Further Electrocardiographic Observations on Direct Epicardial Potentials in Congenital Heart Lesions

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

By R. H. Wasserburger, M.D., W. P. Young, M.D., K. Siebecker, M.D., L. K. Hawkins, M.D., B. Bamforth, M.D., and J. T. King, M.D.

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.1

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.)1 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
Epicardial Site 1

\[ \begin{align*}
A_r &= \text{Septal } r \text{ wave depolarization time.} \\
A_B &= \text{Onset time of } RV \text{ wall depolarization} \\
B_R &= \text{RV wall depolarization time.}
\end{align*} \]

Figure 1

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

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in two, an rs complex in two, and an Rs complex in the remaining patient. The epicardial potentials recorded a distinct 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 r wave, the onset of right ventricular depolarization (measurement 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 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 rR' complex of right ventricular preponderance had an AB measurement.

**Figure 3**
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 AB time and the predominant R' component, with the routine unipolar electrocardiogram, V1 and V6 (50 mm./sec. epicardial paper speed). Note the apparent slurred Rs complex in V1 of patient K. O. (top strip) age 10, shown to be an rR' complex on epicardial study.
Epicardial potentials depicting, 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

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 \textit{S} wave characterized by an 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 aVR and the 26 mm. R' wave in V1 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.

\textbf{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 V1 on the conventional electrocardiogram, an rSr' or rS embryonic r' potential was noted.
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 \( V_1 \) and broad left ventricular \( S \) waves in \( V_5 \) and \( V_7 \). 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).

\[ \begin{align*}
\text{RA} & = m: 3 \text{ mm Hg.} \\
\text{RV} & = 30/0 \text{ mm Hg.} \\
\text{PA} & = 24/10 \text{ mm Hg.} \\
\text{FA} & = 112/78 \text{ mm Hg.} \\
\text{L > R shunt} & = \text{index: 2.8 L/min.} \\
\end{align*} \]
A classic incomplete right bundle-branch block with associated right ventricular preponderance is identified on the conventional electrocardiogram, with a 26-mm. R' wave in V₁, marked right axis deviation, and a predominant late R wave in aV₆. Epicardial sites 1 and 2 exhibit an AB time of >0.03 sec., characteristic of the incomplete right bundle-branch block. Sites 4G and 5G are nearer the atrioventricular groove than the usual epicardial sites 4 and 5 (50 mm/sec. epicardial paper speed).

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 aV₆ 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.

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-
Routine electrocardiogram

V₁ R₃ 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).

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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 initial q waves seen in V₆, V₁, and V₂ are also identified at epicardial sites 1, 2, 3, and 4, implying right-to-left septal depolarization. The configuration of aV₁ again suggests advanced right ventricular hypertension and anatomic right ventricular hypertrophy, which when coupled with the preservation of the left ventricular potential in V₆ and its attendant secondary ST-segment and T-wave changes, implies biventricular preponderance (25 mm/sec., epicardial paper speed).

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 characteristically 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 characteristically subtended laterally to V1, V3R, or V4R superiorly to aVR, and inferiorly to Ve (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.5

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 aVR 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 V3R or V1 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 V5 and V6 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.

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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 aVL. 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 rsSr' 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.

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References


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