Regional Comparison of Midwall Segment and Area Shortening in the Canine Left Ventricle

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SUMMARY. We used ultrasonic segment length gauges to examine the regional behavior of midwall fibers at different sites around the left ventricular minor axis in 12 anesthetized dogs. In six dogs (group I) with circumferentially oriented midwall gauges, significantly greater shortening of anterior than lateral or posterior wall segments was demonstrated over a range of left ventricular end-diastolic pressures from 2 to 18 mm Hg. Normalized end-diastolic segment lengths increased more in the anterior wall as end-diastolic pressure increased, suggesting that regional differences in diastolic distensibility may in part account for the observed shortening differences. To examine the extent to which shortening of longitudinally oriented fibers of the subendocardium and subepicardium might influence the behavior of the midwall circumferential fibers, we implanted mutually perpendicular midwall gauges circumferentially and longitudinally in the anterior and posterior walls in six dogs (group II). Longitudinal shortening of midwall fibers was negligible at low end-diastolic pressures, but increased significantly at higher end-diastolic pressures. In the anterior wall, there was greater circumferential than longitudinal shortening, whereas, in the posterior wall, shortening was similar in the two directions. Finally, we calculated the midwall area subtended by the mutually perpendicular gauges and found the systolic change in midwall area to be similar for the anterior and posterior walls at all end-diastolic pressures. We conclude that midwall fibers demonstrate considerable nonuniformity of contraction at different sites around the minor axis. This finding may be related in part to regional differences in diastolic distensibility or in functional interactions between fiber layers. Despite these complex regional, directional, and volume dependent differences in midwall segment function, the systolic changes in midwall area did not vary regionally. Thus, different midwall sites around the minor axis circumference appear to have similar overall contributions to the ejection of blood. (Circ Res 58: 678–691, 1986)

THE left ventricle is composed of fibers which are oriented predominantly in the circumferential direction in the midwall and in the longitudinal direction in the subepicardium and subendocardium (Streeter et al., 1969). Inasmuch as there are many more circumferential than longitudinal fibers, the left ventricle is often conceived functionally in terms of shortening of these circumferential or hoop axis fibers. This concept is well supported by studies demonstrating that the predominant direction of left ventricular shortening (Hawthorne, 1961; Ross et al., 1967; Herman et al., 1967; Hinds et al., 1969; Tsakiris et al., 1969; Rankin et al., 1976) and work (Gould et al., 1976; Bove et al., 1978; Phillips et al., 1982) is circumferential.

The current study was designed to examine more carefully the behavior of these important circumferential fibers by directly measuring their shortening at several midwall sites around the minor axis circumference. We were particularly interested in the minor axis level because several indices of systolic function estimate the amount of circumferential shortening at this level by measuring the resultant shortening of an internal diameter, radius, or minor axis chord. Although considerable nonuniformity of contraction has been demonstrated by techniques such as left ventriculography (Liedtke et al., 1973; Sniderman et al., 1973; Bove et al., 1978; Gelberg et al., 1979; Klausner et al., 1982; Sheehan et al., 1983), echocardiography (Shapiro et al., 1981; Haendchen et al., 1983) and fluoroscopic tracking of midwall markers (Ingels et al., 1980, 1981), these methods do not directly measure regional circumferential shortening, but rather infer this from the resultant motion which occurs perpendicular to the assumed major direction of shortening.

The first major objective of the current study was to measure circumferential shortening of the midwall fibers directly, at several sites around the minor axis circumference to determine the extent to which shortening is nonuniform. We also wished to examine potential mechanisms for nonuniformity of contraction such as regional differences in end-diastolic pressure-length relationships or adrenergic stimulation.

Our second major objective was to determine whether measuring midwall circumferential shortening alone is adequate to describe the regional contribution of these fibers to ventricular ejection. More specifically, we wished to determine the extent
Experimental Preparations

Twelve adult mongrel dogs (19-32 kg) were anesthetized with intravenous pentobarbital (30 mg/kg), intubated, and ventilated with a Harvard respirator. The heart was exposed through a median sternotomy and bilateral 5th interspace thoracotomy and suspended in a pericardial cradle. In all dogs, a 7F Millar (model PC574) micromanometer catheter was advanced into the left ventricle from the left carotid artery. A 7F fluid-filled pigtail catheter was introduced into the left ventricle from a femoral artery and periodically throughout the experiment, even if there was any drift in this relationship, the fluid-filled catheter was placed back into the left ventricle to ensure that all crystals would be placed to a similar midwall depth. The 5-mm distance from the crystal to the tape "stop" was varied (±0.5-1.0 mm), depending on the size of the dog (to allow for variations in myocardial wall thickness).

The orientation of the segment gauges was determined by use of an epicardial reference system. A series of external long axes were defined with epicardial landmarks to approximate the internal Z-axis (from the mitral aspect of the aortic valve to the apical dimple), which was used by Streeter et al. (1969) to measure myocardial fiber directions. Recently, we found that an external long axis for the anterior wall which passes from the bifurcation of the left main coronary artery to the apical dimple (along the anterior epicardial surface) accurately reflects the internal Z-axis (Freeman et al., 1985). We defined an external long axis for the posterior wall by a line from the inferior pulmonary vein to the apical dimple, in a course roughly parallel to the obtuse marginal branches of the left circumflex coronary artery. An external long axis for the lateral wall was defined by a line midway between the anterior and posterior external long axes.

