THE ORDER OF VENTRICULAR EXCITATION IN HUMAN BUNDLE-BRANCH BLOCK*†

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IN previous articles from this laboratory^{1, 2} it has been pointed out that, in accordance with the laws which govern the flow of electric currents in volume conductors, the potential variations produced by the cardiac muscle are very much greater in magnitude in the immediate neighborhood of the heart than at a distance from it. It has been shown that when one electrode of the string galvanometer is placed upon the precordium, the position of the second electrode, so long as it is distant from the heart, has comparatively little influence upon the form of the ventricular electrocardiogram. Attention has been called to certain resemblances between leads of this type‡ and direct leads of the kind employed by Lewis and Rothschild³ in which one electrode is placed in actual contact with the ventricular muscle and the other upon the chest wall. In both cases the form of the ventricular complex is determined in a very large measure, although not to quite the same extent in the former as in the latter, by the potential variations of the exploring electrode; in both cases the muscle units which lie nearest this electrode exert individually a much greater effect upon its potential than those which are more distant from it.

Curves obtained by leading from points on or near the heart to one of the extremities utilized in taking the three standard indirect leads may be freed from the influence exerted by potential variations of the indifferent electrode by a method which we have recently described.⁴ When this electrode is placed upon the left leg the correction is made by subtracting from each ordinate of the recorded curve one-third of the sum of the deflections, measured in millivolts, inscribed in Leads II and II at the corresponding instant in the cardiac cycle. It is possible in this way to determine, at least approximately, the time course of the potential of the exploring electrode, and thus to eliminate any difference between direct and semidirect leads for which potential variations of the indifferent electrode are responsible.

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‡We term all indirect leads in which one electrode is placed very much closer to the heart than the other *semidirect leads*. We call the electrode which is nearer the heart the *exploring electrode*; that which is more distant, the *indifferent electrode*. We refer to semidirect leads in which the exploring electrode is placed upon the precordium as *precordial leads*.

So far as we are aware, there is no reason to believe that in direct leads of the type under consideration the exploring electrode bears any special relation to the ventricular muscle other than that of great nearness to the fibers lying just beneath it. In direct leads from the outside of the exposed heart, it is true that the exploring electrode is in contact with a surface which, if we neglect the thin epicardium and film of fluid which covers it, is bounded by a di-electric, but this factor does not seem to be an important one in determining the distinctive characteristics of the recorded curve. In leads from the endocardial surface of the heart it is not present, and Lewis and Rothschild found that flooding the pericardium with blood did not materially alter the time of the chief deflections obtained by leading from the immersed epicardial surface. Between direct and semidirect leads there can, therefore, hardly be any fundamental difference. In the latter, as compared to the former, the exploring electrode is more distant from the heart as a whole. Its distance from the nearest muscle units is absolutely greater and relatively greater in comparison with its distance from other parts of the heart. The potential of the indifferent electrode exercises a relatively larger influence in semidirect than in direct leads. Apparently, these are the only respects in which the two methods of leading differ materially. Suppose that we were to start with a direct lead and gradually move the exploring electrode away from the surface of the heart, electrical contact being maintained by surrounding heart and electrode with a medium of approximately the same specific conductivity as the body tissues. The form and amplitude of the recorded deflections must then change in a continuous manner; rapidly at first, but more gradually as the distance of the electrode from the heart increases. Since moving the exploring electrode away from the heart tends to decrease the influence exerted by the muscle units with which it was originally in contact and to increase relatively the influence of the muscle units lying adjacent to them, it is clear that when the area of cardiac surface over which similar potential variations occur simultaneously is extensive all resemblance between the deflections of the direct and those of the final semidirect lead will not be lost until the distance of the exploring electrode from the heart is comparatively great.*

This line of thought and the character of the ventricular deflections in precordial leads led us to suspect that there might be a close relation between the form of these deflections and those which would be obtained by leading directly from the underlying portions of the ventricular wall; and consequently that, by the use of such leads, the general order of ventricular excitation in man might be determined directly. Even if this suspicion should prove unwarranted, it seemed probable that a comparison of the ventricular deflections obtained by semidirect leads in

*The fundamental principle involved here has been discussed by Jeans: "The Mathematical Theory of Electricity and Magnetism," ed. 4, Cambridge University Press, 1923, p. 70.

animals with those obtained by similar leads in man might throw considerable light upon the interpretation of the human electrocardiogram.

EXPERIMENTAL OBSERVATIONS

General Methods.—In the experiments to be described we employed dogs of large size. They were fully anesthetized with sodium amytal given intravenously.* The heart was exposed by splitting the sternum and opening the pericardial sac. The electrodes employed for standard indirect leads were small copper disks sewed under the skin; for direct and semidirect leads we used glass tubes of 3 or 4 mm. bore stoppered at one end with salted kaolin or gelatin and filled with copper sulphate solution into which a bright copper wire was thrust. The actual contact with the heart in direct leads was made by fat-free wool partially imbedded in the kaolin or gelatin plug and moistened with normal salt or Ringer's solution. To hold this in place and to protect the surface of the heart from injury a small piece of soft rubber tubing was slipped over the end of the glass tube.†

Two Einthoven galvanometers coupled together in tandem enabled us to take a direct or semidirect lead and a standard indirect lead simultaneously. In taking the former the exploring electrode was attached to the right-hand terminal of the galvanometer; the indifferent electrode was placed on the left hind leg. The arrangement was therefore such that relative negativity of the exploring electrode produced an upward deflection in the completed curve. Lead I was used as the standard lead; in recording this the galvanometer was employed at the normal sensitivity; a deflection of 1 cm. per millivolt. For the direct or semidirect leads the sensitivity of the galvanometer varied in different instances from one-fourth to one-twentieth of the normal.

To produce bundle-branch block we employed the method used by Lewis,⁵ and by Wilson and Herrmann;⁶ a small knife blade was thrust through the ventricular wall and the bundle branch cut or injured by pressure with the back of the blade. The location of the cut or injury was determined at the end of the experiment.

