A new intracavitary probe for detecting the site of origin of ectopic ventricular beats during one cardiac cycle

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ABSTRACT An olive-shaped probe (25 × 12 mm) with 41 evenly distributed recording electrodes on its surface was introduced into the left ventricles of seven open-chest dogs via the left atrium. In two other dogs a cylindrical probe (40 × 3 mm) was used. Electrical stimuli were delivered at 66 endocardial, midwall, or epicardial sites in the left and right ventricular walls and the septum. Mechanical stimuli were also applied at various epicardial sites. On-line mapping of equipotential contour lines on the surface of the probe invariably revealed a clear-cut potential minimum on the electrode that faced the pacing site. Time of appearance of potential minimum was 3 to 5 msec after endocardial stimuli, 10 to 25 msec for midwall and epicardial pacing, and 30 msec or more for right ventricular stimulation. Simultaneous stimulation at two sites 1.2 cm apart gave rise to two separate minima on the maps. “Pseudoisochrones” derived from electrograms recorded by the new probe were slightly less accurate in indicating the site of origin of extrasystoles. We conclude that equipotential and “isochrone” contour maps recorded from an array of semidirect electrodes, regularly distributed on the surface of an intraventricular probe, provide information on the site of origin (location and intramural depth) of ectopic paced beats in a normal dog heart.


LOCALIZING the site of origin of sustained ventricular tachycardias greatly facilitates the surgical treatment of these arrhythmias. At present, arrhythmias are localized in the catheterization laboratory by mapping the endocardial spread of excitation after inducing the tachycardia. To this end, catheters carrying one or more electrodes are brought into contact with the endocardial surface and multiple direct leads are recorded in sequence. The mapping takes up to 45 min and the exploration is generally limited to 10 to 15 points in the left ventricle.1 An experimental method for simultaneously recording 12 direct leads from the endocardial surface has been described recently.2

An alternative approach that may offer some advantages consists in mapping intraventricular potentials at a distance from the endocardial surface, by means of an intraventricular, olive-shaped or cylindrical multielectrode catheter.3 This proposed procedure is based on the bioelectric field theory: In the early stages of an ectopic beat, the instantaneous distribution of cardiac potentials in the intraventricular blood volume must reflect the site of origin of the ectopic excitation, since this site is known to generate the earliest spatial negativity (see Discussion).

In this investigation we show that intraventricular potential and “isochrone” maps, recorded by an intraventricular probe with numerous semidirect electrodes on its surface, can detect the site of origin (location and intramural depth) of ectopic paced beats in a normal dog heart. Further studies will be necessary to establish whether the same principle can be applied to human sustained ventricular tachycardias, the geometric and electrophysiologic conditions of which are different.

Methods

Nine mongrel dogs weighing 7 to 11 kg were anesthetized with sodium pentobarbital (30 mg/kg iv) and heparinized. The heart was exposed by a left lateral thoracotomy and cradled in the opened pericardium. A purse string was prepared in the left atrial appendage. In seven dogs, a catheter with an ellipsoidal or
FIGURE 1. Schematic illustrating the multielectrode olive-shaped catheter (C) in the left ventricle. Note that it does not necessarily touch the endocardium. Two multiterminal intramural needles (A and B) have been inserted into the left ventricular wall. The cylindrical catheter is also shown (D).

"olive-shaped" perspex tip was inserted through the purse string into the left ventricular cavity (figure 1, C). The "olive" was 25 mm long and 12 mm across. It was surrounded by blood and did not necessarily touch the endocardium. In two other dogs a small cylindrical probe, 3 mm in diameter and 40 mm in length, was used (figure 1, D). The shaft of the catheters was rigid and bent at a right angle to facilitate insertion. To prevent rotation, the extracardiac portion of the catheters was fixed to the ribs. Because of the angular shape of the shaft, this fixation prevented rotation of the probe in the heart during the experiment. The catheters were well tolerated and did not provoke arrhythmias or injury currents. The hearts worked normally for many hours.

Forty silver electrodes were regularly distributed along five circumferences on the surface of the probes, at an angle of 45 degrees from one another. One more electrode was fixed to the distal end of the probe (figure 1, C). This "tip" electrode was not present in the cylindrical probe. The electrodes were small silver disks, 0.1 or 0.5 mm in diameter, and their surface was level with the surface of the probe. A mark on the external portion of the catheter enabled the intraventricular orientation of the electrode columns to be evaluated from the outside. The 40 or 41 electrodes were connected in unipolar fashion to a multichannel instrument that performed on-line amplification, multiplexing, and analog-to-digital conversion of the signals at a sampling rate of 1000 Hz per channel. The common reference electrode was on the left hind leg. The amplitude of the signals ranged between 20 and 60 mV. The digital data were fed into a PDP 11/40 minicomputer and graphically displayed as described below.

