Measurement of Midwall Myocardial Dynamics in Intact Man by Radiography of Surgically Implanted Markers

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SUMMARY

Tiny radiopaque helices (0.85 × 1.5 mm) of pure tantalum wire were implanted by means of a simple inserter instrument into the left ventricular myocardium in 24 patients at the time of cardiac surgery. The markers were positioned in such a way as to outline the profile of the left ventricle when viewed in a 30° right anterior oblique projection. Biplane studies showed that all markers could be placed very nearly in a plane using the surface anatomy of the heart as a guide to implantation. Implantation of markers required approximately two minutes. No intraoperative or postoperative complications ascribable to the markers have occurred. They remain firmly in place and allow acquisition of a noninvasive ventriculogram at any time after surgery.

The dynamic geometry of the left ventricle was determined by analysis of cineradiograms of these markers.

Utilization of a single-plane (right anterior oblique) cineradiogram to obtain measurements of major transverse ventricular diameters, mean circumferential shortening, and circumferential shortening velocity results in underestimation of lengths by 1.4%, overestimation of shortening by 1.2% of end-diastolic length, and overestimation of velocity by 0.05 circ/sec, when compared with values obtained simultaneously from biplane cineradiograms.

We have developed a method for the permanent implantation of tantalum coils into the myocardium at the time of cardiac surgery, using a modification of the technique described by Carlsson and Milne.1 Subsequent visualization of the markers by cineradiography and computer data processing techniques can be used to measure the midwall dynamics of the left ventricle. Extensive animal studies, which showed no operative or postoperative complications and no pathological changes from such implantation,2 encouraged the use of this method in man. In this communication we report our initial experience with this method in 24 patients.

Methods

Intramyocardial Tantalum Markers: Construction and Implantation

Myocardial markers are made by close-winding many turns of metallurgical grade tantalum wire 0.25 mm diameter on a mandrel (0.35 mm diameter). The resultant coil is stretched across a 2 mm grid until a frequency of 3 turns/2 mm is obtained. Three turn sections are cut to 2 mm length, placed back on the mandrel, and compressed to 1.5 mm in length. The three-turn markers have an outer spiral diameter of 0.85 mm as shown in figure 1.

The markers are degreased and cleaned thoroughly by washing sequentially in trichloroethylene, acetone, and mild detergent solution, and rinsed in a large volume of distilled water. They are then packaged for heat sterilization.

An inserter tool is used to place the tantalum coil in the approximate midwall of the left ventricular myocardium. This tool is turned from brass rod to the dimensions shown in figure 1, a 0.35 mm diameter hole is drilled in the conical end, and a 0.35 mm diameter catheter guidewire is heatshrunk into this hole, cut to extend 3 mm beyond the conical end, and sharpened.

Each tantalum marker is implanted in the midwall of the myocardium by threading the point of the inserter tool into the coil and inserting the tool perpendicularly into the myocardium as far as the stop (i.e., the shoulder at the wide end of the conical segment) in the desired location. When the tool is withdrawn, the marker remains entrapped, inserted to the depth determined by the length of the conical segment (5 mm).

Seven markers are placed in the myocardium; at the left ventricular apex, and at three equidistant points from apex...
to base along both the anterolateral and inferior margins of the left ventricle in a pattern outlining the ventricular chamber as seen in a 30° right anterior oblique projection (fig. 2). In addition two silver-tantalum clips are attached to the adventitia of the aorta immediately above the valve commissures to delineate the anterior and posterior aspect as seen in the right anterior oblique projection. These clips serve as a reference for the position of the aortic valve. Since it is not possible to place these clips at the level of the aortic valve they are placed 3 cm above that position.

In general, the highest anterior marker is placed approximately 1 cm below the left atrioventricular groove and approximately 2 cm to the left of the anterior interventricular sulcus (fig. 3 left). The middle and distal anterior markers are inserted along a line between the first marker and the apex so as to divide the anterior segment into three equal portions. The apical coil is inserted obliquely rather than perpendicularly because of frequently observed thinning of the apex. The inferior markers are placed similar to the anterior markers except that the most basal coil is usually located approximately 1 cm from the inferior interventricular sulcus and 1 cm below the atrioventricular groove (fig. 3 middle). No coils are inserted within 5 mm of any visible branch of the coronary arterial system or through epicardial fat or adhesions that obscure the coronary surface anatomy. The implantation of all markers requires approximately two minutes. No intraoperative complications have occurred.

