020A) with a 2.25 MHz transducer. The studies were performed in the week before surgery and at 5 to 23 days (mean 11) after surgery at the earliest time that a high-quality study could be obtained. Images adequate for detailed quantitative analysis could not usually be obtained before the fifth postoperative day.

All patients were studied in the left lateral decubitus position. Because we found that optimal postoperative studies were not always obtained with the same patient position and transducer location as in the preoperative studies, we did not attempt to duplicate exactly patient position and transducer location. Instead we standardized the ultrasonic plane on defined points of reference within the heart. Thus, the parasternal long-axis image was recorded from base to apex in a manner that most closely approximated the long axis of the left ventricle, i.e., with the internal diameter of the left ventricle maximal at the mitral valve level and the IVS imaged along its length as far as the apex of the right ventricle. The apical four-chamber image was obtained by placing the transducer over the palpable apical impulse, with minor adjustments made from this position to maximize the length of the left ventricular long axis. From this position the scan plane was adjusted until the image included both the full excursion of the tricuspid and mitral valve leaflets and both atria.

Stop-frame end-diastolic and end-systolic images were displayed on a video monitor; end-diastole was defined as the peak of the R wave on the simultaneous ECG recording, and end-systole was defined as the smallest ventricular dimension during the last half of the T wave. Endocardial tracings were made on a transparent overlay placed on the monitor screen.

Thickening of the IVS can be assessed from the parasternal long-axis and apical four-chamber views. Because axial resolution of two-dimensional echocardiographic systems is much greater than lateral resolution, a more accurate assessment of septal thickening can be made from the parasternal long-axis view, in which septal targets lie perpendicular to the beam. Thus, both the right ventricular and left ventricular endocardial surfaces of the IVS were drawn at end-diastole and end-systole in the parasternal long-axis view from the level of its junction with the aorta to the apex of the right ventricle (figure 1). Simultaneously derived M mode echocardiographic measurements were made from these two-dimensional recordings with the M mode sector placed through the IVS at a point just below the tips of the mitral valve leaflets.

Quantitative image analysis. Quantitative analysis of systolic thickening of the IVS was determined by measuring area and length of the IVS image in systole and diastole and by defining thickening as a percentage change in average thickness:

\[
\text{mean diastolic thickness} = \frac{\text{area/length of IVS image in diastole}}{\text{mean diastolic thickness}}
\]

\[
\text{mean systolic thickness} = \frac{\text{area/length of IVS image in systole}}{\text{mean diastolic thickness}}
\]

Mean percent change in thickness of the IVS was defined as:

\[
\text{mean systolic thickness} - \text{mean diastolic thickness} \times 100% 
\]

Thickening was directly measured from the M mode recordings and calculated in a similar fashion.

Intraobserver and interobserver variability in the two-dimensional echocardiographic determinations of systolic thickening of the IVS in the parasternal long-axis view were evaluated for 10 patients for the same cardiac cycle by use of the definitions of end-diastole and end-systole as outlined above. Intraobserver variability was 3.8%, and interobserver variability was 4.2%.

Outlines of images of the left ventricular endocardium at end-diastole and end-systole were made from the apical four-chamber view in all patients. Quantitative analysis of regional wall motion was made from the apical four-chamber view with an Irex Cardio 80 computer.

Wall motion was analyzed with both a fixed external frame-of-reference (fixed-axis) system and an internal frame-of-refer-
ence (floating-axis) system. In the fixed-axis system the operator defines the long axis of the diastolic image of the left ventricle by identifying the apex and the midpoint of the mitral valve orifice at the base for the apical four-chamber view. From the midpoint of the long axis, 24 radii are drawn to the systolic and diastolic outlines of the left ventricle (figure 2). Regional wall motion is expressed as percent radius shortening from diastole to systole [(ED - ES)/ED × 100] and is given a positive value if wall motion is normal, i.e., toward the midpoint of the long axis in systole, and a negative value if systolic motion is away from the midpoint. For the purposes of this study, radii 4 to 10 and 15 to 22 were selected to represent motion of the IVS and lateral free wall of the left ventricle in the apical four-chamber view, respectively (figure 2). In the floating-axis system the operator defines the apex and midpoint of the base of the left ventricle of both the diastolic and systolic images (figure 3). The end-systolic image is then transposed so that the long axis and the midpoints of the long axis of each image are exactly superimposed. In this way any effects on regional wall motion of translation and/or rotation of the long axis of the left ventricle from diastole to systole are minimized. Twenty-four radii are again generated, and wall motion is again defined for each radius as described above.

