Studies on the Mechanism of Ventricular Activity

IV. Ventricular Excitation in Segmental and Diffuse Types of Experimental Bundle-Branch Block

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Controlled studies of ventricular excitation were performed in dogs exhibiting various degrees of right and left bundle-branch block. Increases in the intraventricular conduction time during complete bundle-branch block are attributed to free wall as well as septal factors. Incomplete bundle-branch block may be either segmental or diffuse. In the segmental type, delayed excitation is present in only a portion of the involved ventricle. In the diffuse type, delayed excitation of the entire homolateral ventricle occurs, but some portions of the ventricle tend to be delayed to a greater extent than others. Certain segments of the ventricular myocardium appear to be supplied by fixed portions of the conducting system, without cross connections operating physiologically. The clinical implications of these observations are briefly discussed.

In an earlier study of ventricular asynchrony during bundle-branch block, we were impressed by the variation in the "completeness" of the block obtained when an incision was made across the pathway of either bundle-branch. While most phases of complete bundle-branch block have been extensively studied experimentally, comparable investigations of incomplete block have been relatively few. The present investigation was undertaken because we felt that information concerning the changes in ventricular excitation taking place with various degrees of bundle-branch block would contribute toward the understanding of some of the confusing and complex block patterns encountered in clinical electrocardiograms.

Phases of incomplete bundle-branch block investigated experimentally may be summarized as follows: Rothberger and Winterberg cut subdivisions of the bundle-branches and demonstrated little change in limb leads. Wilson and Herrmann and Stenstrom were concerned primarily with the limb leads and demonstration of their derivation from the dextro- and levocardiograms. Sodi-Pallares and his associates noted relationships between various degrees of block and the configuration of the complex recorded from the ventricular cavities and epicardium. References to comprehensive studies of ventricular excitation during incomplete bundle-branch block were not encountered in the literature.

METHODS

Electrocardiographic studies were performed in 20 dogs before and after bundle-branch block was effected. Operative procedures were identical to those described in a previous report. Warm saline solution was frequently applied to prevent drying and cooling of the heart. All direct ventricular leads were taken with small, cotton-tipped, silver-silver chloride electrodes. Immediately after the pericardium was opened, a reference recording electrode was sewn gently to the epicardium of the ventricle contralateral to the side on which bundle-branch block was to be produced. This lead was used as the timing reference in preference to the customarily used lead 2, since the latter undergoes considerable change after the production of bundle-branch block. With a small, cotton-tipped applicator, moistened with a 5 per cent solution of Janus green B in normal saline, 15 to 20 small dots were placed on the ventral and dorsal surfaces of the epicardium of both ventricles. This procedure caused
no electrocardiographic changes and permitted identification of areas throughout the experiment and at autopsy. Unipolar ventricular leads were then taken from each of these labeled areas of the epicardium and recorded simultaneously with the tracing from the reference electrode attached to the epicardium of the unblocked ventricle. Thus, by measurement of the time interval between the intrinsic deflection in the exploring lead and the reference lead, the relative order and time of excitation could be determined for all areas of the ventricles.

These leads, in addition to standard limb leads, were recorded before and after bundle-branch block was effected. In most experiments ventricular cavity leads were also obtained. The cavity electrode consisted of chlorided silver wire sheathed in a plastic catheter with perforations at the tip. It was inserted into the ventricular cavity through an auricular purse-string suture.

We used the onset of the intrinsic deflection for measurement, although evidence has been presented which suggests that actual excitation may coincide with a lower point on the downstroke of the intrinsic deflection. The time relationship of the various ventricular areas to the reference electrode having been established, measurements were corrected so that the earliest area had a time value of zero. This same correction factor was retained after the production of bundle-branch block to facilitate comparison of the pre- and postblock time measurements. This latter procedure seemed permissible since no significant differences in time relationship were noted on the normal ventricle.

All ventricular leads were recorded on a Brush, dual-channel, magnetic oscillograph, running at a paper speed of 125 mm. per second (five times normal speed) and driven through an impedance matching network by Sanborn electrocardiograph preamplifiers and amplifiers. Sensitivity was adjusted so that a 20 mv. standard produced a deflection of 15 mm. With the equipment and the leading techniques described, a relatively high degree of accuracy of time measurements is possible. This was confirmed in subsequent studies of normal ventricles and ventricles with bundle-branch block during which comparisons were made between the Brush recording system and a DuMont cathode-ray oscillograph (model 322A) with a frequency response of 30,000 cycles per second. Despite the great difference in frequency response, time measurements derived from tracings recorded on these two machines were essentially similar.