In each experiment, five to 15 stimulating electrodes were applied to the ventricular muscle. These were either bipolar steel hooks that were attached to the endocardium or the epicardium or multiterminal intramural needles (figure 1). The hearts were paced at a cycle length of 300 msec with 2 msec current pulses just above threshold. Electrical stimuli were delivered to a total of 66 locations in the left or right ventricular free wall or in the septum. Eleven sites were endocardial, 21 at different depths in the ventricular wall, and 34 were epicardial. In one experiment, 10 additional left or right epicardial sites were stimulated mechanically by means of a glass rod. Figure 2 illustrates the approximate location of the left electrical stimuli except the epicardial. In one experiment, spontaneous premature ventricular contractions were provoked by ligating the anterior descending branch of the left coronary artery. In 22 cases, after pacing the heart through an electrode pair, we injected a 12 msec subliminal current pulse into the preparation through one of the two stimulating terminals. The current left the preparation through a distant electrode fixed on the back of the animal. In these conditions, the current lines should flow approximately radially in all directions from the entry point, as shown by McFee and Johnston, and the equipotential surfaces should be concentric spheres. Thus the electrode on the probe spatially closest to the pacing site could be expected to exhibit the highest potential and could therefore be easily identified.

At the end of the experiment, the heart was opened and the spatial relationships between the pacing sites and the olive electrodes were determined by visual inspection before viewing the maps. Since visual inspection permits only an approximate identification of the electrode closest to the pacing site, we also relied on the electrical procedure described above when available.

Data processing and display. The 40 or 41 intraventricular electrogams were displayed on-line or off-line by a Calcomp or Versatec plotter for quality control (figure 3, A). Thereafter the instantaneous potential distribution on the unrolled surface of the probe was displayed automatically in the form of equipotential contour maps (figure 4). We obtained one map for every millisecond during the entire beat. Maps of "pseudoisochrones" were also obtained by determining the time of occurrence of the negative peak of the first derivative of QRS at every electrode site. We use the term pseudoisochrones because they were obtained from indirect leads, whereas true isochrones are derived from direct leads.

Results

Olive-shaped probe
Endocardial stimulation. The QRS complexes recorded
FIGURE 3. A, Unipolar electrograms from the 41 terminals of the olive-shaped probe. The endocardial areas facing the various columns of electrodes are indicated on top of the figure. The pacing electrode was on the lateral endocardium and faced the terminal that recorded the waveform marked by an asterisk. B, Three electrograms (asterisk, star, and circled asterisk) are magnified. S = stimulus artifact. Further explanation in text.

from the intraventricular olive electrode facing the pacing site were always negative. A steep downstroke occurred 1 or 2 msec after the stimulus, so that it was often difficult to separate its onset from the stimulus artifact (figure 3, asterisk). In the remaining electrograms, the downstroke started at a later time (5 to 20 msec) and was often less steep (figure 3, star). Only in one or two limited areas was the downstroke preceded by a small positive peak (e.g., figure 3, circled asterisk). The T waves were mostly positive. The equipotential contour maps exhibited a clear-cut minimum 2 or 3 msec after the end of the stimulus artifact (figure 4, A). A potential minimum is defined as a site more negative (or less positive) than all surrounding sites. A maximum is defined accordingly. The minimum was located on the electrode that faced the stimulated site and remained there for 8 to 18 msec (figure 4, B and C). Its amplitude increased from 1 to 45 mV during this interval. The minimum was surrounded by a negative area covering one-half or three-quarters of the probe. The rest of the probe was positive, with at least one clear-cut maximum. The amplitude of the maximum was low (0.5 to 2.5 mV). Ten to 20 msec after the stimulus the minimum moved to an adjacent position. Later on, the entire surface of the probe became negative. During the ST-T interval, most of the probe’s surface was positive, but the location of the maximum was not closely related to the location of the earliest QRS minimum. The pseudoisochrone map constantly indicated earliest excitation at the site where the early potential minimum appeared (figure 4, A). However, the earliest “activation time” indicated by the isochrones (asterisk) was 7 to 15 msec, whereas the equipotential maps showed a minimum as early as 3 msec (figure 4, A).

