Comparison of Human Ventricular Activation with a Canine Model in Chronic Myocardial Infarction

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SUMMARY
Ventricular activation was studied in 20 patients with ischemic heart disease at the time of surgery for myocardial revascularization. Because most of the activation studies in man were limited to recording of epicardial potentials, a canine model of chronic infarction was also studied. Pre- and postinfarction data were recorded in dogs and correlated with the anatomy of the lesions. Epicardial Q waves, when associated with delayed epicardial activation, were diagnostic of underlying infarctions in areas of the heart that did not normally exhibit Q waves. In areas normally containing Q waves, underlying infarction was associated with Q waves greater in duration than the normal range determined for those areas of the epicardium. The experimental model of chronic infarction showed epicardial delay to be due to slowed intramyocardial activation rather than to delay in Purkinje conduction. Correlations between electrical and anatomic data in two patients suggested that, within limits, the detailed relationships between infarction and activation established with the canine model could be applied to human infarction to understand the genesis of the epicardial potentials and the ECG. The technique was also felt to have a practical clinical application in selection of areas of myocardium for vascular implants or infarctectomy.

Additional Indexing Words:
Conduction delay Electrocardiogram Epicardial mapping
Peri-infarction block Purkinje system Q waves

Improvement in the clinical interpretation of the electrocardiogram in the presence of myocardial infarction will follow from increasingly detailed knowledge of the effects of infarction on the normal electrophysiology of the heart itself. Wilson and associates, in 1935, first described the epicardial effects of experimental myocardial infarction.1 Durrer and associates have since described human2,3 and canine ventricular activation4 in normal states and canine activation in infarcted states.5 Burch has recently described papillary muscle activation in normal and pathologic states.6 Others have studied infarctions that produce midtemporal and terminal changes in the epicardial and electrocardiographic QRS complex.7,8

The present study was designed to increase the clinical application of epicardial electrophysiology by obtaining human epicardial data in normal and infarcted states and correlating these data with laboratory studies of canine models of infarction. In each dog control data were obtained before infarction...
was produced. By this approach, the complexities of cardiac electrical events and individual variations among animals served as constants, making the changes produced by the infarct readily apparent. The increased ability to detect changes from normal and to understand in detail how infarction alters the normal electrophysiology permitted localization of infarctions at the time of surgery and raised new questions about the significance of midtemporal QRS changes, the varying significance of QS patterns in infarction for different regions of the heart, and the implications of conduction abnormalities in the presence of human myocardial infarction.

Methods

Epicardial and selected intramural data were obtained from 20 patients with ischemic heart disease. Control data were also obtained from normotensive patients with no known cardiac disease who underwent thoracotomy for pulmonary lesions.

Epicardial, intramural, and endocardial studies were carried out in 17 adult mongrel dogs of both sexes, weighing 15 to 25 kg. Each animal was anesthetized with intravenous sodium pentobarbital (26 mg/kg) and placed on a mechanical respirator; its heart was exposed through a left fifth interspace thoracotomy. Control and postinfarction points were located with flexible epicardial grids and anatomic landmarks. Infarctions were created in 13 dogs by ligation of one or two branches of the left anterior descending or left circumflex coronary arteries. Septal infarction in one animal was created by ligation of penetrating septal branches of the anterior descending coronary artery while all lateral branches were preserved. An insulated intramural electrode was used in four dogs to create a small area of fibrosis by sending cautery current to a selected terminal. Four weeks after infarction, the animals were again studied. The fibrinous pericardial reaction permitted easy separation of the epicardium from the pericardium. When control studies in two animals were repeated 4 weeks later, there was a slight decrease in epicardial voltage but no change in epicardial activation time or Q-wave duration. Because the time of onset of activation was presumed to be unaffected by infarction, left ventricular cavity potential (LVCP) was used as a reference to relate control to postinfarction activation times for each dog.

