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Echocardiographic Definition of the Left Ventricular Centroid. I. Analysis of Methods for Centroid Calculation From a Single Tomogram

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Quantitation of myocardial contraction requires a frame of reference. Most investigators have sought a single reference frame per image, centered in some manner with respect to the mass of myocardium. Because there is no anatomic marker for the center of the heart, many different approaches have been pursued to identify a centroid of the left ventricle. The issue of whether the reference should be fixed throughout the cardiac cycle or float from image to image has been addressed in previous studies, but the more fundamental question of how a centroid can best be defined has not been answered.

This study examines this basic issue by analysis of variance from observer to observer, cycle to cycle, animal to animal and method to method. Both endocardial and epicardial borders were digitized twice by each of two observers at 1/30 s intervals spanning the cardiac cycle for each of three cardiac cycles in six normal dogs. The left ventricular centroid was calculated by six methods: center of endocardial coordinates, center of epicardial coordinates, center of mid-myocardial (average) coordinates, center of endocardial area, center of epicardial area and center of mid-myocardial (average) area. The path of each centroid was correlated between observers and correlation coefficients were transformed for analysis of variance.

This analysis indicates a best approach to centroid definition through distinct minimization of the variance: the best of the six methods proved to be center of endocardial area.

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Two-dimensional echocardiography provides a dynamic view of wall thickening and wall motion abnormalities that can be documented at the bedside. This has proved useful in the assessment of changes due to ischemia and infarction (1–13). It seems desirable to develop a means of quantifying these abnormalities to increase sensitivity to small changes, reduce subjective bias and standardize readings for research and clinical applications. Various methods have been proposed for quantitation of these abnormalities, but no standard has evolved. A primary difficulty has been the selection of a reference frame for measurement of wall motion. A description of wall motion as abnormal "relative to the rest of the heart" is problematic because it is based on a circular definition: the abnormal region has to be identified first. The only alternative is to construct a reference based on all regions. There are several ways a central reference, or centroid, can be determined, but it has not been established which approach is best.

If one focuses on a widely used research model for wall motion abnormalities, the canine heart imaged in the short-axis view at the mid-papillary muscle level, then three major aspects of the problem may be examined. First, what is the "best" method for calculating a centroid for a single tomographic image of the normal heart? Second, how should the "best" centroid be used to correct for translational motions during the cardiac cycle? Third, what modifications should be applied for analysis of abnormal hearts?

This study addresses the first of these questions by analyzing variance from six different methods for determining a left ventricular centroid from short-axis images of the

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canine heart. The method of analysis does not make any assumptions about the normal pattern of cardiac motion (trajectory of the centroid).

Methods

Echocardiography. Short-axis images at the level of the papillary bases were obtained from six normal dogs (14) with use of an Advanced Technology Laboratories Mark III mechanical sector scanner with a 3 MHz transducer; they were recorded continuously on a Panasonic NV8200 0.5 in. (1.27 cm) video recorder with frame counter. The image data from three cardiac cycles of each dog studied were analyzed on a Sony SVM-1010 videodisk image analysis system by two observers. Image displays were calibrated by imaging a premeasured grid before each study, primarily to eliminate potential errors due to aspect ratio. Two experienced observers independently digitized the epicardial and endocardial border (72 points/border) for each of the 8 to 12 frames (frame rate 30/s) from maximal area (end-diastole) to minimal area (end-systole) for each of three cycles per dog. Each study was traced twice by each observer at 48 h intervals, netting 1,440 data sets and 103,680 coordinate pairs.

Centroid definitions. The borders were defined by the centers of the brightest reflections from epicardium and endocardium traced with a trac-ball digitizer. Using all points from the inner border or the outer border, or both, provides six different choices for centroid, depending on whether one regards the border points only (center of coordinates) or uses the border points to define a region of myocardial mass (center of area). The centroid of each image frame was calculated by each of the following methods on the basis of the coordinates for the two borders (endocardial and epicardial) and the areas subtended by these borders.

Method 1 consisted of the average of the endocardial coordinates:

$$\text{Method 1: } (X_{c1},Y_{c1}) = \frac{1}{72}\Sigma\,(x_i,y_i),$$

where (X_{c1},Y_{c1}) are the coordinates of the centroid, with the subscript c indicating centroid and the subscript number indicating the method; (x_i,y_i) are coordinates of points on the endocardial border. This method is sensitive to outliers because a single aberrant point on the boundary will shift the centroid proportionately.

