Regional Functional Depression Immediately After Ventricular Septal Defect Closure

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Left ventricular ejection is depressed immediately after repair of ventricular septal defect (VSD). Postrepair functional depression seen after VSD closure could result from a reduction in preload. However, other mechanisms could be at work. Functional depression could also be caused by closure of a low-impedance path for left ventricular ejection, the introduction of a stiff akinetic patch, or the operation itself. We reasoned that functional depression mediated by changes in preload or afterload should symmetrically affect end-diastole and end-systole, whereas depression resulting from changes in septal mechanics should be localized. We, therefore, performed segmental wall-motion analysis on intraoperative echocardiograms from patients undergoing VSD and atrial septal defect repair. After VSD closure, there was an asymmetric change in left ventricular end-systolic segment length and a decrease in fractional segment shortening localized to the septal and lateral walls, whereas patients with atrial septal defect had a symmetric increase in fractional shortening. These results suggest that acute functional depression after VSD repair is a result of localized impairment of septal function. (J Am Soc Echocardiogr 2004;17:1066-72.)

We recently reported that left ventricular (LV) ejection monitored by intraoperative transesophageal echocardiography (TEE) was depressed immediately after repair of ventricular septal defect (VSD) but enhanced immediately after repair of atrial septal defect (ASD).[1] One possible explanation for postrepair functional depression in patients with VSD is that an acute intraoperative reduction in LV preload resulting from VSD closure reduces ejection by the Frank-Starling mechanism. This argument is supported by a reduction in echocardiographically measured LV end-diastolic (ED) area (EDA) associated with a reduction in area ejection fraction (EF_a) after VSD closure.[1] A second possibility is that closure of a low-impedance path for LV ejection effectively increases outflow resistance, thus, increasing afterload and depressing ejection.[2] Yet another possibility is that the operation itself or the mechanical properties of the patch used for closure directly impair contraction of septal myocardium.[3,4]

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We reasoned that functional depression mediated by changes in preload or afterload should symmetrically affect ED and end-systole (ES), whereas depression resulting from changes in septal mechanics should be localized, having an asymmetric effect. As an extension of previously unpublished data from this laboratory, we investigated the hypothesis that the decrease in LV function after VSD closure is a result of septal impairment, by conducting segmental wall-motion analysis on intraoperative TEE data from 13 patients undergoing VSD repair. As a comparison group, we also studied 12 patients undergoing ASD repair.

We believe that definition of the regional effects of surgical VSD repair will improve understanding of its implications to LV mechanics and help determine whether changes in surgical technique or patch material properties can help preserve postoperative function.

METHODS

This study was approved by our institutional review board and performed in accordance with our good clinical practice guidelines. Informed consent was obtained from each patient's legal guardian.

Intraoperative Data Acquisition

LV endocardial motion was studied using 2-dimensional TEE in 13 pediatric patients (7 female; 0.3-4.8 years) undergoing surgical correction of VSD by Gore-Tex patch

Table 1 Patient data and bypass variables

	N	Age (y)	BSA (m^2)	CPB (min)	X-clamp (min)	Temp (°C)
VSD	13	1.3 ± 0.4	0.37 ± 0.03	61 ± 4	35 ± 4	33 ± 1
ASD	12	6.5 ± 2.0	0.92 ± 0.18	42 ± 5	22 ± 4	35 ± 1

ASD, Atrial septal defect; *BSA*, body surface area; *CPB*, duration of cardiopulmonary bypass; *Temp*, minimum esophageal temperature; *VSD*, ventricular septal defect; *X-clamp*, duration of aortic cross clamping.
Values are mean ± SEM.