For measuring the time intervals of our curves we have employed the record measuring machine devised by Captain B. H. Elliott and manufactured by the Cambridge Instrument Company.

A Typical Experiment.—We may describe as typical of our usual method of procedure an experiment performed on January 24, 1930. The dog was a large bull terrier. Fig. 1 (Curve 621) shows Leads I and III taken simultaneously before the chest was opened. The heart was fully exposed in the usual way and then covered completely with

*In our experiments this drug produced almost complete vagal paralysis.

†Such electrodes are not, as is often supposed, strictly nonpolarizable. If two of them are placed in contact with copper sulphate solution and connected with the terminals of the string galvanometer, an e.m.f. of ten millivolts suddenly introduced into the circuit will cause evident overshooting due to polarization capacity. This effect is less pronounced the greater the area of the surface of contact between metal and solution.

a large pad of gauze, about 1.5 cm. in thickness, soaked in warm normal salt solution. A series of curves was then taken by leading from various points on this pad to the left leg. (Fig. 2, left hand column.) Through an error in attaching the lead wires these curves were taken in such a way that relative negativity of the leg electrode rather than the exploring electrode yielded an upward deflection. In taking the first curve the exploring electrode was placed in contact with that part of the pad which rested upon the right basal margin of the heart. With each succeeding curve it was moved downward and to the left toward the cardiac apex a distance of approximately 2 cm. The final curve was taken from that part of the pad which lay upon the apex of the left ventricle. The galvanometer was employed at one-fifth the normal sensitivity; that is

Fig. 1.—Experiment of Jan. 24, 1930. No. 621: Leads I and III before opening the dog's chest. No. 625: Leads I and III after pressure upon the right branch of the His bundle. No. 632: Leads I and III after section of the left branch of the His bundle.

to say, the tension of the string was so adjusted that 10 millivolts produced a deflection of 2 cm.

After this series of curves was obtained, the pad was removed and two attempts were made to produce right branch block by pressing upon the right branch of the His bundle with the back of a small knife blade thrust through the wall of the conus just below the pulmonary valve. The second attempt was apparently successful; the resulting change in the form of the electrocardiogram in Leads I and III is shown in Fig. 1 (Curve 625). The heart was again covered with the gauze pad and an-

Fig. 2.—Experiment of Jan. 24, 1930. Each column shows a series of five semidirect leads taken through a pad of gauze placed upon the exposed heart and recorded simultaneously with Lead I. Left-hand column: Taken while the cardiac mechanism was normal. The semidirect leads are upside down (see text). The sensitivity of the galvanometer was normal for Lead I and one-fifth normal for the semidirect leads. Middle column: Right branch block is present. The sensitivity of the galvanometer was one-fourth normal for the semidirect leads. Right-hand column: Left branch block is present. The sensitivity of the galvanometer was one-fifth normal for the first three and one-twentieth normal for the last two semidirect leads. The number on each curve gives the interval in seconds by which the chief upstroke of the semidirect lead follows the onset of R in Lead I. The time marks on the curves indicate intervals of 0.2 second.

Fig. 2. (See legend on opposite page.)

other series of semidirect leads was taken in the same manner as before, except that the lead wires were now properly connected so that relative negativity of the exploring electrode produced an upward deflection. These curves are shown in Fig. 2 (middle column). Of the five curves taken only the last was from that part of the pad overlying the left ventricle. The part of the pad from which the first curve was taken lay beyond the atrioventricular groove. The galvanometer was used at one-fourth the normal sensitivity.

Shortly after these curves were taken the right branch of the His bundle began to recover and within a few minutes the electrocardiogram had returned to the normal type. Two attempts were then made to cut the left branch; the second was apparently successful; the form of the resulting electrocardiogram in Leads I and III is shown in Fig. 1 (Curve 632). The gauze pad was then reapplied and a third series of semidirect leads was taken as before. The first three curves were taken with the galvanometer at one-fifth the normal sensitivity; in taking the last two curves, however, the sensitivity was reduced to one-twentieth normal in order to keep the large downward deflections of the semidirect and the upward deflections of the standard lead both on the narrow film.

A short time after these curves were taken complete heart-block developed; the heart gradually dilated and the animal died. Examination of the right side of the ventricular septum showed two large subendocardial hemorrhages, one on either side of the main stem of the right bundle branch about one centimeter above the base of the anterior papillary muscle. Examination of the left side of the septum showed a deep gash which obviously severed the main stem of the left bundle branch completely. It lay just beneath the aortic valve and one of the valve cusps had been cut at its base. The resulting high-grade aortic insufficiency was probably partly responsible for the final dilatation of the heart.

Additional Observations.—In Fig. 3 we show some curves taken during an experiment performed on January 17, 1930. Curve 602 shows Leads I and III taken after section of the left bundle-branch just below the aortic valves. Curve 603 shows Lead I and a direct lead from the right central region; Curve 604 shows Lead I and a direct lead from the left apex. After these curves were made the heart was covered with a pad of gauze soaked in warm normal salt solution and a series of five semidirect leads was taken as in the experiment previously described. The curves shown in Fig. 3 (Curves 605-1-3-5) are the first, third, and fifth of this series. The sensitivity of the galvanometer was unfortunately not recorded; it was probably one-tenth or one-twentieth normal for the direct leads and one-fourth or one-fifth normal for the semidirect leads. The indifferent electrode was placed on the left hind leg.

Description of Experimental Curves.—With regard to the form and amplitude of the curves which they obtained by leading directly from the ventricular muscle to the chest wall, Lewis and Rothschild³ make

Fig. 3.—Experiment of Jan. 17, 1930. No. 602: Leads I and III after section of the left branch of the His bundle. No. 603: Lead I and a direct lead from the right central region. No. 604: Lead I and a direct lead from the left apex. No. 605: 1, 3, 5: The first, third and fifth of a series of five semidirect leads taken through a pad of gauze placed upon the heart.

the following statement: "The form of the curves taken directly from the ventricle by a single contact is variable. The majority of such curves show an initial dip of variable extent (2-35 millivolts). This dip is relatively slow and usually unbroken, but it may be notched; it

represents the first or extrinsic deflection. There may be a return to the base line before the intrinsic deflection is recorded, but more commonly, the onset of the intrinsic deflection terminates the dip. The upstroke is always very abrupt, and the recorded image of the fiber is consequently faint. Its amplitude, measured from its point of origin, is always considerable (10-80 millivolts).''