Method 2 consisted of the center of mass (center of area) subtended by the endocardial border:

$$\text{Method 2: } (X_{c2},Y_{c2}) = \frac{1}{A}\iint (x,y)\,dA,$$

where (X_{c2},Y_{c2}) are the coordinates for the centroid determined by method 2, A is the area contained in the endocardial border, (x,y) are coordinates of points within the border and dA is an infinitesimal area element corresponding to each (x,y) location. This method is less sensitive to isolated outliers because the area subtended by the boundary is not greatly changed by malposition of a single boundary point.

Methods 3 and 4 corresponded to methods 1 and 2 but were based on the epicardial boundary instead of the endocardial boundary:

$$\text{Method 3: } (X_{c3},Y_{c3}) = \frac{1}{72}\Sigma\,(x_i,y_i),$$

and

$$\text{Method 4: } (X_{c4},Y_{c4}) = \frac{1}{A}\iint (x,y)\,dA,$$

where (X_{c3},Y_{c3}) and (X_{c4},Y_{c4}) are the corresponding centroid coordinates for these two methods, (x_i,y_i) are coordinates of points on the epicardial border and (x,y) are points within the epicardial border. In addition to these four methods of centroid definition, two more related methods were evaluated on the basis of information from both borders.

Method 5 was based on the average of the coordinates from both borders, equivalent to the center of coordinates from mid-myocardium (the average of methods 1 and 3).

Method 6 was based on the area-weighted average from methods 2 and 4.

Data analysis. The identification of the "best" choice of centroid is a difficult problem that requires a specific context and a concrete approach to the ranking. The position of a centroid will shift relative to the transducer during the cardiac cycle, describing a trajectory. This trajectory may differ somewhat from cycle to cycle because of inevitable random cycle-related variations, but it will vary in that its definition is biased by errors in the identification of the points on the ventricular borders (errors that may differ from one observer to another). For concreteness, we assumed that the specific context for "best" was the centroid that minimizes the interobserver variation in trajectories, as evidenced by correlating trajectories measured from different beats and by different observers.

Thus, the criterion for quality of centroid localization is based on correlating the trajectories (Fig. 1) of the centroids obtained on a frame by frame basis by each observer. Because each frame was analyzed twice by each observer, this yielded four interobserver correlation values for each pair of coordinates (108 = 6 methods × 6 cases × 3 cycles/case). These values were normalized by the Fisher Z transform ($z = \tanh^{-1} r$) (15). This provided a testable measure of reproducibility of centroid determination unaffected by translation of coordinates for any recorded cycle. The methods of centroid determination were assessed by general linear model analysis of variance attributable to the following factors: 1) differences among cases (six dogs), 2) differences from beat to beat (three different cardiac cycles),

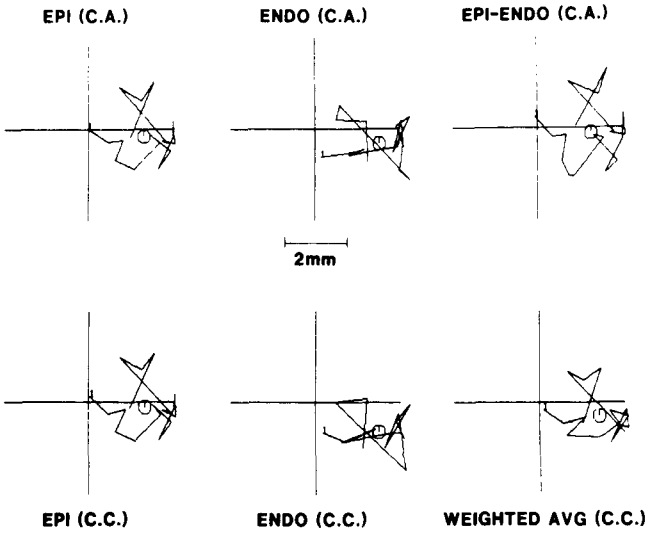


Figure 1. Examples of centroid trajectories observed with use of six different definitions of centroid. Method 1 = endocardial center of coordinates (ENDO C.C.); method 2 = endocardial center of area (ENDO C.A.); method 3 = epicardial center of coordinates (EPI C.C.); method 4 = epicardial center of area (EPI C.A.); method 5 = mid-myocardial center of coordinates (WEIGHTED AVG C.C.); method 6 = mid-myocardial center of area (EPI-ENDO C.A.). Comparison of such trajectories by correlation between observers provided the data in Tables 1 to 4.