(W.L. Gore & Associates, Flagstaff, Ariz) closure. As a comparison group, 12 pediatric patients undergoing primary ASD closure (6 female; 0.7-23.2 years) were also studied. Patients were anesthetized with isofluorane and supplemental agents as needed. Ascending arch and bicaval venous cannulation for cardiopulmonary bypass (CPB) and 1:1 blood cardioplegia were used in all cases. Intraoperative TEE short-axis cross sections at the level of the papillary muscles were obtained immediately before and after CPB for patients who were hemodynamically stable and not on inotropic agents. The images were obtained using either one of two ultrasound systems (Sonos 5500, Hewlett-Packard Co, Palo Alto, Calif; or VingMed CFM800, GE Medical Systems, Milwaukee, Wis) and recorded on videotape. A log of significant intraoperative events that could affect cardiac function, including CPB time, cross-clamp time, exogenous fluid administration, and use of inotropic agents, was also recorded. Patients with other hemodynamically significant defects or in whom inotropic agents were administered were excluded from this study. Group characteristics are presented in Table 1.

Data Analysis

Using a VingMed CFM800 (GE Medical Systems), 3 cardiac cycles from before and after defect closure were chosen for each patient. For each beat, ED was chosen as the frame with the largest LV cross-sectional area and ES as the frame with the smallest. The LV endocardial borders were delineated by manual planimetry, in accordance with standards set by the American Society of Echocardiography.[5] These frames were then digitized for analysis on a personal computer (Dell Computer Corp, Round Rock, Tex). Using routines developed in Matlab (The MathWorks Inc, Natick, Mass), EDA and ES area (ESA) were measured and stroke area (SA) was calculated as the difference between the two:

$$SA = EDA - ESA \quad (1)$$

EF_a was then calculated from these:

$$EF_a = \frac{SA}{EDA} \times 100 \quad (2)$$

For each patient, EDA, ESA, and SA were normalized by dividing by body surface area and the 3 beats averaged. The results were then averaged over each patient group.

Segmental analysis was then performed on the selected frames in Matlab (The MathWorks Inc), as seen in the example from one cardiac cycle from before and after VSD closure in Figure 1. A total of 100 evenly spaced radial chords were generated from the centroids of the traced endocardial border and numbered clockwise so that chord 1 intersected with the midpoint of the posterior wall, 25 the midlateral wall, 50 the midanterior wall, and 75 the midseptum. The midpoint of the posterior wall was visually estimated for each image. The ED and ES borders for each cardiac cycle were then superimposed on each other by aligning their centroids (floating centroid method[6]). Any rotation of the heart during contraction was corrected for by aligning the first ED and ES radial chord. The ED and ES length of each chord was recorded and the change in length from ED to ES (chord shortening) was calculated as the difference between the two. Fractional shortening of each chord from ED to ES was calculated by dividing the chord shortening by ED chord length. Again, the 3 beats were averaged for each patient, chord length and shortening were normalized by dividing by body surface area, and the results averaged over each patient group.

Statistical Analysis

Differences in EDA, ESA, SA, and EF_a before and after defect closure were compared using a 2-tailed paired Student *t* test. Chord lengths, chord shortening, and fractional shortening were compared at the midposterior, lateral, anterior, and septal walls using repeated measures analysis of variance to determine whether there was significant regional variation of these variables. Change in these variables with closure was compared at the same 4 locations using analysis of variance to determine whether regional variation was significant. Post-tests were performed when appropriate by *t* test with the Bonferroni correction for multiple comparisons. All data were analyzed using software (InStat 2.0, GraphPad Software Inc, San Diego, Calif). Significance was defined as a *P* value less than .05 for all tests. Values were reported as mean ± SEM.

RESULTS

Patients with VSD showed a significant decrease in EDA, SA, and EF_a immediately after closure, whereas patients with ASD showed an increase in these parameters, as presented in Table 2.

