Further Electrocardiographic Observations on Direct Epicardial Potentials in Congenital Heart Lesions

Differential Features of Right Ventricular Preponderance and Right Bundle-Branch Block

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Electrocardiographic potentials previously obtained on 15 patients with anatomic right ventricular hypertrophy, viz., tetralogy of Fallot and isolated valvular pulmonic stenosis, revealed a distinct rR' QRS complex to arise from the high medial outflow tract of the hypertrophied right ventricular outflow tract. ²

In an effort to further define the morphologic characteristics of the rR' complex identified with right ventricular hypertrophy, electrocardiographically referred to as right ventricular preponderance and in particular, to differentiate it from the rR' or rsR' complex of incomplete or complete right bundle-branch-block patterns, epicardial potentials have been obtained on a wide variety of congenital heart lesions. Atrial septal defects specifically offered the opportunity to describe the characteristic epicardial potentials of the incomplete right bundle-branch block.

Correlation of the direct epicardial potentials with the clinical unipolar electrocardiogram and the calculated hemodynamic data obtained at the time of cardiac catheterization was also made in an effort to establish the differential electrocardiographic features of right ventricular preponderance and right bundle-branch block.

Materials and Methods

An 8-mm. zinc alloy electrode connected to the V lead of the unipolar electrocardiogram was applied at predetermined sites over the right and left ventricular surfaces at time of corrective open-heart surgery. Epicardial positions 1, 2, and 3 ringed the high medial outflow tract of the right ventricle (crista supraventricularis)—positions 4 and 5 were recorded over the free wall (trabecular surface) and apex of the right ventricle respectively, and positions 6 and 7 were taken over the anterior and lateral aspects of the free wall of the left ventricle respectively. (See Figure 1 for diagrammatic sketch of epicardial sites. ²) Utilization of the bilateral anterior sternal splitting thoracotomy surgical approach allowed excellent exposure of both ventricular surfaces, particularly the high outflow tract of the right ventricle.

All epicardial potentials were recorded on a Sanborn Twin-Beam at paper speeds of 25- and 50-mm. per second. The calculated hemodynamic data were collected from the Cardiovascular Laboratory, University Hospitals.

A total of 130 patients was studied, with 124 instances of congenital heart disease. Included in these data are six patients without cardiac disability, who came to open thoracotomy for surgical excision of a pulmonary lesion. This latter group composes the "normals."

Measurement of the various activation times to the nearest 0.005 second was made on all epicardial potentials obtained over the high medial outflow tract of the right ventricle. Three specific measurements were recorded, as depicted on figure 1: (1) the septal r wave, as measured from the preceding isoelectric line, point A, to the peak of the r wave, (2) the onset of depolarization of the free wall of the right ventricle, as shown by

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Epicardial Site 1

\[ \begin{align*}
Ar &= \text{Septal r wave depolarization time.} \\
AB &= \text{Onset time of RV wall depolarization} \\
BR &= \text{RV wall depolarization time.}
\end{align*} \]

Figure 1

Measurements of the activation times of the right ventricular epicardial potentials. (Schematic drawings.)

measurement AB, and (3) the activation time of the free wall of the right ventricle, measurement BR', referred to as the R' wave measurement.

According to previous hypothesis,2 it was anticipated that measurement AB would be prolonged above the normal value of 0.02 second with the rsR' or rR' configuration of the incomplete right bundle-branch block and complete right bundle-branch block, thereby implying a true delay or "block" in the onset of free right ventricular wall depolarization, whereas it should be normal or "unblocked" with the rR' complex of right ventricular preponderance.