The dogs were divided into two groups. In group I (six dogs), three midwall, circumferentially oriented, ultrasonic segment length gauges were inserted in the anterior, lateral, and posterior walls of the left ventricle (Fig. 1). To ensure that all gauges were oriented circumferentially and were within the same minor axis plane, a length of suture was attached to the apical dimple, then placed over the epicardial course of the anterior external long axis. The suture was cut at approximately the midpoint of the anterior long axis. The anterior wall gauge was implanted at the midventricular level of the cut end of the suture and oriented perpendicular to the course of the suture. This placed the gauge perpendicular to the anterior external long axis and, thus, oriented in the circumferential direction. The cut suture (with one end still attached to the apical dimple) then was placed alternately over the epicardial course of the lateral and posterior external long axes, like a "windshield wiper." The segment gauges in the lateral and posterior walls also were oriented perpendicular to the suture (and thus perpendicular to the lateral and posterior external long axes, respectively) and implanted at the same level as the cut end of the suture. Thus, each of the anterior, lateral, and posterior segment gauges were oriented in the circumferential direction, and were at the same distance from the apical dimple along their respective external long axes. This placed all three gauges in approximately the same minor axis plane.

In group II (six dogs), two sets of midwall ultrasonic segment gauges were inserted in the anterior wall and two in the posterior wall (Fig. 2). One gauge in each wall was placed in the identical circumferential orientation as in group I, i.e., perpendicular to the external long axis, and in the same minor axis circumference. A second gauge in each wall was placed in line with the external long axis of the anterior and posterior wall and, therefore, mutually perpendicular to the first set of circumferential gauges. The circumferential and longitudinal gauges thus subtended segments approximately 1 cm long which were mutually perpendicular and intersected at their respective midpoints.

Each segment length gauge was connected to a sonomicrometer-amplifier system which was calibrated with a signal of known duration. The electrocardiographic lead, central aortic pressure, high and low gain left ventricular pressure, left atrial pressure, and segment length gauge signals were recorded on an eight-channel forced-ink
polygraph (Brush-Clevite, model 2000) at a paper speed of 200 mm/sec (Figs. 3 and 4) and on FM magnetic tape. Respiration was suspended at end-expiration during all measurements for approximately 20 cardiac cycles.

Postmortem examinations were performed to verify the position and orientation of the ultrasonic segment length gauges. In group I animals, the distance from the apical dimple to each crystal was measured along the epicardial course of the appropriate external long axis. These measurements were used to confirm that all crystals were at the same distance from the apical dimple, and thus all three gauges were oriented in the circumferential direction and were within the same circumferential hoop axis. The myocardium then was dissected in the region of each crystal to measure the distance from the epicardial surface to the center of the crystal, to confirm that all gauges were at a similar depth within the midwall.

In group II animals, postmortem radiographic studies were performed to determine the orientation of each segment gauge in relation to the internal Z-axis. The hearts were arrested during diastole with potassium chloride, then fixed with picric acid injected (by power injection)
Experimental Protocol

In all animals, the influence of ventricular volume on segment shortening was examined by obtaining measurements at multiple levels of left ventricular end-diastolic pressure (LVEDP) between 0 and 20 mm Hg. This was accomplished by first inflating the caval occlusion cuff to lower the LVEDP to 0-3 mm Hg for 1-2 minutes. The cuff then was deflated in steps to produce 2-3 mm Hg increases in LVEDP. When the cuff was fully deflated, a solution of 6% dextran in 0.9% saline was infused intravenously to produce progressive 2-3 mm Hg increases in LVEDP to a maximum of 18-20 mm Hg. Measurements were obtained approximately 2-5 minutes after each change in LVEDP to allow the animal to reach steady state.

To determine the influence of increased adrenergic stimulation on regional shortening, a 2-µg intravenous bolus of isoproterenol was administered to four of the group I animals. Measurements were obtained during a control period, during peak drug effect, and during recovery. To examine regional systolic function after reduction in adrenergic tone, we administered a pharmacological dose of propranolol (1 mg/kg, iv) to five dogs of group II. We then repeated measurements at multiple levels of LVEDP from 5 to 20 mm Hg, using the inferior vena cava occlusion cuff and dextran infusion, as described above. Steady state measurements could not be achieved consistently in all five animals at LVEDP levels lower than 5 mm Hg after β-blockade, because marked systemic hypotension occurred frequently.

In one group I animal, the influence of the pericardial cradle and cardiac position was examined. Baseline measurements were obtained with the dog lying on its back and the anterior surface of the heart exposed with a pericardial cradle. In this position, the posterior surface of the heart was in the dependent position. Repeat measurements then were obtained after each of the following maneuvers: (1) the pericardial cradle was released, allowing the heart to fall into the mediastinum, (2) the pericardium was loosely reaproximated with sutures, (3) the chest cavity was closed, (4) the animal was rotated to lie on its side, (5) the animal was rotated further to lie on its
ventral side (so that the anterior surface of the heart was in the dependent location), and (6) the chest was reopened and a slit placed in the posterior pericardium.

