Endocardial catheter mapping: validation of a cineradiographic method for accurate localization of left ventricular sites

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ABSTRACT  To guide surgical therapy for ventricular tachycardia by preoperative endocardial catheter mapping, accurate anatomic localization of arrhythmogenic sites is mandatory. For this reason we developed a mathematical cineradiographic method to compute left ventricular sites relative to three anatomic reference points: the centers of aortic and mitral valve ostia and the left ventricular apex. To validate the method 14 epicardial left ventricular markers were implanted in four dogs to simulate arrhythmogenic sites. Distances between markers and the anatomic references were calculated and the results were compared with postmortem measurements. The difference between calculated and measured distances was 0.5 ±3.1 mm (mean ± SD), confirming accurate localization of anatomic marker sites. However, in surgery the results have to be displayed in a practically applicable, unambiguous way. Therefore, wire skeletons were constructed to represent calculated endocardial marker sites relative to the anatomic reference points. To validate this approach, 14 markers were implanted in the left ventricular subendocardium in four dogs. Wire skeletons were constructed, one for each marker site, and inserted postmortem into the left ventricular cavity via a 2 cm incision. In all cases the correct indication of a marker site by the corresponding wire skeleton was confirmed by fluoroscopic inspection in multiple projections. This wire skeleton technique may enhance the practical usefulness of preoperative endocardial catheter mapping.

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SURGICAL TREATMENT of drug-resistant recurrent ventricular tachycardia (VT) is usually considered in patients with chronic ischemic heart disease.1-5 The site of origin of VT in the subacute and chronic stage of myocardial infarction in most cases has been localized in the subendocardium of the left ventricle or, in some instances, intramurally within the interventricular septum.6-10 Therefore endocardial mapping of electrical activity is considered superior to epicardial mapping as a method of localizing the arrhythmogenic site of these tachycardias. Intraoperative endocardial mapping is an established technique, albeit with important limitations11,7-11: (1) the clinical VT is not always inducible in the operating room; (2) frequently more than one VT morphology is clinically present, but during surgery it is often difficult to induce all different forms of tachycardia or to obtain an adequate map for each morphology; (3) morphologic interpretation is hampered by the absence of the usual precordial electrocardiographic leads and by electrical changes caused by cardiotomy and the opened chest; (4) in addition, normothermic cardiopulmonary bypass limits the time available for intraoperative endocardial mapping.

With preoperative endocardial catheter mapping these problems are not expected.6-8 In patients with chronic ischemic heart disease, the clinically occurring VT morphologies are usually inducible in the catheterization laboratory.12,13 Morphologic interpretation is not a problem and the duration of the study is less important than that during surgery.

The major disadvantage of catheter mapping is the anatomic localization problem if the data are to be used for guiding surgical excision of the arrhythmogenic site. The site of VT origin may be correctly identified by accepted electrophysiologic criteria, but subsequently the electrode position must be estimated from
multiple fluoroscopic projections. Additional inaccuracy may be introduced because there are only few anatomically identifiable landmarks.

In this report we present a mathematical anatomic localization procedure and its validation in an experimental animal preparation. We also describe a technique to identify the position of the calculated sites during surgery.

Methods

By means of a biplane roentgenographic system, a mathematical method can be applied for computation of the spatial location of any given left ventricular site relative to the origin of a Cartesian (x, y, z) coordinate system, which is defined with a radiolucent frame attached to the catheterization table. With small radiopaque pegs that are inserted into the horizontal and vertical wings of this frame at distances of multiples of 1 cm, x, y, and z axes are chosen and calibration performed. The origin of the coordinate system is defined by the point of intersection of these axes. The mathematical principles are described in the Appendix.

To compute the spatial location of a given left ventricular site, simultaneous cineradiograms were generated in frontal and lateral projections to obtain images of the heart, as well as the projections of the calibration pegs in the x and y direction (frontal plane) and in the y and z direction (lateral plane). Simultaneous frontal and lateral end-diastolic frames, identified by means of a simultaneously recorded electrocardiogram, were used for measurements in the x, y, and z direction that are needed for the computations.

