Spread of Electrical Activity Through the Wall of the Ventricle

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Multipolar recording technics have been employed to record the spread of excitation through the wall of the ventricle. The construction of isochronous planes in a block of tissue aids in visualizing the direction of spread. The results give direct support to the idea of fast endocardial spread followed by synecial spread through the wall at a slower rate. No evidence is found that the impulse spreads through the individual cardiac muscle bundles.

The activation of the surface of the heart has been mapped in dogs by Lewis and Rothschild¹ and by Eyster and Meek,² and in several species by Harris³; some information regarding the human heart has been contributed by Barker and co-workers.⁴ Lewis¹ has also contributed information regarding endocardial activation. But few studies have been concerned with the course of electrical impulses in the septum or in the myocardial walls, and only recently have experiments been directed to the spread of activity through the thickness of the myocardium.⁵ ⁶

Studies of intramural potentials have generally been based on recording of potentials from large unipolar electrodes or on the recording of vectors due to masses of cardiac tissue. In some experiments, isolated perfused hearts have been used. Although such studies might give qualitative information, it was felt that only through exact measurements made at many points within the myocardium of the heart in situ could the activation of the ventricle be described accurately. For this purpose, a multipolar electrode was devised which permits recording with a multi-channel oscilloscope at very close points within the heart muscle.

The studies reported furnish information concerning the exact pathway of myocardial excitation, the origin of the individual potentials of the QRS and the importance of the Purkinje tissue and of the muscle bundles that make up the heart in cardiac activation.

METHODS

Experiments have been conducted in 30 open-chested dogs, 3 cats and 1 monkey under barbiturate anesthesia. The multipolar electrodes consist of 14 or 15 fine (50 micra) insulated tungsten wires staggered around a central shaft of 125-micra insulated tungsten. Tungsten is used because of its stiffness. The cut ends of the recording wires are so placed that adjacent terminals are 0.5 to 1.5 mm. apart. The maximum diameter of the entire assembly is approximately 0.3 mm., and the total length over which potentials are recorded varies from 7 to 20 mm. (fig. 1). The distance between recording tips is usually determined under the microscope, using a 0.1 mm. scale. More exact calibrations are made with the electrode in a volume conductor which has an AC potential impressed along the long axis of the electrode. A calibrated potentiometer with accuracy of 0.5 per cent is also oriented along the needle axis. By tuning to a null between an electrode tip and the center tap, it is possible to measure with 0.01 mm. error.

To avoid errors due to slight shifts of the electrode, a 16-channel oscilloscope was constructed. Fourteen channels were used to record simultaneously from all positions of the multipolar electrode, while the two other channels recorded a fixed time-reference and a standard limb lead (fig. 3). The time reference was recorded from a small bipolar electrode placed in the ventricle for the duration of an experiment. This electrode consists of two 50-micron tungsten wires fastened to a fine barbed tungsten shaft.

Sanborn Industrial Amplifiers served as preamplifiers for the multipolar electrodes. The time reference and electrocardiogram were recorded through Tektronix type 122 amplifiers. The over-all frequency response of the Sanborn channels is flat.
to 1500 cycles per second or better, depending on the length of the wires on the multipolar electrodes. The "Tektronix" channels are slightly better. Either an auricular potential or the time reference potential was used with a conventional delay circuit to trigger the sweep. A Grass Kymograph Camera was used to record from all channels simultaneously, and a square wave generator fed signals at 5 millisecond intervals into all channels to facilitate the timing of deflections. Unipolar potentials (each wire against an indifferent electrode) and bipolar potentials (difference between adjacent wires) were recorded for each electrode position.

After the heart was exposed, the timer electrode was placed in the muscle and then the multipolar electrode was inserted in the heart. After the injury potential due to insertion had disappeared (two to four minutes), the potentials were recorded. The multipolar electrode was then moved to a new location or inserted to another depth at the same location.

The number of electrode insertions made in each heart varied from 20 to 50. Whenever the reference electrocardiogram changed appreciably, an experiment was terminated. Electrode pathways within the heart were marked by dipping the electrodes into India ink. The hearts were removed after an experiment and the position of each electrode correlated with the recorded potentials. In most of the later experiments, hearts were sectioned grossly, bleached with hydrogen peroxide and, with or without subsequent bleaching in potassium hydroxide, taken into pure glycerin (fig. 2). This made it possible to trace the electrode paths in cleared sections. Many hearts from these and other dogs have been examined and dissected to determine muscle fiber direction.

**Fig. 1.** One of the multipolar electrodes used in this study. This electrode has 15 terminals staggered around a central shaft. Direct current has been passed through each terminal with the electrode in a bath so that a bubble has been formed. The scale shows millimeter intervals.