**Data Analysis**

All data were played back from FM tape for analog-to-digital conversion at 5-msec intervals using an analog-to-digital computer system. Data from 20 cardiac cycles were averaged. In addition, the electronic derivative of left ventricular pressure (dP/dt) was obtained from tape playback and digitized. The differentiator had a 3-db drop in frequency response at 80 Hz with a phase shift of 90°. For timing purposes, three events were defined: (1) left ventricular end-diastole was taken from the high-gain left ventricular pressure tracing as the pressure trough following atrial systole. In the few cases in which a left ventricular pressure trough could not be readily identified, end-diastole was identified by the time the left ventricular dP/dt increased to 10% of its peak value. The rationale for this criterion was that the time of end-diastole as identified by the left ventricular pressure trough and the time when left ventricular dP/dt reached 10% of its peak value consistently occurred within 10 msec of each other. On the average, end-diastole, as determined by the time of 10% peak LV dP/dt, occurred at a mean of 4.0 ± 4.3 msec after the time of end-diastole, as identified by the trough on the left ventricular pressure tracing; (2) the time of aortic valve opening was identified from the high-fidelity left ventricular pressure tracing; (3) the time of aortic valve closure was similarly defined from the high-fidelity left ventricular pressure tracing. In this case, the pressure at the dicrotic notch was identified from the central aortic pressure tracing as the pressure at aortic valve closure. We then transposed this pressure onto the right ventricular pressure tracing to determine the time of aortic valve closure. The transposition of central aortic pressures (measured with a fluid-filled catheter) onto the high-fidelity left ventricular pressure tracing to time aortic valve opening and closure was an indirect method. However, aortic valve opening and closure occurs at a time when the rate of rise or fall in left ventricular pressure is rapid. Thus, small errors in aortic valve opening or closure pressures obtained from the central aortic pressure tracing would cause only minimal differences in timing (Figs. 3 and 4).

Percent segment shortening was calculated as the percent change in segment length from the time of aortic valve opening to closure. We analyzed percent shortening as a function of LVEDP by selecting beats with LVEDP as close as possible to 2, 6, 10, 14, and 18 mm Hg. We analyzed regional diastolic pressure-length relations by comparing regional end-diastolic segment lengths at LVEDP as close as possible to 6, 10, 14, and 18 mm Hg, after normalizing these values to the end-diastolic segment lengths present at LVEDP of 2 mm Hg.

The influence of the non-circumferential fibers (of the subepicardium and subendocardium) on the shortening of
the midwall circumferential fibers was analyzed in the
group II dogs by comparing systolic changes of midwall
segments in the circumferential and longitudinal direc-
tions in both anterior and posterior walls. We reasoned
that, since the midwall is composed of circumferentially
oriented fibers, any shortening consistently detected per-
pendicular to this orientation will reflect the influence of
the adjacent, more longitudinally oriented fibers (see Dis-
cussion).

In the six animals of group II, we also estimated the
percent change in midwall area during systole for the
anterior and posterior walls. Since in each wall the seg-
ments subtended by the two gauges were perpendicular
and intersected near their midpoint, the ends of each
segment were used to define a quadrangle. The area of
the quadrangle can be determined from the segment
lengths in the circumferential and long axis directions. It
was assumed that the two segment length gauges re-
mained mutually perpendicular during the cardiac cycle.
This assumption seemed reasonable, since in-plane shears
are minimal (Waldman et al., 1985). It can be shown (see
Appendix) that if the percent shortening of the circumfer-
ential segment is "a" and of the long axis segment is "b,"
then the percent change in midwall area is equal to
\[
\frac{(a + b) - ab}{100}
\]

Statistical Analysis

The statistical significance of changes in regional seg-
ment shortening and end-diastolic segment length as
LVEDP increased from 2 to 6, 10, 14, and 18 mm Hg was
tested by analysis of variance for repeated measures (Wi-
ner, 1971). P < 0.05 was considered statistically signifi-
cant. Statistical comparisons of segment shortening data
between the anterior, lateral, and posterior walls, and of
calculated midwall area changes between anterior and
posterior walls were made at each level of LVEDP, using
Tukey's test to compare mean values of different regions
at the same pressure (Winer, 1971).

Results

The average heart rate for all dogs was 118 ± 12
beats/min. In the five group II dogs given intra-
avenous propranolol, the average heart rate was 87
± 20 beats/min after β-blockade. The average
LVEDP used for measurements were 21 ± 1.5, 5.8
± 0.6, 9.6 ± 1.1, 13.6 ± 1.4, and 17.9 ± 3.0 mm Hg.
For convenience, these will subsequently be referred to as LVEDP levels of 2, 6, 10, 14 and 18 mm Hg.

Midwall Segment Shortening in the
Circumferential Direction

In group I animals, percent shortening of circumfer-
ential segments was significantly higher in the anterior
than in the posterior or lateral walls at all
levels of LVEDP (P < 0.01, Table 1). Percent short-
ening of the posterior and lateral segments did not differ at any LVEDP (see Table 1). As LVEDP in-
creased, percent shortening of all segments in-
creased significantly. In group II animals, percent shortening of the anterior circumferential segment
was also greater than the posterior circumferential
segment (P < 0.01) at all LVEDP (Fig. 5).