Records obtained on repeated exploration of the dotted areas usually gave identical time values for specific dots when measured to the nearest 0.001 second. Infrequently, slight errors were encountered owing to minor differences in electrode placement; therefore, in the interpretation of postblock data, time changes of less than 0.004 second have been regarded as probably unreliable.

Recording of limb leads was carried out on the Sanborn Polyviso electrocardiograph. Normal sensitivity and a paper speed of 50 mm. per second (two times normal) were employed.

Ventricular Excitation during Complete Bundle-Branch Block

Figure 1 shows the results of a representative experiment in which complete right bundle-branch block was produced. It can be seen that under control conditions (inner ring of complexes) the wave form in tracings from the
The region of the pulmonary conus is excited 0.024 second later than the earliest area, which has been assigned a time value of 0.000 second. On the left ventricle, complexes exhibit various proportions of R and S and excitation of the latest area occurs 0.024 second after the earliest surface area on the heart. It should be noted that, in this and subsequent illustrations, some of the points shown at the margins of the heart actually lie on its dorsal surface. All diagrams are therefore intended to represent somewhat flattened and expanded views of the heart.

Control limb and cavity leads from this animal showed that the QRS interval measured 0.04 second. The right cavity complex was of the rS type, while that from the left was of the QS type.

After right bundle-branch block is produced (fig. 1, outer ring), right ventricular leads exhibit deflections of the R type, with variable slurring and notching of the upstrokes. Accompanying these changes is an over-all delay in the onset of right ventricular excitation as well as an alteration of the order in which various areas are excited. The delay in the onset of the earliest right ventricular surface excitation in this instance is 0.044 second. In other experiments minimum delays ranging from 0.032 to 0.048 second were observed with right bundle-branch block. In this experiment, also, the time interval between the earliest and latest points excited is 0.024 second in the control and 0.036 second after block, an increase of 0.012 second. This increase ranged from 0.010 to 0.020 second in other animals.

Tracings recorded from the left ventricle show a decrease in the amplitude of the R component, with a disproportional increase in the S component. The QRS complexes are increased in width by the abnormal S wave, but, unlike tracings from the right ventricle, there is no delay or change in the order of surface excitation.

Standard limb leads showed widening and axis shifts characteristic of complete right bundle-branch block. The right ventricular cavity lead exhibited a broad, notched R wave of low amplitude. The initial upstroke and notching in leads from the surface were synchronous with the upstroke and apex of the cavity deflection, as has been noted by others. The left ventricular cavity complex remained a QS but became broader and deeper.

Figure 2 shows the results from a representative experiment in which complete left bundle-branch block was produced. The changes that take place with the production of left bundle-branch block are similar to those already described for right bundle-branch block. Comparison of the outer ring of complexes and time values with the controls in the inner ring demonstrates an over-all delay in left ventricular excitation. In addition, the relative order of surface excitation is altered. The two earliest points are delayed by 0.026 and 0.028 second, respectively, after block. In other animals exhibiting left bundle-branch block, the delay at the earliest point ranged from 0.028 to 0.040 second. It is of interest that the time interval between the earliest and the latest areas excited is 0.014 second in the control.
Fig. 3. Incomplete right bundle-branch block of the segmental type, followed by complete right bundle-branch block. Controls are in the inner ring. Complexes obtained during segmental block occupy the middle ring, while those obtained during complete bundle-branch block occupy the outer ring. Accompanying limb and cavity leads are shown in figure 4.

and 0.048 second after block, an increase of 0.034 second. Similar increases, ranging from 0.012 to 0.034 second, were observed in other animals exhibiting left bundle-branch block.

Accompanying these changed time relationships on the left ventricle is an alteration of wave form characterized by an increased amplitude and width of the R wave and by the appearance of variable notching of the upstroke. Leads from the right ventricle show no change in timing, but undergo changes in wave form characterized by widening and an increase in the depth of previously existing S waves and by the appearance of S waves in areas not formerly possessing them.
Standard limb leads and a left ventricular lead before and after left bundle-branch block showed that the left ventricular cavity complex changed from a QS to an R type deflection of low amplitude which resembles that recorded from the right cavity during right bundle-branch block.

