Epicardial Potential Mapping
Effects of Conducting Media on Isopotential and Isochrone Distributions

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Background. Epicardial excitation sequences, recovery sequences, and potential distributions are recorded from patients during surgery and from animals in the research laboratory for a variety of purposes. During such recordings, a portion of the cardiac surface is exposed to air, and the remainder of the epicardial surface variably is in contact with conductive tissue. No systematic studies document the degree to which these different conditions affect measured excitation times, potential distributions, and/or the configuration of epicardial electrograms.

Methods and Results. Epicardial potential distribution was recorded from five isolated, perfused hearts using a 64-unipolar-lead sock. Data were recorded first with the heart suspended in air and then with the heart immersed in a heated tank filled sequentially to full and half-full levels with conductive Tyrode’s solution and then NaCl-sucrose solution. These solutions had resistivity less than and more than that of blood, respectively, and air was assumed to have infinite resistivity. Epicardial potentials were recorded from two hearts before removal from the chest, both with and without a latex sheet insulating the heart from the pericardial cradle. Amplitude of recorded potentials from both intact and isolated hearts was markedly higher when the heart was surrounded by an insulating medium, but locations of positive and negative regions were less affected by surrounding medium. Isochrone activation maps calculated using the minimum derivative of the QRS (intrinsic deflection) were not affected by the conductivity of media surrounding the heart.

Conclusions. The present study provides evidence that isochrone maps recorded at surgery are not distorted by exposure of the cardiac surface to insulating air. Results suggest that epicardial isochrones recorded during cardiac surgery could be used in patients to assess the accuracy of “inverse” procedures that noninvasively compute epicardial electrograms and isochrones from body surface potentials. (Circulation 1991;84:2513–2521)

Epicardial potential and isochrone maps are extensively recorded, both clinically and experimentally. In this setting, the anterior cardiac surface is exposed to air, and the posterior cardiac surface remains in contact with conductive tissue. Studies by Katz and coworkers1,2 in the 1930s showed that different body positions resulted in changes in the body surface ECG. ECG changes were attributed to varying contact between the heart and different thoracic structures. The recording of multiple epicardial potentials in an open-chest preparation is a newer development. Epicardial isochrones have been recorded during surgery to localize sites of earliest activation in preexcitation syndromes or ventricular tachycardia.3,4 Epicardial potential maps, recovery time maps, and isointegral maps have been recorded in open-chest settings for a variety of purposes, including assessment of arrhythmia vulnerability and detection of nontransmural necrosis.5,6 Systematic studies that document how reliably open-chest epicardial recordings represent closed-chest potential or isochrone distributions are not available. Such information is also important with regard to the inverse problem (i.e., noninvasive computation of epicardial potentials and isochrones from measurement of body surface potentials). Computed epicardial maps reflect the closed-chest situation. It remains uncertain whether epicardial recordings at the time of surgery can be used to verify inverse solutions.
The hypothesis tested in the present study is that epicardial activation sequences calculated from unipolar electrograms are insignificantly different regardless of whether measurements are made with air or a volume conductor surrounding the heart. In other words, time of the intrinsic deflection (minimum dV/dt) of unipolar, epicardial electrograms is not altered by modifying the conductivity of the conductor surrounding the heart. Clearly, the two extreme conditions of conductive versus insulating medium present situations in which current flow and, hence, potential distributions within the heart would be expected to be very different. In addition, unipolar electrogram waveforms would consequently also be different. Figure 1 shows a cartoon of current flow arising from a dipole source located within the myocardium for a surrounding conducting medium (Figure 1A) and an insulating medium (Figure 1B). In the former panel, current may flow outside the heart, whereas in the latter, current is constrained to flow within the myocardium and is tangential to the epicardium at the surface interface. This experimental study was performed to determine whether epicardial electrograms, potential distributions, and activation sequences based on the minimum dV/dt were significantly different when conductivity of the medium surrounding the heart was altered in a systematic fashion.

Methods
Experimental Preparation

Animal experiments conformed to the position of the American Heart Association on research animal use. Five experiments were performed using two dogs per experiment. Dogs were anesthetized with pentobarbital (30 mg/kg). In each experiment, a dog weighing 20–25 kg served as the support dog, and a dog weighing 12–15 kg served as the donor of an isolated heart. In two experiments, epicardial recordings were made from the smaller heart before isolation and removal, with and without insulation of the posterior cardiac surface using a thin sheet of latex rubber. The recordings were made using the 64-
unipolar-lead sock described below for the isolated hearts. Unipolar potentials were recorded against a Wilson central terminal.