The spatial location of a left ventricular site was related to three anatomic reference points: the centers of aortic and mitral valve ostia and the left ventricular apex. These anatomic reference points were identified from the end-diastolic frames of biplane left ventricular cineangiograms and their spatial locations computed in a similar way as described in the Appendix for any given left ventricular site. The anatomic location of a particular left ventricular site can be determined by computing the distances between the spatial location of that site and the spatial locations of the three anatomic reference points. Computations were performed off-line with a computer system.

Validation of the method. The accuracy of the localization procedure was validated quantitatively in four dogs. Radiopaque markers simulating arrhythmogenic sites were implanted in the left ventricular epicardium. Although arrhythmogenic sites are usually located in the left ventricular subendocardium, validation of the principles of the method can be done equally well, but more easily, with epicardial markers.

Beagles weighing 12 to 17 kg were anesthetized with methadone · droperidol (20.0:25.0 mg iv). After endotracheal intubation, ventilation was maintained by a Bird Respirator (N2O:O2 = 1:1). End-tidal CO2 concentration was kept between 4.5% and 5%. Anesthesia was maintained by a methadone · droperidol mixture. The electrocardiogram (leads I, II, and III) and the right femoral arterial pressure were monitored. After induction of muscle relaxation with pancuronium bromide (0.1 mg/kg iv) the heart was exposed via a thoracotomy in the fifth intercostal space. Epicardial markers, consisting of platinum rings with a diameter of 2 mm, were stitched at various sites on the epicardial surface. After chest closure, a No. 7F pigtail catheter was introduced into the left femoral artery and advanced to the left ventricular cavity under fluoroscopic guidance. During brief interruption of ventilation, biplane cineradiography (without contrast material) immediately followed by cineangiography with Isoopaque Coronar (8 ml, flow rate 4 ml/sec) was performed. The markers and the three anatomic reference points were identified on end-diastolic frames. The distances between each marker and the three anatomic references were computed as described in the Appendix. Subsequently, the chest was reopened and the dog was killed by injection of cardioplegic solution into the aortic root. The heart was excised and its end-diastolic volume restored by insertion of a balloon through a lesser than 1 cm incision in the left ventricular apex. The balloon was subsequently filled with water to the end-diastolic volume as calculated from the cineangiogram, according to the method described by Sandler et al.14 The computed distances between epicardial markers and the three anatomic references were compared with postmortem measurements with a bendable brass wire as a caliper.

Identification of the anatomic location during surgery. The second part of the study deals with the identification during surgery of the computed location of the arrhythmogenic site. Endocardial markers were used to simulate these sites. Spatial locations of marker sites and the three anatomic references were computed as described in the Appendix. Instead of defining the anatomic location of a given site by the distances between that site and the three anatomic references, the computed spatial locations can also be used to derive anatomic location in terms of cylinder coordinates (figure 1, A). These coordinates were used to construct a stainless-steel wire skeleton, consisting of a fixed long axis equal to the distance between the left ventricular apex and the center of the aortic valve ostium and flexible side branches, one pointing to the center of the mitral valve ostium (mitral side branch) and the other to a selected implanted endocardial marker (figure 1, B). The site representing the center of the aortic valve ostium was the center of a tilting ring, the diameter of which was equal to that of the aortic valve ostium, calculated from the left ventricular cineangiogram. The tilt of the ring could adjust to the angle between the long axis of the wire skeleton and the aortic valve plane to enable correct positioning of the device in the left ventricular cavity. The angle between the long axis and the mitral side branch was chosen at 30 degrees for easy insertion into the left ventricular cavity, even through a small incision. The side branch pointing to the implanted marker was constructed perpendicular to the long axis.