The epicardial recording system consisted of an electrode with two terminals located 1 mm apart. Unipolar and bipolar data obtained through these terminals were recorded simultaneously with the subject's ECG (and in the dogs with a reference bipolar electrogram) by a DAS-100 system. The ECG complex was altered by thoracotomy, but it remained useful as a constant time reference in the human subjects. Input impedance was $10^{11}$ ohms. All data were recorded on magnetic tape at a speed of 7½ inches/sec. The analog signals were then reproduced on photographic paper by a Honeywell visicorder oscillograph at a paper speed of 500 mm/sec. The frequency response of the entire system was from 0.1 Hz to 1.2 kHz. Because of the short time allowable for human mapping, the timing and configuration of epicardial complexes were considered most important, and in many cases the amplitude of potentials was not obtained (see figs. 1, 4, 8, and 13).

The intramural recording system consisted of plunge needle electrodes (23 gauge) each containing 15 terminals located 1 mm apart. Bipolar data were recorded between consecutive terminals. By convention, the polarity of the bipolar complex was negative if spread of the activation wave was from endocardium to epicardium.

After sacrifice, the canine hearts were fixed by a Zenker's 80% ethanol process, and all sections were stained with a Masson trichrome solution. Prior painting of the plunge electrodes with India ink permitted accurate postmortem correlation of anatomic position with the electrical data that were obtained.

Results

In this study, when two adjacent epicardial or intramural terminals were connected together they generated a bipolar complex. The fast deflection of this complex represented the moment the centroid of the wave front passed between the two terminals, and, therefore, it was used as a measurement of local activation (depolarization). Individual points whose bipolar activation occurred within a selected time period were depicted in some of the illustrations as a homogeneous time zone. This permitted the visualization of the sequence of local activation as a progression of such zones of equal time duration from light to dark tones. Alternatively, by connecting any one epicardial or intramural terminal with a distant leg terminal, a unipolar complex was generated. This complex represented the integrated effects of local and distant events, the latter decreasing in proportion to the square of the distance ($1/r^2$).
**Epicardial Activation**

Epicardial unipolar complexes from a patient with ECG evidence of an anterolateral infarction showed Q waves of long duration anteriorly (fig. 1, A and B) and no Q wave posteriorly (fig. 1C). Postmortem examination showed a correlation between the areas of overlying Q waves and the large subendocardial infarction seen in a tissue cross section taken near the left ventricular apex (fig. 1).

A photomicrograph of a large experimental subendocardial infarction produced in a dog is seen in figure 2. Comparison of the canine control epicardial complexes with those taken after infarction showed that a Q wave was produced over the infarction in all 13 dogs with an infarction diameter greater than 5 mm. In areas of the heart where large epicardial R waves or qR complexes were present in the control state, such as the anterior left ventricle, the ratio of the duration of the Q wave to that of the left ventricular cavity potential (LVCP) was calculated. The ratio was found to increase in proportion to the amount of wall involved. In figure 2, Q/LVCP varied from 0.6 to 0.9, the latter representing a nearly transmural infarction. Although no Q wave was present in the last complex on the right in figure 2, the initial R wave of the control epicardial deflection (see

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**Figure 1**

*Human anterolateral subendocardial infarction in cross section. Preoperative EKG is on the left. Note Q waves of 40- and 64-msec duration in epicardial unipolar complexes A and B over the infarction. No Q wave was present in C, which was not over the infarction. Numbers to the right of the complexes represent local activation times in msec. EPI. UNI. = epicardial unipolar complex; RV = right ventricle; ANT. = anterior; LAT. = lateral; POST. = posterior.*
CONTROL) changed to an initial rsR. The loss of initial positive forces normally generated by the subjacent endocardium resulted in an epicardial Q wave over the infarction and an s wave in areas adjacent to the infarction. Partial loss of the initial positive epicardial deflection was present in the experimental infarctions studied for distances up to 3 cm from the area of infarction.

Use of the epicardial Q wave to localize infarctions must take into consideration the fact that in man, as in the dog, Q waves normally appear over certain areas of the ventricular epicardium. The location and maximum durations of these Q waves were studied in seven patients without infarction who underwent thoracotomy. These data allowed three zones to be constructed over the human epicardial surface (fig. 3). Q waves were not present normally in a zone covering the anterior surface of the right ventricle and approximately the first 2 cm of the left ventricle lateral to the anterior descending coronary artery. Q waves were variably present or absent, and lasted up to 27 msec, in the area overlying the pulmonary outflow tract and in a band of 2–4 cm in width located laterally on the left ventricle but parallel to the anterior descending coronary artery and also posteriorly along the course of the posterior descending branch of the right coronary artery. In the third zone, the remaining lateral and posterior surfaces of the left ventricle, a Q wave was always present and varied in duration from 4 to 32 msec. Not illustrated is the Q-wave phenomenon that occurs at the atrioventricular junctions of the right and left ventricle. Here epicardial
A map of unipolar Q-wave positions and durations over the normal human epicardium. These normal Q-wave zones provide a basis for the interpretation of abnormal Q waves in patients with ischemic heart disease.

unipolar complexes normally showed Q waves of long duration, for they were in essence recording cavity potential from their position over the rim of the ventricular cavities.

