Quantitative Measurement of Left Ventricular Volumes in Man from Radiopaque Epicardial Markers

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SUMMARY The distances between three or four radiopaque markers located on the left ventricular epicardial surface at the apex and in the region of the minor axes in 22 subjects showed close correlations with left ventricular chamber radii, length, volume and wall thickness determined from biplane angiograms over the range of stroke volume. The markers were previously placed during heart surgery. Regression equations relating the distances between epicardial markers and chamber volumes were used to predict volumes for other patients. There was close agreement of end-diastolic, end-systolic, and stroke volumes as determined by the angiographic and epicardial marker methods for premature atrial contraction beats and post premature contraction beats, and in studies performed during rest and exercise. Time-volume curves determined by the epicardial marker and angiographic methods were similar. It is concluded that epicardial marker measurements can be used to quantitate beat-to-beat left ventricular chamber volume and dimension changes.

ANGIOGRAPHY provides a method for determining left ventricular dimensions and volume, but is not suitable for continuous, or for frequently repeated study of changes of volume and dimensions induced by interventions. In man epicardial marker motion has been shown to qualitatively reflect left ventricular dimension changes produced by interventions, but the quantitative relationship between epicardial marker measurements and left ventricular and volume dimensions as determined by angiography has not been evaluated. Radiopaque markers placed on the left ventricular endocardium have been used to measure left ventricular volume and dimension changes in experimental animals. Studies of this method have demonstrated a close relationship between marker distance changes and electromagnetic flow probe measurements of stroke volume, but the volumes computed from these markers overestimate actual chamber volumes. The purpose of the present study was to determine the relationships between measurements made from radiopaque markers attached to the epicardial surface of the left ventricle and measurements of chamber dimensions and volume determined from the left ventricular angiogram, and to test application of these relationships for quantifying beat-to-beat changes of left ventricular dimensions and volume.

Methods

Twenty-two patients were studied who had had four or more silver vascular clips attached to the epicardial surface of the left ventricle at the time of heart surgery. Twenty-one beats. There was close agreement of end-diastolic, end-systolic, and stroke volumes as determined by the angiographic and epicardial marker methods for premature atrial contraction beats and post premature contraction beats, and in studies performed during rest and exercise. Time-volume curves determined by the epicardial marker and angiographic methods were similar. It is concluded that epicardial marker measurements can be used to quantitate beat-to-beat left ventricular chamber volume and dimension changes.

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From the biplane angiograms and cineangiograms, the chamber diameters in the anteroposterior (Rap) and lateral (RLt) projections, chamber lengths (L) and left ventricular volumes were determined using the area-length method. Wall thickness (T) was measured at end diastole and left ventricular mass calculated using the method of Rackley and co-workers. Changes in wall thickness during systole and diastole were then calculated from chamber dimensions by using the equation for computing mass with the assumption that wall mass is constant.

The spatial distances between the epicardial radiopaque markers were determined from the biplane films. Marker positions are illustrated in figure 1. Markers in the anteroposterior view are arbitrarily labeled A, B, C, etc. and corresponding markers in the lateral view are similarly identified. The projected distances between the markers were determined by using an Autotrol 3400 X-Y digitizer with resolution and hardware accuracy of 0.1 mm on-line to a PDP 11/45 computer. For the large film studies, individual marker positions were corrected for X-ray distortion and the spatial distances between the markers computed from X, Y, and Z coordinates by a method similar to that previously described for biplane angiography.

For the biplane cine studies the spatial distances between the markers were also computed from the X, Y, and Z coordinates. For cine filming, the X-ray tubes and image intensifiers were set orthogonal so that the central X-ray beams cross at right angles and are located at the center of each image intensifier as shown in figure 2. It is assumed that the center of each cine frame coincides with the central X-ray beam. The X, Y, Z coordinates were determined using the
TABLE 1. Correlations of Epicardial Marker and Chamber Measurements

<table>
<thead>
<tr>
<th>Subject</th>
<th>Rap</th>
<th>Rlt</th>
<th>L</th>
<th>Vol.</th>
<th>Wall T.</th>
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Abbreviations: Rap = anteroposterior; Rlt = lateral; L = chamber length; T = thickness; LV = left ventricle; Tetra = tetrahedron; Vol = volume.