These regional differences were not unique to the
method used to calculate percent shortening. When shortening was calculated from end diastole (rather
than aortic valve opening) to aortic valve closure,
shortening of circumferential segments remained
significantly higher in the anterior than lateral or
posterior walls, with no significant difference be-
tween the latter two sites. This was true at all
LVEDP. In group I animals, the shortening calcu-
lated from end-diastole to aortic valve closure for
anterior, lateral, and posterior segments at LVEDP
2 mm Hg was 13.5 ± 4.4%, 8.6 ± 5.6%, and 9.5 ±
4.4%, respectively; at LVEDP 6 mm Hg was 16.1 ±
4.6%; 10.1 ± 5.5%, and 9.7 ± 4.0%, respectively; at
LVEDP 10 mm Hg was 16.9 ± 4.8%, 9.9 ± 5.2%
and 9.5 ± 4.0%, respectively; at LVEDP 14 mm Hg
was 17.3 ± 4.8%, 10.0 ± 5.0%, and 10.7 ± 3.8%
respectively; and at LVEDP 18 mm Hg was 17.9 ±
6.3%, 11.8 ± 6.1%, and 11.8 ± 4.5%, respectively.
Thus, at all LVEDP, regional differences in short-
ening persisted, even when including segment
length changes during isovolumic systole.

In the one group I animal that underwent several
maneuvers, shortening was higher in the anterior
than lateral or posterior circumferential segments.
This relationship did not change significantly after
any of the following maneuvers: (1) after the peri-
cardial cradle was dropped, (2) after the pericardium
was reapproximated with sutures, (3) after the chest
was closed, (4) after the dog was turned on its side,
(5) after the dog was turned onto its ventral side, or
(6) after the posterior pericardium was slit.

Midwall Segment Shortening in the Long Axis Direction

There was negligible shortening of midwall long axis segments in both anterior and posterior walls at the lowest LVEDP (2 mm Hg, Fig. 5). As LVEDP increased, percent shortening of both anterior and posterior long axis segments increased significantly.
Although there was a tendency for percent shortening of the anterior long axis segment to be less than the posterior long axis segment at each LVEDP, this difference was not statistically significant. In the anterior wall, percent shortening of circumferential segments was greater than long axis segments at all LVEDP ($P < 0.01$). However, this difference decreased as LVEDP increased (Fig. 5). In contrast, in the posterior wall, percent shortening was not significantly different for circumferential as compared to long axis segments at any LVEDP (see Fig. 5).

**Calculated Systolic Midwall Area Change**

The percent change in midwall area during systole was not significantly different between anterior and posterior walls at each LVEDP (Fig. 5). As LVEDP increased, the systolic percent change in midwall area increased similarly for both anterior and posterior walls in each animal. A linear regression equation was derived from the six group II animals to compare the percent change in midwall area for the anterior and posterior walls as the LVEDP was varied. This equation was $y = 3.6 \pm 0.7x$, where $y$ and $x$ are the percent change in midwall area during systole for the anterior and posterior walls, respectively. The $r$ value for this equation was 0.86.

**Changes in Normalized End-Diastolic Length**

The end-diastolic length increased in all segments as LVEDP increased (Table 2; Fig. 6). In group I

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Normalized Circumferential End-Diastolic Length, Group I ($n = 6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEDP (mm Hg)</td>
<td>Anterior</td>
</tr>
<tr>
<td>6</td>
<td>1.04 ± 0.04</td>
</tr>
<tr>
<td>10</td>
<td>1.09 ± 0.08</td>
</tr>
<tr>
<td>14</td>
<td>1.15 ± 0.11*</td>
</tr>
<tr>
<td>18</td>
<td>1.21 ± 0.09*</td>
</tr>
</tbody>
</table>

Results are expressed as mean ± sd. LVEDP = left ventricular end-diastolic pressure.

* $P < 0.01$, normalized end-diastolic length of anterior or lateral segments significantly higher than in the posterior segment at the same LVEDP. Normalized end-diastolic lengths did not differ between anterior and lateral sites at any LVEDP.
animals (Table 2), as LVEDP increased, normalized end-diastolic lengths increased more in anterior than posterior segments, reaching statistical significance at LVEDP 14 and 18 mm Hg. Lateral wall segments were intermediate, and were not significantly different from anterior segments, but were higher than posterior segments at LVEDP 18 mm Hg. In group II animals (Fig. 6), as LVEDP increased, normalized end-diastolic lengths of anterior circumferential segments increased significantly more than posterior circumferential segments and anterior long axis segments at LVEDP 10, 14, and 18 mm Hg. In the posterior wall, as LVEDP increased, normalized end-diastolic lengths did not differ between circumferential and long axis segments.

Effects of Altering Adrenergic Stimulation

In the four group I animals given intravenous isoproterenol, the heart rate increased from 121 ± 10 to 136 ± 17 beats/min. Percent shortening of the circumferential segments increased from 15.7 ± 5.1% to 19.2 ± 6.0% in the anterior wall, from 7.9 ± 5.2% to 9.3 ± 7.3% in the lateral wall, and from 8.8 ± 3.7% to 9.8 ± 3.4% in the posterior wall. Thus, after acute inotropic stimulation, circumferential segment shortening remained significantly higher in the anterior than lateral or posterior segments (P < 0.05), with no significant difference between the latter two sites.