A modified-Langendorff preparation was used to perfuse an isolated canine heart suspended in a heated tank (Figure 2). Carotid artery pressure and arterial blood gas measurements were made frequently, and circulatory volume and respiratory adjustments were made as necessary. Heat exchangers maintained blood at body temperature. The isolated heart contracted under no-load conditions. Bipolar stimulating electrodes were placed on the right atrium, right ventricle, and left ventricle to provide a variety of activation orders. Unipolar epicardial potentials were recorded from a 64-lead sock pulled over the heart. Leads were made from 0.005-in. silver wire insulated except at the point of attachment to the nylon mesh of the sock. A single reference electrode was placed at the base of the aorta for recording cardiac surface potentials. During data processing, an averaged reference electrode (average of all 64 epicardial leads) was used to display epicardial isopotential maps. Map frames for the isolated heart recordings were displayed at 5-msec intervals for analysis with different scales for positive and negative potentials. Ten isopotential lines were used for each polarity; this ensured that distribution features of both positive and negative potentials were displayed in each map frame even if the amplitude of one polarity was markedly higher than that of the other. Epicardial isochrone maps were calculated using the time of the (7–9) minimum derivative of the QRS of each electrogram.

Epicardial recordings were made with the heart suspended in air, both completely immersed and half immersed in Tyrode’s solution, and then both completely immersed and half immersed in a low-conductivity solution consisting of 280 mM sucrose and 46 mM NaCl. This low-conductivity solution with resistivity of 200 Qcm was formulated to be isotonic and have an approximate conductivity intermediate between that of the thorax (average resistivity, 500 Qcm) and that of blood (average resistivity, 150 Qcm). Tyrode’s solution resistivity was 50 Qcm, and it was used to make conductivity the highest possible compatible with isotonicity to compare with the zero conductivity of air.

Isochrone map-pairs across all activation sequences studied in all dogs were compared by correlation for the conducting and insulating surrounding media. Isopotential maps were so obviously qualitatively different in varying conductive media that quantitative correlations were not calculated.

Results

Selected epicardial electrograms recorded during sinus rhythm in one experiment are shown in Figure 3. Electrograms on the left were recorded with the isolated heart suspended in a full tank of Tyrode’s solution, and recordings on the right were recorded with the heart suspended in air. Both sets of recordings were taken at the same amplifier settings. Similar electrogram differences were noted in all experiments. Amplitudes of potentials recorded with the heart surrounded by air were higher; there also was an obvious change in morphology of the electrograms. The noted changes in repolarization were
FIGURE 3. Selected electrograms from a 64-unipolar-lead sock recorded during sinus rhythm with heart submerged in Tyrode's solution (left) or suspended in warmed air (right). Higher-amplitude electrograms were always recorded in epicardial regions surrounded by nonconductive media.

related to both current-flow differences and temperature changes since the surrounding air was not heated, although the solutions used to surround the heart were heated.

Epicardial isopotential maps recorded from an in situ heart during simultaneous stimulation of the left atrium and anterolateral left ventricle, with and without insulation of the posterior cardiac surface, are shown in Figure 4. Anterior and posterior cardiac surfaces are shown, and the amplifier settings for both recordings were the same. The increase in amplitude of the negative potentials on the posterior cardiac surface during insulation of the heart with a latex rubber sheet is shown by the increased number

FIGURE 4. Epicardial isopotential maps recorded during early QRS in an in situ heart with simultaneous left atrial and left ventricular drive. In each heart pair, left heart is anterior cardiac surface, and right heart is posterior cardiac surface. In heart pair on right, posterior and lateral cardiac surfaces were insulated from surrounding tissue by a latex sheet. Small squares mark the maximum and minimum potentials. Minimum is site of left ventricular stimulation. Scale, 10 mV per contour.
of isopotential lines. Small squares mark the maximum and minimum potentials, and the minimum potential is the site of left ventricular stimulation. The maps were recorded at the same time during ventricular activation. Differences in the pattern of potential distribution between the two states were minimal and were similar in both experiments where the insulating sheet of latex was used.

Figure 5 shows epicardial isopotential maps recorded from an isolated heart during sinus rhythm under the conditions labeled in the figure; this heart is representative of all of the experiments. All maps are displayed for the same time instant during ventricular activation. Small squares mark the locations of maximum and minimum voltages. Plus and minus signs mark the polarity of potentials and electrode sites. In the instance shown during the early QRS, minima marked sites of activation break through to the right ventricular epicardium. This was confirmed from the activation maps and is consistent with previously published reports. Although the centrum of these early QRS negative potentials varied slightly with change in media surrounding the isolated heart, the site of this minimum early in the QRS was always on the right ventricular surface, and it was always marked by dense packing of isopotential lines. The site of breakthrough of activation to the left ventricular epicardium was marked by the similar isopotential map feature of densely packed negative isopotential lines in all experiments. In this figure, the variation in pattern of distribution of isopotential lines with change in surrounding media is apparent. It is much greater than variation in isochrone map patterns described below in Figures 6 and 7. Although it was apparent from just visual evaluation that isopotential maps varied more than isochrone maps depending on conductivity of surrounding media, features of isopotential maps such as general distribution of positive and negative potentials, general shape of isopotential lines, and density of isopotential lines were similar enough to be recognizable in all solutions. This was true even when the actual site of absolute maxima and minima changed at the same time during activation in different surrounding media.

