Onset of Altered Interventricular Septal Motion During Cardiac Surgery
Assessment by Continuous Intraoperative Transesophageal Echocardiography

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Abnormal motion of the interventricular septum is frequently observed after uncomplicated cardiac surgery. We sought to elucidate the mechanism underlying this phenomenon by using continuous echocardiographic imaging of the heart from a constant transesophageal location in 21 patients undergoing their first cardiac operation. Quantitative global and regional functional analyses were performed in each patient at baseline (stage 1), after median sternotomy (stage 2), after sternal retraction (stage 3), after pericardiotomy (stage 4), after completion of cardiopulmonary bypass (stage 5), and after chest closure (stage 6). During the first four surgical stages, mean left ventricular fractional shortening varied little among regions with a fixed reference system (maximum range, 31.6–39.2%; p=NS) but changed dramatically after the discontinuation of cardiopulmonary bypass (stage 5). The apparent medial hypokinesis that was observed (4.9±4.7% [SD]) was accompanied by lateral hyperkinesis (65.2±4.1%, p<0.0001). These regional differences were completely eliminated with a floating reference system (33.6±2.7% for medial, and 34.8±1.7% for lateral; p=NS), suggesting cardiac translation. Quantitative curvature analysis supported this conclusion, with preservation of baseline regional curvature seen throughout the procedure. The mean length of individual translational vectors (reflecting systolic movement of the endocardial centroid) remained minimal (≤1.0 mm) through stage 4 but increased more than fourfold at stage 5, continuing in a medial direction after chest closure (5.2±3.0 mm and 271±6° from anterior). Thus, abnormal postoperative septal motion is not caused by removal of restraining forces of the pericardium or anterior mediastinum but rather appears to be directly related to events occurring during cardiopulmonary bypass. (Circulation 1990;82:1325–1334)

The accurate determination of left ventricular performance can provide important clinical and prognostic information on patients who have undergone cardiac surgery. Because assessment of global function alone may miss subtle but important changes, analysis of regional function has been advocated as a more sensitive and rational approach.1 Unfortunately, the application of traditional methods of wall motion analysis to this population has produced unexpected results.2 In particular, the interventricular septum has often been found to display dysskinetic, or paradoxical, motion that can be demonstrated with a variety of imaging techniques.3 The surprisingly high prevalence of postoperative septal abnormalities has led some investigators to recommend that this region be excluded from analysis.4 The present study was designed to investigate this phenomenon with a new imaging modality that permits continuous assessment of global and regional performance from a fixed reference site during the entire surgical procedure. Special emphasis was placed on the timing and pattern of newly acquired regional motion abnormalities to help provide insight into the pathogenesis of this phenomenon.

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Methods

Using a protocol approved by the Yale University Human Investigations Committee, patients scheduled for elective cardiac surgery were enrolled if they satisfied the criteria of 1) no prior cardiac or thoracic surgical procedure, 2) no history of esophageal symptoms or diseases, and 3) no bundle branch block observed in the preoperative 12-lead electrocardiogram that could interfere with assessment of regional wall motion. Continuous intraoperative two-dimensional echocardiography was performed with a Varian 3400 echocardiograph with a 3.5-MHz transesophageal transducer. The distal end of the transducer was inserted into the esophagus under direct visualization immediately after anesthesia induction; mean insertion depth was 41.5 cm. The probe was positioned and oriented to obtain a short-axis image of the left ventricle at the level of the tips of the mitral valve leaflets. Once positioned, the transducer was not moved during the entire surgical procedure, ensuring a near-constant imaging plane.

Surgical Procedure

Anesthesia was induced with 75–100 μg/kg fentanyl; 0.1 mg/kg pancuronium was used to provide muscle relaxation. The FiO2 was maintained at 1.0 with the addition of isoflurane in low concentration as supplemental inhalational anesthesia if clinically indicated. The patients were rendered hypothermic with a core temperature of 21°C maintained throughout the procedure. All patients were placed on cardiopulmonary bypass with cannulas inserted into the ascending aorta and right atrium; venous drainage was accomplished with a dual-lumen cannula. The asanguinous cardioplegia solution was delivered at 4°C by gravity drainage into the aortic root. In each case, the pericardium was left open at the time of chest closure.