To determine whether regional differences in shortening persisted after ß-adrenergic blockade, segment shortening was compared before and after propranolol at matched LVEDP levels (Table 3). At all matched LVEDP levels, percent shortening decreased in all segments after propranolol. However, the regional differences in percent shortening did not change after propranolol. That is, percent shortening in the anterior circumferential segment remained higher than the anterior long axis, posterior circumferential, and posterior long axis segments.

Table 3

<table>
<thead>
<tr>
<th>LVEDP (mm Hg)</th>
<th>Anterior Circ</th>
<th>Long axis</th>
<th>Posterior Circ</th>
<th>Long axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>C</td>
<td>10.9 ± 3.3*</td>
<td>4.4 ± 6.7</td>
<td>7.0 ± 2.6</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>6.4 ± 3.2*</td>
<td>3.5 ± 5.4</td>
<td>4.2 ± 2.3</td>
</tr>
<tr>
<td>10</td>
<td>C</td>
<td>12.2 ± 3.1*</td>
<td>5.3 ± 7.1</td>
<td>8.2 ± 3.5</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>7.5 ± 2.9*</td>
<td>4.8 ± 4.9</td>
<td>5.5 ± 2.7</td>
</tr>
<tr>
<td>14</td>
<td>C</td>
<td>13.4 ± 3.7*</td>
<td>7.7 ± 6.4</td>
<td>9.3 ± 3.3</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>8.3 ± 2.8*</td>
<td>6.4 ± 3.5</td>
<td>5.9 ± 2.7</td>
</tr>
<tr>
<td>18</td>
<td>C</td>
<td>14.4 ± 2.9*</td>
<td>9.5 ± 6.5</td>
<td>9.7 ± 3.5</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>9.5 ± 1.4*</td>
<td>6.5 ± 3.5</td>
<td>6.9 ± 2.3</td>
</tr>
</tbody>
</table>

Results are expressed as mean ± sd. LVEDP = left ventricular end-diastolic pressure. Circ = circumferential, C = control (before propranolol), and P = propranolol.

* P < 0.05; anterior circumferential shortening significantly higher than shortening of anterior long axis, posterior circumferential and posterior long axis segments at same LVEDP, both during control measurements and after propranolol. In all cases, percent shortening did not differ between the latter three sites.
with no significant difference between the latter three segments. Repeated measures analysis of variance demonstrated no significant interaction between the presence of propranolol and the regional differences in percent shortening.

Postmortem Examination

In the six group I animals, the mean distance from the apical dimple to the anterior, lateral, and posterior segment gauge was 4.3 ± 0.6 cm in each case. The segment gauges were placed at a mean of 48 ± 4%, 53 ± 6%, and 58 ± 8% of the distance from the apical dimple to the base of the left ventricle as measured along the anterior, lateral, and posterior external long axes, respectively. The distance from the apical dimple to each of the three segment gauges did not vary by more than 0.6 cm in any animal. Thus, in each animal, the three segment gauges were roughly within the same minor axis plane. The mean depth below the epicardial surface was 5.3 ± 0.6 mm, 5.2 ± 0.9 mm, and 5.8 ± 0.9 mm for the anterior, lateral, and posterior segment gauges, respectively. This depth did not vary by more than 2 mm between any of the three gauges in any animal. Thus, in each animal, all three segment gauges were at a similar, midwall depth. All gauges were in the middle third of the left ventricular wall.

Postmortem radiographic examinations were obtained in five of the group II animals. The mean angle between the internal Z-axis and the posterior longitudinal and circumferential segment gauges was 1.2 ± 4.3° and 83.3 ± 5.4°, respectively. The mean angle between the posterior longitudinal and circumferential segment gauges was 82.2 ± 4.6°. The mean angle between the internal Z-axis and the anterior longitudinal and circumferential segment gauges was 2.0 ± 5.0° and 98.0 ± 8.0°, respectively. The mean angle between the anterior longitudinal and circumferential segment gauges was 85.2 ± 12.2°. The mean angle between posterior longitudinal and anterior longitudinal segment gauges, i.e., the skew angle, was 8.5 ± 5.8°. In all five animals, this skew angle was less than 15°. Thus, in all animals, each segment gauge was placed very close to the desired circumferential or longitudinal orientation (in fact, all gauges were within 15° of the desired orientation).

Discussion

The midwall circumferential fibers of the left ventricle play an extremely important role in the normal contraction pattern in view of their numerical preponderance in comparison to longitudinally oriented fibers (Streeter et al., 1969), and the observations that the predominant direction of shortening (Hawthorne, 1961; Ross et al., 1967; Herman et al., 1967; Hinds et al., 1969; Tsakiris et al., 1969; Rankin et al., 1976) and work (Gould et al., 1976; Bove et al., 1978; Phillips et al., 1982) is circumferential. These concepts form the basis for several techniques used to estimate systolic function at the level of the left ventricular minor axis. Since shortening at this level is thought to be predominantly circumferential, it is assumed that the resultant decrease in the minor axis diameter or chord will adequately reflect the amount of circumferential shortening.