The curves obtained by semidirect leads may be described in very similar terms. These curves also show an initial dip of variable extent (1-20 millivolts), which is relatively slow and may be unbroken or notched. It is sometimes preceded by a small upright deflection and this is also true of the corresponding deflection of direct leads. This initial dip is followed by an abrupt upward movement of considerable amplitude (5-20 millivolts), which is ordinarily the steepest deflection of the ventricular complex. When this chief upstroke occurs early, it usually carries the string far above the base line; in such cases the initial downward movement is ordinarily of small amplitude, but there are occasional exceptions to this rule. When the chief upstroke occurs late, it usually carries the string only to the base line or a little way beyond it; in such cases the initial downward movement is of large amplitude. Although the upstroke under consideration is generally by far the sharpest deflection of the ventricular complex, being depicted by the thinnest line because it is written by the most rapid movement of the string, it is sometimes little, if at all, steeper than the other deflections. In some instances no deflection of this character is present.

The chief difference between the curves obtained by direct leads and those obtained by semidirect leads lies in the voltages which are on the average much greater in the former. There is also a difference in the relative steepness of the chief upstroke which is greater in direct leads, permitting the more certain identification of this deflection.

We may now examine the curves illustrated in Figs. 2 and 3 in greater detail. In the case of the undamaged heart (Fig. 2, first column), the curves from that part of the gauze pad which lay upon the right ventricle (2, 3, and 4) show a chief upstroke (actually a downstroke because of the error in connecting the lead wires previously mentioned) which comes early, about 0.007 second after the onset of R in Lead I. In the single curve (5), taken from that part of the pad which lay upon the left apex, this deflection comes a little later; about 0.028 second after R. In the first curve, which was taken from that part of the pad which lay above the atrioventricular groove, the ventricular deflections are small.

When right branch block was present, the chief upstroke of those curves which were taken from that part of the pad which lay upon the right ventricle (2, 3, and 4) begins late; about 0.05 or 0.06 second after the onset of R in Lead I. The single curve taken from that part of the

pad which lay upon the left apex (5), on the other hand, shows an early chief upstroke, which begins about 0.018 second after the onset of R. In the fourth curve of this series the chief upstroke is early (0.016 after R), but of small amplitude; a second smaller and more gradual upstroke occurs late (0.39 second after R). It may be pointed out here that curves of transitional type were frequently obtained from that part of the pad which lay near the interventricular groove; in such curves there were sometimes two prominent upstrokes, one early, the other late; in other instances there was no chief upstroke at all; and in still others the chief upstroke fell in a position intermediate between its position in the curves taken more toward the right base and that which it occupied in those taken more toward the left apex. It will be noted that the chief upstrokes of the first three curves of this series do not rise above the base line; the ventricular complexes resemble in general form the ventricular complexes of Lead I.

Turning now to the left branch block series, we find that in those curves (1, 2, and 3) obtained by leading from portions of the pad that lay upon the right ventricle the chief upstroke is early (practically synchronous with R of Lead I) and carries the fiber far above the base line where it remains throughout the remainder of the QRS interval. These complexes resemble in general form the ventricular complexes of Lead I. In the last curve of the series (5), which was taken from that part of the pad which lay upon the left apex, the chief upstroke is late (0.053 second after R) and rises only a little way above the base line, so that the ventricular complex is of the opposite type. The fourth curve is of the transitional type; the chief upstroke occurs about 0.025 second after R.

The curves shown in Fig. 3, which were obtained from a second animal with left branch block, may be compared with those just described. The complexes obtained by leading directly from the right central region (Curve 603) and those obtained by semidirect leads from that part of the pad which lay upon the right ventricle (Curves 605-1-3) are very similar in form. The chief upstroke occurs at approximately the same time in both. The resemblance between the complexes obtained by leading directly from the left ventricle and those obtained from that part of the pad which lay upon it is less striking. The latter complexes are of the transitional type.

Comments.—The experiments described show without question that when bundle-branch block is present the chief upstroke of the ventricular complex in semidirect leads is early when the exploring electrode is placed close to the ventral surface of the contralateral ventricle and late when this electrode is placed close to the surface of the homolateral ventricle. In the former case the fiber usually remains above, in the latter case it usually remains below the base line throughout the greater

part of the QRS interval. During the period of ventricular excitation the mean potential of points near the ventral surface of the contralateral ventricle is usually negative, the mean potential of points near the surface of the homolateral ventricle is usually positive.

We have not attempted to free our experimental curves from effects produced by variations in the potential of the indifferent electrode. The sensitivity of the galvanometer was never increased beyond one-fourth the normal, and the amplitude of the chief deflections of the ventricular complex in semidirect leads of the type employed is so great, when measured in millivolts, in comparison with that of the chief ventricular deflections of standard leads that the subtraction from each ordinate of one-third the sum of the deflections inscribed in Leads II and III at the corresponding instant in the cardiac cycle could not materially alter their form or the time of their occurrence.

Significance of the Chief Ventricular Upstroke in Semidirect Leads.—

It is difficult to avoid the conclusion that the chief upstroke of the ventricular complex in semidirect leads of the kind under consideration corresponds to the intrinsic deflection of direct leads, and that its onset marks the excitation of that portion of the ventricular surface which lies nearest the exploring electrode. While this conclusion is in no way essential to the main thesis of the present article, which is concerned only with a comparison of results obtained by similar methods of leading in animals and in man, it is sufficiently important to merit a brief consideration of certain observations with which it does not seem to be in accord.