To exclude the possibility of perioperative myocardial damage that might alter regional ventricular wall motion, serial cardiac enzyme levels and 12-lead electrocardiograms were performed. None of the patients enrolled experienced a perioperative myocardial infarction, which was defined as the presence of new electrocardiographic Q waves, elevation of the creatine kinase–MB fraction greater than three times normal, or both.

The image of the left ventricle was recorded on magnetic tape at each of the following six surgical stages: stage 1, immediately after insertion and orientation of the transducer (baseline); stage 2, after bisection of the sternum (sternotomy); stage 3, after retraction of the sternal edges (sternal retraction); stage 4, after incision and retraction of the pericardium (pericardiectomy); stage 5, after discontinuation of cardiopulmonary bypass (cardiopulmonary bypass); and stage 6, after reapposition of the sternal halves at the end of the procedure (chest closure). Images were recorded only during periods of sinus rhythm. The endocardial contours were traced off-line by an experienced echocardiographer without knowledge of the patient’s clinical status or surgical procedure. End-diastolic and end-systolic contours were taken from frames of the maximum and minimum endocardial areas, respectively. A magnification correction factor was also recorded from each frame.

Quantitative Analysis

Each traced endocardial contour was digitally entered into a custom analysis program. Global left ventricular size and function were assessed by comparing cavity areas circumscribed by the endocardial contours traced from the short-axis view. Area ejection fraction was defined as the ratio of the differences in end-diastolic and end-systolic areas to the end-diastolic area. A true center-of-area, or centroid, was computed for each tracing. Sixty-four equispaced chords were then constructed that emanated from the center-of-area of the end-diastolic contour. The chords were consecutively numbered in a clockwise direction, starting from anterior. Fractional chordal shortening was defined as the change in chord length from end diastole to end systole divided by the chord length at end diastole, expressed as a percentage. To permit assessment of regional performance independent of intraoperative changes in global function, each value for chordal shortening was normalized to the baseline (stage 1). The endocardial contour was subsequently subdivided into four segments (each encompassing 16 chords) representing the anterior, posterior, medial, and lateral walls of the left ventricle (Figure 1).

Two different reference systems, based on chordal shortening, were used for regional analysis. With the fixed, or external, frame of reference, the spatial relation between the end-diastolic and end-systolic contours was not altered (Figure 2). With the floating, or internal, frame of reference, the centers-of-area of the two contours were superimposed before computation of chordal shortening. In this way, the effects of cardiac translation (if present) on regional wall motion could be minimized.
FIGURE 2.  Schematic of the two reference systems used for regional left ventricular wall motion analysis based on chordal shortening. Outer circles represent endocardial borders at end diastole, and inner contours represent end-systolic borders. Regions of abnormal (dyskinetic) motion are represented by stippled arcs. True regional dysfunction that might occur after cardiac surgery is detected by both fixed and floating reference schemes (lower left). Pure cardiac translation unaccompanied by regional dysfunction also registers as abnormal using fixed but not floating reference system (lower right). (See text for details.)

An alternative method of regional left ventricular function, based on continuous curvature analysis, was also used. With this method, each digitized endocardial contour was resampled to create 64 equally spaced points. The curvature of each point was then estimated with a method developed in our laboratory. Briefly, the angle $\Psi_{(i)}$ was computed for each contour point from the intersection of adjoining line segments. Curvature, $k_{(i)}$, was then computed as the change in angle with respect to the change in segment length:

$$k_{(i)} = \frac{d \Psi_{(i)}}{ds}$$  \hspace{1cm} (1)

For discrete data, this process can be approximated by applying a differentiating digital filter to the set of angles computed at each contour point. This filter used standard techniques of finite impulse response digital design theory. The filter length and low-pass frequency cutoff were set to minimize noise while preserving contour shape information. To permit valid comparisons between endocardial contours of differing areas, all curvature values were normalized to global contour size as follows:

$$k_{(n)} = k_{(i)}/k_{(ref)}$$  \hspace{1cm} (2)

where $k_{(n)}$ and $k_{(i)}$ represent the relative and absolute curvatures at point $i$ on the contour and $k_{(ref)}$ represents the curvature of a reference circle whose circumference equals the endocardial contour perime-

ter. Normalized curvature values of less than 1 indicate flattening relative to the reference circle.