Interobserver variability in the tracing of end-diastolic and end-systolic images from single cardiac cycles has been described in several previous reports from our laboratory\(^\text{14-18}\) and was not tested in this study. However, interobserver variability in the identification of the internal points of reference used to define the long axis of the left ventricle in apical views, i.e., the apex and the midpoint of the mitral valve plane, had not been assessed previously.

When these two points were identified by two separate observers (10 patients studied) and mean shortening of septal and lateral wall radii was subsequently assessed, the interobserver variability was low: the difference between observers for mean septal and lateral percent shortening for the fixed-axis system was 3% and 1%, respectively, and 4% and 3% for the floating-axis system.

**Cardiac enzyme analysis.** Three consecutive blood samples were drawn for analysis of cardiac enzymes immediately after surgery and at 8 hr intervals thereafter. The levels considered to be suggestive of significant myocardial damage in the patient after surgery in our institution would be a total creatine kinase MB activity of greater than 90 IU/l.\(^\text{17}\)

**Electrocardiography.** All patients had a preoperative ECG and daily postoperative ECGs. Perioperative myocardial infarction was considered to have occurred in patients who developed new pathologic Q waves in two or more adjacent leads and who had a concurrent rise in cardiac enzymes.

**Radionuclide ventriculography.** First-pass radioventriculography was performed in all subjects in the week before surgery and 7 to 10 days after surgery. Count acquisition was started immediately after an intravenous injection of a bolus of 10 mCi of \(^{99m}\)Tc pertechnetate with the patient in the 30 degree left anterior oblique position and with 20 degrees of caudal tilt to the collimator. With this method and projection, excellent correlation in the estimation of ejection fraction with contrast ventriculography has been demonstrated.\(^\text{18}\)

**Statistical analysis.** Statistical analyses were performed with a programmable Monroe 325 desk-top calculator. Means and SDs were calculated with Monroe’s Alpha 315 Univariate Statistics Pak. Statistical significance was determined with the t test for dependent means from Monroe’s Alpha 325 Significance Pak.

**Results**

Of the 30 patients initially entered into the study, 10 patients were excluded: three because of moderate to large pericardial effusions, four because of deterioration of the quality of the echocardiographic image after operation preventing quantitative analysis, and three due to perioperative myocardial infarctions. Thus, a total of 20 patients were analyzed for regional wall

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**FIGURE 2.** Example of wall motion analysis with 24 radii drawn from the midpoint of the long axis of the left ventricular outline. Radii 4 through 10 were considered “septal” and 15 through 22 “lateral.” MPS of each radius is plotted on the adjacent histogram.

**FIGURE 3.** Schematic representation illustrating the fixed- and floating-axis systems for analysis of regional wall motion. In each illustration only radii 4, 10, 15, and 22 have been represented; for the fixed-axis system these were derived as shown in figure 2. For the floating-axis system the long axis of both diastolic and systolic images are defined, the midpoint is identified, and the long axes are then superimposed, and 24 radii are again generated from the midpoint.
motion with the apical four-chamber view and for percent septal thickening in the parasternal long-axis view (table 1). In all of these patients the postoperative clinical course was uncomplicated. Seventeen patients underwent CABG to the left anterior descending coronary artery, and in 16 of 17 patients the flow in this graft measured intraoperatively was greater than 100 ml/min. Flow rates of this magnitude have been associated with graft patency rates of greater than 90% at 1 year in our institution. Three patients underwent aortic valve replacement for aortic stenosis, two of whom underwent concomitant CABG. One patient had a median sternotomy and pericardiectomy but was not placed on cardiopulmonary bypass (table 1).