same X-Y digitizer-computer system described above. The floating zero of the digitizer was set at the center of the projected frame. The coordinates as determined from the projected cine frames are distorted by various elements of this system as follows: 1) X-ray beam divergence; 2) image intensifier magnification; 3) cine camera magnification; 4) projection system magnification; and 5) pin cushion distortion. Distortion due to these factors was considered and corrected for by application of the equations which follow (equations 1 to 8). To apply these equations certain conditions with respect to the equipment must be satisfied and these are as follows. 1) The X-ray tubes and image intensifiers must be arranged orthogonally as described; 2) the X-ray tube to image intensifier distances are fixed and constant; 3) the image intensifier, camera and projector as a system provide a constant magnification.

Figure 2 illustrates the biplane cine and projection system with an object being filmed. In this figure (a) and (l) are the X and Y coordinates, respectively, for the location of this object in a spatial, or three-dimensional system. The Z coordinate is perpendicular to the illustration and is common to both projections. The magnified views of (a) and (l) are a' and l'. Correction factors for this magnification were experimentally determined for each plane at distances of 10-30 cm (1.0 cm increments) from each image intensifier with films of a ruled grid. These correction factors were used to compute linear regression equations which were applied to determine correction factors for any object-to-image intensifier distance. Pin cushion effect was disregarded because with our equipment correction factors differed by less than 2.5% to within 1.0 cm of the outer margin of the projected image.

Using the above conditions and data, the AP and Lt correction factors (F<sub>A</sub> and F<sub>L</sub>, respectively) are expressed by the following equations:

\[ F_A = m_A \Delta_x + b_A \]  
\[ F_L = m_L \Delta_l + b_L \]  
\[ (1) \]  
\[ (2) \]

where \( m_A \) and \( m_L \) are the slopes of the regression equations used for correction and \( b_A \) and \( b_L \) are the offsets. From figure 1 it can also be seen that

\[ \Delta_x = p_A + l \]  
\[ \Delta_l = p_L - a \]  
\[ (3) \]  
\[ (4) \]

\( p_A \) and \( p_L \) are measured as positive quantities, therefore \( p_A \) is positive in equation 3.)

Substituting equations 3 and 4 into 1 and 2,

\[ \frac{a}{d_l} = F_A = m_A(p_A + l) + b_A \]  
\[ (5) \]

**Figure 1.** A triangle in three dimensional space is constructed using any combination of three epicardial markers (A, B, C) from AP and lateral films.

**Figure 2.** Schematic representation of the biplane cine filming equipment. \( h_s \) and \( h_l \) are the AP and lateral (LT) X-ray tube-to-film distances, respectively. \( p_x \) and \( p_l \) are the central X-ray beam-to-image intensifier distances as illustrated. \( \Delta_x \) and \( \Delta_l \) are the object-to-image intensifier distances in the AP and lateral directions respectively. The actual location of the object is at the intersection of lines (a) and (l).
\[ f = F_a = m_L (p_L - a) + b_L \]
\[ \text{Solving for } F_a \text{ and } F_L \text{ from equations 5 and 6,} \]
\[ F_a = \frac{m_a (p_a + f' [m_L p_L + b_L]) + b_A}{1 + a'm_a l'm_L} \]
\[ F_L = \frac{m_L (p_L - a' [m_A p_A + b_A]) + b_L}{1 + a'm_a l'm_L} \]

The correction factors \( F_a \) and \( F_L \) were determined and applied to correct the location of each individual marker which was found necessary, particularly in the exercise studies in which the subjects' position with respect to the X-ray tubes and films often changed during the course of the studies. From the corrected X-Z coordinates of AP frames and Y-Z coordinates of lateral frames, the distances between each pair of clips (AB, BC, AC, etc.) in three-dimensional space were calculated according to the formula:

\[ AB = \sqrt{X^2 + Y^2 + Z^2} \]

(9)

Where \( X, Y, \) and \( Z \) are the corrected projected distances between markers A and B on the respective X, Y, Z axes as determined from the AP and lateral films. BC and AC were similarly computed.