**Translational Vector Analysis**

To estimate the extent and direction of cardiac translation during each cardiac cycle, spacial movement of the center-of-area from end diastole to end systole was computed as a vectorial quantity for each surgical stage. In each patient, the vectors derived from the last five surgical stages were subtracted from that computed at baseline (stage 1) to help eliminate any apparent translation caused by preexistent regional wall motion abnormalities. The final result, hereafter known as the "translational vector," represents an index of the extent and direction of any translation that might occur during the course of the surgical procedure.

**Statistics**

Twenty-five patients were enrolled in the study. Of these, three were excluded due to an inability to obtain an optimal short-axis orientation, and one was excluded due to an incomplete surgical procedure. Statistical comparisons of mean values were performed with repeated-measures one-way and two-way analyses of variance (ANOVAs); multiple comparisons were made with Scheffe's and Newman-Keuls post hoc tests where appropriate. A one-sample Kolmogorov-Smirnov goodness-of-fit was used to test for uniform distribution of individual translational vector angles in each stage. A $p$ value of 0.05 was considered statistically significant. Values are given as mean±SD unless otherwise stated.

**Reproducibility of Measurement**

Measurement variability was assessed by randomly selecting 20% of patients for reanalysis by means of a random number table. Mean interobserver variability for fractional chordal shortening, computed in each region, was 6.7±5.6% with a fixed reference and 4.4±2.6% with a floating reference. Mean intraobserver variability was 11.5±8.3% with a fixed reference and 3.9±3.2% with a floating reference. For area ejection fraction, mean interobserver and intraobserver variabilities were 6.4±4.4% and 3.0±1.8%, respectively.

**Results**

**Preoperative Characteristics**

Baseline characteristics of the study population are given in Table 1. Mean patient age was 59.6 years. Approximately half of the patients had historical or electrocardiographic evidence of a prior myocardial infarction. Preoperative cardiac catheterization demonstrated an average of 2.3±0.7 vessels with significant stenoses in patients undergoing coronary surgery. Preexistent regional wall motion abnormalities were observed during contrast ventriculography in nine patients, with areas of involvement equally divided between the anterior and inferior regions of the left ventricle.
TABLE 1. Characteristics of Study Population

<table>
<thead>
<tr>
<th>Clinical</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients (n)</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Mean age (yr)</td>
<td>59.6±9.6</td>
<td></td>
</tr>
<tr>
<td>Men/women</td>
<td>16/5</td>
<td></td>
</tr>
<tr>
<td>Previous myocardial infarction (n) (%)</td>
<td>10 (48)</td>
<td></td>
</tr>
</tbody>
</table>

Catheterization

<table>
<thead>
<tr>
<th>Vessels with CAD (n)</th>
<th>2.3±0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ejection fraction (%)</td>
<td>54.9±9.7</td>
</tr>
<tr>
<td>Regional wall motion abnormalities (n) (%)</td>
<td>9 (43)</td>
</tr>
</tbody>
</table>

Surgical procedure performed (n) (%)

| Coronary                  | 18 (86) |
| Valvular                   | 2 (9)   |
| Both coronary and valvular | 1 (5)   |

CAD, number of vessels with >50% diameter narrowing in patients undergoing coronary artery surgery. Values are given as mean±SD.

(one patient exhibited both). The majority of patients (86%) underwent coronary artery surgery alone; surgery consisted of saphenous vein and/or internal mammary grafting. Two patients received prosthetic valves in both the mitral and aortic positions, and one underwent combined aortic valve replacement and coronary surgery. Although the small numbers involved precluded formal statistical analysis, the observed results appeared independent of the type of surgical procedure performed.

Intraoperative Global Ventricular Performance

Global left ventricular chamber size and systolic function were assessed during each surgical stage in each patient (Table 2). Overall, there was a slight decrease in area ejection fraction during the last two surgical stages (after cardiopulmonary bypass and chest closure, p<0.01). This decline in function resulted from both a slight decrease in end-diastolic area and a statistically nonsignificant increase in end-systolic area.