The application of these normal values to the study of an anterior infarction in the human heart is shown in figure 4. The epicardial unipolar complex (fig. 4B), from an area with no normal Q wave, showed a QS pattern. Figure 4C, from an area with a normal Q-wave duration of up to 27 msec, had a Q-wave duration of 50 msec. Figures 4A and 4D, on the other hand, fell within the normal range of Q-wave duration for their respective epicardial areas. The infarction, therefore, lay under areas B and C at this level of the heart.

The wave forms of these human epicardial unipolar complexes were compared with the preoperative precordial ECG leads taken from overlying points on the patient's chest. In figure 4, A and V₁ demonstrated a similar rS pattern; B and V₂ were QS complexes with notching on the down slope; C and V₄ were QRs patterns; and D and V₅ were similar in their initial and midtemporal configuration.

In addition to Q-wave changes, this human heart also showed a delay in epicardial activation time over the anterior infarction, as seen by the location of the latest isochrone (67–81 msec) in figure 4. The finding of concurrent abnormal Q waves and delayed activation time over the infarcted area was similar to that observed in all of the experimental free ventricular wall infarctions (fig. 2). The characteristics of this epicardial delay were studied in detail in the laboratory model of infarction by comparison with the animals' control activation patterns. Figure 5 shows a three dimensional drawing of an experimental infarction and the overlying delay. This area of the anterior free ventricular wall showed early apical activation at 34 msec (the white oval in fig. 5A) in the control state, and was totally depolarized by 46 msec. After subendocardial infarction (fig. 5B) the early apical breakthrough is absent, and depolarization over the epicenter of the infarction is not completed until 64 msec—
Human anterior infarction. A, B, C, and D on heart illustrations are locations where unipolar epicardial potentials (above) were recorded. Preoperative precordial EKG leads are at the bottom. Note the correlation between each epicardial complex and the respective precordial lead that overlies that region of the heart, e.g., A and V1. The spread of epicardial activation is represented by four equal time zones. The key to the activation time is shown below. EPI. UNI. = epicardial unipolar complexes; ANT. = anterior; LEFT LAT. = left lateral projection of the heart.

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well after the QRS complex in the dog's lead II ECG has ended (see fig. 5B). The characteristic pattern of the isochrones of this delayed activation was one of concentric circles that became smaller and closer.

A canine model of anterior septal infarction was also studied. After control epicardial data were obtained, small areas of septal infarction were produced (see Methods). Figure 6 shows the changes produced. The activation times adjacent to the unipolar complexes remained essentially unchanged, but a QS pattern developed in complex B, and a qRS pattern appeared in A. The R-wave amplitude of the complexes over the left ventricle (fig. 6, C, D, and E) was diminished after the infarction.

The epicardial effect of very small infarctions was also studied in four animals. A small area of fibrosis of 2-5 mm in diameter, simulating chronic infarction, was placed at various levels of the ventricular wall by sending a cauterizing current to a selected terminal on an intramural electrode (see Methods). Figure 7 shows a fibrotic area of 2 mm in diameter produced in a canine heart by this technique. The burned area was activated in the control state at 9 msec (see CONTROL
**Figure 5**

Canine model of postinfarction delay in epicardial activation. (A) Control ECG and activation sequence for a 3 x 3 cm area of the anterior left ventricular epicardial surface. (B) ECG and activation sequence for the same area 4 weeks postinfarction. Note the increasingly delayed activation centered over the subendocardial infarction. The key to the activation time is shown below. R.V. = right ventricle; APEX L.V. = apex of the left ventricle.