The experiments which Lewis and his collaborators^{3, 7} carried out to show that the intrinsic deflection of direct leads signals the arrival of the excitatory process beneath the exploring electrode suggest that no similar deflection can be expected to occur in leads in which this electrode is not in actual contact with the heart muscle. The intrinsic deflection was first identified in leads in which both electrodes were placed upon the auricular surface along a line radiating from the sinus node, the galvanometer connections being made in such a way that relative negativity of the proximal electrode (that nearest the node) produced an upward deflection. It was shown that when the electrodes were placed near the tip of the right auricular appendix the intrinsic deflection disappeared when the base of the appendix was crushed in such a way as to prevent the excitatory process from progressing beneath them; the first extrinsic deflection, on the other hand, remained. It was also shown that when the electrodes were moved along a line stretching from the sinus node up the superior or down the inferior vena cava the intrinsic deflection disappeared at the moment that the proximal electrode passed the border of the muscle which surrounds each of these vessels near its orifice.

With reference to the intrinsic deflection in direct leads from the ventricle, in which only one electrode (the exploring electrode) was placed upon the muscle, the other (the indifferent electrode) being in contact with the chest wall, it was shown that the time of this deflection, with reference to the deflections of Lead II, was not altered by moving the indifferent electrode. It was also demonstrated that the intrinsic deflection fell later and later as the exploring electrode was moved up the conus arteriosus, and that it disappeared when the muscle boundary at the junction of conus and pulmonary artery was crossed.

We have repeated these last experiments. In leads from the conus arteriosus the ventricular complex ordinarily begins with a small upward deflection followed by a sharp and deep dip. This dip is terminated by the onset of the intrinsic deflection which carries the string back to the base line or a little way beyond it. The intrinsic deflection is late. When the exploring electrode is moved across the muscle border on to the pulmonary artery, the form of the ventricular complex changes and the chief upstroke is early. This procedure is not equivalent to moving the exploring electrode away from the heart along a line normal to its surface, for it involves placing this electrode opposite an opening, the valve orifice, in the ventricular wall. We have pointed out elsewhere⁸ that the potential of any point in the body, in so far as it is influenced by the heart beat, is determined theoretically according to the following equation:

$$V = \Phi\Omega$$

where V is the potential of the point; Φ , a constant; and Ω , the solid angle subtended at this point by the surface which separates active from resting muscle. This angle is positive or negative according as the positive or the negative side (resting or active side) of the surface in question faces toward the apex of the cone which defines it. Throughout the greater part of the QRS interval a point on the pulmonary artery near the valve and one on the conus arteriosus must lie on opposite sides of this surface and must have potentials unlike in sign. The former facing toward the interior of the heart is on the negative side; it becomes negative early and remains so until the greater part of the ventricular muscle has passed into the active state. The latter remains negative only until the activation of the subendocardial muscle of the conus places it on the positive side of the active-resting surface.

Lewis and Rothschild⁸ mention that when the exploring electrode is introduced into the ventricular cavity an early reading (i.e., an early intrinsic deflection) is obtained even when the electrode is not in contact with the endocardial surface of the heart except through the blood. This observation, which we have also made, indicates that intrinsic or intrinsic-like deflections are, in the case of the ventricular muscle, by no means peculiar to direct leads.

In the case of the auricular muscle semidirect leads yield no sharp deflections. We have pointed out that when, starting with a direct lead, we move the exploring electrode away from the heart wall through a conducting medium, we tend to decrease the influence of the muscle units with which it was originally in contact and to increase relatively the influence of the muscle units that surround them. The effect must be somewhat, although not exactly, the same as that produced by increasing the size of the electrode. It is clear that the potential of the electrode at any instant must be determined by the mean potential of the area with which it is in contact. If the potential of some points of this area is changing in one direction and the potential of other points is changing in the opposite direction the potential of the exploring electrode may remain nearly stationary. In the case of the auricle, increasing the size of the exploring electrode causes a rapid degradation of the recorded curve with a disappearance of all sharp deflections, because such neighboring points as are arranged radially with reference to the sinus node pass through similar changes in potential, not simultaneously but in succession, displaying similar potentials when they bear a similar relation to the crest of the excitation wave. No similar effect occurs in the case of the ventricle. Here the excitatory process spreads outward through the ventricular wall and all points over relatively large areas pass through similar potential levels at the same time. At any instant the average potential over a small area and the average potential over a large area are therefore very nearly equal.

CLINICAL OBSERVATIONS

For precordial leads we employed small copper disks, about one inch in diameter, which were soldered to binding posts. The skin was cleaned with alcohol and with soap and water. The electrodes were smeared with a commercial preparation manufactured for use in diathermy treatments and were held in place with adhesive tape. Four or five electrodes were arranged diagonally across the precordium, the first being placed, as a rule, to the right of the sternum in the third or fourth intercostal space near the right border of cardiac dullness, and the last beyond the left border of dullness in the region of the apex beat. The indifferent electrode was placed on the left leg. The galvanometer was employed at approximately one-half the normal sensitivity and Lead I was recorded simultaneously with each precordial lead.

The exploring electrode was, of course, considerably further from the surface of the heart in these leads than in the semidirect leads employed in our animal experiments. In order not to increase the distance to an extent that would make comparison hazardous, we chose, in so far as possible, patients of slight build, avoiding the obese and the emphysematous. It should be noted that the left ventricle is much less favor-

ably situated for our purpose than the right. The surface which it presents anteriorly is small in extent and is covered by a relatively thick layer of tissue. Leads from the central precordium, which overlies the anterior surface of the right ventricle, are therefore of more value for comparison with the experimental leads than those from the region of the apex beat or beyond. It is naturally not possible to say precisely where the interventricular groove lies with reference to the landmarks of the anterior chest wall in any given case, since this must depend upon

Fig. 4.—Case 1. Leads I and II on the left; Leads I and III on the right. The electrocardiogram is of the normal type.