**Fig. 2.** A bleached and cleared section of one of the hearts studied. India ink left by insertions may be seen up the septum, across it, and across the thin wall of the right ventricle.

**Results**

Typical records made with a multipolar electrode inserted in the wall of the right ventricle are shown in figure 3. These show the potentials at each wire with respect to an indifferent lead (Channels 1–14). No fast deflection appears in the first four unipolar records. Such records are produced by electrodes within the cavity. Tracings from electrodes in positions 5 to 11 indicate action potentials in the myocardium. The records from the last two electrode positions (13, 14) show a positive potential followed by a slow negative wave. Here, the electrodes, although connected to the surface by a thin film of conducting fluid, were known at the time of the experiment to...
be above the surface of the ventricle. These records are typical of those made above the epicardial surface. Electrode 12 shows some rapid activity and is probably close to the epicardial surface.

Bipolar potentials from the same electrode position are shown in figure 4. Channel 1 shows the potential difference between 1 and 2 of the unipolars; channel 2, the difference between 2 and 3; and so forth. If the lower-numbered electrode is negative with respect to the higher, the deflection is downward.

The records such as are shown in figures 3 and 4 may be used in conjunction with the measurements of distance along an electrode for a plot of time against depth. Potentials recorded from several electrode insertions in one experiment are plotted in this way in figure 5.

With the multipolar recording technic, it has been possible to record potentials from a single insertion without appreciable change over a period of an hour. During this time the electrode might move slightly, but the time-distance plot from it was not changed. Nor have recorded potentials been found to change relationship to the timer with a change in heart rate from 120 to 150.

Time-distance plots give information about rates of conduction but they do not permit a detailed analysis of the activity of a block of tissue. It is, however, possible to reconstruct a block of tissue and note the time of activation of a large number of points along several needle insertions. Once this has been done,
Fig. 6. A block of tissue which is bounded by four electrode insertions (1-4). Time of excitation at different depths with reference to the timer electrode appears opposite each terminal. Dotted lines show isochronous planes at 0, 5, and 10 milliseconds after the reference. The 15 millisecond plane is not indicated but could be drawn in part from the data shown. The lower right figure shows the location of this block in the left ventricle.

Fig. 7. Plot of isochronous planes along the anterior coronary artery of the left ventricle. Numbers show the time of activation with reference to the timer electrode. Electrode insertions used for reconstruction are indicated by 15 small dots; the time reference electrode, by the large dot. The block intersects the anterior papillary muscle.

points excited simultaneously can be connected to form planes, referred to as isochronous planes.

The activation of an entire block of tissue in the left ventricle is shown directly and through a plot of isochronous planes in figure 6. Spread of activity in a larger block from the same vicinity is drawn in figure 7. In this section of tissue the electrical activity originated near the intersection of wall and septum, and moved to the left, toward base and apex and from within outward. A section of the anterior right ventricle is depicted in figures 8 and 9. Isochronous planes are presented in figure 8 and the times of excitation in figure 9. The disorganized sequence of early points which appears in the electrode insertion nearest the apex is typical of insertions in this mid right ventricular region. The insertion slightly
FIG. 8. Isochronous planes drawn from the data of figure 9, showing the location of the tissue in the heart.

The movement continues from endocardium to epicardium. In some of the insertions, slight but significant reversals of direction, which are not due to papillary penetration, extend over one or two millimeters.

DISCUSSION

Interpretation of Records. The unipolar and bipolar records obtained in this study supplement each other in the determination of the spread of activity. The unipolar potentials above this one pierced the anterior papillary muscle which apparently accounts for the very early points found near the tip. From the figures presented, it is obvious that the position of the zero plane is somewhat arbitrary. The invasion in this section moves toward the base in a direction parallel to the interventricular sulcus and from endocardium to epicardium.

Figure 10 shows the activation of a small block of tissue near the posterior papillary muscle of the left ventricle. Excitation of this block begins under the papillary muscle in the two right insertions and spreads briefly toward both cavity and surface. After all of the tissue beneath the origin has been excited,
help to indicate whether or not the electrode is in muscle, and may tell what activity precedes or follows that at the tip. The bipolar records give an indication of time of activation and help also to differentiate electrodes within muscle from those outside. The shape and amplitude of a unipolar potential determine where the corresponding wire lies. Whether the electrode is in the cavity or muscle, or above the surface connected to the heart by conducting solution, nearby depolarization will produce a negative (downward) deflection, usually from 25 to 60 millivolts. An electrode above the surface shows at times a smaller negative potential.

Activity preceding the negative potential gives some clue to the electrode location. Within muscle, or on or above the surface, a positive potential usually precedes the negative wave. This indicates the approach of activation. Since most tissue bordering the cavity is early, a cavity electrode usually sees receding (negative) activity.