Techniques such as contrast left ventriculography (Liedtke et al., 1973; Sniderman et al., 1973; Bove et al., 1978; Gelberg et al., 1979; Klausner et al., 1982; Sheehan et al., 1983) and echocardiography (Shapiro et al., 1981; Haendchen et al., 1983) demonstrate considerable nonuniformity of the contraction process. However, these techniques a priori impose a certain level of uniformity on the contraction process by presuming that different endocardial sites will all move along a perpendicular pathway to a common long axis, or along a prescribed radial pathway to a common center of mass. Any motion which occurs off of these prescribed pathways will not be measured, leading to an uncertain degree of inaccuracies in estimates of regional function. Although a variety of reference and coordinate systems have been proposed, even the best of these may yield results which correlate poorly with midwall dynamics (Ingels et al., 1980, 1981). Techniques such as tracking of implanted myocardial markers (Ingels et al., 1980, 1981) or measurement of regional wall thickness changes (Nakamura et al., 1982; Hattori et al., 1982; Haendchen et al., 1983) obviate some of these problems, but still infer the degree of circumferential shortening based on measuring resultant motion in a direction perpendicular to the direction of shortening. Measurement of epicardial (Kong et al., 1971) or midwall (LeWinter et al., 1975) myocardial segment shortening provides a more direct assessment of local regional function. Ultrasonic segment length gauges are particularly well suited for measurement of regional function, since the piezoelectric crystals are small and may be oriented within and in the direction of a specified and reasonably homogeneous group of fibers. Such techniques also minimize the contribution of complex three-dimensional motion (Ingels et al., 1975) to regional measurements and eliminate the need for any external reference system for analysis.

Using these methods, the first major objective of this study was to determine the extent to which shortening of the midwall circumferential fibers around the minor axis was non-uniform. The results of our group I studies indicate that midwall circumferential shortening was significantly greater in the anterior than lateral or posterior walls of the left ventricle around the minor axis circumference. These regional differences were present over a wide range of LVEDP. The level of adrenergic stimulation did not influence these results, as midwall circumferential shortening remained greater in the anterior than posterior walls after both acute adrenergic stimulation and β-blockade with propranolol. As LVEDP was increased, there was a greater increase in normalized end-diastolic segment length in anterior
than posterior circumferential segments, with lateral segments intermediate. This suggests the possibility of regional differences in diastolic distension as one mechanism for the nonuniformity of circumferential contraction observed (see below).

These regional differences were not likely due to the position of the heart in our experimental preparation, i.e., due to the heart resting with the posterior surface in a dependent position in a pericardial cradle. In one group I animal, anterior wall shortening remained greater than lateral or posterior wall shortening when the animal was resting on its side or ventral surface (i.e., with the lateral or anterior wall of the left ventricle in a dependent position), and after releasing the pericardial cradle, closing the pericardium, or slitting the pericardium open in a posterior position. Although this study does not examine the influence of the pericardium on regional ventricular function, these results indicate that neither the pericardium nor cardiac position were major mechanisms underlying the regional differences in segment shortening.

The second major objective of this study was to ascertain whether measurement of midwall circumferential shortening alone is sufficient to describe the regional contribution of different midwall sites to the ejection of blood. Although the bulk of left ventricular fibers are oriented in the circumferential direction, the mathematical observation that usual measurements of circumferential shortening are too small to account for normal ejection fractions (Sallin, 1969) indicates that shortening of the more longitudinally oriented fibers must in some way contribute significantly to normal ventricular ejection. Functional interactions between fiber layers, or "tethering" effects, have been studied in ischemic models (Weintraub et al., 1981; Gallagher et al., 1982; Hattori et al., 1982), but not in the normal left ventricle. Thus, the question of how these longitudinally oriented fibers behave in relation to the circumferential fibers has both clinical and theoretical significance.

To address the question of functional interactions between fiber layers, we simultaneously measured regional midwall segments in the circumferential and longitudinal directions. We reasoned that if the midwall circumferential fibers do not functionally interact with differently oriented fibers, then the maximum shortening of these fibers will occur along their principal axis, i.e., circumferentially. Further, if there are no functional interactions, no shortening should occur in a direction which is perpendicular to the principal axis. Indeed, if ultrasonic gauges are used to measure segment behavior perpendicular to the principal axis, net lengthening might occur due to fiber thickening during ejection (Spotnitz et al., 1982). Conversely, if shortening is detected with longitudinal midwall gauges oriented perpendicular to the principal fiber direction, this would indicate that the longitudinally oriented fibers of the subendocardium and subepicardium do functionally inter-

teract with the midwall circumferential fibers. Furthermore, the ratio of midwall shortening in the direction of the principal fiber axis to shortening perpendicular to the principal axis would constitute an index of the importance of such interactions.

