The Electrocardiogram, Vectorcardiogram, and Ventricular Gradient in the Tetralogy of Fallot

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There has been increasing interest in the physiologic rather than the anatomic disturbances in tetralogy of Fallot. Accordingly, the degree of pulmonary stenosis and the size of the ventricular septal defect are the factors of physiologic importance in this congenital anomaly. The dextroposition of the aorta is functional due to the high ventricular septal defect, and the right ventricular hypertrophy is secondary to the pulmonary stenosis. Thus, tetralogy of Fallot embraces a spectrum of hemodynamic possibilities depending upon the relative degree of pulmonary stenosis and the size of the interventricular septal defect. At one extreme is the patient with complete pulmonary atresia and a large interventricular septal defect (pseudotruncus arteriosus) and, at the other, minimal pulmonary stenosis with a small interventricular septal defect. Between the extremes many physiologic possibilities exist, depending upon the relative severity of the two defects. There are, however, three distinct hemodynamic possibilities: (1) right-to-left intracardiac shunt at rest, (2) no right-to-left intracardiac shunt at rest but a right-to-left shunt upon exercise, and (3) a left-to-right intracardiac shunt but no right-to-left shunt either at rest or with exercise. In the first two instances a small left-to-right shunt may exist which is usually less than systemic blood flow. A fourth, exceedingly rare possibility exists which includes patients with pulmonary stenosis and interventricular septal defect but no intracardiac shunt either right-to-left or left-to-right at rest or upon exercise. Such a classification obviates such terms as cyanotic tetralogy of Fallot or "balanced tetralogy." The present study was undertaken to determine if the electrocardiogram and vectorcardiogram in tetralogy of Fallot reflect the physiologic variations described.

Materials and Methods

The electrocardiograms of 140 patients with tetralogy of Fallot from the Charity Hospital of Louisiana in New Orleans were studied. The patients ranged in age from 2 months to 42 years, the mean being 8.2 years. Of the 140 patients 69 were male and 71 were female; 78, white, and 62, Negro. The diagnosis was made from clinical, roentgenologic, and laboratory data. All of the patients had arterial oxygen saturation determined at rest and upon exercise while breathing air and oxygen. Ninety-one patients had cardiac catheterization. Angiocardiography was performed in 32 patients. The diagnosis of tetralogy of Fallot was confirmed at autopsy in 26 patients.

Electrocardiograms were recorded within a few days of cardiac catheterization in all except three of the 91 patients catheterized. Spatial vectorcardiograms were recorded in 33 patients with use of the tetrahedral reference system as previously described. The ventricular gradient of Wilson was calculated for all of the electrocardiograms, which were enlarged four times by projection with an epidiascope in order to trace and measure the appropriate complexes. The normal values used in this study for \( A_{QS} \) were \(-21.5^\circ \) to \( 104.9^\circ \) and \( 3.1 \) to \( 40.6 \mu \) s. and for \( G \), \( 2.2^\circ \) to \( 72.2^\circ \) and \( 13.5 \) to \( 78.9 \mu \) s.

The patients were divided into three groups according to the hemodynamic data, as already discussed: (1) right-to-left intracardiac shunt at rest, (2) right-to-left intracardiac shunt upon exercise only, and (3) no right-to-left intracardiac shunt but a left-to-right shunt. In this series of 140 patients with pulmonary stenosis and interventricular septal defect 107 patients were in group I, 14 patients in group II, and 19 patients in group III.

The patients in group I were all cyanotic at rest. The right ventricular pressure in all patients in whom cardiac catheterization was performed was essentially equal to the systemic arterial pressure. The mean right-to-left shunt equaled 46 per cent of the systemic venous return (table 1). The magnitude of the right-to-left shunt at rest varied over a wide range (15 to 90 per cent systemic venous return) as did the arterial blood...
oxygen saturation with the patient breathing oxygen at rest. Upon exercise there was frequently a precipitous decrease in the arterial blood oxygen saturation. The average arterial blood oxygen saturation while at rest breathing oxygen was 89 per cent, the value declining to 52 per cent with exercise. In some of the patients in group I a small left-to-right shunt existed at rest but disappeared with exercise in every instance. The magnitude of this shunt never exceeded systemic blood flow.

The patients included in group II were acyanotic at rest but developed a right-to-left shunt upon exercise. The right ventricular systolic pressure tended to be lower in these patients than in those of group I (table 1). Since the systemic arterial resistance must have equaled the resistance offered by the stenotic pulmonary valve at rest, there was no shunt across the interventricular septal defect. However, with exercise, increase in systemic venous return as well as the more forceful vigor of right ventricular contraction resulted in an increase in pulmonary arterial resistance so that a right-to-left shunt developed.