Table 1. Interobserver Correlations for the Trajectory of X Coordinates Spanned by the Centroid of Each Frame Throughout the Cardiac Cycle as Determined by Each of the Six Methods (average correlation computed by Z transforms, mean, inverse Z transform)

Study No.	A	C	M1	M2	M3	M4	M5	M6
1	A	1	0.82	0.82	0.36	0.44	0.68	0.45
2	A	2	0.79	0.82	0.16	0.45	0.67	0.48
3	A	3	0.81	0.84	0.51	0.70	0.78	0.72
4	B	1	0.59	0.76	0.25	0.54	0.47	0.59
5	B	2	0.52	0.66	−0.49	−0.04	−0.27	−0.20
6	B	3	0.57	0.73	−0.07	−0.20	0.29	−0.21
7	C	1	0.78	0.83	0.75	0.79	0.82	0.81
8	C	2	0.81	0.85	0.77	0.81	0.82	0.83
9	C	3	0.79	0.83	0.66	0.80	0.76	0.81
10	D	1	0.78	0.80	−0.02	0.54	0.47	0.63
11	D	2	0.65	0.83	0.26	0.68	0.62	0.72
12	D	3	0.58	0.77	0.32	0.57	0.68	0.63
13	E	1	0.77	0.84	−0.23	0.24	0.21	0.44
14	E	2	0.26	0.72	0.22	0.54	0.28	0.61
15	E	3	0.74	0.84	0.19	0.53	0.67	0.57
16	F	1	0.29	0.66	0.20	0.28	0.34	0.35
17	F	2	0.48	0.67	−0.01	0.36	0.30	0.38
18	F	3	0.77	0.77	0.14	0.59	0.63	0.63

Data indicate how closely different observers agreed in determining the relative locations of the centroid. The first column (A) indicates which dog and the second column (C) which of the fully digitized cardiac cycles provided the correlation data. The correlation analysis was performed for each of two readings by each observer applying the six methods of centroid determination discussed in the text. Method 1 (M1) is the average of endocardial border coordinates and method 2 (M2) is the center of area subtended by those coordinates. Methods 3 (M3) and 4 (M4) are average of coordinates and center of area, respectively, based on the epicardial coordinates. Methods 5 (M5) and 6 (M6) are average of coordinates and center of area for the mean of endocardial and epicardial coordinates (that is, mid-myocardium), respectively. Interobserver correlations were analyzed for each of six dogs (A to F) and each of three cardiac cycles (1 to 3) per dog.

and 3) differences among methods. Observed differences were ranked by the method of least linear contrast. The Satterthwaite formula was used to determine degrees of freedom in the mixed effects model (16,17). Data analysis was performed on a CDC 6600 computer, using BMD8V statistical analysis software.

Results

Centroid trajectories. Analysis of the variance in correlations between trajectories for each centroid reveals how differences in the apparent motion relate to variation in cardiac cycle, observer and method of centroid definition. Tables 1 and 2 list the average interobserver correlations of centroid trajectory. Thus, a value of 1 indicates that the observers identify the same trajectory and a value of 0 indicates that there is no relation between the trajectories identified. These data allow examination of the sources of variance to identify whether or not the definition of centroid makes a significant contribution to the observed variation. Tables 1 and 2 present results for the X_c and Y_c coordinates, respectively, computed by means of Fisher's Z transform, which is needed for the analysis of variance. Values are the pooled r values for correlation (obtained by the inverse transform), shown because of the greater familiarity of the r value statistic. Analysis of these data (Tables 3 and 4) revealed that beat to beat differences are insignificant ($p > 0.25$), whereas differences among dogs are notable ($p < 0.01$) and differences due to method are significant ($p < 0.001$).

Ranking the methods. After the different methods were determined not to be equally reliable, the results were ranked by the method of least linear contrast. *For the X_c coordinate, method 2 proved to have the highest reliability*, followed by method 1. Furthermore, method 4 ranked higher than method 3 (Fig. 2 to 4). Figure 2 shows the higher correlations by method 2 (endocardial center of mass) compared with method 1 (average of endocardial coordinates). Figure 3 shows that method 2 also achieved higher correlations than either of the epicardium-based centroids (methods 3 and 4). Figure 4 favorably compares method 2 with the mid-myocardium–based centroids (methods 5 and 6).