Subendocardial, midwall, and epicardial pacing. When the stimulus was delivered at increasing distances from the endocardium through the terminals of an intramural needle inserted into the free wall (figure 1), the following results were obtained.

Electrograms. The electrograms recorded from the electrode closest to the tip of the needle showed a flat or very slowly descending initial segment followed by a clear-cut downstroke (figure 5). Little or no initial positivity was observed. The flat segment lasted 6 to 25 msec, its duration being longer when the stimuli were applied at increasing distances from the endocardium (figure 5). In the other electrograms from the probe, the downstroke started even later and was preceded by a flat segment or by a positive peak.

Maps. The potential distribution on the surface of the probe invariably showed one minimum, which was located on the area that faced the pacing site, whether the stimulus was subendocardial, midwall, or epicardial. However, the minimum appeared progressively later (6 to 20 msec) when the stimulus was delivered at increasing distances from the endocardium (figure 6, A to C). During this latency, ill-defined potential patterns and low-potential values were observed on the probe, at least with the resolution afforded by our equipment, i.e., 0.1 mV in the low-gain setting. The minimum remained in the same position for about 10 to 20 msec and its voltage progressively increased.
from −0.3 to about −12 mV. Thereafter the minimum moved to an adjacent area and its voltage increased to −15 or −30 mV. One maximum was observed in varying sites during this interval.

In all cases, the potential minimum appeared on the probe at a time when excitation had not yet reached the endocardium, as revealed by the potential profile along the intramural needle (see, for instance, figure 7, relating to epicardial stimulation). Endocardial breakthrough occurred later, 12 to 35 msec after the stimulus, as revealed by the needle electrodes. At that time, the voltage of the minimum on the probe increased to 15 or 30 mV and its location moved slightly, as mentioned above.

The repolarization maximum appeared on the probe well before the end of the QRS complex in an area that was close to the site where the electrical signs of endocardial breakthrough (high negativity, high gradients) had occurred on the probe. The repolarization pattern remained comparatively stable throughout the ST-T interval.

The “excitation time” indicated by the pseudoisochrones varied from 12 to 30 msec in the various experiments. It was always delayed 5 to 10 msec in relation to the time of appearance of the early minimum and was longest for epicardial stimulation. The “earliest site” indicated by the isochrones was close to but not identical to the area where the early minimum had appeared (figure 6, D to F). Generally, the earliest site was located where the minimum moved 20 to 30 msec after the stimulus. Thus the intramural depths of the pacing site could be deduced approximately from the length of the flat portion in the electrograms, from the increasingly delayed time of appearance of the early minimum in the equipotential contour maps, and from the “pseudoexcitation time” on the isochrone maps.

Double stimulation. In two dogs, two subendocardial sites, close to the tip of needles A and B in figure 1,

**FIGURE 4.** Same stimulation as in figure 3. A through C, Distribution of equipotential lines on the unrolled surface of the olive-shaped probe at three time instants indicated by the vertical bar intersecting the electrograms at the bottom of each map. The numbers adjacent to each bar indicate time (msec) between stimulus and the instant shown on the map. Maximum negativity and positivity are indicated by − and +. The voltage of the maximum and minimum and the step between adjacent lines are indicated (mV) at the bottom of each image. Negative lines are dashed. First continuous line close to dashed lines is the zero line. D, Pseudoisochrones relating to the same beat. The numbers indicate the time after the stimulus (msec) when the minimum derivative occurred in the unipolar electrograms. P = posterior; S = septal; A = anterior; L = lateral.
were stimulated first separately then simultaneously. The single stimuli generated isopotential patterns on the probe that were similar to those previously described for subendocardial pacing, with one minimum facing the tip of the relevant electrode. These maps are illustrated in figure 8, A, for stimulus site A and in figure 8, B, for stimulus site B. Simultaneous stimulation of both sites gave rise to potential patterns with two clear-cut minima (figure 8, C). The two minima appeared approximately 10 msec after the double stimulus and maintained their position for about 10 msec. Their voltage varied from an initial −0.5 to −5 or −6 mV. Later on, the two minima merged into a single minimum of higher amplitude (−30 or −40 mV).

Pseudoisochrone contour maps (not presented) indicated two early areas on the probe that were close to but not identical to the sites where the two early minima had appeared. Also, the local excitation times at the two early sites were 21 and 24 msec after the stimulus, which is much later than the time of appearance of the two early minima (8 to 10 msec).