Intraoperative Regional Function Assessed by Chordal Shortening

The 16 chords representing each endocardial segment (anterior, posterior, medial, and lateral) were averaged to reflect overall motion in the four areas of the ventricle (Table 3). During the first four surgical stages (baseline to after pericardiotomy), mean fractional shortening varied little among regions with either reference system (maximum range, 31.6±39.2%, p=NS). However, marked differences in regional function were evident with a fixed reference immediately after the discontinuation of cardiopulmonary bypass (stage 5). Fractional shortening averaged 65.2±4.1% for the lateral wall but only 49.4±7.7% for the medial wall (p<0.0001). This same pattern of lateral hyperkinesis and medial hypokinesis and dyskinesis continued after chest closure but with an even more striking disparity between regions (76.8±10.7 versus −10.2±7.4%, respectively; p<0.0001). As shown in Figure 3, this regional difference was completely eliminated with the floating reference system (33.7±1.5% versus 31.6±2.4%, respectively; p=NS). In fact, with a floating reference, regional motion averaged from all 21 patients varied less than eight percentage points over all regions during the entire surgical procedure. In concert with these results was the appearance of dyskinetic chords in only the last two surgical stages and only with a fixed reference (Table 3).

The overall impact of the choice of reference system can be easily observed when the data are displayed in a graphic format (Figure 4). Mean fractional shortening values derived from the 21 patients are plotted for each of the 64 chords and for each surgical stage. As demonstrated in the top graph depicting the fixed reference system, the consistent, uniform wall motion observed in all regions during the first four surgical stages contrasts sharply with marked nonuniformity observed thereafter. Moreover, the extent and pattern of hypokinesis and dyskinesis seen with stages 5 and 6 in the medial wall (chords 40–55) closely mimic the pattern of hyperkinesis found with the lateral wall (chords 8–23). The lower graph clearly demonstrates that all apparent wall motion abnormalities in the final two surgical stages completely disappear when the same data are analyzed with a floating reference system.

Intraoperative Regional Function Assessed by Curvature Analysis

Curvature analysis permits the assessment of regional ventricular function independent of a frame

TABLE 2. Intraoperative Global Left Ventricular Size and Function

<table>
<thead>
<tr>
<th>Surgical stage</th>
<th>End-diastolic area</th>
<th>End-systolic area</th>
<th>Area ejection fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm²</td>
<td>%Δ baseline</td>
<td>cm²</td>
</tr>
<tr>
<td>1 (baseline)</td>
<td>22.6±10.0</td>
<td>0</td>
<td>10.1±6.2</td>
</tr>
<tr>
<td>2 (sternotomy)</td>
<td>21.8±9.6</td>
<td>−3.8±12.3</td>
<td>9.5±5.8</td>
</tr>
<tr>
<td>3 (sternal retraction)</td>
<td>21.5±9.4</td>
<td>−4.7±11.9</td>
<td>9.4±5.7</td>
</tr>
<tr>
<td>4 (pericardiotomy)</td>
<td>22.0±8.7</td>
<td>−2.9±17.0</td>
<td>9.7±5.4</td>
</tr>
<tr>
<td>5 (cardiopulmonary bypass)</td>
<td>20.9±9.4</td>
<td>−7.6±20.9</td>
<td>10.8±6.4</td>
</tr>
<tr>
<td>6 (chest closure)</td>
<td>19.5±9.8*</td>
<td>−13.9±19.4</td>
<td>11.1±6.7</td>
</tr>
</tbody>
</table>

Area, area contained within the short-axis endocardial contour; %Δ baseline, percent change to the baseline value (mean±coefficient of variation).

*p<0.01 versus baseline.

Values are given as mean±SD.
of reference. Accordingly, continuous measurement of normalized curvature was performed on each systolic contour. Mean curvature analysis data derived from all 21 patients are displayed in Figure 5, with each curve depicting one surgical stage. The mean systolic curvature can be seen to vary somewhat at different regions along the baseline (stage 1) curves (range, 0.82–1.15). More important, the curves for all five subsequent surgical stages closely parallel the baseline curve, which strongly suggests that regional wall motion as measured by this analysis technique remained at baseline throughout the entire procedure.