For each set of three clip coordinates in three-dimensional space, the area of a spatial triangle \((ABC)\) was computed using the following formula:\(^{14}\)

\[ \text{AREA} = \sqrt{S \cdot (S-AB) \cdot (S-AC) \cdot (S-BC)} \]

where \( S = \frac{AB + BC + AC}{2} \)

In 13 subjects the volume of a tetrahedron formed by four markers was computed. This tetrahedron was determined by a marker at the apex and three about the approximate minor axes, located anteriorly, posteriorly and on the free wall as previously described.

The area of the above spatial triangle was related to chamber volume, dimensions, and wall thickness computed from the same pair of biplane angiographic films. Volume of the tetrahedron and chamber volume were also related. For all subjects the measurements were made from each pair of biplane films over one cardiac cycle, including both systole and diastole and correlated as is shown in table 1 and figure 3. These relationships were accordingly determined over a range of volume change represented by the stroke volume and included both systole and diastole.

In each patient undergoing biplane cineangiography a spatial triangle formed by three clips was identified; the area change of this triangle during cardiac contraction was linearly related to angiographic volume change. In the majority of the subjects this was the triangle formed by the markers located on the anterior, inferior, and apical surfaces of the left ventricle. The regression equation of the biplane cineangiographic volume-spatial triangle relationship which had the strongest correlation for a given patient was used when the epicardial marker measurements were applied to determine the volume changes of other beats (tables 2 and 3).

The reproducibility of the clip measurements and calculations as determined by two technicians was tested. Human plus hardware consistency for individual marker measurements was determined by correlating 124 digitized coordinates of two markers from 62 cine frames determined by one technician with the same coordinates as determined separately by another. The mean values were identical and the standard error of estimate was 0.6 mm. In another study two technicians separately determined marker distances from frames over one cardiac cycle from each of two patients. The chamber volumes computed from these

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**Figure 3.** Panels from left to right: Spatial area of triangle formed by clips related to 1) minor axis of left ventricular chamber in antero-posterior projection \((r = 0.98)\); 2) minor axis in lateral projection \((r = 0.97)\); 3) long axis \((r = 0.91)\); 4) wall thickness \((r = 0.97)\); 5) chamber volume \((r = 0.98, y = 13.6x-272)\). Volume and dimensions during systole are indicated by black circles and diastole by white circles.
measurements as determined by the two technicians correlated highly \((r = 0.98\) to 0.99) and agreement was within 5 ml for end-diastolic volumes and 1 ml for end-systolic volumes. The standard error of the estimates were two to three ml, which represented 2-3% of the stroke volumes of these beats.

The use of marker measurements to quantitate volume changes and to determine left ventricular volume curves in beats other than those used for deriving the regression equations was studied in seven subjects. In one subject, volumes and volume curves were determined from marker measurements from a beat immediately prior to angiography and compared with the angiographic values determined from the calibration beat (fig. 4). In subjects in whom several beats during angiography had adequate ventricular chamber opacification for volume calculations, the regression equation determined from the sinus, “calibration,” beat was applied to the marker measurements and used to predict left ventricular volume, volume changes, and volume curves of a subsequent sinus beat in three subjects, and premature atrial contraction beats, or beats following premature contractions in four subjects. Volumes predicted from marker measurements were compared with volumes determined independently from the biplane cineangiograms and the data are presented in table 2.

In two subjects, the epicardial marker method was tested for determining chamber volumes during exercise (table 3). Left ventricular biplane cineangiograms were performed at rest and during exercise at a level of 300 kiloponds per minute. The regression equations which related marker distances to chamber volumes for the resting studies were determined and applied to compute chamber volumes from marker distances for the exercise studies. The chamber volumes computed from the markers were compared with chamber volumes computed from the images of the opacified chamber for the same beats during the exercise studies (table 3).

**Results**

The coefficients of correlation between epicardial marker measurement and angiographic measurements are listed in table 1. The observations are over a range of end-diastolic volumes of 101-387 and end-systolic volumes of 19-262 ml for the different subjects. Three-dimensional spatial triangle areas calculated from epicardial marker measurements correlate highly with angiographically determined left ventricular radii in the AP plane \((r = 0.72\) to 0.98) and the lateral plane \((r = 0.75\) to 0.99), and the longest length \((r = 0.30\) to 0.95), volume \((r = 0.80\) to 0.99), and wall thickness \((r = 0.95\) to 0.99). The coefficient of correlation between spatial triangle area and angiographically determined left ventricular volume exceeded 0.95 in all but two subjects. Where values are not given, they were not computed because all four markers could not be visualized, or because wall thickness could not be adequately visualized for measurement. In subject 6, only the spatial triangle and volume relationships were computed.