Use of the wire skeleton was validated in four dogs. The heart was exposed as before, and markers consisting of platinum spheres with a diameter of 1 mm were introduced into the subendocardium by puncture from various left ventricular epicardial sites as described by Heethaar et al.15 Wire skeletons, each representing a selected marker relative to the three anatomic reference points, were constructed as described above. The dogs were killed by injecting cardioplegic solution into the aortic root. A 2 cm incision into the left ventricular apex was made for consecutive insertion of the different wire skeletons, one for each marker, into the left ventricular cavity (figure 1, C). Correct indication of endocardial marker sites was verified by fluoroscopic inspection in multiple projections.

Statistical analysis. Data are expressed as mean ± SD. The differences between calculated and measured distances from epicardial markers to the three anatomic references in the first part of the study were assumed to be samples from a normal distribution. Student’s t test for paired samples was used to compare calculated and measured distances. A probability value of .05 was accepted as the limit of significance. The ratio of two variance estimates was compared with the critical value of the F distribution with the appropriate degrees of freedom (F test for comparison of two variance estimates from independent normal samples).

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Results

Quantitative validation of anatomically localized sites. The results in four dogs with 14 implanted epicardial markers are summarized in Table 1 and are graphically presented in Figure 2. The difference between all 42 calculated and measured distances was $0.5 \pm 3.1$ mm, with a 95% confidence interval for the SD of 2.5 mm $< \sigma < 3.9$ mm. In 37 of the 42 distances this difference was less than 5 mm. Relative to individual reference points, these differences were as follows: to center of aortic valve, $1.0 \pm 2.2$ mm; to center of mitral valve, $0.4 \pm 3.7$ mm; and to left ventricular apex, $0.1 \pm 3.4$ mm. These mean differences were not statistically different from zero (Student’s t test). The standard deviation of these differences was significantly smaller for the aortic compared with the mitral reference point ($F$ test, $0.025 < p < 0.05$).

Identification of anatomically localized sites by the wire skeleton technique. In four dogs, 14 endocardial markers were anatomically localized and each was identified with a different wire skeleton. Insertion of the wire skeleton into the left ventricular cavity was always possible through a 2 cm apical incision, the minimal size of the incision being determined by the diameter of the tilting aortic ring. Although the flexibility of the side branches allowed easy insertion, the long mitral side branch had to be manipulated between the chordae toward the center of the mitral valve ostium with a pair of tweezers. Fluoroscopic inspection in multiple projections verified that a selected marker was correctly
TABLE 1
Comparison of calculated and measured distances between epicardial markers and the three anatomic references

<table>
<thead>
<tr>
<th>Dog No</th>
<th>Marker implantation site</th>
<th>C</th>
<th>M</th>
<th>C</th>
<th>M</th>
<th>C</th>
<th>M</th>
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<td>45</td>
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<td>23</td>
<td>26</td>
<td>56</td>
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<td>44</td>
<td>39</td>
<td>42</td>
<td>39</td>
<td>36</td>
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<td>42</td>
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<tr>
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<td>41</td>
<td>33</td>
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</tr>
<tr>
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<td>34</td>
<td>28</td>
<td>53</td>
<td>54</td>
</tr>
<tr>
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<td>43</td>
<td>37</td>
<td>39</td>
<td>28</td>
<td>32</td>
</tr>
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<tr>
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<tr>
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<td>50</td>
<td>43</td>
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<tr>
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</table>

M-CA = distance between marker and center of the aortic valve ostium; M-CM = distance between marker and center of the mitral valve ostium; M-LVA = distance between marker and left ventricular apex; C = calculated distance; M = measured distance.

Discussion

The purpose of this study was to validate a mathematical method for accurate anatomic localization of epicardial sites. This would enhance the usefulness of identification of arrhythmogenic sites by catheter mapping. The wire skeleton method was developed to enable the surgeon to identify the computed location of an arrhythmogenic site.