A representative example of segmental analysis from a patient undergoing VSD repair can be seen in

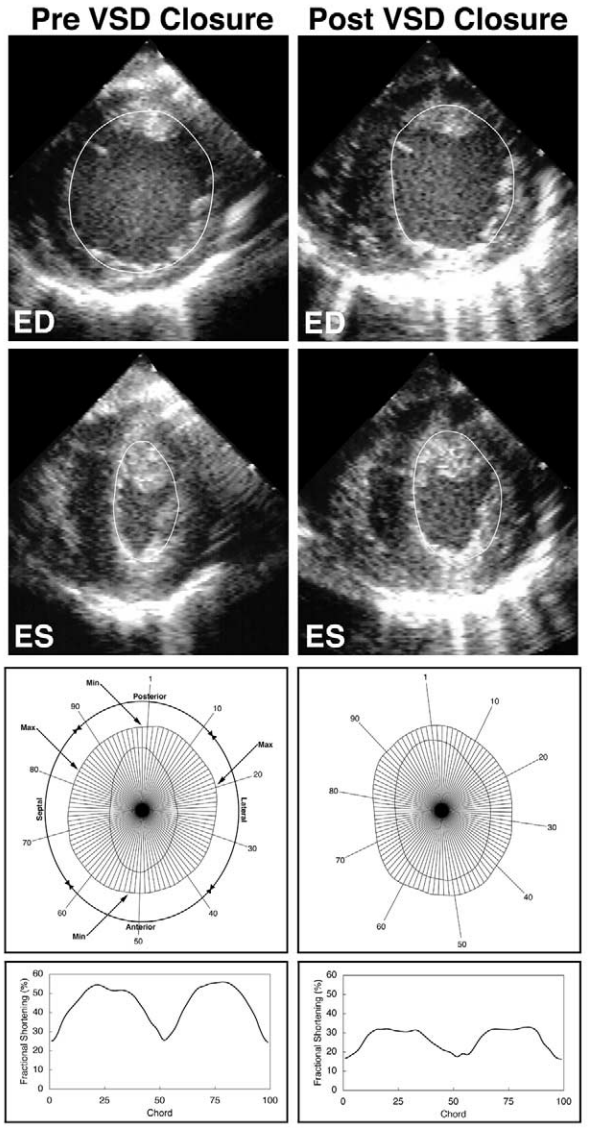

Figure 1 Representative segmental wall-motion analysis from patient undergoing ventricular septal defect (VSD) repair before (*left*) and after (*right*) closure. *Upper two panels*, Traced left ventricular endocardial borders at end-diastole (ED) and end-systole (ES). Note symmetric change in ED chord length compared with asymmetric change in ES chord length with defect closure. *Third panel*, Radial chords generated from aligned centroids of superimposed borders. Areas considered to be posterior, lateral, anterior, and septal walls are shown, as are chords of local maximal (*Max*) and minimal (*Min*) fractional shortening before VSD closure. *Fourth panel*, Regional distribution of fractional shortening of each chord from ED to ES. Note decrease in fractional shortening in midseptal and lateral walls.

Figure 1. One sees that there was a symmetric change in ED chord length after operation whereas the change in ES chord length was asymmetric, with the septal and lateral chords increasing in length. This meant a reduced fractional shortening in the septal and lateral walls.

The mean indexed ED and ES chord lengths and chord shortening for the VSD group (±SEM) are presented in Figure 2. VSD closure had a symmetric effect on ED and an asymmetric effect on ES. In all cases, chord lengths were smaller in the septal and lateral than the anterior and posterior walls, representing an elliptical cross section. Examining the change in chord length with repair, there was a symmetric decrease in ED chord length, whereas there was regional variation in the change in ES chord length. The septal and lateral wall chords increased in length whereas there was little to no change in the length of the posterior and anterior chords, so ES shape became slightly more circular. This meant that before VSD closure, there was greater chord shortening in the septal and lateral than the anterior and posterior walls, whereas after operation, there was no longer a regional difference in chord shortening; chord shortening decreased more in the septal and lateral walls. Mean values at the midposterior, lateral, anterior, and septal walls before and after VSD closure are given in Table 3.