**Radionuclide ventriculography.** Preoperative and postoperative radionuclide ventriculography was performed in 17 patients. The mean postoperative ejection fraction of this group (48 ± 10%) was unchanged from the preoperative value (45 ± 8%, p = NS). Only one of the 17 patients (No. 12) had a decrease in ejection fraction from the preoperative study to the postoperative study of more than 2% (48% to 39%); his ECG remained normal, the peak creatine kinase MB activity was only 30 IU/l, and myocardial infarct scintigraphy (99mTc PYP) was negative 48 hr after operation.

**TABLE 1** Characteristics of the study populations

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Preoperative ECG</th>
<th>Diagnosis</th>
<th>No. of diseased vessels</th>
<th>% Obstruction LAD</th>
<th>Surgical procedure</th>
<th>LAD bypassed (yes/no)</th>
<th>LAD graft flow (ml/min)</th>
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<td>N1</td>
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<td>60</td>
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<td>3</td>
<td>99</td>
<td>CABG × 3</td>
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<td>150</td>
</tr>
<tr>
<td>3</td>
<td>N1</td>
<td>CAD</td>
<td>3</td>
<td>100</td>
<td>CABG × 3</td>
<td>Y</td>
<td>100</td>
</tr>
<tr>
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<td>3</td>
<td>99</td>
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<tr>
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<td>0</td>
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<td>NA</td>
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<tr>
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<td>AS</td>
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<td>0</td>
<td>AVR</td>
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</tr>
<tr>
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<td>LVH</td>
<td>AS</td>
<td>0</td>
<td>0</td>
<td>MS/P</td>
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N1 = normal; IMI = inferiour myocardial infarction; LVH = left ventricular hypertrophy; MS/P = median sternotomy and pericardiectomy; NA = not available.

**Systolic thickening of the IVS.** Analysis of the data on systolic septal thickening showed that there was a nonsignificant trend toward an improvement in septal thickening after surgery when measured by M mode (mean preoperative, 19 ± 14%, postoperative 27 ± 15%, p = NS) and by two-dimensional echocardiography (mean preoperative 26 ± 10%, postoperative 33 ± 15%, p = .12).

One patient had significant deterioration in systolic septal thickening (36% before surgery to 0% after surgery). Systolic thickening has previously been shown to be a highly sensitive index of systolic function, and because our primary objective was to assess regional wall motion only in patients with normal systolic function, this patient was excluded from the analysis of endocardial wall motion. Thus there were 19 patients with no significant deterioration in septal systolic function as determined by systolic-thickening analysis who were further analyzed for changes in wall motion in the apical four-chamber view.

**Endocardial motion of the IVS.** On fixed-axis analysis of the apical four-chamber view, preoperative MPS of the septal radii was 20 ± 6%. After surgery this value was −8 ± 15% (p < .001); that is, there was mean lengthening of the septal radii (figure 4A). With the floating-axis system, mean percent shortening (MPS)
FIGURE 4. A, MPS of septal radii with the fixed-axis system. MPS of the group deteriorated significantly after surgery (postoperative mean $-8 \pm 15\%$) from before surgery (preoperative mean $22 \pm 10\%; p < .001$). Closed circle = CABG; open circle = aortic valve replacement. B, With the floating-axis system MPS of the group was unchanged after surgery (postoperative mean $22 \pm 10\%$) from before surgery (preoperative mean $25 \pm 8\%; p = NS$).

of septal radii after surgery ($22 \pm 10\%$) was unchanged from the preoperative value of $25 \pm 8\%$ ($p = NS$, figure 4B). By M mode echocardiography, mean preoperative septal motion was $5 \pm 2$ mm, and after surgery this fell to $0.9 \pm 2.3$ mm ($p < .001$). Analysis of the images from a typical patient is presented in figure 5.