In the first part of the study, implanted epicardial markers were used to simulate arrhythmogenic sites. Although these sites are usually located subendocardially in the left ventricle, validation of the accuracy of the method is independent of the actual site of marker implantation, that is, it applies equally well to the spatial localization of endocardial, intramural, or epicardial sites. The accuracy of the spatial localization of an implanted marker would be diminished only if its identification on the cineradiogram was uncertain. This was not the case. Radiopaque markers were clearly visible at every site on the heart, be it epicardial or subendocardial. Furthermore, postmortem measurements of the distances between a subendocardial marker and the anatomic reference points proved to be difficult to perform without seriously disturbing the anatomy of the left ventricular wall. Hence, epicardial markers were used for validation of the method.

The anatomic location of a marker was derived from its spatial location and that of three anatomic reference points: the centers of the aortic and mitral valve ostia and the left ventricular apex. This choice was prompted by the following considerations: First, the anatomic references should be well identifiable in both left ventricular cineangiographic projections. Second, to achieve the highest accuracy in localizing the marker site, the selected anatomic reference points should not be located too close to each other. Third, each anatomic reference must be easily identifiable after left ventricular cardiomyotomy. Considering valve ostia as circular or elliptical structures, the center of the ostium is easily determined if the ostial circumference can be recognized from both cineangiograms. The aortic valve ostial circumference was easy to define in both the frontal and lateral roentgenographic projection, whereas recognition of the mitral valve ostial contour appeared to be more difficult, especially in the frontal plane, due to overprojection of the spine. This may explain the wider variation between the calculated and measured distances of a marker relative to the mitral valve ostium center as compared with the aortic ostial center (0.4 ± 3.7 mm for the mitral valve and 1.0 ± 2.2 mm for the aortic valve). For the left ventricular apex, the

FIGURE 2. Relationship between calculated and measured distances of epicardial markers to the anatomic reference points. The solid line is the line of identity. M-CA = distance between marker and center of the aortic valve ostium; M-CM = distance between marker and center of the mitral valve ostium; M-LVA = distance between marker and left ventricular apex.
Positioning from the constructed site, arrhythmogenic markers were identified on the epicardial surface by cineangiography, the aortic and mitral valves were opened, and the ventricles were inspected mortem. The aortic and mitral cusps were resected, and this assumption was validated by cineangiography during the subsequent localization steps. Cineradiography for localization of markers was immediately followed by cineangiography for identification of anatomic reference points. To ensure that in both instances the sites of interest were in the same position, we measured fluoroscopic markers as computed at the onset of the QRS complex. At that point the ostial contours of the aortic and mitral valve were relatively easy to identify. In addition, comparison with postmortem measurements was facilitated at end-diastole because the ventricle was relaxed. Finally, during cineradiography and cineangiography, respiration was interrupted and body movements were prevented by muscle relaxation. Therefore the accuracy of anatomic localization of a marker site (arrhythmogenic site) will depend primarily on the ability to identify the anatomic reference points on the cineangiograms.

Although the postmortem intracavitary volume was made equal to the calculated end-diastolic volume, validation of the method might be hampered by postmortem changes of left ventricular wall properties. Our results, however, suggest that this was not an important limitation.

The maximum difference between calculated and measured distances from implanted markers to the three anatomic references was 7 mm, and in 37 of the 42 distances (88%) the difference was less than 5 mm. These results hold promise for guiding surgical therapy of VT. Josephson et al. localized arrhythmogenic sites anatomically within 4 to 8 cm² by estimation from multiple fluoroscopic projections. If this area is considered as the surface of a circle surrounding the true arrhythmogenic site, the radius of the circle is 11 to 16 mm, corresponding to the uncertainty in one direction. The results obtained with our mathematical approach (≤ 7 mm) compare favorably with this estimate. However, in the patient study of Josephson et al., a marked change in left ventricular anatomy caused by aneurysm formation was reported.

In the second part of this study, a wire skeleton was constructed from the spatially known sites of interest. Positioning of the wire skeleton into the left ventricle through a 2 cm apical incision was governed by the three anatomic reference points (figure 1, C). One side branch pointed to a marker (arrhythmogenic site). The position of the side branch was qualitatively correct on multiple fluoroscopic projections in all 14 instances. The wire skeleton apparently prevented the relaxed postmortem ventricle from gross distortion.