The electrocardiographic criteria for right ventricular preponderance, right bundle-branch block, right bundle-branch block with associated right ventricular preponderance, and biventricular preponderance6 initially require definition. Right ventricular preponderance: An rR' QRS complex in V3R, V1, or V6, which on casual inspection may present as a slurred or pure R, a qR or an Rs complex; a predominant late R wave in aVR (requiring an Rs complex in aVL for significance), a relative loss of left ventricular potential in V5, V6 with a deep non-broadened S wave, right axis deviation and a QRS duration of <0.10 second. Right bundle-branch block: An rR' or rsR' complex in V3R, V1, or V6 with an associated broad S wave over the left ventricular leads, V5 and V6. A QRS duration of 0.12 second or more with a complete right bundle-branch block and less than 0.12 second with an incomplete right bundle-branch block. The left ventricular qR potential is most often of normal amplitude. A broad but not predominant late R wave is seen in aVR. Right ventricular preponderance with right bundle-branch block: Associated criteria to those of the right bundle-branch block include a predominant late R wave in aVR, relative loss of left ventricular potential in V5 and V6, and large amplitude R' waves in the right precordial leads, usually greater than 15 mm. Biventricular preponderance: Prominent left ventricular potential with a delay in left ventricular activation time,3 rsR' or rR' right preordial QRS complexes and a large amplitude, equiphasic rSR' (or an apparent QR complex) in aVR.

Results

To simplify these data, they will be dealt with initially according to specific anatomic lesions, with a subsequent re-evaluation of the entire study.

Isolated Anatomic Right Ventricular Hypertrophy
(Tetralogy of Fallot, Pentalogy of Fallot, Isolated Valvular Pulmonic Stenosis and Pulmonic Stenosis with Associated Atrial Septal Defects, 38 Patients)

The electrocardiographic classification consisted of 29 instances of classic right ventricular preponderance, with five instances of right ventricular preponderance with an incomplete right bundle-branch block and a single instance of right ventricular preponderance with a complete right bundle-branch block. The three remaining electrocardiograms revealed an uncomplicated, incomplete right bundle-branch block, a normal tracing, and early left ventricular preponderance; the latter patient had an aeyanotic tetralogy of Fallot.

Of the 29 instances of classic right ventricular preponderance on the conventional electrocardiogram, V3R or V1 presented as rR' complexes in 24 patients, a slurred R wave
in two, an rs complex in two, and an Rs complex in the remaining patient. The epicardial potentials recorded a distinct \textit{rR'} complex arising from the high medial outflow tract of the right ventricle in all instances.

The mean values for inscription times of the septal \textit{r} wave, the onset of right ventricular depolarization (measurement \textit{AB}), and the activation time of the free wall of the right ventricle respectively of these 29 patients were 0.015, 0.020, and 0.034 second (representative epicardial potential seen in fig. 2). Measurement \textit{AB} appears to be the critical determination, as the mean value of 0.02 second suggests a normal onset of free right ventricular wall depolarization. To point out its predictability, 27 of the 29 patients with the \textit{rR'} complex of right ventricular preponderance had an \textit{AB} measurement

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Figure 2}
\end{figure}

\textit{The characteristic epicardial potentials recorded at site 1 on 2 patients with right ventricular preponderance. Note the short \textit{AB} time of 0.02 sec. (50 mm./sec. epicardial paper speed).}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Figure 3}
\end{figure}

\textit{Right ventricular preponderance. Correlation of epicardial site 1 potentials from patients aged 21 months to 39 years with variants of pulmonic stenosis and assumed anatomic right ventricular hypertrophy, depicting the short \textit{AB} time and the predominant \textit{R'} component, with the routine unipolar electrocardiogram, \textit{V}_1 and \textit{V}_6 (50 mm./sec. epicardial paper speed). Note the apparent slurred \textit{Rs} complex in \textit{V}_1 of patient K. O. (top strip) age 10, shown to be an \textit{rR'} complex on epicardial study.}
of 0.02 second. The two exceptions included isolated measurements of 0.015 and 0.025 second. Measurement of the R' wave, depicting the activation time through the free wall of the right ventricle, characteristicly measured 0.035 second.

Epicardial potentials depicting the short AB time and the tall R' component identified with right ventricular preponderance (correlated with the unipolar chest leads V1 and V6) are shown in figures 3 and 4.

Atrial Septal Defects (Ostium Secundum)

Twenty-five of the 28 routine electrocardiograms on the patients with isolated atrial septal defects disclosed a classic incomplete right bundle-branch block, with rsR' right precordial QRS complexes and broad left ventricular s waves. One revealed right ventricular preponderance with an incomplete right bundle-branch block and two had normal tracings.