The mean values of fractional shortening for the VSD and ASD groups (±SEM) are presented in Figure 3. The depression in function after VSD closure was asymmetric, with the greatest decrease localized to the septal and lateral wall segments. Before VSD repair, fractional shortening was greater in the septal and lateral than the anterior and posterior walls. After repair, fractional shortening was still greater in the septal and lateral walls, however, the decrease was significantly greater at these points, resulting in a more uniform regional distribution of fractional shortening. The ASD group showed similar fractional shortening in all areas, with a symmetric increase after defect closure. Mean values at the midposterior, lateral, anterior, and septal walls before and after defect closure are given in Table 4.

DISCUSSION

We analyzed LV function using intraoperative echocardiographic short-axis images for patients undergoing closure of VSD and ASD. Decrease in fractional shortening after VSD closure was greatest in the septal and lateral wall segments. At the same time, after defect repair there was an asymmetric change in ES chord length whereas ED chord lengths changed symmetrically. In the patients with ASD, however, the increase in fractional shortening was symmetric. This suggests that acute functional depression after VSD repair is a result of localized impairment of LV function, whereas improvement

Table 2 Intraoperative echocardiographic and hemodynamic parameters

		HR (beats/min)	EDA* (cm^2/m^2)	ESA* (cm^2/m^2)	SA* (cm^2/m^2)	EF_a (%)
VSD	PRE	130 ± 5	20.5 ± 2.2	8.5 ± 1.0	12.0 ± 1.4	59 ± 2
	POST	138 ± 5	17.4 ± 2.0†	9.2 ± 1.0	8.2 ± 1.1†	47 ± 2†
ASD	PRE	126 ± 9	9.2 ± 0.7	4.4 ± 0.4	4.8 ± 0.5	52 ± 3
	POST	128 ± 13	11.4 ± 0.5†	4.9 ± 0.5	6.5 ± 0.5†	60 ± 3†

ASD, Atrial septal defect; *EDA,* end-diastolic area; EF_a, area ejection fraction; *ESA,* end-systolic area; *HR,* heart rate; *POST,* postdefect closure; *PRE,* predefect closure; *VSD,* ventricular septal defect.
*Normalized by body surface area (m^2); †$P < .05$ versus PRE.
Values are mean ± SEM.

for patients with ASD is a global effect. Furthermore, we suggest that the observed regional depression seen for patients with VSD is caused by depression of septal function.

LV Preload

After VSD repair, reduced preload from a decrease in LV volume could explain LV functional depression. In our previous study, depressed EF_a immediately after VSD repair was associated with reduced EDA, whereas improved EF_a was associated with increased EDA after ASD closure, suggesting that changes in preload were the primary determinant of changes in function immediately after VSD closure.[1] This is in agreement with a previous study showing decreased LV ejection fraction along with a decreased ED volume 1 week after corrective operation for VSD.[4] With a change in preload, one would expect that changes in ED and ES shape would be the same. However, segmental analysis in this study found an asymmetric change in ES chord length with a symmetric change in ED chord length. At the same time, postrepair fractional shortening along the septal-lateral wall dimension was depressed to a far greater extent than along the anterior-posterior dimension. Under abnormal loading conditions before VSD closure regional fractional shortening was heterogeneous and after VSD closure it moved toward a regionally homogeneous pattern of contraction. In the patients with ASD, however, there was a symmetric change in fractional shortening. Therefore, preload can account for the change in contraction seen in the VSD group only if ventricular shape changes during contraction are strongly preload dependent. Available data on the preload dependence of LV shape changes are, therefore, discussed briefly below.