Fig. 5.—Case 1. A series of four precordial leads, each recorded simultaneously with Lead I. The introduction of one millivolt into the circuit produced a deflection of 7 mm. in semidirect Leads I and III, and of 8 mm. in semidirect Leads II and IV.

the position of the heart and the relative size of the two ventricles. By arranging a number of electrodes along a line approximately at right angles to this groove, this difficulty is to a large extent avoided. It is possible, however, that in some instances our line of electrodes was not extended sufficiently far to the left to obtain semidirect leads from the left ventricular surface.

CASE 1.—The patient was a boy, aged seventeen years, who gave a history of rheumatic fever and chorea. On examination there was questionable slight enlargement of the heart and a soft systolic murmur at the apex and at the base.

Fig. 6.—Case 2. Leads I and II are shown on the right, and Leads I and III on the left. Typical bundle-branch block of the common type with a QRS interval of 0.169 second.

Fig. 7.—Case 2. A series of five precordial leads, each recorded simultaneously with Lead I. In the semidirect leads one millivolt produced a deflection of 7 mm. in Lead I, 5 mm. in Lead II, 8.5 mm. in Lead III, 6 mm. in Lead IV, and 5 mm. in Lead V.

There was a third sound in early diastole at the apex. Slight rheumatic involvement of the mitral valve was suspected. The electrocardiogram was of the normal type (Fig. 4). Four precordial leads were taken: (1) from the right sternal edge at the fourth costal cartilage; (2) from the left sternal edge at the fourth costal cartilage; (3) from a point midway between (2) and (4); (4) from the fifth intercostal space just beyond the nipple line. The curves are shown in Fig. 5; in the first three the onset of the chief upstroke is relatively early (0.007 to 0.014 second after the onset of R in Lead I) and the preliminary downward movement of the fiber is of small amplitude. In the fourth curve the downward movement is large and the upstroke is later (0.032 second after R). These curves may be compared with those shown in the left-hand column of Fig. 2.

CASE 2.—The patient was a man, aged sixty-one years, with a history of long standing hypertension (systolic blood pressure—225 mm. Hg) and cardiac weakness with shortness of breath, engorgement of the liver, and edema. The heart was greatly enlarged; there were no valve lesions. The electrocardiogram showed typical bundle-branch block of the common type (Fig. 6) with a QRS interval of approximately 0.169 second. A series of five precordial leads was taken: (1) from the right sternal edge in the fourth intercostal space; (2) from the left sternal

TABLE I (CASE 2)

TIME	V _F	-V ₁ +V _F	-V ₁	-V ₅ +V _F	-V ₅	I	II	II (CAL)	III	α DE- GREES
0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.9	0.0	0.0	-
0.0062	1.0	-2.0	-3.0	0.0	-1.0	0.0	0.0	1.5	1.5	90
0.0124	3.1	-9.0	-12.1	0.0	-3.1	0.0	4.4	4.6	4.6	90
0.0186	5.6	-19.0	-24.6	10.0	4.4	1.5	10.2	9.2	7.7	81
0.0248	8.4	-10.0	-18.4	11.7	3.3	3.9	12.5	14.6	10.7	75
0.0310	3.3	12.0	8.7	-1.7	-5.0	6.9	8.1	8.4	1.5	39
0.0372	2.3	55.0	52.7	-17.0	-19.3	11.5	0.7	2.3	-9.2	-21
0.0434	-11.1	75.0	86.1	-51.5	-40.4	19.2	-7.3	-7.0	-26.2	-45
0.0496	-18.2	84.0	102.2	-86.6	-68.4	25.4	-14.7	-14.6	-40.0	-51
0.0558	-21.3	87.0	108.3	-115.0	-93.7	30.0	-16.2	-17.0	-47.0	-51
0.0620	-21.0	91.0	112.0	-137.0	-116.0	32.4	-13.9	-15.3	-47.7	-48
0.0682	-22.1	103.0	125.1	-153.0	-130.9	33.8	-14.7	-16.2	-50.0	-48
0.0744	-24.7	91.5	116.2	-176.0	-151.3	37.0	-17.6	-18.5	-55.5	-49
0.0806	-27.5	92.0	119.5	-195.0	-167.5	42.5	-21.3	-20.0	-62.5	-48
0.0868	-32.4	94.5	126.9	-198.0	-165.6	47.7	-22.8	-24.8	-72.5	-50
0.0940	-36.8	91.0	127.8	-202.0	-165.2	51.6	-29.4	-29.4	-81.0	-51
0.1002	-39.3	83.0	122.3	-218.0	-178.7	50.0	-30.2	-34.0	-84.0	-54
0.1064	-36.4	72.0	108.4	-198.0	-161.6	44.7	-28.6	-32.3	-77.0	-55
0.1126	-33.8	55.0	88.8	-183.0	-149.2	40.0	-26.5	-30.7	-70.7	-56
0.1188	-31.2	45.0	76.2	-170.0	-138.8	35.4	-24.3	-29.6	-64.0	-58
0.1250	-26.5	34.0	60.5	-137.0	-110.5	31.6	-22.0	-23.9	-55.5	-56
0.1312	-24.6	26.0	50.6	-113.0	-88.4	26.2	-20.6	-23.8	-50.0	-58
0.1374	-21.5	21.0	42.5	-85.0	-63.5	21.6	-18.4	-21.4	-43.0	-60
0.1436	-18.4	16.0	34.4	-63.2	-44.8	20.0	-15.4	-17.6	-37.6	-58
0.1498	-13.6	11.0	24.6	-48.2	-34.6	17.7	-12.5	-11.5	-29.2	-53
0.1560	-10.9	6.0	16.9	-25.0	-14.1	15.4	-10.3	-8.2	-24.6	-49
0.1620	-9.5	1.0	10.5	-6.7	-2.8	13.1	-7.3	-7.7	-20.8	-51
0.1682	-5.9	-4.0	1.9	16.7	22.6	8.5	-6.6	-4.6	-13.1	-50
0.1744	-1.7	-9.0	-7.3	40.0	41.7	2.3	-2.9	-1.5	-3.8	-53
0.1806	-0.2	-15.0	-14.8	43.0	43.2	-2.3	-0.7	-1.5	0.8	-170
0.1868	3.8	-18.0	-21.8	45.0	41.2	-5.4	0.0	3.1	8.5	129