**Analysis of Translational Vectors**

Apparent intraoperative cardiac translation was analyzed through the use of vectors depicting spatial movement of the endocardial center-of-area from its end-diastolic to end-systolic position. As shown in Figure 6, this motion was minimal at baseline but quite evident throughout the cardiac cycle at the completion of the surgical procedure. A stage-by-stage summary of translational vectors for each patient is given in Figure 7. Note that the vectors were of low magnitude and randomly directed after the first three intraoperative events (stages 2–4). Immediately after the cessation of cardiopulmonary bypass (stage 5), medial systolic translation was apparent in nearly all patients. This phenomenon persisted after chest closure (stage 6). The average length of the individual vectors demonstrated a more than fourfold increase \( p<0.0001 \) between stages 4 and 5 (Table 4). Moreover, although the distributions of angles of these vectors were statistically random, during the first four stages \( p=NS \) a highly significant pattern of medial orientation was evident for stages 5 and 6 \( p<0.0001 \). These effects are best summarized by vectorally averaging the data from each individual patient, thereby incorporating measures of both magnitude and direction into one vector for each stage. The resulting mean translational vectors are shown in Figure 8.

**Discussion**

During the past 15 years, many studies have confirmed the frequent appearance of abnormal motion of the interventricular septum after uncomplicated cardiac surgery.\(^3,6,8–18\) The reported incidence of this interesting observation varies from 56% to 100%, with detection possible by a variety of imaging techniques, including cineangiography, radionuclide angiocardiography, and echocardiography.\(^3,9,10\) In general, the extent of this abnormality is not subtle, with many patients exhibiting frank paradoxical septal motion. Imaging studies performed within days or even hours of the completion of surgery have verified that this finding is present early in the postoperative period.\(^18\) Although altered septal motion may persist for life, several investigators have noted a tendency toward resolution when serial studies are performed over a period of months to years.\(^9,10,12\)
Several theories have been proposed to unify and explain these empirical observations. Evidence exists implicating localized myocardial ischemia in the pathogenesis of this phenomenon.\(^9\)\(^{20}\) Most studies, however, have been unable to corroborate this earlier work and have not reported electrocardiographic changes, myocardial enzyme release, or septal thallium perfusion defects in the vast majority of patients exhibiting this phenomenon. In addition, the high incidence and consistent pattern of altered septal motion coupled with its occurrence in surgical patients without coronary artery disease make this theory even less plausible. Many other factors are known to affect septal motion, including right ventricular volume overload, altered transseptal pressure gradient, and large pericardial effusion.\(^12\)\(^{20}–^{22}\) but none of these would be anticipated in the majority of postoperative patients.

More recent studies with standard postoperative echocardiography have revealed that reduced motion of the interventricular septum is regularly accompanied by increased contraction of the posterior wall.\(^6\)\(^{14}\) Furthermore, the extent of systolic thickening of the septum generally remains normal despite its paradoxical movement.\(^6\)\(^{12}\) These findings raise the possibility of global cardiac movement within the chest during systole, with the diminished motion of the septum an apparent artifact of imaging the heart from a fixed point of reference such as the outer chest wall. Kerber and Litchfield postulated that this “total cardiac motion” resulted from fixation of the heart anteriorly by septal cardiac adhesions.\(^12\) This

**Figure 3.** Frame-by-frame wall motion analysis from a representative patient recorded after completion of surgical procedure (stage 6). Time is shown on x axis, chord number around endocardial perimeter on y axis, and inward motion on z axis. Fixed reference analysis demonstrates medial akinesis (chords 40–55) and lateral hyperkinesis (chords 8–23) at end systole (left), an effect not observed with a floating reference (right).

**Figure 4.** Mean regional fractional shortening from all 21 patients shown for each of 64 chords. Regional wall motion analyzed by fixed reference scheme (top) is uniform for first four surgical stages but shows marked and reciprocal regional abnormalities during the two stages that follow cardiopulmonary bypass. All apparent abnormalities disappear when same data are analyzed with floating reference scheme (bottom).
explanation is inconsistent, however, with the identification of altered septal motion within hours of surgery\textsuperscript{18} and the tendency toward resolution with time.\textsuperscript{9,10,12}

It is logical that pericardium may play an important role in minimizing global movement of the heart. Indeed, paradoxical septal motion is often seen in patients lacking a pericardium, either due to its congenital absence or to its surgical removal for treatment of constrictive pericarditis.\textsuperscript{6} Some researchers have suggested that the pericardiotomy required for most cardiac surgical procedures effectively removes the restraining forces of the pericardium, allowing the heart to shift in an anteromedial direction during each cardiac cycle.\textsuperscript{9,11} However, three independent studies have failed to show any correlation between the frequency or severity of altered septal motion and the presence of surgical closure of the pericardium.\textsuperscript{3,12,18}