Distinct rsR' or rR' potentials were identified at epicardial sites 1 or 2 in all but a single patient (a 12-year-old child with a normal routine electrocardiogram, who exhibited an rS complex in V1).

The mean measurements of the epicardial r wave, AB deflection, and the R' component for the 25 patients exhibiting the incomplete right bundle-branch block were 0.015, 0.032, and 0.035 second, respectively (representative epicardial potential seen in figure 5). Measurement AB, depicting the onset of right ventricular depolarization, appeared to be delayed, implying a “block” in onset of right

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**Figure 4**
Right ventricular preponderance. Correlation of epicardial site 1 potentials on patients aged 5 to 37 years with anatomic right ventricular hypertrophy (isolated pulmonic stenosis or variants of tetralogy of Fallot), with the routine unipolar electrocardiogram, V1 and V6: Note the short AB time and predominant R' component on epicardial study. (25 mm./sec. epicardial paper speed). The RS complex in V1 of patient J.M. (fourth strip) age 16 years, and the apparent qR in V1 of patient J.N. (fifth strip) age 16 years are shown to be rR' complexes on epicardial study.

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ventricular activation. To show the consistency of this measurement, 22 of the 26 instances of the incomplete right bundle-branch block had AB measurements of 0.03 second or greater, with three instances of 0.025 second (minimum value) and a single instance of 0.04 second (maximum value).

A classic incomplete right bundle-branch block associated with a low right ventricular pressure, moderate left-to-right shunt atrial septal defect is identified in figure 6. A distinctly prolonged AB time of >0.03 second is noted at epicardial sites 1 and 2.

The broad left ventricular S wave characteristically seen with incomplete right bundle-branch block is a bit more subtle on the tracing of figure 7, with an AB time approaching 0.04 second noted on epicardial study.

A more classic incomplete right bundle-branch block with associated right ventricular preponderance is seen in figure 8. Although an atrial septal defect was the existing anatomic lesion here, entirely similar electrocardiograms are documented with instances of isolated pulmonic stenosis and tetralogy of Fallot. The marked degree of right axis deviation, tall late R wave in aV\textsubscript{R} and the 26 mm. R′ wave in V\textsubscript{1} all suggest associated right ventricular preponderance. Epicardial measurements AB at sites 1 and 2 are recorded as >0.03 second, again characteristic of that associated with an incomplete right bundle-branch block.

**Ventricular Septal Defects (43 Patients)**

The conventional electrocardiogram showed a wide variation. Of the 24 patients having a right ventricular systolic pressure of <60 mm. Hg, 14 had a normal tracing, four had an incomplete right bundle-branch block, four had left ventricular preponderance, and two exhibited biventricular preponderance. Conversely, of the 19 patients with right ventricular pressures greater than 60 mm. Hg, only two had a normal electrocardiogram, two had an incomplete right bundle-branch block, nine had biventricular preponderance (including five instances of incomplete right bundle-branch block), and six had right ventricular preponderance, two of whom had an associated complete right bundle-branch block, and one an incomplete right bundle-branch block.

Because of the variability in right precordial QRS complex configuration, from a normal rS complex to the combined morphology of right ventricular preponderance with a complete right bundle-branch block, no distinctive epicardial potential could be identified other than that occurring with a normal right precordial rS complex, an incomplete right bundle-branch block, a complete right bundle-branch block, and right ventricular preponderance, either isolated or associated with an incomplete right bundle-branch block or a complete right bundle-branch block.

If a normal rS complex was identified in V\textsubscript{1} on the conventional electrocardiogram, an rSr′ or rS embryonic r′ potential was noted.

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*Figure 5*

The characteristic epicardial potential recorded at site 1 on a patient with an atrial septal defect presenting with an incomplete right bundle-branch block. Note the AB time of 0.035 sec. and an R′ inscription time of 0.03 sec. (50 mm./sec. paper speed).
A classic incomplete right bundle-branch block associated with an atrial septal defect is seen on the routine electrocardiogram, with an rsR' complex present in V₁ and broad left ventricular S waves in V₅ and V₇. Epicardial sites 1 and 2 disclose rsR' complexes with AB measurements of > 0.03 sec (50 mm/sec epicardial paper speed).