BIPOLAR. Comparison of the postcautery unipolar epicardial complexes with the control complexes showed changes ranging from a decreased slope of the ascending limb of the R wave at 9 msec to increased notching of the initial R wave. In all four dogs no Q waves were generated by the small areas of fibrosis, and no delay in epicardial activation time was observed. Thus, a small midtemporal loss of positive forces in the unipolar electrogram was the sole evidence of this area of fibrosis in the canine heart. Also note that the unipolar complexes that exhibited the greatest change in configuration were not those most proximal to the lesion.

**Intramural Activation**

The effect of infarction on the spread of the activation wave front through the free ventricular wall was studied in order to understand how the characteristic epicardial effects, and, therefore, body surface ECG effects, were generated.

Data from human intramural bipolar electrodes were obtained in two patients from areas of infarction (fig. 8). The region of infarction showed areas of complex fragmentation of the wave front and loss of fast activity (see 7-mm level of fig. 8), areas of multiple wave fronts (3.5-mm level), and a synchronous wave front in the intact subepicardial tissue (1.5-mm level). The epicardial unipolar complex overlying this area showed a QS pattern with the small r wave on the negative slope of the Q wave at 44 msec coinciding in time with subepicardial activation.

The canine model of chronic infarction produced abnormalities of the intramural...
bipolar complexes similar to those obtained in human infarction. A photomicrograph of an experimental infarction with bipolar data from six intramural locations is shown in figure 9. Loss of all local fast activity (except Purkinje) was seen (fig. 9E). Late activation was present (fig. 9C) in association with an island of intact muscle surrounded by scar. Desynchronized wave fronts at 31 and 34 msec were present (fig. 9B) at the periphery of the infarct, and a fast single complex indicating a synchronous wave front characterized the intact subepicardium (fig. 9, A and D). Similar phenomena were present in all 12 intramural studies of experimental infarctions.

Placement of multiple plunge electrodes in parallel rows with the same epicardial grid for control and postinfarction studies permitted reconstruction of the intramural activation sequence over large areas of the ventricular wall in the 12 animals studied. Control data from intramural electrodes in the free wall of the canine left ventricle showed an endocardial-to-epicardial spread of the activating wave front in many regions (fig. 10A). One month after infarction (fig. 10B) these areas of simple inner-outer activation showed the following characteristics (fig. 10C). In the infarcted area, the wall was thinned, a small rim of viable tissue persisted endocardially, the activation wave front was slowed, activation of the subepicardium was late, and the latest area of activation occurred in small isolated segments of myocardium adjacent to the infarcted area (see area activated at 62
msec in fig. 10C and its time relationship to the dog’s QRS in the figure to the side).

Many areas of the normal free ventricular wall, however, demonstrated a more complex activation pattern. In all areas of papillary muscle or large trabeculations, the activation wave spread bidirectionally, that is, toward the epicardium and the endocardium simultaneously. Figure 11A shows this normal pattern of canine papillary muscle activation. In figure 11B the area of infarction that was produced is shown in black, and in figure 11C the changed activation sequence is shown. Activation was not only delayed on the epicardium overlying the infarction, but there also was an area of equally late delay in the shrunken papillary muscle itself.

**Endocardial Activation**

This study evaluated the relative contribution of intramural slowing versus Purkinje conduction delay in generating the epicardial delay seen over infarctions. The photomicrograph in figure 9 shows a Purkinje trunk insertion under an area of experimental canine infarction. Figure 9F shows the early fast potential of large amplitude recorded from a plunge electrode in contact with the free Purkinje trunk. Figure 9E shows a fast Purkinje potential from an endocardial terminal with marked fragmentation of the adjacent muscle potential. In the control study the Purkinje potential in this area was followed by a fast muscle potential 12 msec later. Figure 9C shows a Purkinje potential at 6 msec followed by fragmentation and a delayed muscle activation potential at 38 msec, whereas only 8 msec elapsed before onset of the muscle potential in the control study at this site.

In two dogs the infarction was adjacent to an area of abundant Purkinje fibers. Figure 12A shows the endocardial surface of the anterior wall of the left ventricle with the area of subendocardial infarction outlined in white. Of the 36 intramural electrodes placed through this tissue in the postinfarction study,
Figure 8
Bipolar electrograms from an intramural electrode in human subendocardial infarction. Note the marked fragmentation of complexes indicating desynchronization and slowing of the wave front as it traverses the infarction. EPIC. = epicardium; EPI. UNI. = epicardial unipolar complex; INTRAMURAL BIP. = intramural bipolar complex.