Eight of the subjects in table 1 had focal areas of ventricular hypokinesia: inferior in subjects 10, 12, 19, and 21; anterior in subjects 11, 13, 16, and 17. The correlation coefficients in these subjects were similar to those obtained in the other subjects with symmetrically contracting ventricles. No subjects had aneurysms or focal dyskinetic areas.

Also shown in table 1 are the correlation coefficients for

| Table 2. Comparison of Volume Changes Determined by Angiography and Epicardial Marker Prediction in Varying Beats |
|---|---|---|---|---|---|
| **Subject** | **Beat type** | **Vol (ml) range by angio** | **Predict vol range marker (Δ)** | **r (Δ)** | **SEE (Δ)** | **Predict vol range marker (T)** | **r (T)** | **SEE (T)** |
| 9 | PAC | 72-29 | 77-30 | 0.99 | 4 | 77-30 | 0.98 | 4 |
| 10 | Post PAC | 102-26 | 98-23 | 0.99 | 3 | 98-27 | 0.98 | 3 |
| 11 | NSR, Ref. | 101-39 | 95-39 | 0.98 | 4 | 96-38 | 0.99 | 3 |
| 12 | Post PVC | 180-101 | 183-104 | 0.97 | 6 | 180-100 | 0.94 | 9 |
| 13 | NSR, Ref. | 165-108 | 169-111 | 0.96 | 6 | 180-117 | 0.87 | 11 |
| 14 | NSR, Ref. | 175-115 | 180-109 | 0.96 | 6 | 175-109 | 0.91 | 8 |
| 15 | PAC | 129-38 | 131-42 | 0.99 | 3 | 126-38 | 0.99 | 4 |
| 16 | NSR, Ref. | 105-59 | 106-58 | 0.99 | 5 | 99-60 | 0.90 | 5 |
| 17 | NSR, Ref. | 101-40 | 90-40 | 0.96 | 5 | 83-39 | 0.86 | 9 |
| 18 | PAC | 86-44 | 78-47 | 0.98 | 5 | 81-44 | 0.86 | 11 |
| 19 | Post PAC | 123-34 | 112-39 | 0.95 | 9 | 96-32 | 0.87 | 14 |

**Abbreviations:** PAC = premature atrial contraction; NSR = normal sinus beat; Ref = beat used for marker calibration; Marker \((Δ)\) = spatial triangle area from 3 markers; Marker \((T)\) = tetrahedron volume from 4 markers; \(r\) = correlation coefficient; \(SEE\) = standard error of estimate.

| Table 3. Comparison of Volume Changes Determined by Angiography and Epicardial Marker Prediction during Exercise |
|---|---|---|---|---|---|
| **Subject** | **Beat type** | **Vol (ml) range by angio** | **Predict vol range marker (Δ)** | **r (Δ)** | **SEE (Δ)** | **Predict vol range marker (T)** | **r (T)** | **SEE (T)** |
| 15 | NSR | 116-23 | 116-28 | 0.98 | 6 | 118-14 | 0.95 | 9 |
| 16 | NSR, Ref. | 121-26 | 123-29 | 0.97 | 8 | 114-13 | 0.96 | 9 |
| 17 | NSR | 127-29 | 118-30 | 0.96 | 9 | 117-14 | 0.97 | 8 |
| 18 | Exercise | 139-31 | 130-26 | 0.95 | 11 | 120-39 | 0.95 | 11 |
| 22 | NSR, Ref. | 136-50 | 130-52 | 0.95 | 10 | 114-13 | 0.96 | 9 |
| 23 | Exercise | 127-21 | 123-20 | 0.99 | 6 | 114-13 | 0.96 | 9 |