The broad left ventricular S waves of the incomplete right bundle-branch block are not as apparent on this electrocardiogram, due to slurring of the proximal limb of the S waves. Epicardial potential sites 1 and 2 reveal rsR' complexes, with AB measurements of 0.04 sec (50 mm/sec epicardial paper speed).
over the right ventricular outflow tract. This is clearly shown on figure 9, where an AB time of 0.025 second and an R' inscription time of 0.02 second are noted at epicardial site 2. The mean values for 15 such instances were 0.015, 0.026, and 0.021 second, respectively. Although AB measurement was prolonged above that inscribed with right ventricular preponderance, the delay was more apparent than real and resulted from the deep and predominant S wave, with measurement AB beginning at the preceding isoelectric line and terminating at the nadir of the S wave. The R' inscription time was uniformly rapid, as shown by the mean value of 0.021 second. This epicardial configuration and measurement was valid in all entities that presented a normal right precordial rS configuration.

If a classic incomplete right bundle-branch block or complete right bundle-branch block were associated with the ventricular septal defect, epicardial potentials revealed the characteristic measurements of the right bundle-branch block, with an AB time of 0.03 second or greater with the incomplete right bundle-branch block and 0.04 second or greater with the complete right bundle-branch block.

The single instance of a qR complex recorded at epicardial sites 1, 2, and 3 in the entire study occurred with a ventricular septal defect, seen in figure 10. The right precordial leads, V5, V1, and V2, likewise presented an apparent qR complex. The predominant late R wave in aV_R again suggested advanced right ventricular hypertension and anatomic right ventricular hypertrophy. Right-to-left septal depolarization seemingly is operative here to explain the initial septal q wave.4

Atrioventricular Cushion Defects (AV Communis)

Contrary to the suggestion by Burchell et al.,5 that a developmental left bundle-branch block exists with this entity, epicardial po-
EPICARDIAL POTENTIALS

Routine electrocardiogram

V1 V3 V4 V5 V6

R.P. age 4 yrs. Ventricular Septal Defect

RA = m: 4 mm Hg.
RV = 34/0 mm Hg.
PA = 25/11 mm Hg.
FA = 92/60 mm Hg.

L>R shunt = Index: 6.8 L/min.

Figure 9

A normal rS complex is identified in V1, with an rsR′ complex at epicardial site 2, the latter having an AB time of 0.03 sec., and an R′ inscription time of 0.02 sec. (50 mm./sec. epicardial paper speed).

A normal rS complex is identified in V1, with an rsR′ complex at epicardial site 2, the latter having an AB time of 0.03 sec., and an R′ inscription time of 0.02 sec.

Electrocardiograms of representative epicardial potentials are illustrated. Potential over the right ventricular outflow tract yielded rsR′ complexes typical of incomplete right bundle-branch block or complete right bundle-branch block in seven of the eight patients. Four patients had incomplete right bundle-branch blocks and two had complete right bundle-branch blocks on their conventional electrocardiogram associated with apparent left axis deviation. The two remaining patients exhibited right ventricular preponderance and biventricular preponderance, respectively, on their routine tracing (the latter showing an incomplete right bundle-branch block). An example of a complete right bundle-branch block with apparent left axis deviation is shown on the conventional electrocardiogram of figure 11, with a prolonged AB time and an R′ inscription time of 0.06 second at epicardial sites 1 and 2 (total QRS time 0.15 second).

Complete Right Bundle-Branch Block

This electrocardiographic entity requires special comment. A total of five instances occurred in the entire study, two with atrioventricular cushion defects, two with ventricular septal defects, and one with a valvular pulmonic stenosis. Measurement AB was further prolonged over that found with the incomplete right bundle-branch block, again implying a delay or "block" in onset of right ventricular depolarization. The mean measurements for the septal r wave, onset of right ventricular depolarization (AB), and depolarization of the free wall of the right ventricle with complete right bundle-branch block were 0.015, 0.038, and 0.061 second, respectively.
The prolonged activation time through the free wall of the right ventricle varies with the duration of the total QRS inscription time. The greater the total QRS duration the more prolonged R' inscription time would be observed.