Group III included acyanotic patients who had a large left-to-right shunt but no right-to-left shunt either at rest or with exercise. In these patients the right ventricular systolic pressure was less than in those in groups I and II and lower than systemic arterial pressure (table 1). The gradient across the pulmonic valve was at least 35 mm. Hg in all of these patients. This gradient was considered to indicate organic stenosis. Patients with a gradient of less than 35 mm. Hg were considered to have interventricular septal defect with a functional pulmonary stenosis due to hypertrophy of the outflow tract and were not included in this study.

Results

The Electrocardiogram

Group I: Patients with Right-to-Left Intracardiac Shunt at Rest (107 Patients)

The electrocardiographic manifestations for group I patients are summarized in table 1 and figures 1 through 4.

The P Wave. The P-R interval was prolonged in only one patient. Right atrial enlargement was not a common finding in this group of patients. The P wave exceeded 2.3 mm. in lead II or III in 30 patients (28 per cent). A definite Q wave in the precordial leads recorded to the right of the transition zone, considered by some to indicate right atrial enlargement, was present in 34 patients (32 per cent). In many patients the P wave appeared peaked or tent-shaped but it was not abnormally tall or wide. There was no disturbance in rhythm in any of the patients.
| Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients | Number of patients |
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| I                 | 107               | 108               | 46                | 0.4               | 130               | 32.3              | 45                | 27.8              | 11.7              | 76                | 0.88              | 75                | 13                | 0.134             | 0.080             | 0.035             | 60                |
| II                | 14                | 96                | ex. only          | 1.5               | 107               | 34.9              | 48                | 42.7              | 11.8              | 86                | 0.85              | 64                | 50                | 0.142             | 0.082             | 0.042             | 78                |
| III               | 19                | 83                | —                 | 3.5               | 90                | 29.9              | 64                | 32.5              | 75                | 57.0              | 0.95              | 33                | 89                | 0.146             | 0.086             | 0.031             | 33                |
ECG and sVCG of a patient with classic tetralogy of Fallot with a Q wave of large magnitude in lead III (group I, type B). Note that in the sVCG there is a small deflection of the initial portion of the QRS sE-loop to the right and inferiorly resulting in an almost undetectable initial positive deflection in lead III. The QRS sE-loop is then projected sharply posteriorly, superiorly, and to the left resulting in an initial deep rS wave in lead III.

ECG and sVCG of a patient with classic tetralogy of Fallot with a Q wave of large magnitude in lead III (group I, type B). Note that in the sVCG there is a small deflection of the initial portion of the QRS sE-loop to the right and inferiorly resulting in an almost undetectable initial positive deflection in lead III. The QRS sE-loop is then projected sharply posteriorly, superiorly, and to the left resulting in an initial deep rS wave in lead III.

displayed a prominent R wave but rarely an S wave. A Q wave was usually present in this lead. There was an R and usually an S wave of large magnitude in lead V₁. The mean R/S ratio in lead V₁ was 8.5. The R wave in lead V₆ tended to be of greater magnitude than in types A and B, and the S wave was deep. The R/S ratio in lead V₆ was less than unity in 30 per cent of the patients (mean ratio, 1.2), whereas in types A and B the R/S ratio in lead V₆ was less than unity in 66 patients (62 per cent).

Type D pattern of the QRS complex was present in 11 patients (10 per cent) of group I (fig. 4). The R wave in lead I was usually prominent, equal to or exceeding the S wave in five of the 11 patients (45 per cent). A Q wave was usually present in lead III. The R wave in lead V₁ was of less magnitude than in the other types so that the R/S ratio was less in patients of type D than in any of the other types (mean ratio, 7.3). The R wave tended to be prominent in lead V₆ and the R/S ratio was greater than unity in all patients (mean ratio, 4.5).

The T Wave. The T wave in the 107 patients of group I tended to show little abnormality. The T wave was upright in standard leads I and II in almost all of the patients but was inverted in lead III in 31 patients (29 per cent) and diphasic or isoelectric in five patients (5 per cent). The T wave was inverted in V₁ in 61 patients (57 per cent), in V₂ in 20 patients (19 per cent), in V₄ in 10 patients (9 per cent) and in V₆ in seven patients (6 per cent).