Informed consent for implantation of markers and subsequent radiographic studies has been obtained from 24 patients to date, 13 of whom underwent cardiac transplantation and 11 of whom underwent aortocoronary bypass grafting or valve replacement. A total of 168 tantalum coils have been implanted in the myocardium in these patients. Two patients, both cardiac transplant recipients, have died postoperatively. In both of these cases careful microscopic examination of the intramyocardial markers was performed.

Postoperative Radiographic Data Acquisition

Quantitative parameters of left ventricular segmental dynamics were determined postoperatively by analysis of the motions of the myocardial markers as visualized radiographically.

Resting single-plane (30° right anterior oblique) cardiac fluoroscopy was performed at end-inspiration using a Philips 300 ma generator with a Philips 9" intensifier coupled to an Ampex DR10A video disc recorder at 30 frames per second. The analog ECG signal was recorded as a horizontal bar superimposed on the video image, the length of which corresponds to the amplitude of the electrocardiographic signal. This provided precise identification of QRS onset, peak, and decay in relation to the frame-by-frame video image.

Magnification factor was determined echographically utilizing a protractor-like device which permits calculation of the distance between the left ventricular center and the table top. Using previously determined magnification constants obtained from fluoroscopy of a lead grid containing multiple 1 cm squares, the proper correction factor was determined.

At the conclusion of each fluoroscopic study, the video recordings were replayed in a frame-by-frame (stop motion) manner and the XY co-ordinates of the marker images identified using a Tektronix light-pen coupled to a Hewlett-Packard 2115A minicomputer. This computer corrected the marker image coordinates for the magnification of the radiographic system and punched on paper tape the XY coordinates of each marker for each frame. The position of all myocardial markers for each frame of three complete cardiac cycles was delineated. The digital data on the punched
tape were read on a teletype terminal and transmitted via telephone line to a CDC-6700 digital computer.

Data Reduction and Analysis

Programs for calculating instantaneous intramyocardial dynamics were stored permanently in the CDC-6700 digital computer which was used for all calculations, and all plotting was accomplished by a CDC-280 microfilm graphics unit driven by the 6700.

The position of the aortic valve ring was established by translation of the coordinates of each aortic marker. Comparison of the postoperative ventricular outline and the preoperative contrast ventriculogram established the required coordinate translations. When no preoperative ventriculogram existed (e.g. donor hearts), an estimate of valve position was made by translating the aortic marker coordinates by 3.0 cm as described in the "Implantation" section above.

The instantaneous lengths of transverse muscle segments between pairs of myocardial markers (see fig. 2 for nomenclature) were calculated and plotted as shown in figure 4.

The longitudinal axis L was derived for each frame using the apical marker and the midpoint of the aortic valve as end points (fig. 2) and the instantaneous length of this axis was calculated and plotted as shown in figure 5.

The instantaneous lengths of the six minor radii (R1–R6, fig. 2) were calculated as the perpendicular distances between the corresponding markers and the longitudinal axis for each frame, smoothed by averaging data from consecutive frames, and plotted as shown in figure 6.

The average minor diameter (Davge) was calculated for each frame as 1/3 the sum of the six minor radii, and plotted as shown in figure 5. The time when Davge was a maximum, (within 67 msec after the peak of the electrocardiograph R wave), was defined as end diastole. End systole for each beat was defined as the time when Davge was a minimum. A superimposed plot was made of the marker silhouettes at end diastole and end systole as shown in figure 7. For each beat, each length was expressed as a percentage of its length at end diastole, and these data were plotted for 167 msec of systole as shown in figure 8.

Mean systolic shortening (S) was calculated as the percentage shortening of the average ventricular diameter (Davge) from end diastole to end systole.

Note in figure 8 that radial segments shorten at con-

Figure 3

Left) Anterior aspect of the heart showing anterior and apical sites (X) for marker implantation. Middle) Posterior aspect of the heart showing posterior sites (X) for marker implantation. Right) Anterior aspect of the heart showing marker sites (X) lying in the projection plane.

Figure 4

Dynamics of transverse ventricular diameters in patient H.A. Davge – – – – – – – – – – – – – – – – – – – , Davge – – – – – – – – – – , time of R wave peak □.
considerably different velocities. In order to characterize this shortening by a single velocity, the normalized mean circumferential shortening velocity during ejection (V) was calculated as the negative slope (determined from the end points on fig. 8) of the average normalized diameter DN_{avg}. Ventricular cross-sections in the vicinity of each diameter were assumed circular; thus, velocity of the normalized chamber diameter was equal to that of the normalized circumference. This definition of velocity represents a modification of that originally proposed by Karliner et al. (based on a single minor axis diameter) which has been shown to be sensitive in separating normal from abnormal left ventricular dynamics in man.