The measurements are expressed in units of 0.02 millivolt. V_F is the potential of the left leg. -V₁+V_F is precordial Lead I as recorded. -V₁ is minus the potential of precordial point 1. -V₅+V_F is precordial Lead V as recorded. -V₅ is minus the potential of precordial point 5. II (cal) is Lead II calculated by the addition of Leads I and III.

edge in the fifth intercostal space; (3) from the sixth rib in the midclavicular line; (4) from the sixth intercostal space 2.5 cm. medial to the anterior axillary line, and (5) from the seventh rib in the anterior axillary line. These curves are shown in Fig. 7; in the first two the chief upstroke is early (about 0.007-0.008 second after the onset of R in Lead I) and the complexes resemble those of Lead I in form. In the third curve the main upstroke is deeply notched; the chief upward movement occurs about 0.053 second after R. In the last two curves the chief upstroke is late (0.072 to 0.089 second after R) and rises only a little way above the base line.

In order to show that potential variations of the indifferent electrode were not an important factor in determining the form of the ventricular complexes of these precordial leads we have computed the potential variations of the first and fifth points investigated. The numerical data are given in Table I. The original curves were enlarged about five diameters by optical projection, traced on coördinate paper, and measured. All measurements are expressed in units of 0.02 millivolt. We give the potential values corresponding to instants separated by equal time intervals. The table gives in order the potential of the left leg (V_F); the recorded and corrected potentials of Points 1 and 5; and the measurements of the ventricular complexes of the standard leads. In the case of Lead II we give both the measurements of the recorded curve and the values calculated by adding the deflections of Leads I and III. In the last column of the table the angle α which defines the position of the electrical axis is given. It will be noted that during the early part of the QRS interval there is a counter-clockwise rotation of the electrical axis of the type described by Lewis⁵ in cases of branch block of the common type. While the potential variations of the indifferent electrode are by no means without influence upon the form of the precordial curves, the elimination of this influence does not materially alter the general outline of the ventricular complex or the time of occurrence of the chief upstroke.

TABLE II

CASE 3						CASE 7	
TIME	V_F	$-V_3+V_F$	$-V_3$	$-V_4+V_F$	$-V_4$	TIME	V_F
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.008	0.6	-10.0	-10.6	-4.0	-4.6	0.0098	-0.6
0.016	4.0	-34.0	-38.0	-16.0	-20.0	0.0196	-0.6
0.024	4.6	-56.0	-60.6	-34.0	-38.6	0.0294	2.3
0.032	3.3	-70.0	-73.3	-50.0	-53.3	0.0392	16.0
0.040	-4.0	-84.0	-80.0	-66.0	-62.0	0.0490	54.0
0.048	-18.3	-94.0	-75.7	-80.0	-61.7	0.0588	78.0
0.056	-29.6	-76.0	-46.4	-82.0	-52.4	0.0686	85.0
0.064	-28.0	-10.0	18.0	-82.0	-54.0	0.0784	62.0
0.072	-29.0	16.0	45.0	-84.0	-55.0	0.0882	33.3
0.080	-34.0	40.0	74.0	-86.0	-52.0	0.0980	5.3
0.088	-41.3	30.0	71.3	-90.0	-48.7	0.1078	-5.0
0.096	-53.3	-26.0	27.3	-78.0	-24.7	0.1176	-15.0
0.104	-51.0	-40.0	11.0	-50.0	1.0	0.1274	-12.6
0.112	-39.0	-16.0	23.0	-26.0	13.0		
0.120	-29.6	0.0	29.6	0.0	29.6		
0.128	-9.0	2.0	11.0	10.0	19.0		
0.136	-0.6	4.0	4.6	16.0	16.6		
0.144	0.6	4.0	3.4	18.0	17.4		

All measurements are given in units of 0.02 millivolt.

V_F is the potential of the left leg.

$-V_3+V_F$ is the deflection in precordial Lead III as recorded; $-V_4+V_F$ is the deflection in precordial Lead V as recorded.

V_3 is the potential of precordial point 3; V_4 , the potential of precordial point 4.

CASE 3.—The subject was a woman, aged sixty-six years, who complained of palpitation, weakness, and dyspnea. Examination showed a large adenomatous goiter, and conspicuous enlargement of the heart. The blood pressure was moderately elevated (170/60); and there was considerable sclerosis of the peripheral arteries. A systolic and a diastolic murmur were heard in the aortic area and a systolic murmur and gallop rhythm at the apex. There were no signs of cardiac failure.

Fig. 8.—Case 3. Leads I and II on the left and Leads I and III on the right. Typical bundle-branch block of the common type. The QRS interval measures 0.134 second.

Fig. 9.—Case 3. A series of five precordial leads, each recorded simultaneously with Lead I. In the semidirect leads one millivolt produced a deflection of 5 mm. in Leads I, II, and IV, and of 4.5 mm. in Lead III.

The electrocardiogram showed typical branch block of the common type (Fig. 8) with a QRS interval of approximately 0.134 second. Four precordial leads were taken: (1) from the fourth intercostal space just to the right of the sternum; (2) from the fourth intercostal space just to the left of the sternum; (3) from the apex (fifth intercostal space, 11 cm. from the midline); (4) from the sixth intercostal space at the anterior axillary line (15 cm. from the midline). These curves are shown in Fig. 9. In the first two leads the chief ventricular upstroke is early (0.01 second after R); the third curve is of the transitional type with two up-

strokes; in the fourth curve the chief upstroke is very late (0.102 second after R) but not particularly sharp. In this case we have computed the potential variations of the third and fourth points investigated. The numerical data appear in Table II. While the recorded ventricular complexes are considerably altered by this cor-

Fig. 10.—Case 4. Leads I and II on the left and Leads I and III on the right. Bundle-branch block of the common type with a QRS interval of 0.146 second.