If functional interactions between fiber layers do occur, it is not clear whether midwall fibers are influenced more by subendocardial or subepicardial fibers, or whether both regions exert a similar influence. It may be inferred that subendocardial fibers are more important, in view of their greater contribution to systolic wall thickening and the greater segment shortening of subendocardial than subepicardial segments (Sabbah et al., 1981; Gallagher et al., 1982). However, these transmural differences may be explained by geometric constraints rather than regional differences in function. If the left ventricle is modeled as a thick-walled sphere and myocardial mass remains constant, then systolic wall thickening and segment shortening must be greater in the inner (endocardial) than outer (epicardial) layers (Arts et al., 1979; Sabbah et al., 1981). Furthermore, if models of left ventricular contraction allow for torsion (a rotation of the apex in relation to the base around the long axis of the left ventricle), then, despite greater circumferential shortening in endocardial than epicardial layers, sarcomere shortening is similar in the two layers (Arts et al., 1979). Thus, subendocardial and subepicardial fibers may be equally important in influencing midwall fibers. However, this must remain speculative, as our techniques do not separate the relative contributions of subendocardial and subepicardial fibers in regard to functional interactions with the midwall fiber layer.

In our group II animals, we found negligible shortening of midwall fibers in the longitudinal direction in both anterior and posterior walls at the lowest level of LVEDP. Indeed, in the anterior wall there was, on the average, net lengthening in the longitudinal direction. At higher LVEDP, there was progressively greater longitudinal shortening of midwall fibers in both anterior and posterior walls. These findings suggest that at higher volumes, the longitudinally oriented fibers of the subendocardium and subepicardium have an important influence on the midwall circumferential fibers. The increased midwall long axis shortening as LVEDP increased may be related to recruitment of subendocardial and subepicardial sarcomeres at higher ventricular volumes, as demonstrated by Yoran et al. (1973) for the anterior wall. Additional evidence that the extent of functional interaction between fiber layers may change in relation to ventricular volume is suggested by our anterior wall data in which the ratio of midwall circumferential to long axis shortening was large at low LVEDP, but decreased progressively as LVEDP increased. Furthermore, regional variation in these functional interactions between fiber layers is suggested by the finding that in the posterior wall (in contrast to the anterior wall), midwall shortening in the circumferential and
longitudinal directions was of similar magnitude over a wide range of LVEDP. Interestingly, despite these complex regional, directional, and volume-dependent differences in midwall segment shortening, systolic changes in midwall area were similar in the anterior and posterior walls over a wide range of LVEDP. Thus, the overall contribution of the two areas toward ejection of blood would appear comparable. These results indicate that measurement of midwall fiber shortening in the direction of their principal axis alone is insufficient to characterize the contribution of these fibers to ventricular ejection. This is particularly true in the posterior wall where measurement of shortening in the direction of the local midwall fiber axis alone will not detect the equivalent amount of shortening which is occurring in a direction perpendicular to this fiber orientation.

Regional differences in the extent to which shortening of longitudinally oriented fibers influences the behavior of the midwall circumferential fibers may be a mechanism underlying the observed regional differences in midwall circumferential shortening. For example, if forces generated by the longitudinal fibers during contraction function to oppose contraction of the circumferential fibers, this would result in less circumferential shortening than would have occurred in the absence of functional interactions between fiber layers. The tendency for longitudinal shortening to be greater in the posterior than anterior wall might thus account for the lower circumferential shortening of the posterior wall.

Several other mechanisms could play a role in explaining greater anterior than posterior or lateral midwall circumferential shortening. These include regional differences in the classic determinants of fiber shortening (inotropic state, preload, and afterload), and regional differences in fiber angle distribution.

With regard to regional differences in myocardial inotropic state, it is of interest that higher catecholamine levels have been reported for the left ventricular base than apex (Angelakos, 1965; Kaye et al., 1970; Pierpont et al., 1984). The functional consequences of these findings are unclear, and similar comparisons between anterior and posterior walls have not been made. Nonetheless, it is unlikely that regional differences in adrenergic stimulation are sufficient to explain our findings, since anterior circumferential shortening remained higher than posterior circumferential shortening both after acute inotropic stimulation with isoproterenol and after β-adrenergic blockade with pharmacological doses of propranolol. Furthermore, regional differences in adrenergic stimulation should also be reflected by greater anterior than posterior longitudinal shortening, which was not observed.

With regard to regional differences in preload and utilization of the Frank-Starling mechanism, our findings might be explained at the sarcomere level by longer anterior than posterior or lateral wall sarcomere lengths. We found anterior wall segments in the circumferential direction to be more extensible than posterior wall segments at end-diastole between LVEDP 2 and 18 mm Hg. This finding could be related to either regional differences in diastolic stress distribution or true differences in muscle stiffness, a distinction that cannot be made with our techniques. If diastolic sarcomere lengths are directly related to segment length measurements, this difference in segment extension could be associated with longer sarcomere lengths in the anterior wall and, hence, greater shortening. By this reasoning, there should be greater anterior wall shortening in both circumferential and longitudinal directions. However, we found only circumferential shortening to be greater in the anterior than posterior wall. In fact, longitudinal shortening tended to be greater in the posterior than anterior wall. Alternatively, it is possible that intrinsic regional differences in sarcomere lengths could be present independent of the determinants of regional lengthening. Although a transmural distribution of sarcomere lengths has been demonstrated within the anterior wall (Yoran et al., 1973; Grimm et al., 1981), a direct regional comparison of sarcomere lengths between anterior and posterior walls has not yet been undertaken. Thus, while regional differences in diastolic sarcomere lengths may contribute to regional shortening differences, a definitive answer to this question requires a direct regional comparison of diastolic sarcomere lengths.