Cavity and surface electrodes sum the activity of more fibers than an electrode in muscle, and negative potentials in these records usually develop over more than 5 milliseconds while intramuscular electrodes show depolarization, usually taking 2 to 4 milliseconds. In the records presented, the cavity potential has a slow negative deflection which shows movement of excitation away from the recording point (fig. 3, nos. 1–4). The intramuscular potential has mainly a fast negative wave (nos. 5 to 11). However, when activity nearby precedes that at the electrode tip, there is a positive (approaching) wave (nos. 7 and 8) before depolarization.

An intramuscular potential showing no initial positivity can arise in two instances: first, when the electrode is in an early site of ventricular activity, and second, when approaching activity occupies so small a volume of tissue that it gives rise to no appreciable positive deflection. A sharp rise in the approaching wave indicates that nearby muscle is probably responsible for activity at the recording locus; a slower rise is less significant, since it indicates either a small conducting system to the locus or local injury. An electrode above the surface of the heart but connected to it by a conducting solution, as ours usually are, shows a positive (approaching) potential, since the surface is later than deeper tissue. With surface depolarization, this returns to the base line. Two successive electrodes above the surface usually have almost identically shaped waves (fig. 3, nos. 13, 14).

Potentials which are predominantly positive in unipolar electrograms and which show no fast negative deflection may be obtained from superficial injured tissue or nonmuscular tissue. This tissue will act as a source of potential for active tissue, but there will be no local depolarization. These potentials are similar to those recorded precordially. They are not "intramural" potentials. A detailed discussion of unipolar potentials may be found in the work of Wilson.7

A glance at figures 3 and 4 will show that the bipolar records of figure 4 have a much shorter duration, because potentials common to both are eliminated. For this reason, the bipolar record is not influenced by activity at a distance. Two successive electrodes in the cavity show little or no bipolar activity and the same is true of electrodes above the cardiac surface (fig. 4, nos. 1–3, 13, 14).

The deflection of the bipolar record indicates the direction of spread of activity. The convention used here is such that negativity of a deep electrode with respect to a more superficial one gives a downward deflection. A succession of such downward deflections indicates spread from within outward (fig. 4, nos. 8–12). A reversal point will have a diphasic potential (no. 5) while spread from outside in gives an upward deflection (no. 6). Such directions always check with the time of activation, as plotted from the peak of a bipolar record.

The peaks of bipolar records give the same time-distance plots as tripolar records (alternate electrodes connected and recorded against the central terminal). They are theoretically superior to the bipolar for determination of time of local activation, but it requires regular electrode intervals and a complicated switching system. We have found our bipolar records to be equally accurate and far less difficult to
take than tripolar records. The determination of time of activation from a unipolar record is subject to great error. The inflection point of the negative wave is usually considered the time of local activation, but this inflection point is not easy to detect. Bipolar records have been used by many of the investigators who have worked on the problem of surface excitation, and the discrepancies in certain other investigations can be considered the result of efforts to measure accurate time of activation from the apex or initial deflection of a unipolar record. These points may be influenced by activity distant from the electrode. Both unipolar and bipolar records are necessary in a determination of this sort.

Adequate criteria have not been formally organized for the recording of cardiac action potentials. The entire process of depolarization as recorded with our electrodes occupied 2 to 3 milliseconds in most cases. With intracellular microelectrodes, Draper and Weidmann recorded potentials with a rise time of less than 1 millisecond in the false tendon of the dog heart. Accurate recording of the shape of the depolarization wave within heart muscle with electrodes of the size we use will require a recording system with an over-all frequency response of at least 500 cycles. The speed of conduction in muscle is such that a response of 300 cycles per second is adequate for electrodes 1 mm. apart.

Some investigators have attempted to plot epicardial excitation to the millisecond using ink-writing galvanometers. The frequency response of these pens prohibits attempts to read times so accurately. Such investigations have appeared in the last decade and are technically far inferior to the work of Lewis and Rothschild as well as to that of some later investigators.

**Sequence of Excitation.** Our study of the activation of the intraventricular septum is not complete and will not be presented at this time. We have studied the activation of the anterior wall most extensively; our records of the posterior surface are not as complete but do bear out the conclusions we shall state. The earliest points activated in the wall are on the endocardial surfaces of both ventricles at the junction of free wall and septum in the midanterior region. The endocardium is excited before the overlying epicardium. The movement of excitation is toward base and apex and toward the left and right as well as from within outward. We have some evidence that the endocardium may be activated simultaneously at many points after the earliest points mentioned above. The apparent speed along an electrode insertion normal to the wall varies from 150 to 600 mm. per second.