When one of the two simultaneous stimuli was subendocardial and the other subepicardial, the potential pattern caused by the subendocardial stimulus prevailed and often obscured the effects of the epicardial stimulus.

Square-wave injection. Injection of a short, subliminar current pulse through one of the terminals that had been previously used for pacing gave rise to a clear-cut potential maximum, which, in 17 out of 22 cases, was located on the same site on the probe where electrical pacing elicited an early excitation minimum (figure 8, D). In five cases the maximum was one electrode position away from the location of the excitation minimum.

Right ventricular stimulation. Electrical and mechanical stimuli delivered on the right ventricular epicardium gave rise to a potential minimum on the septal portion of the probe (figure 9, A). The minimum appeared considerably later than after left ventricular stimulation, i.e., 30 to 55 vs 3 to 25 msec. Large, initially positive waves were often observed on the electrograms. The isochrones confirmed the delayed activation (30 to 50 msec) of a septal area.

Mechanical stimulation. Mechanical stimuli were delivered at eight epicardial sites on the left ventricular surface. The electrograms recorded from the probe and the isopotential maps were similar to those obtained after electrical stimulation, and the location of the ear-

FIGURE 5. Electrograms from electrode facing the tip of the intramural needle B in figure 1. A, Subendocardial; B, midwall; C, epicardial pacing. The downstroke started increasingly later after the stimulus from A to C (10 to 18 msec). Arrows indicate the stimulus artifact (S).
ly minimum was in good agreement with the location of the epicardial stimulus. In several cases the stimulus fell on the final portion of the preceding T wave, and this fact entailed an error in the selection of the baseline. Despite this error, the maps exhibited a clear-cut minimum at the expected place.

**Spontaneous premature ventricular contractions.** In one dog we occluded the anterior descending coronary artery at the end of the experiment. Many premature ventricular contractions occurred. The electrograms exhibited typical ST elevation. Again, it was impossible to select a correct baseline because of the presence of undetectable diastolic injury potentials during the T-Q interval. Despite these baseline errors, the maps relating to the spontaneous extrasystoles were similar to those obtained after electrical stimulation and exhibited a clear-cut early minimum that pointed toward the border of the ischemic area. In these cases, however, the actual site of origin of the extrasystole was unknown, and it was impossible to establish whether the location of the minimum on the probe correctly indicated the real site.

**Cylindrical probe.** After introducing the 3 mm cylindrical probe into the left ventricle of two dogs, 10 sites on the left ventricular surface were paced in sequence in each dog. Isopotential contour maps representing the potential distribution on the unrolled surface of the probe invariably showed a potential minimum that pointed toward the pacing site (figure 9, B). However, the minimum was somewhat less “peaked” than observed in the maps derived from the olive-shaped probe, as could be expected because of the shorter distance between adjacent electrodes along a horizontal row (figure 1).

**Discussion**

In this investigation we tried to establish whether intraventricular maps of cardiac potentials, recorded at
some distance from the endocardial wall by means of an olive-shaped or cylindrical probe, could detect the site of origin of ectopic beats in a normal dog heart.

The proposed procedure is based on the classic solid-angle theory. If we consider an excitation wavefront to be equivalent to a uniform dipole layer, then the potential at any point P in the surrounding volume conductor will be proportional to the solid angle subtended by the rim of the wavefront to point P, provided some assumptions are verified. In the case of an ectopic beat starting from an endocardial site (figure 10, A), the wavefront will take a semiellipsoidal shape during the early stages of propagation because the conduction velocity is about twice as high along fibers than across fibers. If many electrodes are distributed on the surface of an intracavitary spherical, olive-shaped, or cylindrical probe, the electrode closest to the starting point of the ectopic beat will detect the rim of the wavefront with the largest solid angle and will therefore record the highest negativity (figure 10). Mapping the potential distribution on the surface of the probe during the initial 5 to 20 msec after the onset of excitation must therefore reveal which point on the probe is facing the site of origin of that particular beat. If the position and orientation of the probe in the heart are known, the site of origin of the beat can be easily assessed.

Figure 10, A, refers to an endocardial origin. When the starting point is intramural or epicardial, the highest negativity will be recorded by the electrode closest to the site of endocardial breakthrough, as soon as breakthrough occurs (figure 10, B) or even earlier, as discussed below.