Isochrone maps of epicardial activation in an isolated heart during right atrial stimulation at a cycle length of 350 msec are shown in Figure 6. Again, the findings are representative of all experiments. Labels beneath each set of maps indicate the conditions of recording. Plus signs indicate electrode sites, not polarity. Activation was determined by calculation of the time of the minimum derivative of the QRS of each electrogram. In all experiments under all conditions, epicardial activation during sinus rhythm began in the lower, anterior right ventricle. The time contour interval in the isochrone maps is 10 msec.

The similarity of all isochrone maps with this activation order is apparent, especially when compared with the isopotential maps in Figure 5.

Figure 7 shows isochrone maps with the same format as Figure 6 but with simultaneous stimulation of the right atrium and left ventricle at a cycle length of 350 msec. The site of left ventricular stimulation was anterolateral and basal and is marked by an asterisk. The differences in activation pattern compared with Figure 6 are clearly apparent, as is the similarity of activation maps in this activation order with varying solutions. The correlation coefficients within activation orders across varying conductive media were 0.94–0.98 in all five experiments.

Discussion

The purposes of electrophysiological recordings from the epicardial surface in an open-chest setting are to define normal physiology or record electrophysiological derangements useful in diagnosis or therapy of human disease. We are aware of no systematic study of the effects on epicardial potentials when there are differing conductivities of media surrounding the heart. In the present study, it was found that changes in conductivity of media surrounding the heart have variable effects on the form of recorded epicardial potentials, but the finding common to all experiments was an inverse relation between amplitude of recorded potentials and conductivity of the surrounding media.

The changes in electrogram form and amplitude with varying conductive media had no significant effect on the determination of epicardial activation sequence using the minimum derivative of the QRS of epicardial electrograms. The present study provides reassuring evidence that isochrone maps of epicardial activation recorded in an open-chest configuration accurately reflect closed-chest epicardial activation. Previous studies have demonstrated the validity of using activation recovery intervals to measure repolarization, and these measurements have used the time of the minimum derivative of the QRS of unipolar electrograms to mark local activation time.4,2 A recently reported study has also provided an analytic derivation of the theoretic basis for using unipolar electrograms to measure activation and recovery in relation to transmembrane action potential measurement as well as documenting reliability of the electrogram measures under a variety of conditions, including graded ischemia." The reproducibility of epicardial activation sequence in these studies is further evidence of the stability of using the minimum dV/dt of the QRS to mark activation time under a variety of conditions. The results of the present study are also applicable to endocardial recordings. The same findings would be expected in an open-heart, open-chest preparation. Because recovery was not expected to be stable under the conditions of these experiments, no evaluation of recovery times or properties with changing conductivities was attempted.

Isopotential maps in this study varied considerably in amplitude and configuration in different media. However, densely packed isopotential lines still revealed
FIGURE 5. Early QRS epicardial isopotential maps during sinus rhythm in one heart suspended in media as labeled. In each heart pair, anterior cardiac surface is on left, and posterior surface is on right. + and −, polarity; ■, maxima and minima. All maps are from same time after beginning of QRS. 1/2 refers to apical half of heart suspended in solution named. Upper half of heart was surrounded by air. Ten contour lines were used for each polarity for assessment of potential distribution pattern (see “Methods”).

epicardial activation breakthrough sites and, more generally, wavefront configuration in all media. For example, the minimum potential recorded on the anterior cardiac surface during the early QRS that is associated with right ventricular breakthrough during supraventricular activation varied in amplitude and configuration but only minimally in location with differing media. The general shape of potential distributions and location of regions of high potential gradients tended to be preserved regardless of surrounding media, although absolute values of potentials varied. This suggests that marked departures from normal distribution of isopotential maps in open-chest recording situations probably represent myocardial abnormalities rather than differences between open- and closed-chest recording conditions.
FIGURE 6. Epicardial isochrone maps during right atrial stimulation. In each cardiac pair, anterior surface is on left, and posterior surface is on right. Full and 1/2 refer to filling of tank surrounding isolated heart. +, Electrode sites. There is greater similarity of activation maps in different media compared with isopotential maps in Figure 5. Scale, 5 msec/activation line. Activation line begins on anterior right ventricle.

The findings of the present study, especially with respect to humans, have special relevance to validation of computed solutions to the inverse problem, the attempt to calculate epicardial potentials from recorded body surface potentials. Although inverse solutions have been applied to studies of human cardiac pathology, direct confirmation of the solutions used has not been attempted. Results of the present study suggest that epicardial recordings during surgery used as isopotential maps are unlikely to exactly reflect closed-chest epicardial potentials but that general features may be useful in checking an inverse solution. Results suggest that isochrone activation maps as a method for validating computed solutions of the inverse problem are likely to be more precise.
FIGURE 7. Epicardial isochrone maps with same conventions as in Figure 6 except different activation order of simultaneous right atrial and left ventricular stimulation. Activation maps are again nearly identical despite differences in conductivity of surrounding media. Small square marks site of anterior left ventricular stimulation site. Scale, 5 msec/activation line.

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