For the Y_c coordinate, the rank order was comparable, except that the differences in rank were less distinct (Tables 3 and 4). This indicates that the center of mass was as good as or more reliable than the center of coordinates, whether

Table 2. Average Interobserver Correlations for the Trajectory of Y Coordinates for Each of the Six Methods for Each of Three Cardiac Cycles From Each of Six Dogs

Study No.	A	C	M1	M2	M3	M4	M5	M6
1	A	1	0.70	0.82	0.35	0.49	0.58	0.47
2	A	2	0.58	0.77	0.08	0.42	0.45	0.38
3	A	3	0.39	0.46	0.18	0.41	0.12	0.41
4	B	1	0.56	0.70	0.42	−0.15	0.29	−0.23
5	B	2	0.71	0.77	0.23	−0.35	0.29	−0.38
6	B	3	0.74	0.74	−0.43	−0.14	0.10	−0.05
7	C	1	0.83	0.81	0.37	0.71	0.75	0.75
8	C	2	0.61	0.80	0.44	0.63	0.68	0.69
9	C	3	0.77	0.78	0.68	0.79	0.80	0.79
10	D	1	0.72	0.52	0.19	0.42	0.50	0.41
11	D	2	0.67	0.48	0.20	0.24	0.31	0.27
12	D	3	0.48	0.62	0.44	0.46	0.61	0.45
13	E	1	0.35	0.62	0.32	0.26	0.29	0.30
14	E	2	0.68	0.65	0.55	0.76	0.70	0.77
15	E	3	0.02	0.50	0.04	0.37	0.17	0.29
16	F	1	0.62	0.40	0.03	−0.03	0.13	−0.06
17	F	2	0.63	0.52	−0.13	−0.23	0.19	−0.23
18	F	3	0.51	−0.51	0.13	0.08	−0.05	−0.09

As in Table 1, data indicate how closely different observers agreed in determining the trajectory of the centroid; Table 1 reports the agreement for the X coordinate, Table 2 for the Y coordinate. Column headings A (animal), C (cycle) and M1–M6 (method) as in Table 1.

based on endocardial or epicardial boundaries. Furthermore, the centroid calculations based on the endocardial border ranked higher than those based on the epicardial border for both X_c and Y_c. Thus, endocardial center of mass ranked highest and epicardial center of coordinates ranked lowest.

Reliability of different methods. This study examined the reliability of different methods to determine a central reference, or centroid, from individual short-axis image frames of the normal canine left ventricle for the purposes of measuring wall motion. The results showed that beat to beat variation was not significant, whereas differences among cases (dogs) and among methods were important. Furthermore, the experimental design allowed rank ordering of the reliability of the six methods analyzed. Endocardial data proved more reliable than epicardial data and center of mass proved more reliable than center of coordinates. The combination of data from endocardial and epicardial borders did not improve the reliability of centroid determination. The differences in method distinguished rank order of reliability more for the lateral position of the centroid (X_c) than for its vertical position (Y_c). Endocardial center of mass (the center of mass for the blood pool) proved most reliable. These results are consistent with the concept that center of area calculations are less sensitive to fluctuations in the assignment of border points than are center of coordinate calculations. Furthermore, they indicate that endocardial border tracings yield the best interobserver correlations among centroid trajectories. Further support for this conclusion comes from the concordance of the observations made on X_c and Y_c. The greater separation of rank for X_c could be explained by greater room for errors in the lateral directions

Table 3. Analysis of Variance for the Z Transformed Interobserver Correlations for X Coordinate Trajectories

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F	F′	p Value	Mean Z	r[tanh (Z)]
Animal (A)	6.6907	5	1.3381	7.98		<0.005		
Cycle (C)	0.3553	2	0.1777	1.06		>0.25		
Method (M)	6.5912	5	1.3182		18.99	<0.001		
AC	1.6772	10	0.1677					
AM	1.3850	25	0.0554					
CM	0.1567	10	0.0157					
ACM	1.5670	50	0.0313					
Total	18.4231	107						
Method								
1							0.8371	0.68
2							1.0665	0.79
3							0.2579	0.25
4							0.5797	0.52
5							0.6291	0.56
6							0.6316	0.56