Symbols are as described in table 2.
the relationship of the volume of a tetrahedron formed by four markers and chamber volume in 13 subjects. The values were 0.77 to 0.99, and in most instances, similar to the close correlations which were found for spatial triangles and chamber volumes. However, in subjects 12, 14, 17, 20, and 21 the correlation of chamber of tetrahedron volumes was less close than for the chamber volume and spatial triangle area. The basis for the differences in these four subjects may at least in part be due to the following. The data on spatial triangles in table 1 represent the closest correlations when the apical and two other markers are used, whereas the tetrahedron volume calculations, of course, require use of four markers. The individual marker distances and volume correlations with this fourth marker were often not as close as for the individual distances and volume correlations for the other three markers. Because of this the triangle correlations which use three markers were often closer than correlations using four markers. Because the area of a triangle is a square function, in contrast to the cubic function for volume, it is possible that over a larger range of volume changes than was studied a curvilinear relationship would be found between the area and volume measurements. For this reason, the volume of the tetrahedron may be a theoretically preferable reference for calibration for large volume changes, but the computations require measurements of four, rather than three, markers and accordingly are more tedious.

Figure 3 shows the relationships between the spatial area of the triangle defined by the markers and chamber minor axes in the AP and lateral projections, the long axis, wall thickness, and volume in one subject. The correlation coefficients show close relationships between these measurements. The regression equation that defines the relationship between chamber volume and clip distance for this subject is given in the lower middle panel of figure 3. In this illustration the values during systole are coded as solid circles and diastole, open circles. There is some hysteresis when systolic and diastolic spatial marker triangle areas and chamber volumes are compared, demonstrating that marker distance-volume relationships differ somewhat during systole and diastole and in particular at end systole and early diastole.

This was a common finding in these subjects, but was usually not marked, as is evident from the correlation coefficients given in table 1.

The regression equation which was determined from the triangle area and chamber volume relationships as illustrated in figure 3 was applied to determine the volume curve of the opacified and a subsequent nonopacified beat as is illustrated in figure 4. The end-diastolic and end-systolic volumes and volume curves determined from the spatial triangle areas are similar to the angiographically determined values for both the "calibration beat" and the subsequent nonopacified beat. Figure 4 also illustrates that the angiographically determined left ventricular volume curve and the volume curve predicted using the regression equation and clip measurements from this patient are similar.

In figure 5 are shown time-volume data from two separate normal sinus beats from the same subject: one determined from epicardial clips and the other from a biplane cineangiogram. The regression equation relating the area of the triangle defined by the clips to chamber volume in this subject was determined, and applied to clip measurements made from biplane films taken of a beat several seconds prior to the angiocardiography. The end-diastolic and end-systolic volumes are similar as are the time-volume plots during systole. The filling limbs differ somewhat, which may be a consequence of the slightly slower heart rate that was present during the beat used for the clip-determined volume curve. The contribution of atrial contraction to ventricular filling is clearly visible from the changes in the slope of the diastolic filling limb of both curves. This is also evident in the volume curves illustrated in figure 3.

In tables 2 and 3 are shown data comparing chamber volumes of normal sinus beats computed from epicardial markers and the angiographic images of the ventricular chamber in two subjects (12 and 15). The regression equations relating marker distances and chamber volume for the reference normal sinus beats were applied to compute
volumes for other normal sinus beats when there was continued opacification of the ventricular chamber. There was close agreement between volumes computed by the angiographic and epicardial marker methods, similar to that demonstrated in figure 4.

The relationship of changes of spatial triangle area and tetrahedron volume to beat-to-beat changes of chamber volume due to premature contractions was determined in four subjects (9, 12, 13, and 14), as is also shown in table 2. For the PAC beats in subjects 9, 13, and 14 the relationships were determined for systole alone in that this provided data on the systolic portion of a beat with a shortened preceding R-R interval and reduced end-diastolic volume and reduced stroke volume. As shown in figure 5, these relationships would be obscured by including the multiple observations during the prolonged ventricular filling period which follows the premature contraction. Post-premature contraction beats were studied in subjects 9, 12, and 14 and for these the relationships for volumes computed by the marker and angiographic methods during both systole and diastole were determined. These data show a close relationship between end-diastolic, end-systolic, and stroke volumes determined by the epicardial marker and angiographic methods for the same heart beats. Furthermore, high correlation coefficients (0.95 to 0.99) were obtained from a comparison of volumes computed for all heart beats. Thus there is a close agreement between volumes computed by these two methods over the entire range of volumes studied for these beats. These relationships are also illustrated for subject 9 in figure 5 in which the volume curve computed from epicardial marker measurements is compared with angiographic determinations of volume for an atrial premature contraction beat. Not only are the end-diastolic, end-systolic, and stroke volumes nearly identical, but the volume curves are also very similar.