Clinical application. The wire skeleton is designed for clinical application. Preliminary results with 12 arrhythmogenic sites in eight patients will be described in a subsequent article. A discrepancy of 1 cm or less was found between the arrhythmogenic site as determined by catheter mapping and the site obtained at intraoperative mapping. The wire skeleton proved easy to handle by the cardiac surgeon. During positioning of the device, however, care must be taken not to damage the chordae.

In conclusion, our data demonstrate that the position of any left ventricular site can be accurately calculated and anatomically localized by means of a wire skeleton. The wire skeleton, which is constructed on the basis of data obtained in the catheterization laboratory, may enable the surgeon to correctly identify arrhythmogenic sites.

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Appendix

Spatial localization of left ventricular marker and anatomic reference points. For the computation of the coordinates of a given left ventricular site (marker M) and the anatomic reference points, a biplane roentgenographic system is used (figure 3). For maximal accuracy of the method, the optimal axes of the roentgenographic systems are chosen perpendicular. The x-ray intensifier screens by I₁ and I₂. A carthesian (x, y, z) coordinate system is defined with a radiolucent frame. With small radiopaque pegs that can be inserted into this frame, x, y, and z axes can be chosen and calibration can be performed as well. These axes define the origin O. P₁ and P₂ represent the frontal and lateral projections of marker M.

Because x-rays travel along straight lines, the marker M must be on the line FₗP₂ as well as F₁P₂. Hence its spatial location is at their point of intersection. To compute the spatial location of M, the following elements of vector analysis are used:

1. Let a be a vector pointing from an origin O (figure 4, a); then the line l through a can be written as λa, where λ is a scalar and −∞ ≤ λ ≤ ∞.

2. Let b be a second vector pointing from O (figure 4, b). The line l₁ parallel to l can be written as λa + b.

3. Let a and b be two vectors pointing from the same origin (figure 4, c). The vector (b−a) is then found with help of the parallelogram construction.

From l through 3 it follows that the line FₗP₂ can be written as a + λ(b−a) (figure 4, d).
Similarly the line through the x-ray focus $F_i$ and the projection $P_i$ can be written as \( \bar{c} + \mu(d-c) \).

The marker position (point of intersection of $F_iP_i$ and $F_1P_1$) can be found by solving \( \lambda \) and \( \mu \) from the equation:

\[
\bar{a} + \lambda(\bar{b}-\bar{a}) = \bar{c} + \mu(d-c) \quad (1)
\]

This actually represents three equations for the \( x \), \( y \), and \( z \) components of the vectors. However, since \( P_1P_1 \) and \( F_1P_1 \) are within one plane, it is sufficient to solve \( \lambda \) and \( \mu \) from only two equations.

The vector components \( a_x \), \( a_y \), \( a_z \), and \( c_x \), \( c_y \), \( c_z \), and \( c_z \) are calculated from measurements of the roentgenographic system components relative to the frame. Also, the distance of the image intensifier screens \( I_i \) and \( I_l \) to the \( xy \) and \( yz \) plane of the frame are measured, yielding \( b_x \) and \( d_z \), respectively. Computing the positions of the projections \( P_i \) and \( P_l \) yields values for \( b_y \) and \( d_x \), and \( d_y \), respectively. With these values \( \lambda \) and \( \mu \) can be solved from equation 1, yielding the spatial coordinates of the marker. The spatial coordinates of the three anatomic references to the same origin \( O \) are computed in a similar way.