Sources of variance analyzed were animal (A), cardiac cycle (C), method (M) and their joint interactions (AC, AM, ACM). The data support the conclusion (at $p = 0.001$) that the methods differ significantly with respect to reproducibility of X coordinate trajectories. Furthermore, the centroid trajectory differs from animal to animal ($p < 0.005$), but does not differ significantly from cycle to cycle in a given animal ($p > 0.25$). Data were further analyzed by the method of least linear contrast, which ranked the methods in the following order in terms of best reproducibility of centroid X coordinate trajectory: 2, 5, 1, 4, 3 and 6. The F′ test rejected H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5$ in favor of H_1: at least one μ_i different at the confidence level $p = 0.001$, where H_0 = null hypothesis, H_1 = alternate hypothesis and μ_i = mean Z value for correlation of X coordinate trajectories by method i. The least linear contrast of 0.1503 identified the rank order as $\mu_2 > \mu_5, \mu_1, \mu_4 > \mu_3 > \mu_6$.

Table 4. Analysis of Variance for the Z Transformed Interobserver Correlation for Y Coordinate Trajectories

Sources of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F	F′	p Value	Mean Z	r[tanh (Z)]
Animal (A)	5.8138	5	1.1628	6.73		<0.01		
Cycle (C)	0.1204	2	0.0602	0.35		>0.25		
Method (M)	4.4933	5	0.8987		6.52	<0.001		
AC	1.7273	10	0.1727					
AM	3.0533	25	0.1221					
CM	0.1988	10	0.0199					
ACM	1.3768	50	0.0275					
Total	16.7837	107						
Method								
1							0.7139	0.61
2							0.7898	0.66
3							0.2470	0.24
4							0.3311	0.32
5							0.4482	0.42
6							0.3333	0.32

As in Table 3, the sources of variance analyzed were animal (A), cardiac cycle (C), method (M) and their joint interactions (AC, AM, ACM). Data for the Y coordinate show that the methods differ significantly ($p < 0.001$); the trajectory is different for different animals ($p < 0.01$), but is not significantly different for different cycles in a given animal ($p > 0.25$). Data were further analyzed by the method of least linear contrast, which ranked the methods in the following order in terms of best reproducibility of centroid Y coordinate trajectory: 2, 5, 1, 4, 3 and 6. The F′ test rejected H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = \mu_6$ in favor of H_1: at least one μ_i different at the confidence level $p = 0.001$, where H_0 = null hypothesis, H_1 = alternate hypothesis and μ_i = mean Z value for correlations of Y trajectories by method i. The least linear contrast of 0.255 identified the rank order as $\mu_2, \mu_5, \mu_1, \mu_4 > \mu_3, \mu_6$.

as a result of the lower resolution perpendicular to the ultrasound beam (18). The location of the papillary muscles and anisotropy of hand-eye coordination could also contribute to this minor X-Y difference.

Centroid trajectories and normal wall motion in different normal dogs. It is interesting to note the significant differences among the centroid trajectories for different normal dogs. It points out a strength of this study design, which avoided a priori assumptions about normal trajectory. In particular, this study specifically did not assume that normal wall motion is symmetric in space or time or that the normal "best" centroid trajectory would have minimal variation over space or time. An assumption of symmetry in space would presume equal motion for all normal segments (anteroseptal, posteroseptal and so on), whereas symmetry in time would equate contraction and relaxation phases. Similarly, an assumption of minimal centroid variation would require that translational movements of the heart vary negligibly despite normal anatomic and physiologic differences. It has not been established that normal contractile patterns

Figure 2. Comparison of centroid correlations for the X_c coordinate (methods 1 and 2). Mean interobserver correlations are given for each dog for methods 1 and 2; these correspond to data in Table 1. A correlation of 1 would indicate perfect interobserver reproducibility, whereas a correlation of 0 would indicate no correspondence of the X coordinate trajectories determined by different observers using the same method. **Bars** mark 1 standard error. Method 1 is endocardial average of coordinates; method 2 is endocardial center of area. Center of area is theoretically less sensitive to misplacement of a boundary point. The interobserver trajectory correlations are higher using method 2, indicating better agreement.