For each patient beat-by-beat values of normalized circumferential velocity and mean shortening, and the mean and standard deviation of normalized circumferential velocity and mean shortening, and heart rate, were obtained.

System Accuracy and Reproducibility

A phantom consisting of a planar matrix of radiopaque markers whose interpoint distances were accurately known, was placed in the radiographic system and its fluoroscopic image recorded on the video disc recorder. The XY coordinates of nine points on the phantom were measured 12 times each, and all 36 possible interpoint distances (ranging from 2 to 9 cm) were calculated for each measurement. The mean for each interpoint distance was determined, and the pooled standard deviation from all measurements was calculated from the sum of the squares of the deviation of each measurement from its corresponding mean.

The reproducibility of measurement of actual myocardial length was calculated as the standard deviation of 24 segmental lengths measured three times each during ventricular systole in one patient.

To determine day-to-day reproducibility of these parameters, six patients in stable clinical condition were studied. Each patient had three-beat cineradiographic sequences recorded on two consecutive days, and mean values of S, V and transverse Ls were measured. The significance of any day-to-day variations was determined by the paired t-test.

Biplane Studies

In an effort to determine the errors which result from measuring three dimensional myocardial segmental dynamics from single-plane cineradiograms, biplane radiographic studies were performed in seven patients. Marker image coordinates were measured from simultaneously exposed RAO and LAO projections using a Nikon shadowgraph-measuring microscope. A radiopaque sphere of known diameter was placed at the level of the heart and imaged in both projections to determine the magnification factor applicable in each projection. Actual length of the principal transverse segments (2–8, 3–7, 4–6) was calculated as the hypotenuse of a right triangle whose adjacent legs were 1) the projected length of the segment in the RAO view, and 2) the difference in height above the table of the markers in question in the LAO view. The angle which each segment made with the RAO plane was also calculated from these triangles, being defined as positive if the anterior marker was higher than the corresponding posterior marker. Corresponding segmental lengths calculated from the RAO projection only were compared with the true length as determined from the biplane studies. Shortening of each segment was calculated and expressed as a percentage of end-diastolic lengths from both biplane and single-plane data and these values were compared. Similarly, S and V were calculated from both biplane and single-plane data and these values were compared.

Results

In 24 patients studied to date there have been no operative or postoperative complications attributable to marker implantation. Two patients died following cardiac transplantation, one from intractable graft rejection, the other from pulmonary infection. Post-mortem microscopic sections of the transplanted hearts showed no necrosis or inflammatory reaction associated with the coils. Small numbers of fibroblasts around the coils suggested an early stage of insheathing by a thin fibrous layer.

A frame from each projection of a biplane cineradiogram in patient E.M. (fig. 9) shows that the markers were placed in a plane parallel to the 30° RAO projection.

The means and standard deviations of the angles between the major transverse segments (2–8, 3–7, Table 1

<table>
<thead>
<tr>
<th>Segment</th>
<th>θ ED</th>
<th>θ ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{28}</td>
<td>-9.4</td>
<td>(8.2)*</td>
</tr>
<tr>
<td>D_{27}</td>
<td>-2.8</td>
<td>(4.1)</td>
</tr>
<tr>
<td>D_{46}</td>
<td>8.8</td>
<td>(5.9)</td>
</tr>
<tr>
<td>Composite</td>
<td>-1.1</td>
<td>(9.7)</td>
</tr>
</tbody>
</table>

*Values in parentheses are standard deviations.

Abbreviations: ED = end diastole; ES = end systole.

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Figure 6

*Dynamics of six ventricular radii in patient H.A.*
4–6) and the projection plane in seven patients, measured from the biplane films, are given for end diastole and end systole in table 1.

Measurement of the radiopaque grid established that mean measured lengths were 2.7% less than actual lengths, and that the reproducibility (pooled SD) of length measurement was 0.04 cm.

The errors in measuring segmental lengths at end diastole and end systole and segmental shortening from single plane (RAO) projections are summarized in table 2. In repeated determinations, the reproducibility (SD) of myocardial segmental measurement was found to be 0.07 cm.

The mean and standard deviation of mean segmental shortening and normalized circumferential velocity, determined by comparison of RAO and biplane data, are given in table 3. The errors incurred in using single-plane data to determine values for shortening and normalized velocity are also given in this table.