**Determination of anatomic localization as the distance between spatial locations.** From the spatial coordinates of a marker \( (x, y, z) \) and those of an anatomic reference point \( (x_a, y_a, z_a) \), their mutual distance \( D \) is calculated from:

\[
D = \sqrt{(x-x_a)^2 + (y-y_a)^2 + (z-z_a)^2} \quad (2)
\]

**Transformation from carthesian \((x, y, z)\) to cylinder coordinates \((z, \rho, \phi)\).** Let:

\[
(x_a, y_a, z_a) \text{ be coordinates of the left ventricular apex} \\
(x_m, y_m, z_m) \text{ be coordinates of the center of the mitral valve ostium} \\
(x_n, y_n, z_n) \text{ be coordinates of the center of the aortic valve ostium} \\
(x, y, z) \text{ be coordinates of the marker,}
\]

then

\[
z = \frac{(x-z)(x-x_a)+(y-y)(y-y_a)+(z-z)(z-z_a)}{c} \quad (3)
\]

where

\[
c = \sqrt{(x-x_a)^2 + (y-y_a)^2 + (z-z_a)^2}
\]

\[
\rho = \frac{2\sqrt{s(s-a)(s-b)(s-c)}}{c} \quad (4)
\]

where

\[
a = \sqrt{(x-x)^2 + (y-y)^2 + (z-z)^2}
\]

\[
b = \sqrt{(x-x)^2 + (y-y)^2 + (z-z)^2}
\]

\[
s = \frac{1}{2}(a+b+c)
\]
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FIGURE 4. A, Schematic representation of a vector \( \vec{a} \), pointing from an origin \( O \) and the line \( l \), which contains all end points of the vectors \( \vec{a} \) 
\( (-\infty \leq \lambda \leq \infty) \). \( B \). The line \( l_1 \) parallel to \( l \) is obtained by adding a vector \( \vec{b} \) to all vectors along \( l \). \( C \). The parallel-lel construction is shown to obtain the vector \( (\vec{b} - \vec{a}) \) from \( \vec{b} \) and \( (\vec{a}) \). \( D \), A line through \( (\vec{b} - \vec{a}) \) is shown and a line parallel to this line \( (\vec{a} + \lambda(\vec{b} - \vec{a})) \). This line is obtained by adding the vector \( \vec{a} \) to all points on \( \lambda(\vec{b} - \vec{a}) \).

\[
\phi = \frac{\sqrt{(x_p - x)(x_q - x_m) + (y_p - y)(y_q - y_m) + (z_p - z)(z_q - z_m)}}{\sqrt{(x_p - x)^2 + (y_p - y)^2 + (z_p - z)^2}}
\]

where \( x_p = x + \alpha(x_q - x_m), y_p = y + \alpha(y_q - y_m), \) and \( z_p = z + \alpha(z_q - z_m); \) \( x_p, y_p, \) and \( z_p \) are the coordinates of the projection of the marker on the cylinder axis, with

\[
\alpha = \frac{(x - x_m)(x_q - x_m) + (y - y_m)(y_q - y_m) + (z - z_m)(z_q - z_m)}{c^2}
\]

and \( x_q = x + \beta(x_q - x_m), y_q = y + \beta(y_q - y_m), \) and \( z_q = z + \beta(z_q - z_m); \) \( x_q, y_q, \) and \( z_q \) are the coordinates of the projection of the center of the mitral valve ostium on the cylinder axis, with

\[
\beta = \frac{(x_m - x_q)(x_m - x) + (y_m - y_q)(y_m - y) + (z_m - z_q)(z_m - z)}{c^2}
\]

Practical considerations and image distortion. For the computation of the spatial coordinates of markers and anatomic reference points, equation 1 needs to be solved. In practice, however, there are situations in which the two lines do not have a point of intersection but cross each other at a small distance because of slight inaccuracies in measuring the various distances and because of pincushion distortion of the image intensifier. To correct for this distortion, a grid with 1 cm spacing is filmed in two directions and each x-ray film frame with markers and anatomic reference points is corrected by means of a digital image analysis system. If the two lines do not have a point of intersection, their shortest distance is computed, being a segment perpendicular to both lines. The midpoint of this segment is considered as the marker position. This segment never exceeded 3 mm.

References


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