28 showed Purkinje potentials. Their activation times in msec after a reference time are shown in white circles. The times are later than those in figure 9 because the endocardial surface shown is much greater. India ink from the electrode shafts marked the endocardial position of these points and permitted accurate postmortem anatomic localization. Lines representing the activation sequence of these points are shown in figure 12B. The endocardial wave front velocity perpendicular to these time lines was 1.4 m/sec, a velocity compatible with specialized conduction tissue and three times the speed of normal myocardial tissue propagation.

Epicardial Delay due to Block in Purkinje Propagation
Not all features of human infarctions correlated with the canine model of infarction. Figure 13 represents human data that did not fit the experimental mode. Postmortem study established the presence of an anterior infarction (black area in fig. 13B), but no Q waves were present in the epicardial unipolar electrograms from this area (fig. 13C). The patient's ECG showed a pattern consistent with conduction delay, and the epicardial activation sequence showed the area of latest activation to lie at the base of the anterior ventricle (fig. 13D) and not over the infarction. Tissue sections through the infarction revealed a marked fibrotic thickening of discrete endocardial areas (fig. 13A), a finding seen in none of the canine models of chronic infarction.

Discussion

Design of Study
By obtaining control intramural and epicardial activation data in the same experimental animal, the present study was able to show in detail how subsequent infarction alters the normal pattern. Comparisons were made between the epicardial excitation patterns in the "normal" human subjects and in patients with chronic infarction, and emphasis was placed upon determining ranges of normal for human Q waves and epicardial activation patterns. Definition of abnormal findings was then based on the normal values, and the significance of abnormal human data was determined by interpolation from the canine model.

Epicardial Effects of Intramural-Subendocardial Infarction
Subendocardial infarction in man (fig. 1) generated epicardial Q waves and a delayed epicardial activation time. The concurrence of these two phenomena permitted accurate localization of underlying infarctions. The canine model (fig. 2) of subendocardial infarction correlated well with these clinical findings. The dog model suggested that an estimate of wall thickness involved in the infarction could be semiquantitative. In areas of the heart where complexes with large R waves (Rs or qR) were present normally in the epicardial unipolar electrogram, such as
the anterior left ventricle, the postinfarction Q/LVCP ratio was found to be a useful guide to the approximate size of the underlying infarction (fig. 2). The greater the transmural involvement, the closer the ratio approached a value of 1.0. The study also demonstrated that ratios such as these were unreliable indices in epicardial areas normally having an rS pattern, such as the anterior ventricle overlying the ventricular septum and the right ventricle. In these areas a small infarct readily produced loss of the initial, small r wave, creating a QS pattern that erroneously appeared as a large transmural infarction (fig. 4B). The same principles apply to the standard ECG, for a QS pattern in V₁ and V₂ does not imply as large an infarct as does a QS pattern in leads V₃ and V₄ or a QR complex in V₅ and V₆.

The description from the noninfarcted human hearts of characteristic zones of Q-wave presence and duration was an attempt to establish objective guidelines for making the distinction between normal and abnormal Q waves. It has previously been pointed out by Roos and coworkers³ that Q waves may occur normally in the left ventricular epicardial unipolar complexes. Our normal values suggest that the Q waves recorded by Roos et al. from the left ventricle near the anterior descending coronary artery were abnormal and suggest underlying infarction.

**Effect of Septal Infarction on Right Ventricular Unipolar Potentials**

Studies of the canine model of septal infarction showed a characteristic picture of abnormal Q waves in right ventricular epicardial unipolar electrograms in association with no delay in right ventricular epicardial activation (fig. 6). Anatomic correlation showed that the normal bowing of the ventricular septum into the right ventricular cavity is extensive in man and the dog and explains why Q waves appeared on the right ventricular surface instead of over the sites of septal attachment. There was no associated epicardial delay because the right ventricular...
free wall was intact. The control epicardial rS complex, the thinness of the right ventricular wall, and the excellent conductive characteristics of cavity blood probably explain why the underlying septal Q waves have enough magnitude to overcome the initial positive forces in the overlying right ventricular epicardium. The decrease in R-wave amplitude noted over the adjacent anterior left ventricle may have been a reflection of the loss of initial positive forces caused by the septal infarctions.