**Ventricular Excitation during Incomplete Bundle-Branch Block**

In this series the usual technic of producing this disorder, by means of an incision perpendicular to the base-to-apex axis of the septum, occasionally produced either minor changes in the standard electrocardiogram or moderate changes commonly regarded as indicating incomplete bundle-branch block. In other animals, an attempt was made to produce incomplete bundle lesions by septal incisions parallel to the base-to-apex axis of the septum. Studies of ventricular excitation in these animals revealed two general types of incomplete bundle-branch block, herein referred to as segmental and diffuse. We noted that segmental blocks occurred chiefly with the longitudinal type of septal incision, diffuse blocks with more or less superficial, transverse septal incisions which failed to produce complete bundle-branch block. Transient forms of block were excluded by careful checks of the limb lead electrocardiogram before and after each exploration.

In the segmental type, the septal incision resulted in delayed excitation of only a segment of the homolateral ventricle, without influence on the excitation time of the remaining areas. Changes in the QRS complex in limb leads consisted largely of minimal widening and a slight shift in the electrical axis. Parallel observations were made in both right and left bundle lesions. Figure 3 shows the results of a typical segmental type of incomplete right bundle-branch block. The innermost ring of complexes represents the control tracings, the middle ring those obtained after production of incomplete block, and the outermost ring those obtained after production of complete block. In the middle ring, complexes from the delayed areas are edged in black. Delayed excitation is evident only in apical and more dorsal segments of the right ventricle. Some alteration in wave form is evident in most areas, with a trend toward an increase in the R/S ratio or disappearance of the S wave in blocked segments and decrease in the R/S ratio in normal areas. Minimal widening of the complex is evident in most areas.

Limb leads (fig. 4) show some change in configuration with minimal widening of the QRS detectable in lead 2 and possibly in lead 1. The tiny R wave is absent in the right cavity lead after segmental block, and the left cavity QS is of increased amplitude. After complete right bundle-branch block (fig. 3), a low, broad R followed by a tiny S is recorded from the right and a QS of increased amplitude is recorded from the left cavity. Limb leads are recorded at 50 mm.

**Fig. 4.** After the segmental type of incomplete right bundle-branch block (fig. 3) slight axis shift is evident in limb leads with slight widening of the QRS detectable in lead 2 and possibly in lead 1. Limb leads in the third column show changes characteristic of complete right bundle-branch block. The tiny R wave is absent in the right cavity lead after segmental block, and the left cavity QS is of increased amplitude. After complete right bundle-branch block (fig. 3), a low, broad R followed by a tiny S is recorded from the right and a QS of increased amplitude is recorded from the left cavity. Limb leads are recorded at 50 mm.
Fig. 5. Progressive degrees of left bundle-branch block in the same heart. Records from the right ventricle are shown in A; those from the left are shown in B. Controls are in the innermost ring. Deflections obtained during segmental block are in the second ring, and those during diffuse block are in the third ring. The outermost ring shows deflections during complete left bundle-branch block.

noted that all the areas involved by the segmental block undergo an additional delay after complete bundle-branch block except one area near the right apex. This point is now the earliest point on the right ventricle. Limb leads (Fig. 4) are characteristic of complete right bundle-branch block, and the right cavity lead exhibits a peculiar Rs deflection of low amplitude. The QS complex of the left cavity is of increased amplitude and occurs considerably in advance of the major deflection in the simultaneously recorded right cavity lead.

In the diffuse type of incomplete bundle-branch block, excitation of all areas of the homolateral ventricle was somewhat delayed, but the delay was not uniform. This was accompanied by moderate widening and axis shift of the QRS complexes in limb leads. In these instances, additional incision of the septum produced an increased delay in most areas and changes in the limb leads characteristic of complete bundle-branch block. Similar results were obtained with both right and left bundle lesions.
CONTROL . SEGMENTAL . DIFFUSE . COMPLETE

LEAD I
RIGHT CAVITY
LEFT CAVITY

FIG. 6. Limb and cavity leads recorded during the progressive degrees of left bundle-branch block illustrated in figure 5. During incomplete left bundle-branch block of the segmental type, limb lead complexes exhibit minor changes in configuration but no widening. With diffuse, incomplete left bundle-branch block, the limb leads exhibit more marked changes with moderate widening of the QRS. Limb leads recorded during complete left bundle-branch block are typical. The right cavity deflection during diffuse block remains an rS but exhibits moderate widening. The accompanying left cavity complex consists of only a low positive deflection. After complete left bundle-branch block, the small R is absent in the right cavity deflection and the left cavity exhibits a positive deflection of slightly increased amplitude. Limb leads are recorded at 50 mm.