In subjects 15 and 22 in table 3, who had resting and exercise studies, end-diastolic, end-systolic, and stroke volumes determined by the epicardial marker method showed close agreement with these same values determined by the angiographic method for the same heart beats. The high correlation coefficients also indicate a close correlation between the volumes computed by these two methods over the entire range of volumes studied.

Discussion

There has been no proven method for quantifying beat-to-beat changes of left ventricular dimensions and volume in man that is suitable for accurate, frequently repeatable, and acceptably safe application. Quantitative left ventricular angiography requires heart catheterization and has been reported to produce a significant increase in left ventricular volume beginning three to five beats after the injection of contrast medium. The duration of this effect in man is not precisely known, but animal studies and observations in man suggest that studies should be separated by at least 15 minutes if return to baseline state is to be assumed.

Alternative methods of quantitatively changes in left ventricular volume in man include indicator dilution techniques and echocardiography. Indicator dilution methods have theoretical limitations. More importantly, only end-systolic, end-diastolic, and stroke volumes can be measured and the method is inaccurate in patients with irregular rhythms or valvular regurgitation. Echocardiographic measurements of left ventricular dimensions correlate significantly with angiographically determined left ventricular dimensions and volumes, but assumptions regarding left ventricular geometry introduce errors in volume calculations, particularly in patients with large hearts. The mean velocity of left ventricular circumference change during systole as measured from echocardiograms has also been shown to correlate significantly with values determined from cineangiograms. Echocardiography dimensions have been demonstrated to change appropriately during interventions in man, and when used to compute stroke volume changes, have been shown to give values that correlate significantly with changes determined by the indicator-dilution method. Ventricular filling rates, curves of circumference change during systole and diastole, and volume curves have also been calculated from echocardiograms, but the accuracy of these derived data has not been evaluated by comparison with results of other methods. By and large the relationships between echocardiographic measurements and chamber dimensions and volume in the reported studies have not been as close as those found for epicardial markers in this study. However, the relationships in this study were determined differently and for each individual subject so that the results are not really comparable.

Radiopaque epicardial marker measurements were shown by Harrison et al. to be sensitive to left ventricular dimensional changes produced by interventions such as deep breathing, the Valsalva maneuver, pacing, exercise, isoproterenol, and methoxamine. In these studies, changes in the distances between markers were determined, but these were not related to changes of ventricular chamber dimensions and volumes. McDonald demonstrated a reduced shortening of the distances between epicardial markers in man with left ventricular hypertrophy following valve replacement for aortic valve stenosis. Recently, Ingels and co-workers have described a method for studying midwall myocardial dynamics through the use of tantalum wire helices implanted at the time of surgery in man.

Mitchell and co-workers have described beat-to-beat changes in left ventricular volumes calculated from the distances between radiopaque beads placed on the endocardium. The changes of ventricular volume during systole as determined by this method correlated closely with electromagnetic flow probe measurements of stroke volume. However, the end-diastolic and end-systolic volumes as computed from the markers substantially exceed the previously reported values for canine left ventricular end-diastolic and end-systolic volumes. Direct studies in the same hearts comparing volumes calculated from endocardial markers with angiographic or cast volumes have not been reported. More recently transverse internal chamber diameters were shown by Bishop and Horwitz to correlate significantly with thermodilution estimates of left ventricular end-diastolic volume and even more accurately with cast volumes of canine hearts. Continuous measurements of left ventricular volumes in dogs using mechanically recorded epicardial dimension measurements have been reported by Davila et al. and shown to correlate closely with single
plane angiographic measurements, which in turn were closely related to the actual volumes of left ventricular casts.29

In the present study, the changes of spatial distance between epicardial markers and changes of left ventricular chamber dimensions and volume determined from angiograms are shown to have significant linear relationships. The lowest coefficient of correlation were between spatial triangle areas and left ventricular long axes. This is probably due to the difficulty in making precise long axis measurements from late systolic films and the difficulty in exactly identifying aortic valve level, combined with the comparatively small absolute reduction in the long axis during left ventricular systole. The coefficients of correlation between spatial triangle areas and left ventricular anteroposterior and lateral minor axes as determined from biaxial angiograms were higher. Correlations of marker distance changes with left ventricular volume and wall thickness changes demonstrated the strongest relationships, as is illustrated in table 1.