Effects of Small Infarcts on Epicardial Unipolar Potentials

Much discussion and experimental work has centered around the effect of very small infarctions on the epicardium or the electrocardiogram. Creation of small areas of fibrosis by cautery overcame the difficulty encountered by Abildskov in using formalin injections to create such an effect. Control potentials could also be recorded from multiple terminals on the cautery electrode prior to cauterization, thus permitting placement of small infarcts at any desired level in the ventricular wall. Small subendocardial infarcts prior to this study have been thought to produce early QRS changes but were shown to produce midtemporal QRS notching (fig. 7). The explanation for this is that distant electrical forces had already generated a positive deflection in the epicardial unipolar complex before the underlying subendocardium was activated. Thus, midtemporal QRS changes do not necessarily imply a midwall infarction. An infarct must, therefore, be of a certain volume in order to create an initial Q wave on the epicardium (fig. 2) and larger still to create a Q wave in the distant chest or limb ECG terminal. A further observation made from studying small experimental infarctions (less than 5 mm in diameter) was that the maximum epicardial effect was often present in an area not directly over the site of

*Figure 10*

Canine infarction in cross section of free ventricular wall. (A) Control intramural activation sequence (see time key above). (B) Tissue 4 weeks postinfarction. (C) Postinfarction activation sequence (see time key in A). This illustrates the mechanism for the epicardial delay shown in figure 5. However, note that the latest area activated (62 msec) is located intramurally. Its time relationship to the dog’s QRS complex is shown in the figure on the right. The arrows indicate the direction of the activation front, which in this study was parallel to the epicardium.

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Canine infarction in cross section of ventricular wall containing the anterolateral papillary muscle. (A) Control intramural activation sequence (see time key below). (B) Outline of infarcted zone (black area). (C) Postinfarction activation sequence. Note both the epicardial and intramural delay of activation in C. The intramural delay occurred in islands of viable tissue surrounded by fibrosis. P.M. = papillary muscle.

Bidirectional Intramural Activation

Most models relating ventricular activation to the ECG in infarction assume a simple endocardial-to-epicardial spread of the wave front in the normal regions of the ventricle. Areas of the free ventricular wall with a smooth endocardial surface were found to exhibit such an inner-outer pattern of activation (fig. 10A). However, areas adjacent to papillary muscles or associated with marked endocardial irregularity and trabeculations typically exhibited complex activation patterns of the inner half of the wall (fig. 11A). Bidirectional activation was often present, a phenomenon recently described by Burch in the anterolateral canine papillary muscle. He and others have suggested that bidirectional activation is due to Purkinje fibers penetrating deep into the ventricular wall. The present study suggested that early midwall activation and resultant bidirectional waves were the result of deep endocardial invaginations between cavitary projections in areas of papillary muscle and large trabeculations (fig. 11A).

Mechanism of Epicardial Delay

Abnormal Intramural Activation

The study of human infarction showed that epicardial delay occurred regularly over infarctions and that it presented a characteristic activation sequence of concentric time zones which became closer together as one centered over the infarction. The canine infarction...
CHRONIC MYOCARDIAL INFARCTION

Figure 12

Canine endocardial Purkinje activation postinfarction. (A) The anatomy of the Purkinje network, which overlies a chronic subendocardial infarction (area enclosed by the white line). The area of infarction was determined from microscopic study of six tissue sections made through the tissue block. Postinfarction Purkinje activation times from 28 points are designated in msec by the numbers. (B) The Purkinje activation sequence constructed from the data in A. Propagation velocity perpendicular to the direction of spread was 1.4 m/sec. Pap. M. = papillary muscle; L. V. Apex = left ventricular apex.

served as a useful model for the study of this delay (fig. 5).