Figure 5 illustrates an instance in which we were fortunate enough to obtain, in sequence, segmental and diffuse types of incomplete left bundle-branch block, and complete block in the same animal. Control tracings occupy the innermost ring. Segmental block is represented by the second ring of complexes and diffuse block by the third ring. The complexes in the outermost ring were obtained after complete left bundle-branch block. In this animal the segmental block involved the major portion of the left ventricle (second ring complexes from delayed segments are edged with black). The S component is decreased or absent in these areas. Limb leads (fig. 6) show minor changes in configuration but no perceptible widening.

After production of the diffuse type of incomplete block, excitation of the entire left ventricle is delayed (third ring of complexes, fig. 5B). Limb leads (fig. 6) exhibit moderate widening and altered configurations. Contrary to what might be expected, an rS is still recorded from the right cavity. The left cavity complex has changed from a QS to an R wave of very low amplitude.

With complete left bundle block (outer ring of complexes, fig. 5A and B) an additional delay in excitation is produced in most areas on the left; the several points excepted lie near the base of the left ventricle. Apparently the earlier incomplete bundle lesion produced the maximum delay possible in these areas. Limb leads (fig. 6) show changes characteristic of complete left bundle-branch block. The small R wave having disappeared, the right cavity lead now exhibits a QS, and the left cavity registers an R wave of increased amplitude.

DISCUSSION

It has been commonly supposed that in bundle-branch block, the excitatory process, after slow septal transmission from the unblocked side, spreads over the blocked side in a relatively normal fashion via the Purkinje system. The possibility has also been suggested that, after slow septal transmission, the excitatory process may spread slowly throughout the ventricle with bundle-branch block by way of muscular pathways. In the experiments reported here, the onset of surface excitation (earliest point) on a ventricle with complete bundle-branch block was delayed by 0.026 to 0.042 second, with no significant difference between right and left. Since transmural conduction time is largely excluded in calculation of the delay in surface excitation, it is generally believed that this delay occurs proximal to the free wall as the result of a septal conduction defect. Direct studies of the septum during complete bundle-branch block have revealed that delayed excitation does not occur in all areas of the homolateral septal surface. Since the excitation times of some areas remain unchanged, it may be erroneous to assume that slow transmission of excitation across the septum is responsible for the delays encountered in leads from the ventricular surface. It has been proposed that the principal conduction defect

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in bundle-branch block occurs on the homolateral side of the septum and that it is limited to a narrow band marking the junction between right and left ventricular components of the septum.\textsuperscript{11}

In our studies, after complete right or left bundle-branch block was produced, the time interval separating the earliest and the latest points on the homolateral ventricle was increased by 0.010 to 0.028 second over the control. It would appear, therefore, that with complete bundle-branch block, not only is there a delay in the onset of activation of the blocked ventricle, but also the spread of activation, once begun, occupies a greater time interval. Thus, free wall as well as septal factors contribute to the production of the increased intraventricular conduction time that accompanies complete bundle-branch block.

In view of the complex mode of ventricular excitation, measurement of the time interval separating the earliest and latest points of excitation on either ventricle is recognized to be of little value for estimation of rates of conduction. However, in support of earlier beliefs, it may be noted that the length of this interval, which in the homolateral ventricle averages 0.040 second after bundle-branch block, seems to preclude the possibility of conduction by way of muscular pathways. On the basis of 300 to 500 mm per second, which is usually accepted as the maximum rate for myogenic ventricular conduction, excitation would have progressed only 20 mm or less in 0.040 second. Thus the altered interelectrode time relationships observed in surface leads are more in keeping with those expected to result from conduction over lengthened (less direct) Purkinje pathways. Although the measured time values do not eliminate the possibility of some more superficial type of rapid, parallel-fiber conduction,\textsuperscript{12} evidence has been obtained that excitation of the homolateral free ventricular wall during bundle branch block is accomplished by a spread from endocardium to epicardium as occurs in the normal ventricle.\textsuperscript{14}