Preload Dependence of LV Shape Changes

In a study by Olsen et al[7] it was found that dynamic shape changes in conscious dogs do in fact depend on preload. Considering the shape of the ventricle in long-axis section, they described linear relationships between an index of shape and volume in both diastole and systole. The two relationships intersected in the normal working volume range of the canine ventricle, with the result that canine LV

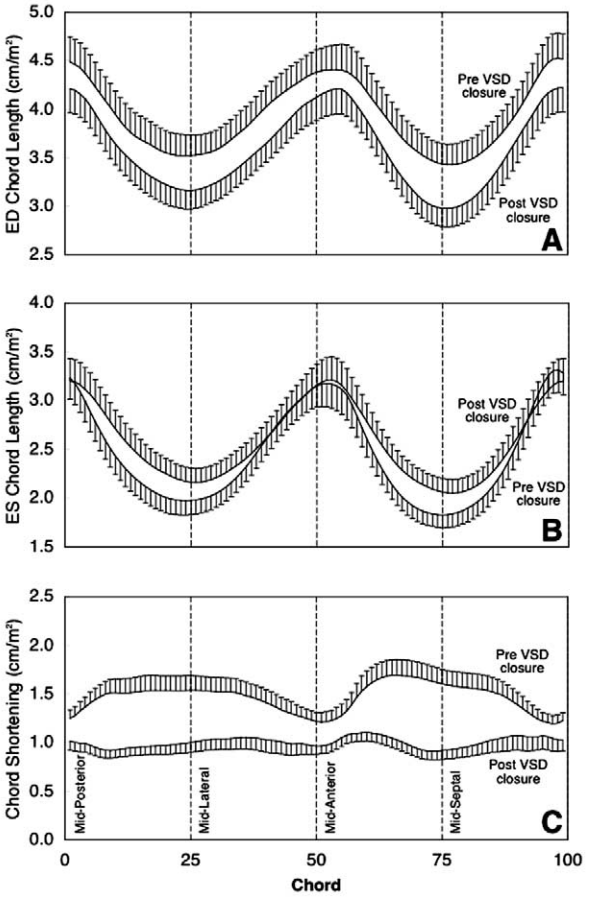

Figure 2 End-diastolic (ED) and end-systolic (ES) chord length and chord shortening before and after ventricular septal defect (VSD) closure presented as mean ± SEM. Midpoints of posterior, lateral, anterior, and septal walls are indicated by *vertical dashed lines.* **A,** With closure there was symmetric decrease in ED chord length. **B,** There was regional variation in change in ES chord length with repair; septal and lateral wall chords increased in length whereas there was little to no change in length of posterior and anterior chords. **C,** Before closure there was greater chord shortening in septal and lateral walls, which disappeared with repair.

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Table 3 End-diastolic and end-systolic chord length and chord shortening in patients with ventricular septal defect at the midposterior, lateral, anterior, and septal walls

	ED chord length* (cm/m^2)				ES chord length* (cm/m^2)			
	Post	**Lat**	**Ant**	**Sept**	**Post**	**Lat**	**Ant**	**Sept**
PRE	4.5 ± 0.3	3.5 ± 0.2†	4.4 ± 0.2	3.4 ± 0.2†	3.2 ± 0.2	2.0 ± 0.2†	3.2 ± 0.2	1.8 ± 0.1†
POST	4.2 ± 0.3	3.2 ± 0.2†	4.1 ± 0.2	3.0 ± 0.2†	3.2 ± 0.2	2.2 ± 0.2†‡	3.1 ± 0.2	2.1 ± 0.1†‡

Ant, Midanterior wall; *ED,* end diastolic; *ES,* end-systolic; *Lat,* midlateral wall; *Post,* midposterior wall; *POST,* postdefect closure; *PRE,* predefect closure; *Sept,* midseptal wall.
*Normalized by body surface area (m^2). †$P < .05$ versus post and ant; ‡$P < .05$ for change with closure versus post and ant.
Values are mean ± SEM.