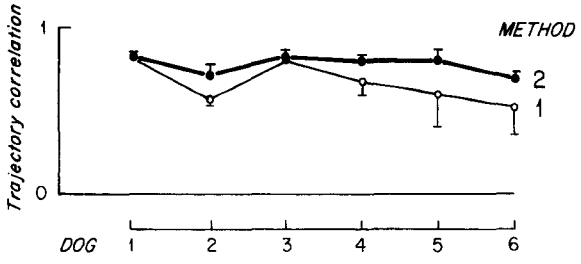
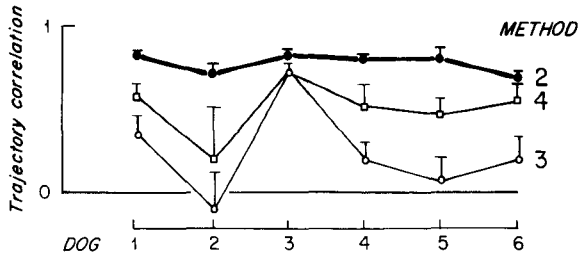


Figure 3. Comparison of centroid correlations for the X_c coordinate (methods 2, 3 and 4). Mean interobserver correlations are given for each dog for methods 2, 3 and 4; these correspond to data in Table 1. **Bars** mark 1 standard error. Method 2 is endocardial center of area; methods 3 and 4 are epicardial average of coordinates and center of area, respectively. The interobserver trajectory correlations are higher using method 2, indicating better agreement between different observers using endocardial center of area.



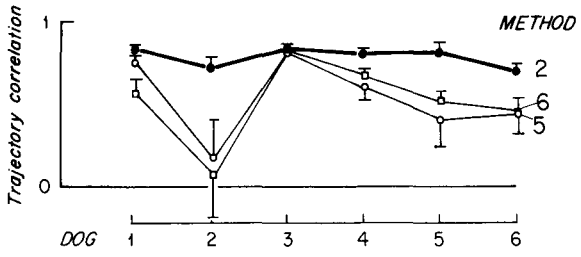


Figure 4. Comparison of centroid correlations for the X_c coordinate (methods 2, 5 and 6). Mean interobserver correlations are given for each dog for methods 2, 5 and 6. Method 2 is endocardial center of area; methods 5 and 6 are mid-myocardial average of coordinates and center of area, respectively. The interobserver trajectory correlations are higher using method 2. See Figure 2 for further details.

are homogenous or symmetric (19–22). This study demonstrated significant differences among centroid trajectories for different normal dogs, differences that were reproducible from beat to beat for different observers and that could not be observed if the trajectory was fixed by assumption for analysis.

Comparison with other methods. This study did not evaluate all possible methods for choosing a central reference, which are manifold. For example several studies (23,24) have chosen as centroid the midpoint of a line drawn from the mid or posterior septum to the furthest antipodal point on the opposite wall. Those methods are determined, in effect, by the exact position of only two points on the boundary. If there is any distortion of the shape of the left ventricle, such methods will either ignore the shape factor (if those two points are not shifted by it) or may be markedly affected (if either point is shifted as a consequence). Because signal to noise ratio, a fundamental measure of data quality, generally improves in proportion to the square root of the number of samples, the methods presented, based on 72 or 144 sampled coordinate pairs, seem inherently more reliable than any two point method. Thus, on theoretic grounds, the scope of this study was limited to the evaluation of methods based on all of the digitized border points of the endocardium or epicardium, or both. Another method used at other sites defines a centerline midway between the end-diastolic and end-systolic contours in the short-axis view (13) or chooses one or the other as a fixed frame (25). These are used for radial measurements and are based on only two time points; they do not provide sufficient data to analyze trajectory.

Previous studies. It is difficult to compare our results with previous work because other studies did not address the specific questions addressed in our study. Garrison et al. (24) reported the use of 16 or 32 points around epicardial and endocardial borders for centroid determination, but they did not assess the impact of computational method on the reliability of the result. However, Eaton et al. (3) did report interobserver variation related to centroid determination, measuring segmental lengths to endocardium and wall thickness. They observed no significant differences for the former and significant differences for the latter. Although other potential causes for differences were present, it is interesting to note that the former relates to endocardial definition, whereas the latter (wall thickness) also depends on epicardial definition.

Conclusions. Numerous approaches to selection of a reference standard for wall motion analysis of short-axis echocardiographic images of the canine left ventricle have been proposed. Choosing among these is an important problem because the exact choice of reference affects all measurements. With regard to the choice of a central reference (centroid) for single image frames of the normal heart, several conclusions may be drawn. Methods based on the endocardial border ranked higher in interobserver correlation of trajectory than did methods based on the epicardial border. Methods based on center of mass did as well or better than methods based on the center of coordinates (better for X_c). Different hearts have distinct trajectories, which are reproducible from beat to beat. Interobserver differences in epicardial border recognition produce inconsistencies that limit its usefulness in wall motion analysis compared with endocardial definition.

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