We also compared the difference between septal motion on the fixed- vs floating-axis systems. Before surgery there was very little translation or rotation of the ventricle since MPS of the septal radii was $20 \pm 6\%$ on fixed-system vs $25 \pm 8\%$ on floating-system analysis ($p = NS$). After surgery, however, there was a marked difference: septal shortening was $-8 \pm 15\%$ with fixed-system analysis, but $+22 \pm 10\%$ ($p < .001$) with floating-system analysis.

To determine whether translation or rotation of the long axis of the left ventricle was more important in creating this change, we measured the degree of rotation of the long axes from end-diastole to end-systole. The mean degree of rotation was $3 \pm 1$ degree in the postoperative studies, and $1 \pm 0.2$ degree in the preoperative studies. Thus translation of the entire long axis rather than rotation of this axis appears predominantly to account for the apparent deterioration in postoperative IVS motion.

After surgery, 13 of 19 patients (68%) demonstrated paradoxical motion defined as net negative shortening (i.e., lengthening) of septal radii with a fixed-axis system. With the floating-axis system, in no patient did septal motion become paradoxical. The septum of the patient excluded from the group analysis because of deterioration in septal thickening did, however, remain paradoxical on floating-axis analysis.

Endocardial motion of the lateral wall. A similar approach was used to analyze lateral wall motion. There was a significant increase in lateral wall motion after surgery when it was analyzed by the fixed-axis system. Thus MPS of the lateral wall radii increased from a preoperative value of $16 \pm 5\%$ to $28 \pm 9\%$ in the postoperative study ($p < .001$) (figure 6A). When the floating-axis system was used, the MPS of the lateral wall radii was $12 \pm 5\%$, which was not significantly changed from the preoperative value of $15 \pm 5\%$. (figure 6B).

Discussion

Our study used quantitative two-dimensional echocardiography to examine changes in septal motion after surgery. None of our patients had ECG, enzymatic, or radionuclide ventriculographic evidence of perioperative myocardial damage. Furthermore, all had an uncomplicated clinical course. Our method of analysis avoids sampling only a small and discrete part of the septum as is done in M mode echocardiography and, consequently, also avoids the problem of changes in the site of such measurements in serial studies. We have examined both septal systolic thickening and regional wall motion quantitatively. We have shown that in our group of patients, systolic septal thickening was preserved, indicating that systolic function remained intact after surgery.

Despite the observation that systolic septal function appeared to be preserved or even enhanced after CABG, centripetal motion of the IVS deteriorated significantly when studied by fixed-axis analysis of the apical four-chamber view. However, when we analyzed the motion of the IVS and lateral wall using the internal landmarks of the left ventricle in both diastole and systole by transposing or “floating” the long axis of the left ventricle in systole over the diastolic long
axis, the results were different. Centripetal motion of the IVS was not significantly changed after surgery from that before surgery. Furthermore, the apparent increase in lateral wall motion seen by fixed-axis analysis was not seen with the floating-axis system. Thus the change in septal and lateral wall motion was completely corrected with the floating-axis system.

Taken collectively our data suggest that changes in motion of the IVS and left ventricular lateral wall seen in fixed-axis analysis are an artifact created by motion of the entire heart within the chest cavity during systole. This motion is almost entirely due to translation of the long axis of the left ventricle because mean rotation of the long axis was only 3 degrees in the postoperative studies. Thus anteromedial translation of the entire heart in systole appears to be the sole explanation of apparent paradoxical septal motion in most patients after CABG.