The most recent theory, advocated by Force et al,\textsuperscript{6} implicates the disruption of the structures in the anterior mediastinum that follows median sternotomy. This loss of extracardiac constraint permits the heart to shift anteriorly during systole. With time, postoperative adhesions could gradually replace disrupted mediastinal structures, accounting for the time-dependent resolution of altered septal motion shown in several studies.\textsuperscript{9,10,12} Although appealing, there are no direct data to support this theory. In general, previous studies investigating the mechanism of postoperative altered septal motion have analyzed imaging data obtained days to weeks after surgery. Data derived from this one point in time are obviously limited in their ability to elucidate the underlying mechanism, as the influences of all intra-operative processes remain obscure. We theorized that continuous imaging throughout surgery may help validate or repudiate the theories of pathogenesis discussed above. Intraoperative two-dimensional transesophageal echocardiography was chosen for several reasons.\textsuperscript{23} First, continuous imaging spanning the initiation and termination of surgery is possible. Second, image quality is generally excellent, without the interposition of bone or lung tissue that may limit the transthoracic approach. Third, the operative field is not cluttered by equipment or additional personnel, and the operation can proceed without interruption. Finally, fixed positioning of the transducer within the esophagus ensures a near-constant orientation and imaging plane.

Visual analysis of our data revealed new or worsened septal motion abnormalities in all 21 patients after the completion of their surgical procedures (stage 6). This incidence rate is higher than in many studies, possibly due to the occurrence of imaging immediately after surgery and to the use of two-dimensional imaging to identify mediolateral motion abnormalities that may have been missed by prior M-mode studies. Quantitative analysis of endocardial wall motion with a fixed frame of reference confirmed the visual impression. By stage 6, frank dyskinesis was seen in 16 patients (76%) and involved an average of 29.7%
of the endocardial perimeter. Overall, maximum dyskinesis was observed in chord 50 located in the posterior septum (281° from anterior), with a mean fractional shortening of -17.4%. Inspection of Figure 4 reveals that this pattern of hypokinesis and dyskinesis seen in stage 6 in the medial wall is closely mirrored by the hyperkinesis present in the lateral wall. This pattern would be expected if global heart motion or cardiac translation was responsible for the abnormalities observed. When the apparent effects of translation were removed by the superimposition of systolic and diastolic centroids (Figure 4), mean wall motion in all regions returned to the presurgical state. Although the lack of fixed anatomical fiducial points in our images precluded attempts at correcting cardiac rotation, previous research has shown this to be only a minor contributor to overall motion.24

Most regional analysis techniques that rely on endocardial motion require a frame of reference that may distort the results. Although our data suggest that the floating reference is superior to the fixed reference in the assessment of the postoperative cardiac patient, this technique may display a slight tendency to minimize or mask true wall motion abnormalities.24,25 Endocardial curvature analysis is not subject to this source of error because no reference frame is required.21,26,27 In our patients, mean systolic curvature at baseline varied as much as 33.2% along the endocardial perimeter. However, Figure 5 shows the strong tendency of regional curvature to track the true baseline curve in all surgical stages with a maximum of 22.5% deviation (mean, 6.6±5.1% deviation) from baseline in any stage and at any point along the endocardial contour. This observation speaks strongly against true regional wall motion abnormalities in the genesis of postoperative altered septal motion.

**FIGURE 7. Translational vectors for each patient after each surgical stage. All vectors are corrected for baseline motion. A, anterior; L, lateral; M, medial; P, posterior. (See text for details.)**

**TABLE 4. Length of Translational Vectors**

<table>
<thead>
<tr>
<th>Surgical stage</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual translational vectors (mm)</td>
<td>1.0 ±0.5</td>
<td>1.0 ±0.5</td>
<td>1.0 ±0.9</td>
<td>4.6 ±2.9*</td>
<td>5.2 ±3.0*</td>
</tr>
<tr>
<td>Mean translational vectors (mm)</td>
<td>0.6</td>
<td>0.3</td>
<td>0.2</td>
<td>4.3</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Individual translational vectors refer to mean length of each vector derived from all patients irrespective of angle. Mean translational vector length represents the vectoral mean of each individual vector in each stage, incorporating both angle and length. This later measurement produces one value for each stage; hence, standard statistical comparisons are not relevant.