Incomplete Right Bundle-Branch Block Identified with Right Ventricular or Biventricular Preponderance

Irrespective of the presence of associated right ventricular or biventricular preponderance, if an incomplete right bundle-branch block with the broad left ventricular S wave were noted on the conventional electrocardiogram, a delayed AB time of 0.03 second or more was identified on epicardial potentials over the right ventricular outflow tract; identical to and characteristic of the epicardial potentials recorded with the incomplete right bundle-branch block of atrial septal defects.

Discussion

The epicardial potentials obtained at open thoracotomy offer a distinctive and definitive approach to clinical electrocardiography, particularly in the field of congenital heart disease. In the most basic expression, rR' or rsR' QRS complexes were identified as arising from the high medial right ventricular outflow tract with anatomic right ventricular hypertrophy and with incomplete right bun-
The apparent horizontal cardiac position and complete right bundle-branch block, identified on the routine electrocardiogram, are suggestive features of atrioventricular cushion defects. Epicardial potentials at sites 1 and 2 yielded rsR' complexes, with an AB time of 0.04 sec. and an R' inscription time of 0.06 sec., characteristic of a complete right bundle-branch block (50 mm./sec. epicardial paper speed).

A critical difference in measurement of the various potentials of the QRS complexes, however, was noted with right ventricular preponderance, the electrocardiographic expression of anatomic right ventricular hypertrophy, namely, the onset of right ventricular depolarization was characteristic recorded as 0.02 second. This suggests a normal onset of depolarization of the hypertrophied right ventricle. From the conventional electrocardiographic standpoint, the pattern of right ventricular preponderance is distinctive from that of either the incomplete right bundle-branch block, the complete right bundle-branch block or the incomplete right bundle-branch block associated with right ventricular preponderance. It consists of an rR' complex in V₃R or V₁ which may present as a slurred R wave or a slurred Rs complex, an apparent pure R wave or a qR complex, depending upon the anatomic reference of the heart position and the anterior chest wall. This rR' potential, arising from the hypertrophied right ventricular outflow tract, is characteristic subtended laterally to V₁, V₃R, or V₄R superiorly to aV_R, and inferiorly to V_E (ensiform process). The left ventricular potential, although of normal configuration on epicardial study, is reflected to V₆ and V₇ as a qrS complex, with the deep but not broadened S waves resulting from the reciprocal dominant R' complex of the hypertrophied right ventricle.

With instances of incomplete right bundle-branch block and complete right bundle-
branch block, the mean value for measurement AB was prolonged to 0.03 and 0.038 second, respectively, seemingly implying a delay or ‘‘block’’ in onset of right ventricular wall depolarization. This ‘‘block’’ is readily appreciated on the conventional electrocardiogram by the broad but not necessarily deep S waves over the left ventricular leads due to the delayed onset of the right ventricular R' potential.

It was previously suggested that the high incidence of incomplete right bundle-branch blocks identified with atrial septal defects was a physiologic attempt or expression to facilitate right ventricular emptying, necessitated by the large volume of blood presented to the right ventricle with atrial systole. Certainly there is no ready anatomic lesion to explain its incidence.3

A complicating feature of unequivocal anatomic right ventricular hypertrophy and its electrocardiographic expression are unequivocal instances of an incomplete right bundle-branch block associated with isolated valvular pulmonic stenosis. Here, the finding of the tall predominant late R wave in aV_R on the conventional electrocardiogram empirically foretells right ventricular hypertension and anatomic right ventricular hypertrophy.6 This potential is not identified with instances of uncomplicated (low right ventricular pressure) incomplete right bundle-branch block. The presence of an R' component in V_3R or V_1 greater than 10 mm. with an incomplete right bundle-branch block, and 15 mm. with a complete right bundle-branch block and the relative loss of left ventricular potential in V_5 and V_6 have also been held as probable expressions of coexisting anatomic right ventricular hypertrophy with an incomplete right bundle-branch block.7 Although helpful, they are not invariable findings.