The results of our experiments were in accord with...
the above theory. Intraventricular potential maps recorded with an array of semidirect leads were able to identify the site of origin of paced ectopic beats starting from more than 60 points distributed in the left ventricular walls and septum of normal dog hearts. The procedure also revealed whether the site of origin was subendocardial, midwall, or epicardial (figures 5 and 6). Intraventricular maps gave accurate results even in the presence of superimposed fields, as occurred when the premature contraction started before repolarization of the previous beat was completed.

Endocardial stimuli 1.2 or 1.5 cm apart were generally distinguished and correctly localized by the maps. However, we did not attempt to determine the resolving power of the method systematically. The theoretical resolution is equal to the total area of ventricular endocardium divided by the number of electrodes on the probe, i.e., about 1.5 cm² in the hearts we studied.

The procedure could not be expected to work properly when the ectopic beats started from the right ventricular wall. However, the right ventricular origin was clearly suggested by the unusually long latency preceding the appearance of a minimum on the septal portion of the maps derived from the olive-shaped probe (30 to 55 msec) and by the large positive initial wave that was often observed in the electrograms (figure 9, A).

Pseudoisochrones detected the site of origin correctly when it was subendocardial. When the pacing site was midwall or epicardial, isochrone maps yielded slightly different results as compared to equipotential contour maps. The differences, however, rarely exceeded one electrode position. Also, the excitation times indicated by the isochrone maps were delayed (up to 12 msec) in relation to the time of appearance of the earliest clear-cut minimum on the equipotential contour maps. It is worth mentioning here that isochrone maps are rigorous only if derived from direct leads, whereas the electrodes on the probe did not actually touch the heart muscle. On the other hand, isochrones have the advantage of requiring only one map to reveal the approximate site of earliest excitation. Moreover, they don't need baseline identification, which can be advantageous during tachycardias or in the presence of injury currents.

After epicardial stimulation, positive deflections were often absent in the electrograms recorded at sites facing the stimulating electrode on the olive-shaped probe, contrary to what could be expected from the solid-angle theory. After midwall and epicardial stimulation, a clear-cut minimum appeared in the maps, about 10 msec before endocardial breakthrough. This behavior is caused by the electrical anisotropy of the heart muscle, which affects the electric field generated by a spreading wavefront. When the wavefront travels in an epicardial-to-endocardial direction or vice versa,
i.e., perpendicularly to the main direction of myocardial fibers, it is generally preceded by a negative area that is sensed by the intracavitary electrodes well before endocardial breakthrough occurs. After breakthrough, a still greater negativity develops. These findings confirm previous data from this and other laboratories, showing that the solid-angle theory does not apply rigorously to the electric field generated by a spreading wavefront.5–9 However, it can be shown that, anisotropy notwithstanding, the intracavitary electrode closest to the site of origin of an ectopic beat will still record the highest negativity.8

Our canine data, promising though they are, do not enable us to establish whether the same method can be used to localize human ventricular tachycardias. A number of problems must be solved before this question can be answered. First, there are the technical problems relating to the feasibility of a multilead percutaneous catheter to be used in a closed-chest situation. Our results show that a multilead cylindrical probe no larger than an ordinary No. 9F catheter (3 mm) revealed the pacing site in dog hearts. On the other hand, multilead balloon catheters with radiopaque markers to localize the electrodes in a closed-chest situation are within the reach of modern technology and are currently being developed (personal communication from the USCI Division of C. R. Bard Inc.). Automated systems for mapping cardiac potentials on-line are widely described in the literature10 and some are commercially available.

Second, human tachycardias pose a number of electrophysiologic problems. The geometry of an infarcted heart is often irregular, as are conduction velocity and tissue conductivity. These conditions may affect the electric field considerably. Also, it is not clear how a reentrant tachycardia would be sensed by the intraventricular probe.11 Despite these difficulties, it still remains true that a starting wavefront must generate a local negativity in the intracavitary blood as soon as it reaches the endocardium. Even if the distance between the surface of the probe and the endocardial wall is not uniform, there must be one electrode on the probe that is closer than any other electrode to the starting point of the arrhythmic beat. This electrode should record the highest negativity in the early stages of excitation.

These considerations indicate that intracavitary maps deserve further studies. Their performance should be evaluated in animal preparations of sustained ventricular tachycardias, as a preliminary step toward clinical trials. If successful, the method would offer some advantages over present-day sequential, direct recordings in the catheterization laboratory, since a complete intraventricular map can be obtained automatically in a few minutes and the recording time can be limited to one cardiac cycle. This may be particularly useful when several types of tachycardia must be localized in the same patient.

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