These studies showed that the epicardial delay was due to abnormal spread as the wave front passed through the ventricular wall and not to the delay of the Purkinje impulse in its arrival at the underlying endocardium (fig. 9). Tangential spread, when viewed from the epicardium over areas of infarction and contrasted with the widely spaced time zones over normal myocardium, suggested slower subepicardial spread (fig. 5B). However, calculation of the velocity along the axis of propagation indicated a rate of 0.5 m/sec, which was within the range for normal myocardial activation. Thus, the delay was due to slow propagation within the subendocardial-intramural infarct and late activation of the overlying subepicardium by wave fronts that had to travel an abnormally long distance, but at a normal velocity from adjacent, intact myocardial regions. Correlations between the anatomic (fig. 9) and electrical data (figs. 9 and 12) from this study gave evidence for routine Purkinje survival under subendocardial infarctions of the free ventricular wall. There is pathologic evidence that the same circumstances exist in human myocardial infarction. A persistent viable endocardial rim of tissue is a common finding under subendocardial infarctions in human heart specimens.

Postulated Mechanism of Intrainfarction Block

This study showed a good correlation between the behavior of depolarization wave fronts in areas of human infarction (fig. 8) and canine infarction (fig. 9). Both were characterized by areas of complete loss of fast deflections in bipolar complexes due to absent local activation, other areas of desynchronization with several distinct wave fronts present, a delay in wave front velocity, and a subsequent delay in activation of the overlying epicardium.
Anatomic-electrical studies in the canine model demonstrated a good correlation between the fragmented potentials and the distributed clusters of viable myocardium within the infarct (fig. 9). Because these clusters were few and widely separated by fibrotic tissue, the activation was desynchronized. If we assume that propagation velocity is a function of current density and current density is related to the degree of synchronous activation of a region of the myocardium, then desynchronization would result in a decrease in the space-time current, and propagation velocity would decrease. This is postulated to be the mechanism of intramural block.

**Epicardial Delay due to Block in Purkinje Propagation**

In the patient studied who presented with a conduction delay in the preoperative ECG (fig. 13), there was marked fibrotic thickening of endocardial areas adjacent to the myocardial infarction (fig. 13A). The thickening covered an area that has been shown by Watt to produce late activation of the anterobasal left ventricle, as in this patient, when the anterior division of the left Purkinje system is divided. Edwards has described a similar phenomenon in cases of myocarditis with congestive failure and says this represents an endocardial hyperplastic response to the
stretched ventricular chamber of a failing heart.\textsuperscript{10} Whatever the etiology, attention is drawn to this case as representing a phenomenon that cannot be explained by focal, ischemic necrosis of Purkinje tissue alone, for in the canine model the Purkinje system remained intact in all infarctions.

It would appear that endocardial sclerosis in this patient altered the sequence of activation, thus masking the expected effect of the infarct on the early part of QRS. Interference with the spread of endocardial excitation over the Purkinje network of the anterior left ventricle wall could have delayed the wave front in that it actually reached the area of infarction and adjacent myocardium after the initial QRS forces had already been generated in the unipolar complexes.

**Clinical Implications**

Epicardial maps of the human heart show delayed activation and prolonged Q waves over areas of underlying infarctions. This technique may be useful for revascularization surgery or infarctectomy.

Small "silent" subendocardial infarctions may produce midtemporal changes in the overlying QRS complex, a fact that places renewed emphasis on the clinical significance of these changes.

More detailed correlations are needed to conclusively relate certain electrocardiographic features to the underlying anatomic and electrophysiologic changes in the ventricles in myocardial infarction. However, in view of the present information obtained directly from the heart, it appears that hypotheses that relate all forms of "conduction delay" in infarction to focal ischemic lesions in specific branches of the endocardial Purkinje system are oversimplifications.\textsuperscript{11} The clinical implication is that ECG evidence of conduction delay may represent either of two basic mechanisms: (a) abnormal intramural activation or (b) abnormal Purkinje activation. The data obtained in this study suggest that processes other than ischemic necrosis per se may be a basis for the abnormality in Purkinje propagation when it is present in patients with myocardial infarction.

**Acknowledgment**

The authors would like to express their gratitude to Drs. Paul A. Ebert, H. Newland Oldham, Jr., Will C. Sealy, and W. Glenn Young, Jr. for permission to study their patients. Also, they would like to acknowledge the exemplary work of their electronics consultant, Mr. Jack H. Kasell, and of Mr. Colie B. Clark, Jr. and Mr. William A. Shepherd.

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Comparison of Human Ventricular Activation with a Canine Model in Chronic Myocardial Infarction
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Circulation. 1971;44:74-89
doi: 10.1161/01.CIR.44.1.74
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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