The apparent speed and direction of electrical activity along a needle insertion are not the true speed and direction. To determine the true values, the construction of isochronous planes is essential. Without the construction of these planes, a false estimate of speed of conduction through muscle can easily be made. An electrode inserted perpendicular to the direction of excitation will show almost simultaneous activation of all points and give an excessively high value for apparent speed of conduction. Indeed, if any angle exists between the electrodes and the direction of invasion, a high value will be found.

It is often possible from our data to draw isochronous planes a millisecond apart, but the results are not very different from those presented for 5 millisecond intervals. A series of lines drawn perpendicular to these planes must indicate the direction of movement of the cardiac impulse. The distance between the planes is proportional to the speed of conduction. From isochronous planes we get an average speed of 300 mm. per second through the wall.

Through the subendocardial layer, speed has obviously been higher, but we do not have enough points to construct very many isochronous planes intersecting the endocardium. If we use our incomplete information to calculate a speed, however, we get an average speed of 1.8 meters per second, values range from 1.2 to 5.0 meters per second. It is possible that mixtures of fast and slow conducting tissue as well as a lack of points may contribute to errors in estimating conduction speed. The values are in general agreement with the figure of 400 mm. per second reported for cardiac...
muscle fibers by Lewis and Rothschild and 2.0 meters per second reported for the false tendon of the dog by Draper and Weidmann.

The thesis has been advanced that the fast component of cardiac excitation is parallel to muscle fibers. We have not sufficient endocardial points to refute this statement unconditionally for the entire heart. However, in the right ventricle (fig. 8), where several planes cut the endocardial surface, there is no correspondence between the subendocardial fiber direction and the subendocardial direction of conduction. In the left ventricle (fig. 7) the fast subendocardial spread is not parallel to endocardial fiber direction. Until more data is accumulated, we can say that in most of the heart there is no apparent relationship between fast spread of excitation and fiber direction.

It has been suggested that the electrical activity is channeled within the muscle bundles that make up the heart. This hypothesis seems contradicted by the lack of correspondence between muscle fiber orientation and the direction of electrical spread. It is further contradicted by the lack of discontinuities in the majority of electrode insertions in the wall. If the impulse were channeled within a particular muscle bundle, the distance traversed to such a point as the base of the right ventricle might, as has been stated, be quite different for the deep and the superficial bundles. However, electrodes in this vicinity show an orderly progression from within outward, with no sign that a different course is followed through the various bundles. In none of our isochronous planes is there any evidence of a streaming of activity within a particular bundle.

One further conclusion may be reached from this data: the connective tissue which has been described as separating the muscle bundles is not a barrier to conduction.

The lack of reversals of direction along a needle track, which is almost universal, leads to the conclusion that the fast conduction which occurs near the endocardium does not in general extend along the branches of the Purkinje tissue which have been described as ramifying into the wall. If these branches had the very rapid speed found on the endocardium, we might often have an early point along a needle insertion, but this is not the case. Such early points are found, particularly when a needle pierces a papillary muscle, but they are not common enough to support the view that there is a rapid system penetrating the wall. The few out-of-sequence points which are found in the wall may be artefacts due to slight injury. They may be caused by slight variations in conduction speed to adjacent points through the muscle or, alternately, by penetration of a fast conducting system into the wall.

Our results provide direct support for the concept of syncytial excitation of the myocardium. It appears from our results that the heart is excited by a rapidly conducting system near the endocardium and that from there, activity spreads more slowly into the wall either through a syncytial system with equal conduction in all directions or along a specialized conduction system which has a slower rate and which is oriented perpendicular to the wall. No evidence exists to support this second possibility. Although the existence of an anatomic syncytium has been questioned, our results indicate a syncytial spread of electrical activity.

Our results are in excellent accord with the views of Sir Thomas Lewis regarding the earliest points of activity and the course and syncytial nature of ventricular invasion. We have been unsuccessful in preliminary attempts to stain Purkinje tissue and cannot correlate its distribution with the spread of activity.

Preliminary studies have been reported on the spread of electrical activity through the ventricular septum and are being extended. Histologic studies relative to these studies are being continued.

Conclusion

The spread of electrical activity through the wall of the ventricle has been investigated with multipolar recording technics. Through most of the ventricle, rapid subendocardial activation is followed by slow spread perpendicular to the epicardial and endocardial surfaces. The rapid subendocardial spread may be via
the Purkinje tissue, but this has not been established.

The conduction of impulses in the wall of the heart is such that the muscle must be considered a functional syncytium. Conduction through the wall is not parallel to muscle fibers nor is it channeled through the individual muscle bundles which make up the tissue. It is not interrupted by connective tissue barriers.

It does not appear that branches of a rapid conduction system often function to cause early excitation of intramural points.

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