Fig. 11.—Case 4. A series of five precordial leads. In the semidirect leads one millivolt produced a deflection of 5.5 mm. in Lead I, 5 mm. in Leads II, III, IV, and V.

rection, their chief features remain. It is obvious that similar correction could not significantly change the form of the complexes of the first two leads.

CASE 4.—The subject was a man, aged sixty-seven years, with general arteriosclerosis. The heart was definitely enlarged; and there was a harsh systolic murmur both at the apex and at the base. The blood pressure was moderately raised

(150/80). There was evidence of mild cardiac weakness. The electrocardiogram showed typical branch block of the common type (Fig. 10) with a QRS interval of 0.146 second. Five precordial leads were taken: (1) from the fifth costal cartilage at the right sternal margin; (2) from the fifth costal cartilage at the left sternal margin; (3) from the fifth intercostal space 4 or 5 cm. from the left sternal margin; (4) from the apex (fifth intercostal space 2 cm. inside the anterior axillary line); (5) from the sixth intercostal space in the anterior axillary line. These curves are shown in Fig. 11; the chief upstroke is obviously early in the first two

Fig. 12.—Case 5. Leads I and II above, and Leads I and III below. Auricular fibrillation is present. The first complex of each lead is of the normal type. The last two complexes are characteristic of branch block of the rare type. The QRS interval of the narrower complexes measures 0.099 second; that of the broader complexes, 0.135 second.

leads. In the remaining leads the curves are of small amplitude and show no sharp deflections; nevertheless, the principal upstroke is later.

CASE 5.—The patient was a boy, aged seventeen years, with typical mitral stenosis and auricular fibrillation. He gave a clear history of rheumatic fever. In the electrocardiogram two types of ventricular complexes occurred; during periods when the heart rate was slow the ventricular complexes were of the type suggesting slight right ventricular preponderance (QRS interval, 0.099 second); whenever the heart rate quickened there was a sudden transition to broad (QRS interval, 0.135 second) diphasic complexes of the type seen in the rare form of branch block

Fig. 13.—Case 5. A series of five precordial leads. The sensitivity of the galvanometer was approximately one-half normal for the first four semidirect leads and one-third normal for the fifth.

(Fig. 12). Five precordial leads were taken: (1) from the fourth intercostal space just to the right of the right border of cardiac dullness (5 cm. to the right of the right sternal margin); (2) from a point just to the left of the middle of the sternum at the level of the fifth costal cartilage; (3) from the fifth intercostal space just to the right of the left nipple line; (4) from the point of maximum pulsation; (5) from the seventh intercostal space in the anterior axillary line and just beyond the maximum impulse. These curves are shown in Fig. 13. In the first lead, which was taken over the right auricle, the auricular oscillations are very prominent. In the second and third leads the chief upstroke is relatively early when the ventricular complexes are of the normal type, and relatively late when they are of the abnormal type. In the last two leads the chief upstroke occurs at about the same time when the ventricular complexes are of the narrow type as when they are of the broad type; it is rather late in both cases. It should be noted that all of the complexes

TABLE III (CASE 5)

TIME	V_F	$-V_5+V_F$	$-V_5$	V_F	$-V_5+V_F$	$-V_5$
	ABNORMAL COMPLEXES	ABNORMAL COMPLEXES	ABNORMAL COMPLEXES	NORMAL COMPLEXES	NORMAL COMPLEXES	NORMAL COMPLEXES
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.009	-3.0	6.0	9.0	0.3	3.0	2.7
0.018	-2.0	7.5	9.5	-0.3	12.0	12.3
0.027	0.0	-6.0	-6.0	-3.0	3.0	6.0
0.036	4.3	-36.0	-40.3	-1.3	-9.0	-7.7
0.045	11.3	-57.0	-68.3	4.0	-27.0	-31.0
0.054	41.3	-96.0	-137.3	15.3	-42.0	-57.3
0.063	25.6	-66.0	-91.6	30.6	-63.0	-93.6
0.072	17.6	54.0	36.4	64.6	-51.0	-115.6
0.081	11.3	60.0	48.7	51.6	45.0	-6.6
0.090	15.3	60.0	44.7	18.6	0.0	-18.6
0.099	17.0	57.0	40.0	2.6	0.0	-2.6
0.108	14.0	39.0	25.0	-0.6	0.0	0.6
0.117	5.6	15.0	9.4	-2.0	0.0	2.0
0.126	1.5	0.0	-1.5			
0.135	-1.0	-6.0	-5.0			
0.144	-2.3	-9.0	-6.7			
0.153	-3.3	-9.0	-5.7			

All measurements are given in units of 0.02 millivolt. V_F is the potential of the left leg. $-V_5+V_F$ is the deflection in precordial Lead V as recorded. V_5 is the potential of precordial point 5.

of the last precordial lead are of the same form up to the point where the chief upstroke occurs.

We have computed the potential variations of the point from which the last lead was taken. The numerical data are given in Table III. Although correction alters the form of the recorded ventricular complexes of this lead, it does not materially alter the amplitude or time of the chief upstroke.

CASE 6.—The subject was a man, aged sixty-two years, with hypertension (184/120), general arteriosclerosis, enlargement of the heart, and myocardial weakness. No valve lesions were present. The electrocardiogram showed bundle-branch block of the rare type with a QRS interval of 0.14 second. Five precordial leads were taken: (1) from the fifth costal cartilage at the right sternal edge; (2) from the fifth costal cartilage at the left sternal edge; (3) from the fifth intercostal space midway between the left sternal edge and the left midclavicular line; (4) from the fifth intercostal space 3 cm. medial to the anterior axillary line; (5) from the fifth intercostal space at the anterior axillary line. These curves are shown in Fig. 15.

In the first two leads the chief upstroke is late (0.097 second after the onset of R). In the third lead the ventricular complex is of small amplitude. In the last two leads the chief upstroke comes at the time that the peak of R is written and about 0.03 second earlier than the chief upstroke of the first two leads.