Group II: Patients with Right-to-Left Shunt upon Exercise Only (14 Patients)

The electrocardiographic manifestations for group II patients are summarized in table 1 and figure 5.

The P Wave. The height of the P wave exceeded 2.3 mm. in four of the 14 patients (35 per cent), and a definite Q wave was
found in lead V1 in three patients. The P-R interval was normal in all patients of group II. There were no rhythm disturbances in any of the patients.

The QRS Complex. One patient had a QRS interval of 0.10 second and an RSR' complex in V1. Another patient had classical complete right bundle-branch block. Based on the configuration of the QRS complex, two patients had patterns of type A, two of type B, and 10 of type D as discussed for group I (fig. 5). The R/S ratio in lead V1 was abnormally high in 86 per cent of the patients (table 1). The R wave exceeded the S wave in magnitude in lead I in four patients (28 per cent) and the R/S ratio in V6 was greater than unity in 71 per cent of the patients (mean ratio, 1.7).

The T Wave. Three patients (21 per cent) of group II had inverted T waves in lead I, and four patients (28 per cent) had inverted T waves in lead III. Eight patients (57 per cent) had inverted T waves in V1; two (14 per cent) had inverted T waves in V2; and one had inverted T waves in V4 and V6.

Group III: Patients without Right-to-Left Shunt Even with Exercise (19 Patients)

The electrocardiographic manifestations for group III are summarized in table 1 and figure 6. The electrocardiograms of this group of patients tended to display the patterns previously described for uncomplicated ventricular septal defect.7

The P Wave. The P wave did not exceed 2.3 mm. in height in any of the patients of group III. The P-R interval was prolonged in two patients. There were no disturbances in rhythm in any of the patients.

The QRS Complex. Six patients had electrocardiograms with “incomplete” right bundle-branch block (QRS interval, 0.10 second and RSR’ in lead V1). The R wave in lead I was prominent and was of greater magnitude than the S wave in seven patients. An S1S2S3 pattern (concordant S waves) (fig. 6B) was present in the standard leads in 45 per cent of the patients. A Q wave was present in lead III in 6 patients (33 per cent), and in lead V6 in 16 patients (89 per cent) (table 1). The Q wave was of considerable magnitude in lead V6 in four patients, a fairly frequent finding in uncomplicated ventricular septal defect.7 The mean R/S ratio in lead V1 was less in this group (mean ratio, 3.2) than in groups I and II (table 1). The R/S ratio in lead V6 exceeded unity in all of the patients (mean ratio, 10.0) (fig. 6).

The T Wave. The T wave was negative in lead I in two patients and in lead III in three patients. The T wave was inverted in lead V1 in 11 patients (58 per cent), in lead V2 in three patients (16 per cent), and in leads V4 and V6 in one patient.

The Ventricular Gradient

The characteristics of ΛQRS, ΛT, and Λ for the three groups of patients with tetralogy of Fallot are summarized in table 2 and figure 7.

Group I: Patients with Right-to-Left Intracardiac Shunt at Rest (107 Patients)

Before describing the ΛQRS, ΛT, and Λ for the four electrocardiographic types encountered in this group, a general description of these parameters for group I is given.

The ΛQRS was directed to the right and inferiorly or superiorly in the frontal plane in most of the patients. The majority of the vectors were located in the fourth and fifth sextants of the triaxial reference system. ΛQRS was deviated more to the right than normal in 82 patients (77 per cent). The mean direction of ΛQRS was 130° and the mean magnitude was 32.3 μV. s. (table 1, fig. 7).

The projection of ΛT in the frontal plane was inferior and to the left in most of the patients. Occasionally it was directed to the left and superiorly. The mean direction of ΛT was 45° in the frontal plane, the mean magnitude being 27.8 μV. s. (table 1, fig. 7).

The ventricular gradient (Λ) was directed inferiorly and either vertically or to the right in most of the patients. The mean direction of Λ in the frontal plane was 91° and the mean magnitude was 43.8 μV. s. (table 1, fig. 7). The ventricular gradient was abnormal in magnitude or direction in 91 of the 107 patients (85 per cent). In 47 patients (44 per cent) the angle between ΛQRS and Λ was
abnormally large, and the angle between $\mathbf{G}$ and $\mathbf{A}_T$ was abnormally large in 67 patients (63 per cent) (table 2). $\mathbf{G}$ was directed more to the right than normal in 86 patients (80 per cent). In seven patients (6 per cent) $\mathbf{G}$ was abnormally large and in 11 patients (10 per cent) $\mathbf{G}$ was of less magnitude than normal.