Since the change in wall thickness during the cardiac cycle is calculated using the equation for left ventricular mass derived by Rackley et al.,8 which in turn is derived from the measurements used for left ventricular volume calculations, the close agreement between r values from volume correlations and those from wall thickness correlations is not unexpected.

The coefficients of correlation between spatial triangle areas and tetrahedron volumes and ventricular chamber volumes determined from biaxial cineangiograms in the 16 subjects (with biaxial cineangiograms, table 1) were 0.96 to 0.99 over the range of volume represented by stroke volume and including both systole and diastole. These high correlation coefficients demonstrate a close agreement between volumes computed by the epicardial marker and angiographic methods throughout the cardiac cycle over the range of stroke volume. This indicates that the regression equations relating epicardial marker distances and chamber volume can be applied to epicardial marker measurements to compute ventricular volume curves from the marker measurements alone. Such an application is demonstrated in figures 4, 5, and 6 which show close agreement between ventricular volume curves determined by the marker and angiographic methods. Because of the close correlation of these marker measurements and chamber dimension and wall thickness changes, the epicardial marker technique can also be applied to determine curves of these parameters as a function of time within the cardiac cycle, once calibration has been performed using angiographic data.

The dimension and volume data relationships to epicardial marker distances showed some hysteresis when systole and diastole were compared as illustrated for volume in figure 2. This was most evident at end-systole and early diastole, but in no case was it marked as is evident by the high regression coefficients in most subjects. The hysteresis suggests that ventricular shape with respect to volume differs during late systole and early diastole. If this indeed is the case, which seems likely, then any method that is used to derive an index of volume changes over the course of the cardiac cycle from measurements of a ventricular dimension will potentially have inaccuracies due to such shape changes.

This would apply to echocardiography or sensors placed on the epicardial or endocardial surface to record dimensional changes. To further improve the accuracy of this marker method and the correlation coefficients determined from relating marker distance changes and volume change, separate regression equations could be computed for systole and diastole.

The data from studies described in table 2 demonstrate that changes of end-diastolic volume, end-systolic volume, and stroke volume, and indeed, volume changes throughout systole and diastole during atrial premature contraction beats and post-premature contraction beats can be determined from epicardial marker measurements alone. This then is under conditions where there are acute changes of ventricular diastolic volume, end-systolic volume, afterload, and contractility as a consequence of an acute change of ventricular rate. In addition, it was shown in two subjects that ventricular volume changes during exercise could be quantified from epicardial measurements which were calibrated from biaxial cineangiograms performed with the patients resting prior to exercise (table 3).

It is of interest that in the studies described in table 2 the largest increase in end-diastolic volume over the reference normal sinus beat was 22 ml (subject 14) and in most subjects it was substantially less. The leveling off of the ventricular filling curve with a prolonged filling period is shown in figure 5. This is probably because in most resting recumbent subjects, the left ventricle at end-diastole is relatively stiff with low compliance. The extent to which the left ventricle in man in the recumbent position acutely increases end-diastolic volume with physiologic stress is unknown, but these studies suggest that the changes would not be great.

Angiographic measurements of left ventricular volume require certain assumptions regarding left ventricular geometry.40 These assumptions have been tested in postmortem hearts and regression equations have been determined which can be applied to computed volumes in order to more
accurately reflect actual left ventricular volumes.  Stroke volume, as measured angiographically, has in turn been shown to agree closely with stroke volume as determined by Fick and indicator-dilution methods. According to the strong relationship between spatial triangle areas defined by epicardial markers and the angiographic volume measurements reported in this study, can be applied quantitatively to determine left ventricular volume changes with assumptions that are similar to those inherent in the area-length angiographic method itself. In addition, it is assumed that the relationship between clip measurements and angiographic volume remains reasonably linear over the volume range under consideration and that there are no changes of ventricular shape that will alter the relationships between dimensions and volume established at the time of the epicardial marker calibration.