From repeated measurements of the same beats, the reproducibility (SD) of mean segmental shortening (S) and normalized velocity (V) was found to be 1.0% EDL and 0.02 circ/sec respectively.

Day-to-day variations in length, shortening and normalized velocity were not significant in patients in stable clinical condition.

The accuracy and reproducibility of the single-plane technique are considered adequate for a number of clinical studies currently underway in these laboratories. Two examples serve to illustrate data obtained by this technique.

In patient P.S., a cardiac transplant recipient who sustained repeated episodes of acute graft rejection during the first eight postoperative weeks, sequential studies showed a continuous decline in S and V (fig. 10). Subsequent studies obtained after successful

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**Table 2**

<table>
<thead>
<tr>
<th>Segment</th>
<th>DED</th>
<th>DES</th>
<th>Shortening error (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>-2.2 (2.7)*</td>
<td>-3.8 (4.2)</td>
<td>1.4 (1.5)</td>
</tr>
<tr>
<td>D3</td>
<td>-0.3 (0.4)</td>
<td>-0.3 (0.6)</td>
<td>0.0 (0.1)</td>
</tr>
<tr>
<td>D4</td>
<td>-1.5 (1.7)</td>
<td>-5.0 (5.1)</td>
<td>2.7 (2.6)</td>
</tr>
<tr>
<td>Composite</td>
<td>-1.4 (1.9)</td>
<td>-3.1 (4.2)</td>
<td>1.4 (2.0)</td>
</tr>
</tbody>
</table>

*Values in parentheses are standard deviations.

---

**Table 3**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Biplane</th>
<th>Single plane</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean systolic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>shortening (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity (circ/sec)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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*Values in parentheses are standard deviations.

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Figure 7

Two frames of reconstructed noninvasive cineventriculogram of one beat in patient H.A. End diastolic frame , End systolic frame . The unconnected symbols at the top represent the aortic clips. Solid symbols are computer-generated coordinates of the aortic valve.

**Figure 8**

Dynamics of normalized radii and mean diameter (in percent of their end-diastolic lengths) for one beat in patient H.A. R1 , R2 , R3 , R4 , R5 , R6 , Davg . Note the early systolic bulging in the anterior wall (R2).
retransplantation showed increase of these parameters to values exceeding baseline values for the first graft.

Patient H.A., who underwent a coronary artery bypass graft for proximal occlusion of the left anterior descending coronary artery, exhibited moderate anteroapical hypokinesis with otherwise normal left ventricular dynamics in the preoperative cineventriculogram. A postoperative study of marker dynamics six days after operation (figs. 4–8) showed continued anteroapical hypokinesis with early paradoxical systolic bulging in segment R2. On postoperative day 39 the paradoxical bulging in segment R2 disappeared, and an increase in V and S were noted (fig. 10).

Discussion

Harrison et al. first measured external dimensions of ventricular chambers throughout the cardiac cycle in intact, unanesthetized human subjects. Silver tantalum clips were sutured to the epicardium at the time of operation and the relative positions of these markers were measured over the course of many cardiac cycles from calibrated cineradiographs. This series of studies was carried out from 1962 through 1965 at the National Institutes of Health to determine the effects of various physiologic and pharmacologic interventions on epicardial dynamics. More recently, McDonald has utilized a similar technique to study epicardial dynamics of the human left ventricle during systole and the effects of hypertrophy on these dynamics.

In 1969, Wildenthal et al. demonstrated in experimental animals a significant difference between ventricular dynamics measured from epicardial and midwall markers. This finding, together with Streeter’s observation that the bulk of myocardial fibers in the left ventricle are oriented circumferen-
The 2.7% mean system error in measurement of segmental length arises from a small uncertainty in the determination of the magnification factor due to uncertainties in the relative positions of the image intensifier screen, object, and X-ray source.

The system reproducibility figure of .04 cm arises from the resolution limit of the light pen system, parallax, and operator variability in positioning the light-pen cursor.

The single-plane approximation of segmental length results in an underestimation of true segmental length as shown in table 2. This results in slight overestimation of segmental shortening.

Similarly, the single-plane approximation of mean systolic shortening and normalized velocity results in overestimation of these parameters as shown in table 3.

Mean systolic shortening (S) and normalized circumferential velocity (V), as derived in this study, reflect over-all ventricular dynamics, and are not unduly influenced by aberrant motion in a single ventricular segment. Such aberrant dynamics are readily detected by inspection of the family of segmental shortening curves (e.g. figs. 6, 8).

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