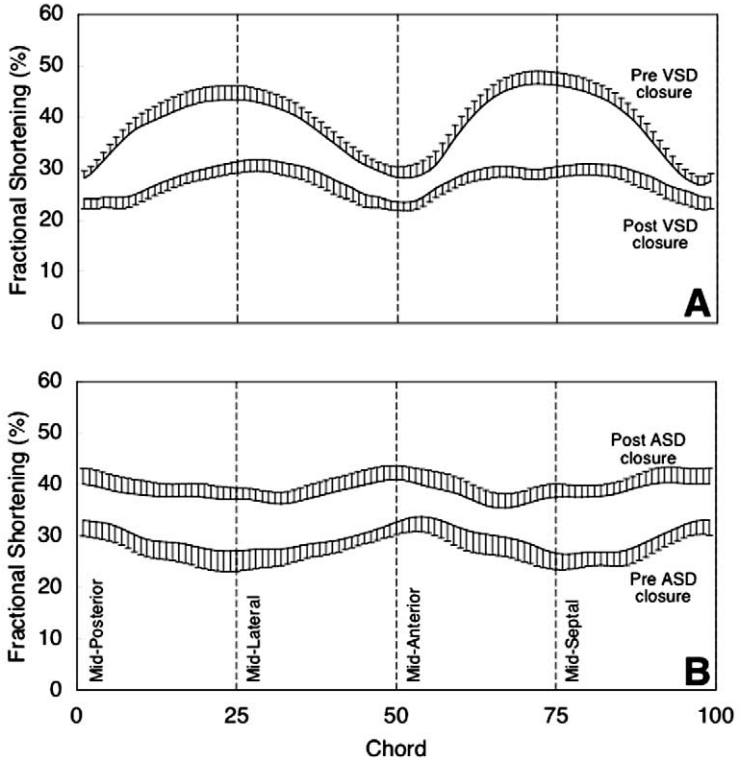

Figure 3 Fractional shortening before and after ventricular septal defect (VSD) and atrial septal defect (ASD) closure presented as mean ± SEM. Midpoints of posterior, lateral, anterior, and septal walls are indicated by *vertical dashed lines.* **A,** Before VSD closure there was greater fractional shortening in septal and lateral walls, which became more uniform after repair. **B,** With ASD closure there was symmetric increase in fractional shortening.

Table 4 Fractional shortening in patients with ventricular and atrial septal defects at the midposterior, lateral, anterior, and septal walls

	VSD fractional shortening (%)				ASD fractional shortening (%)			
	Post	**Lat**	**Ant**	**Sept**	**Post**	**Lat**	**Ant**	**Sept**
Pre	28 ± 1	43 ± 3*	28 ± 2	46 ± 2*	33 ± 3	27 ± 4	33 ± 2	27 ± 3
Post	24 ± 2	31 ± 2†*	24 ± 2	30 ± 2†*	40 ± 3	37 ± 2	41 ± 3	38 ± 3

Ant, Midanterior wall; *ASD,* atrial septal defect; *Lat,* midlateral wall; *Post,* midposterior wall; *POST,* postdefect closure; *PRE,* predefect closure; *Sept,* midseptal wall; *VSD,* ventricular septal defect.
*$P < .05$ versus post and ant; †$P < .05$ for change with closure versus post and ant.
Normalized by body surface area (m^2).
Values are mean ± SEM.

Table 3 Continued

Chord shortening* (cm/m²)			
Post	**Lat**	**Ant**	**Sept**
1.3 ± 0.1	1.5 ± 0.1†	1.2 ± 0.1	1.6 ± 0.1†
1.0 ± 0.1	1.0 ± 0.1‡	1.0 ± 0.1	0.9 ± 0.1‡

became more elliptical when contracting from a large ED volume but more circular when contracting from a small ED volume.

Our findings could be explained by a similar set of relationships operating in the short-axis section. However, previous studies provide no evidence for the necessary preload-dependent short-axis shape changes. In conscious dogs, Olsen et al[8] found distinct linear relationships between septal-lateral and anterior-posterior diameters in diastole and systole. However, these curves did not intersect over the wide volume range studied and predicted short-axis ellipticalization during contraction from any ED volume. In 77 normal, pressure-overloaded, and volume-overloaded children, Villoria et al[9] found preload-dependent ellipticalization in long-axis section but no difference between shortening in the two short-axis dimensions.