It is concluded that epicardial markers provide a sensitive means of quantitating left ventricular dimension and volume changes in man, but the results would suggest the following limitations. 1) Epicardial markers can only be placed at the time of surgery, and in each patient, epicardial marker measurements must be calibrated by means of a postoperative biplane angiogram. 2) The change in distance between pairs of markers is small, 5 to 15 mm in most cases, so the measurements of marker distances must be precise. Since for determining dimension and volume curves, the positions of three or more clips must be digitized from each of 30 to 60 frames for a single beat, the measurements are tedious to perform. 3) Interventions expected to produce large volume changes, beyond those described in this report, will require further study to document relationships. 4) If interventions induce changes of ventricular shape relative to volume, or focal contraction abnormalities, the epicardial marker method may not accurately detect chamber dimension and volume changes.

In summary, a significant linear relationship was demonstrated in the distances between radiopaque epicardial markers and angiographically determined left ventricular dimension and volume changes. The relationships were used to calibrate marker measurements so that chamber volume and volume changes could be quantitated without further use of angiography. This appears to be a method for determining ventricular response to interventions in man. If routinely placed at the time of surgery, such markers, following calibration by angiography, might provide a means for following serial changes in left ventricular function, assuming no substantial changes of ventricular mass or shape relative to volume develop.

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Cardioversion and “False Positive” Technetium-99m Stannous Pyrophosphate Myocardial Scintigrams


SUMMARY The present studies performed in experimental animals demonstrate that electrical direct current cardioversion can produce skeletal muscle damage and increased technetium-99m stannous pyrophosphate (99mTc-PYP) uptake; in experimental animals the electrically damaged skeletal muscle shows necrosis with extensive calcium deposition. In addition, the frequent administration of high energy cardioversion produces myocardial necrosis with calcium deposition, increased 99mTc-PYP myocardial uptake and a positive 99mTc-PYP myocardial scintigram. The data indicate that, if diagnostic 99mTc-PYP myocardial scintigraphy is contemplated after cardioversion, paddle placement should be slightly removed from the anteroposterior projection of the heart on the external chest wall to avoid possible subsequent confusion between increased myocardial and skeletal muscle uptake of 99mTc-PYP. If multiple high energy cardioversion episodes are necessary, myocardial necrosis resulting from electrical injury may occur and be responsible for increased myocardial uptake of 99mTc-PYP with a resultant positive 99mTc-PYP myocardial scintigram.

IN AN EFFORT TO ESTABLISH more precisely the occurrence of myocardial infarction in patients admitted to the hospital with a suggestive clinical history, radioisotope imaging of the heart with technetium-99m stannous pyrophosphate (99mTc-PYP) is routinely performed in patients admitted to the Parkland Memorial Hospital coronary care unit.1-4 Our experience with this myocardial imaging procedure during the past two years has confirmed its sensitivity in detecting and localizing areas of recent myocardial damage.1-4 The development of a positive 99mTc-PYP myocardial scintigram correlates well with standard serum enzyme and electrocardiographic markers of myocardial infarction.4-8

In view of recent published clinical and experimental studies demonstrating both chest wall and myocardial muscle necrosis following transthoracic direct current (DC) countershock,9-14 we felt it important to determine the effect cardioversion might have on the interpretation of a subsequent 99mTc-PYP scintigram; that is, might cardioversion cause sufficient chest wall muscle necrosis and 99mTc-PYP uptake to produce a false positive scintigram? Accordingly, we have performed an experimental study to determine whether skeletal and/or heart muscle takes up increased amounts of 99mTc-PYP after cardioversion in dogs.

Methods

Twelve dogs were studied in the experimental investigation. Each dog was anesthetized with intravenous nembutal (15 mg/kg), intubated and ventilated with a Harvard respirator. In two dogs the chest was opened through a left lateral thoracotomy and the heart exposed. In these two animals cardioversion paddles were applied directly to the heart and two consecutive direct current discharges, each of 10 watt seconds, were applied. The chest was then closed and the animals allowed to recover. In the remaining ten dogs cardioversion paddles were applied directly to the closed chest wall with one paddle positioned over the sternum and the other one over the cardiac apex. Five of the dogs received a single 200 watt second discharge, three received five con-
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