CASE 7.—The subject was a woman, aged thirty-two years, with mitral stenosis, who gave a history of rheumatic fever. There were no signs of cardiac failure; the heart was moderately enlarged. The electrocardiogram showed diphasic ventricular

Fig. 14.—Case 6. Leads I and II on the left; Leads I and III on the right. Bundle branch block of the rare type with a QRS interval of 0.14 second.

Fig. 15.—Case 6. A series of five precordial leads, each recorded simultaneously with Lead I. In the semidirect leads one millivolt produced a deflection of 6 to 6.5 mm.

complexes with a QRS interval of 0.105 second. The complexes were not conspicuously notched, but were otherwise strongly suggestive of bundle-branch block of the rare type. Four precordial leads were taken: (1) from the third intercostal space near the right border of the sternum; (2) from the third intercostal space near the left border of the sternum; (3) from the fourth intercostal space 8.5 cm.

Fig. 16.—Case 7. Leads I and II on the left; Leads I and III on the right. Bundle-branch block of the rare type with a QRS interval of 0.105.

Fig. 17.—A series of four precordial leads each recorded simultaneously with Lead I. In the semidirect leads one millivolt produced a deflection of 5 mm. in Lead I, 9 mm. in Leads II and III. In the case of IV the standardization was not recorded on the film.

to the left of the midline; (4) from the sixth intercostal space near the anterior axillary line. These curves are shown in Fig. 17. In the first two leads, the chief ventricular upstroke is late. The ventricular complex of the third lead is of the transitional type with two principal upstrokes. In the last lead the chief upstroke is relatively early. We have computed the potential variations of the indifferent electrode (Table III); they are too small to alter materially the form of the ventricular complexes or the time or amplitude of the chief upstroke.

Discussion.—In all of the cases of bundle-branch block studied the first leads of the series taken, those from the right and central portions

of the precordium, have yielded ventricular complexes similar to those obtained in the cases described; the chief upstroke of these leads has always been early in the common type of branch block and late in the rare type. These complexes have always resembled those of Lead I in general outline. It should be noted that in so far as the potential variations of the indifferent electrode are effective, they tend to produce a ventricular complex of the opposite type.

The form of the complexes obtained by leading from points further to the left has, on the other hand, varied considerably. In branch block of the common type these complexes were sometimes of small amplitude, and showed no sharp deflections. Sometimes there was no deflection which could be regarded as a principal upstroke; when such a deflection could be recognized, it always occurred later than the chief upstroke of the earlier leads of the series, but it often rose so slowly as to make the evaluation of its significance difficult or impossible. It may have been in these cases that the exploring electrode was too far from the surface of the heart for our purpose, or that the investigation was not carried far enough to the left to enter the left ventricular field proper.

The three cases of bundle-branch block of the rare type which we have discussed are the only ones that we have had the opportunity of studying. It will be noted that although the chief upstrokes of the precordial leads taken from the left side of the precordium in this type of branch block are early in comparison with the chief upstrokes of leads from the right side of the precordium in the same subject, they are relatively late when compared with the earliest chief upstrokes obtained in branch block of the common type. This observation is consistent with the fact that the chief upstrokes obtained from the left side of the precordium are later than those obtained from the right side in cases in which the ventricular complex of the electrocardiogram is of the normal type. In most cases of bundle-branch block the heart is greatly hypertrophied. It cannot be assumed that the hypertrophy and the myocardial changes present are confined to the muscle of the homolateral ventricle. It is not surprising therefore that the earliest chief upstrokes obtained in cases of branch block are sometimes later than the chief upstrokes obtained by leading from the same part of the precordium in normal subjects.

When the complexes yielded by serial precordial leads in clinical bundle-branch block are compared with those obtained by serial semi-direct leads in experimental canine branch block, it is clear that the common type of clinical branch block must be left branch block, not right, and that the rare type of clinical branch block must be right, not left. This conclusion is in harmony with the form of the complexes obtained by Barker, Macleod, and Alexander⁹ by electric stimulation of the exposed human heart.

It is hoped that serial precordial leads may aid in the solution of other problems, such as the location of the conduction defect in various types of intraventricular block, the order of ventricular excitation in ventricular hypertrophy, and certain problems connected with the T-deflection, particularly those which relate to the location of the infarcted area in coronary thrombosis. We do not wish, however, to give the impression that the curves obtained by this method of leading are always easy to interpret. We have found, for instance, that ventricular extrasystoles of the type in which the most prominent deflection of the ventricular complex is downward in Lead I and upward in Lead III do not always yield, as might be expected, results similar to those obtained in the rare type of branch block. Except for bundle-branch block, however, too few cases of any one type have been examined to permit any definite conclusions to be drawn at this time.

SUMMARY

Leads in which one electrode (the exploring electrode) is placed close to the heart and the other (the indifferent electrode) at a distance from it are semidirect leads. In experiments on dogs serial semidirect leads were taken from the surface of a pad of gauze soaked in warm normal salt solution and laid upon the exposed heart. The galvanometer connections were made in such a way that relative negativity of the exploring electrode yielded an upward deflection in the completed curve.

In animals in which bundle-branch block had been produced, the chief upstroke of the ventricular complex occurred early in those semidirect leads in which the exploring electrode was close to the surface of the contralateral, and late in those leads in which this electrode was close to the surface of the homolateral ventricle. In the former case the mean potential of the exploring electrode during the QRS interval was usually negative; in the latter case, usually positive.

In precordial leads the exploring electrode is placed on the precordium and the indifferent electrode on the left leg.

Serial precordial leads in cases of clinical bundle-branch block of the common type yield results similar to those obtained by semidirect leads in experimental left branch block. In the rare type of bundle-branch block they yield results similar to those obtained in experimental right branch block.

The common type of bundle-branch block is left branch block; the rare type, right branch block.

The chief ventricular upstroke of semidirect leads, in which the exploring electrode is placed close to the ventricular surface, corresponds to the intrinsic deflection of direct leads from the ventricles in which a single contact is placed upon the muscle.

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