It has not been fully appreciated that the mechanisms in incomplete bundle-branch block may be variable and complex. The present studies call attention to the existence of two distinct types of incomplete block. In the first, or segmental, type, ventricular excitation may be delayed only in certain specific areas of the homolateral ventricle. Although it may be altered, it is probable—particularly since the areas involved by the segmental block usually undergo additional delay with the production of complete bundle-branch block—that transseptal conduction is not implicated in the resulting defect. It seems more likely that the delay results from passage of the excitation process over a longer (less direct) pathway within the homolateral ventricle.

As shown earlier (figs. 4 and 6), relatively little change in limb leads accompanies the segmental type of incomplete block. However, greater changes are possible and, in fact, were observed in one of the animals studied. The more marked changes in timing and wave form are usually limited to a relatively small portion of one ventricle. Similar findings in the clinical electrocardiogram have been recognized and classified in the category of "focal intraventricular blocks."\textsuperscript{16}-\textsuperscript{17} Although there is some inclination to regard these as peripheral blocks, it seems likely that many may represent varieties of segmental bundle-branch block.

The diffuse type of incomplete bundle-branch block, which is characterized by delayed excitation over the entire homolateral ventricle, is accompanied by variable QRS widening and axis shift in limb leads. Although it has been commonly supposed that the homolateral ventricle undergoes a uniform delay in excitation during incomplete bundle-branch block,\textsuperscript{17} the mechanism appears to be somewhat more complex. Our investigations indicate that the delays in excitation are not uniform and that they often tend to be minimal in some areas and maximal in others. That these delayed areas may have a more or less segmental distribution is supported by observations that the production of complete block may fail to produce an additional delay in some of the latest areas while increasing the delay in others. It would appear, therefore, that all degrees of block and an almost endless number of ventricular excitation patterns are possible, depending on which of the bundle-branch com-
ponents or subdivisions are involved and the extent to which conduction within each pathway is impeded.

Clinical recognition of incomplete bundle-branch block and its complex mechanisms is limited to some extent by the fact that chest leads are at best only semidirect. In addition, the most marked delays and wave form changes may be localized to a relatively small area of one ventricle. Therefore, depending on the orientation and extent of this area, greater or lesser effects may be apparent in standard limb and chest leads. This view is supported to some extent by other experimental observations and by extensive clinical studies of incomplete right bundle-branch block by Barker and Valencia. 18

SUMMARY AND CONCLUSIONS
The pattern of ventricular excitation before and after bundle-branch block was studied in 20 dogs by means of multiple unipolar direct leads recorded at rapid electrocardiographic paper speeds and timed against a fixed ventricular reference electrode.

In complete bundle-branch block the onset of ventricular excitation on the side of the lesion was found to be delayed by 0.026 to 0.042 second. This delay is considered to be primarily septal in origin, although its nature remains obscure. In addition, the time interval between the earliest and the latest points of excitation on the blocked ventricle was increased by 0.012 to 0.028 second over the control. It is suggested that the free wall as well as the septum contribute to the total defect that occurs with complete bundle-branch block.

Two types of incomplete bundle-branch block are reported. In the segmental type, produced by damage to subdivisions of either bundle branch, delayed excitation was found in only a portion of the homolateral ventricle, while excitation in remaining areas showed no change from the control measurements. This was accompanied by relatively slight alteration of limb lead electrocardiograms.

In the diffuse type, produced by greater or lesser damage of all the components of either main bundle branch, various degrees of delayed excitation were demonstrable in all areas of the homolateral ventricle. This type was accompanied by moderate changes in the limb lead complexes.

In both types of incomplete block, it was possible to produce changes in ventricular and limb leads considered characteristic of complete bundle-branch block by making a septal incision calculated to transect the main bundle branch.

The findings suggest that certain segments of the ventricular myocardium are supplied by fixed portions of the conducting system, without cross connections operating physiologically.

The clinical implication of these studies is considered briefly.

REFERENCES


Studies on the Mechanism of Ventricular Activity: IV. Ventricular Excitation in Segmental and Diffuse Types of Experimental Bundle-Branch Block
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