Various theories have been advanced to explain anterior swinging of the heart after cardiac surgery. There does not appear to be any change in the configuration of the ventricle. By qualitative inspec-

FIGURE 5. A, Preoperative fixed-axis analysis illustrating normal centripetal motion of septum and lateral walls. B, Definition of the long axis of the diastolic and systolic outline demonstrating very little translation or rotation in the apical four-chamber plane. C, Postoperative fixed-axis analysis illustrating mean lengthening of the septal radii in systole. D, Definition of the long axis of the postoperative diastolic and systolic outlines demonstrating anteromedial translation in systole. This translation is corrected by superimposing the systolic and diastolic long axes. E, Postoperative floating-axis analysis illustrating normalization of septal and lateral wall motion.
FIGURE 6. A, MPS of lateral wall radii analyzed by the fixed-axis system. MPS of the group improved significantly after surgery (postoperative mean 28 ± 9%) from before surgery (preoperative mean 16 ± 5%; p < .001). Closed circles = CABG; open circles = aortic valve replacement. B, When the floating-axis system was used, MPS of lateral wall radii was unchanged after surgery (postoperative mean 12 ± 5%) from before surgery (preoperative mean 15 ± 5%, p = NS).

Kerber and Lichfield\textsuperscript{12} noted no change in the shape of the IVS on two-dimensional echocardiography in their patients with paradoxical septal motion. It has been hypothesized that anterior swinging of the heart may be caused by the development of adhesions tethering the heart to the anterior chest wall.\textsuperscript{6, 12} This theory does not seem plausible because abnormal septal motion can be detected early after surgery and, indeed, was present in some of our patients in the recovery room on the day of surgery. Furthermore, there is a tendency for such abnormal motion to correct in the weeks after surgery in the period when one would expect adhesions to be forming.\textsuperscript{6, 11} It appears to us and others\textsuperscript{13} that this abnormal motion is more likely to be due to a removal of constraints to anterior motion of the entire heart in systole. In normal subjects it is well recognized that centripetal motion of the IVS is less than that of the left ventricular posterior wall when concomitant thickening of all walls is equal. This suggests that there is slight overall anterior motion to the heart in systole in normal subjects.\textsuperscript{21} When the heart is exposed through a median sternotomy the areolar tissue and thymic remnants that comprise the anterior mediastinum are disrupted and displaced. The two sides of the sternum and the anterior portion of the thoracic cage are retracted and distorted. The pericardium is incised and stretched apart to facilitate access to the heart. It appears that any or all of these maneuvers might release constraints on the natural tendency of the heart to move anteriorly with systole. Pericardiectomy may be the least important of these factors because abnormal septal motion occurs whether or not the pericardium is left open after surgery.\textsuperscript{5} The gradual resolution of abnormal septal motion seen during the first postoperative year would thus seem to be best explained by the gradual reconstitution of anterior mediastinal structures.

A major conclusion of our study is that any noninvasive technique that uses a fixed external frame of reference to assess regional function in patients after cardiac surgery may incorporate a systematic error. With radionuclide ventriculography as an example, an artifact affecting septal motion has been suspected and has led investigators to discard the septum from their analyses.\textsuperscript{1-3} But the possibility that this artifact affects other walls as well has not been adequately addressed. From our analysis, it appears that a false improvement in lateral wall motion would be as significant a problem as the well-described deterioration in septal motion. As seen by radionuclide ventriculography, lateral motion may improve in up to 71% of those patients with preoperative lateral wall motion abnormalities.\textsuperscript{8} The proportion of asynergic segments showing improvement by quantitative contrast ventriculography with an internal frame of reference is much lower (25%).\textsuperscript{21} In a qualitative two-dimensional echocardiographic study, Rubenson et al.\textsuperscript{4} found that deterioration in septal motion after CABG was accompanied by improvement in motion of posterior and lateral wall segments, including those that had been abnormal before surgery. These results can be explained by anteromedial translation of the entire heart during systole. Therefore, it would appear that noninvasive methods of analyzing regional wall motion after cardiac surgery are liable to systematic error when wall motion is assessed with an external frame of reference.

This study also provides an alternative means of noninvasive assessment of regional wall motion after cardiac surgery. Systolic thickening analysis of each wall would be an ideal method, but it is unlikely with the lateral resolution of currently available echocardiographic instruments and the limited number of acoustic windows that all left ventricular regions could be analyzed quantitatively with the use of data on thickening.
especially in the early postoperative state. However, a combination of wall-thickening analysis with two-dimensional echocardiography and endocardial motion analysis with a floating-axis system should be feasible as demonstrated here.

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