*p<0.0001 compared with either stage 2, stage 3, or stage 4.
Analysis of regional myocardial thickening during systolic contraction provides an alternative technique for the assessment of regional function independent of one anatomical reference. Visual assessment of systolic thickening in our population demonstrates no change in any region throughout the entire procedure. However, marginal epicardial image definition in many patients, particularly at the medial and lateral walls, precluded quantitative comparison. This problem is often the limiting factor in the use of this technique and has prevented its widespread application.

We have applied the concept of vectorial analysis to help quantitate cardiac translation and pinpoint its onset. The resulting translational vector incorporates measures of direction and magnitude of apparent global movement of the heart from end diastole to end systole relative to its baseline presurgical state. Figure 7 displays these vectors for each patient at each surgical stage. After sternotomy, sternal retraction, and pericardiotomy, the vectors were of low magnitude (mean, 1.0±0.6 mm) and randomly directed. After cardiopulmonary bypass, mean vector length increased markedly (4.6±2.9 mm, p<0.0001). This pattern remained after chest closure (mean, 5.2±3.0 mm) with all vectors directed medially (mean, 271±6° from anterior). Hence, removal of potential restraints of cardiac motion by sternotomy or pericardiotomy did not result in cardiac translation. Moreover, all translation observed after the completion of surgery developed during cardiopulmonary bypass.

At first glance, these results appear in conflict with two recent studies that also used intraoperative imaging. Schnitger et al found normal septal motion during the entire surgical procedure in all patients using M-mode echocardiography, with abnormal motion universally present 6 hours postoperatively. Using two-dimensional echo imaging, Feneley et al performed similar studies with the uniformly normal septal motion documented just before chest closure often becoming paradoxical within 2 hours of surgery. Why the onset of altered septal motion should be limited to the early postoperative period was not addressed in these studies. However, in both investigations the ultrasonic transducer was placed in direct contact with the heart for all intraoperative imaging. By permitting the transducer to move with the beating heart, this arrangement effectively eliminated the opportunity to uncover any cardiac translation that might occur. This problem was circumvented in the present study by using a fixed extracardiac reference (i.e., the esophagus) for all imaging.

The results of our study provide important insights into the mechanism underlying altered septal motion. We observed the preservation of baseline wall motion patterns throughout the early operative period, including after incision and retraction of the anterior mediastinal contents and pericardium. Hence, it is doubtful that these structures "restrain" global heart movement as previously theorized. In contrast, marked changes in apparent wall motion were evident within seconds of reestablishing sinus rhythm after cardiopulmonary bypass. This observation appeared to be independent of the type of surgery performed. Therefore, this phenomenon is directly related to the use of cardiopulmonary bypass or surgical manipulations that occur during this time period. Support for our findings can be derived from Akins et al. These investigators used radionuclide ventriculography to study interventricular septal motion in 22 patients undergoing one-vessel coronary artery surgery. All 11 individuals receiving cardiopulmonary bypass developed altered septal motion despite the use of two different myocardial preservation techniques; this compares with one of the 11 patients whose procedure did not include cardiopulmonary bypass. Although this study has been criticized on methodological grounds, the results are nevertheless impressive.

Why the events occurring during cardiopulmonary bypass should regularly lead to apparent cardiac translation cannot be resolved from the present study. This situation does not appear to reflect bypass time or preservation techniques, and the effect does not appear to be cumulative as no additional disturbance in septal motion was apparent in three additional patients studied with our technique during a second cardiac surgical procedure. Classic intraoperative ischemia seems an unlikely cause as only one patient in our series exhibited transient ST deviation during imaging. The potential role of cardiac manipulation and site of conduit anastomoses remain to be determined. It seems likely, however, that the use of cardiopulmonary bypass is an obligatory step in the genesis of classic postoperative altered septal motion.

**Figure 8.** Mean translational vectors for each stage, representing vectorial averages derived from all 21 patients. (See text for details.)
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References

Key Words: regional wall motion analysis • left ventricular function • interventricular septum • echocardiography, transesophageal • surgery
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