LV Afterload

Increased afterload caused by closure of a low-impedance left-to-right outflow path during VSD repair could also explain LV functional depression.[2] With increased afterload, one would have expected that ES chord length would have increased symmetrically. We observed an asymmetric increase in ES chord length, however, suggesting instead a local effect of VSD closure on contraction.

Septal Function

A less complex explanation of our results is that septal function was directly impaired as a consequence of surgical repair of VSD.[3,4] The insertion of the akinetic and relatively stiff Gore-Tex patch (W.L. Gore & Associates) into the septum could increase the afterload (wall stress) placed on adjacent myocardium and reduce shortening. A shift in the transseptal pressure gradient after repair may alter the curvature of the septum and thereby also alter the stress on the myocardium. The insertion of the patch could also cause a change in septal compliance. Finally, local damage from suture placement could account for reduced septal motion after closure.

Methodologic Considerations

A floating centroid was used for segmental analysis in this study because it best corrects for expected large translational motion associated with CPB.[6,10] However, Wiske et al[6] showed that when assessing regional wall motion with hypokinesia of one region a floating centroid was drawn toward the abnormal segment, diminishing the extent of abnormal motion and projecting it to the contralateral wall. Thus, the similar extent of fractional shortening observed in the septal and lateral wall, and the anterior and posterior wall, in this study could have been a result of the floating centroid; more of the shortening may have been in one wall than the other. Patterns of heterogeneous radial shortening have been observed in normal hearts by Moore et al,[11] who reported greater radial inward displacement in the lateral wall than the septum. During contraction the lateral wall forces blood directly toward the septum, so lateral wall shortening might have been further enhanced by the presence of a low-impedance VSD shunt. In this case, closure could have reduced motion in the septal-lateral wall direction by reducing primarily lateral wall rather than septal contraction. Shape-based analysis[12] looking at local curvature of these regions will be required to further establish the region or regions responsible for the changes observed.

Limitations and Sources of Error

In our experience, the use of TEE can result in some ellipticalization of the LV cross-section due to foreshortening when compared to optimally oriented epicardial echocardiography. While acquiring the echocardiographic images during operation, all efforts were made to optimize the imaging plane in order to minimize this effect, some foreshortening may still have occurred. As well, care was taken to ensure that the TEE short-axis section was at the same anatomic location in the ventricle in each patient. Since cross-sectional contraction has been shown to vary depending on the location of the image in the ventricle,[13] errors in positioning could have produced errors in the observed pattern of contraction. At the same time, the location of the defect on the septum in relation to the location of the short-axis section would affect how much of the defect or patch's effect on wall motion was observed in the echocardiographic image. Unfortunately, no information was available on the location of each patient's VSD.

The size of the defect and resulting left-to-right shunt affects LV ED volume[14,15] and fractional shortening of the LV dimension.[16] So this, and the size of the patch necessary for closure, may influence the degree of change in wall motion seen after operation. In the children studied, however, no quantitative data was available about the size of the defect or shunt, or the size of the patch required for repair, so the results could not be normalized for these variables.

Conclusion

We performed segmental wall-motion analysis on intraoperative echocardiographic data from patients undergoing surgical correction for VSD and ASD. After VSD closure there was a symmetric change in LV ED segment length whereas ES segment length changed asymmetrically. This meant a decrease in wall motion localized to the septal and lateral wall segments. In the patients with ASD, there was a symmetric increase in fractional shortening after repair. From these results we suggest that acute functional depression after VSD repair is caused by localized impairment of septal function as a result of the placement of the repair patch or the operation itself. Further work is needed to better localize the observed regional functional depression and to determine whether changes in surgical technique or patch material properties can preserve function after VSD repair.

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