Obviously, regional differences in systolic wall stress could also result in differences in midwall, circumferential shortening. However, estimates of regional wall stress based on a standard, Laplace law approach or on more complicated analyses remain highly controversial and give qualitatively different estimates depending on the assumptions employed (Huisman et al., 1980; Yin, 1981). Also, at present, direct measurements of wall tension are technically unsatisfactory. We therefore did not attempt any regional wall stress estimates in our experiments. Nevertheless, a complete description of the factors influencing regional shortening awaits the development of satisfactory approaches for either estimating or measuring regional stress distribution.

Finally, although midwall fibers are oriented circumferentially in the anterior, lateral, and posterior walls, quantitative differences in transmural fiber angle distributions at these sites, i.e., regional differences in the relative numbers of circumferential fibers, also could account for regional variations in shortening patterns. However, based on the work of Streeter et al. (1966; 1969; Ross and Streeter, 1975), any such differences would appear to be minimal at best.

In summary, we have demonstrated that circumferential, midwall shortening is nonuniform around the minor axis circumference. These regional differences in midwall segment shortening do not appear to be due to regional differences in adrenergic stim-
ulation or transmural fiber angle distribution, but may be in part related to regional differences in diastolic distensibility and in functional interactions between adjacent fiber layers. Although the influence of shortening of the longitudinally oriented fibers of the subendocardium and subepicardium on midwall shortening is minimal at low ventricular volumes, there are significant functional interactions between fiber layers at higher volumes, particularly in the posterior wall. Despite the complexity of these regional differences in midwall segment shortening, the overall systolic change of midwall area is similar for anterior and posterior walls over a wide range of ventricular volumes, suggesting that these midwall sites make similar contributions to the ejection of blood.

Appendix

In group II animals, two ultrasonic segment gauges were placed in a mutually perpendicular orientation in both anterior and posterior midwalls to measure segment lengths in both the circumferential and longitudinal directions as shown schematically in Figure 7. In this figure, the two crystals that were used to measure a circumferential segment are indicated by points marked "C," and those used to measure a longitudinal segment, by "L." The circumferential and longitudinal segments intersect at the point marked "O." The position of the circumferential crystals at end-diastole is "C_d" and at end systole is "C_s." Similarly, longitudinally oriented crystals at end diastole are at "L_d" and at end-systole at "L_s." The area subtended by the two segment gauges is described by a quadrangle obtained by connecting the ends of each segment gauge. The quadrangle connecting crystals at end diastole is shown by the outer solid figure and represents end-diastolic midwall area. The inner quadrangle shown with dotted lines is the end-systolic midwall area. If the assumption is made that the point of intersection between the two segments ("O") does not change between diastole and systole, and that the two segments remain mutually perpendicular, then the problem of calculating the change in quadrangle area from end diastole to end systole is reduced to calculating the change in area for any of the four quadrants of the quadrangle, as shown in Figure 8. The assumption that the two segment gauges remain mutually perpendicular during the cardiac cycle presumes that there is minimal in-plane shear. This has been validated in recent studies (Waldman et al., 1985).

If the circumferential and long axis segment lengths at end diastole are x and y, respectively, and at end systole, x' and y', respectively (Fig. 8), then the area of the diastolic triangle (AD) is:

$$AD = \frac{xy}{2}$$  (1)

and the systolic area (AS) is:

$$AS = \frac{x'y'}{2}.$$  (2)

The percent change in area (%ΔA) from end diastole to end systole is:

$$%\Delta A = \frac{(AD - AS)}{AD} \cdot 100.$$  (3)

By substitution of Equations 1 and 2 into Equation 3, and by rearrangement, we have:

$$%\Delta A = \left(\frac{(xy - x'y')}{xy}\right) \cdot 100$$

$$= \left[1 - \left(\frac{x'}{x} \frac{y'}{y}\right)\right] \cdot 100.$$  (4)

If a = the percent change in circumferential segment length from end diastole to end systole, and b = the...
percent change in long axis segment length, then
\[ a = \frac{x - x'}{x} \cdot 100 \tag{5} \]
and
\[ b = \frac{y - y'}{y} \cdot 100, \tag{6} \]
which may be rearranged to:
\[ a = 1 - \frac{x'}{x} \cdot 100 \quad \text{or} \quad \frac{x'}{x} = 1 - \frac{a}{100} \tag{7} \]
and
\[ b = 1 - \frac{y'}{y} \cdot 100 \quad \text{or} \quad \frac{y'}{y} = 1 - \frac{b}{100}. \tag{8} \]
By substituting Equations 7 and 8 into Equation 4,
\[ \%\Delta A = \left[ 1 - \left( 1 - \frac{a}{100} \right) \left( 1 - \frac{b}{100} \right) \right] \cdot 100 \]
\[ = \left[ 1 - \left( 1 - \frac{a}{100} \right) - \frac{b}{100} + \frac{ab}{100^2} \right] \cdot 100 \tag{9} \]
\[ = \left( \frac{a}{100} + \frac{b}{100} - \frac{ab}{100^2} \right) \cdot 100 \]
\[ = a + b - \frac{ab}{100}. \tag{10} \]
Equation 9 will give the percent change in midwall area from end diastole to end systole (\%ΔA) in terms of the percent change in circumferential (a) and long axis (b) segment lengths.

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