If rS or rSR' QRS configurations present in the right precordial leads of the conventional electrocardiogram, rSR' potentials are identified on epicardial study over the right ventricular outflow tract, with fairly reproducible time measurements of the various components. It is only suggested that the rR' QRS complex of right ventricular preponderance is an exaggeration of the normal right ventricular potential.

J.A. 23 yrs. Atrial Septal Defect

\[
\text{RV} = 35/0 \text{ mm Hg.} \\
L > R \text{ shunt index: } 9.7 \text{ L/min.}
\]

Figure 12

The qR right precordial QRS complex seen in V_1 is identified as an rsR' complex at V_3R, which is verified at epicardial sites 1 and 2, the latter exhibiting an AB time of >0.03 sec., characteristic of an incomplete right bundle-branch block (50 mm/sec. epicardial paper speed).
Four additional highlights of these epicardial data include:

1. Although the right precordial QRS complexes may present as apparent pure or slurred R waves or Rs complexes with right ventricular preponderance, they are in fact rR' complexes, where the initial septal r wave is fused on the ascending limb of the R' wave. If additional exploratory right chest leads are taken in the prime and subprime positions of V1, V3R, and V4R, the rR' configuration will invariably be recorded.

2. The qR right precordial QRS complex, held as an expression of an enlarged right atrium and assumed anatomic right ventricular hypertrophy is actually an rsR' complex, either of right ventricular preponderance or an incomplete right bundle-branch block, as identified by epicardial study, with the initial septal r wave being lost in the preceding isoelectric line. The apparent initial q wave is actually the s wave of the rsR' complex. Seven such instances were recorded in the current study, with a representative epicardial potential shown in figure 12.

3. The free wall or trabecular surface of the right ventricle characteristically gives rise to an RS or rs complex on epicardial study, which is usually subtended to augmented limb lead aVR. This rs or RS trabecular potential is well seen in figures 6, 9, and 10.

4. Normal left ventricular potential (qR complex) is regularly identified over the posterolateral surface of the left ventricle, shown in figures 6, 7, 8, and 11.

In general, the current epicardial data are in agreement with those of Barbato et al., 9,12 Brusca et al.,10,13 and Caruso et al.,11 who found varying degrees of rR', rsR', and R waves arising from the right ventricular outflow tract. Inadequate exposure of the right ventricular outflow has limited the epicardial data of others, McGregor,14 Herold et al.,15 Groedel et al.,16 and Jouve et al.17

Summary

Epicardial electromotive potentials have been recorded at the time of open thoracotomy on 130 patients, 124 having congenital heart disease.

These data confirm characteristic epicardial potentials with right ventricular preponderance, incomplete right bundle-branch block, and complete right bundle-branch block, as well as with normal rS and rSr' complexes, as identified in the right precordial leads of unipolar electrocardiograms.

The major differential feature between right ventricular preponderance and incomplete right bundle-branch block is a critical difference in onset of depolarization of the free wall of the right ventricle. This measurement, AB of figure 1, is 0.02 second with right ventricular preponderance and 0.03 second or greater with incomplete right bundle-branch block.

Although rR' or rsR' right precordial QRS complexes are identified with both right ventricular preponderance and incomplete right bundle-branch block, the broad left ventricular S wave of the incomplete right bundle-branch block aids in differentiating them on the conventional electrocardiogram.

A tall predominant late R wave in aVR, arising from the R' component of the rR' potential of the hypertrophied right ventricular outflow tract, serves to denote an advanced degree of right ventricular hypertrophy, whether the classic pattern of right ventricular preponderance or an incomplete right bundle-branch block associated with right ventricular preponderance presents on the routine electrocardiogram.

The apparent slurred or pure R waves, the Rs and qR right precordial QRS complexes, seen with instances of right ventricular preponderance or incomplete right bundle-branch block, are actually rR' or rsR' complexes. Additional exploratory right anterior chest leads will invariably bring out the initial septal r wave component.

The rR' or rsR' potentials of right ventricular preponderance or right bundle-branch block arise from a relatively selective site of the high medial outflow tract of the right ventricle.
DIRECT EPICARDIAL POTENTIALS

References
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