In patients with type A electrocardiograms the characteristics of the $\mathbf{A}_{QRS}$, $\mathbf{A}_T$, and $\mathbf{G}$ were similar to those described for type A. The mean direction of $\mathbf{A}_{QRS}$ in the frontal plane was 137° and the mean magnitude, 27.8 $\mu$V. s., whereas the mean direction of $\mathbf{G}$ was 91° and its mean magnitude 34.3 $\mu$V. s. The $\mathbf{A}_{QRS}$ was deviated more to the right than normal in 15 of the 21 patients (71 per cent). In 18 of the patients (86 per cent) $\mathbf{G}$ was directed more to the right than normal, and the angles between $\mathbf{A}_{QRS}$ and $\mathbf{G}$ and $\mathbf{G}$ and $\mathbf{A}_T$ were abnormally wide in 67 per cent and 65 per cent of the patients, respectively. The mean direction of $\mathbf{G}$ in the frontal plane was 92° and the mean magnitude was 33.7 $\mu$V. s.

In patients with type B electrocardiograms the characteristics of the $\mathbf{A}_{QRS}$, $\mathbf{A}_T$, and $\mathbf{G}$ were similar to those described for type A. The mean direction of $\mathbf{A}_{QRS}$ in the frontal plane was 137° and the mean magnitude, 27.8 $\mu$V. s., whereas the mean direction of $\mathbf{G}$ was 91° and its mean magnitude 34.3 $\mu$V. s. The $\mathbf{A}_{QRS}$ was deviated more to the right than normal in 15 of the 21 patients (71 per cent). In 18 of the patients (86 per cent) $\mathbf{G}$ was directed more to the right than normal, and the angles between $\mathbf{A}_{QRS}$ and $\mathbf{G}$ and $\mathbf{G}$ and $\mathbf{A}_T$ were abnormally wide in 67 per cent and 76 per cent of the patients, respectively. Three
Figure 4

ECG and sVCG from two older patients with tetralogy of Fallot. The high R waves present in leads I, V₅, and V₆ of the electrocardiograms from these two patients were typical of the ECG from older patients with tetralogy of Fallot. The orientation of the QRS sE-loop to the left was also frequent.

of the 21 patients had normal ventricular gradients.

In patients with type C electrocardiograms the mean AQRS was located at 119° in the frontal plane and the mean magnitude was 28.0 µV. s. The degree of rightward deviation of AQRS was abnormal in six of the 10 patients (60 per cent). The ventricular gradient (G) was projected inferiorly either vertically or slightly to the right in the frontal plane. The mean direction of G was 95° and the mean magnitude, 42.8 µV. s. G was deviated to the right beyond the normal in 4 patients (40 per cent). The angle between AQRS and G was
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ECG and sVCG of a patient from group II with a right-to-left intracardiac shunt upon exercise only. Note the well-developed R waves in leads I, V5, and V6 and the moderately deep S wave in lead V1.

Group II: Patients with Right-to-Left Shunt on Exercise Only (14 Patients)

\( \hat{A}_{QRS} \) tended to be directed inferiorly and to the right in the frontal plane projection (fig. 7). The mean direction of \( \hat{A}_{QRS} \) was 107° and the mean magnitude, 34.9 \( \mu \)V. s. \( \hat{A}_{QRS} \) was deviated more to the right than normal in 11 patients and more to the left than normal in one patient.

\( \hat{A}_{T} \) was fairly consistently oriented inferiorly and to the left in the frontal plane. The mean direction of \( \hat{A}_{T} \) was 48° and the mean magnitude 42.7 \( \mu \)V. s. (fig. 7).

The ventricular gradient (\( \hat{G} \)) was projected inferiorly and to the left in the frontal plane, its mean direction and magnitude being 69° and 62.5 \( \mu \)V. s., respectively (fig. 7). In two patients the ventricular gradient was normal. In 11 patients \( \hat{G} \) was deviated more to the right than normal and in one patient more to the left than normal. The angle between \( \hat{A}_{QRS} \) and \( \hat{G} \) was abnormally wide in seven pa-
Figure 6
ECG and sVCG from two patients in group III. In patient no. 30 (A) there is a prominent R wave in leads I, V5, and V6 and a terminal projection in the sVCG. In patient no. 32 (B) note the S2S3S4 pattern in the standard leads, the rSR' pattern in
patients (50 per cent) and the angle between G and A_T was abnormally wide in six patients (43 per cent) (table 2).

Group III: Patients without Right-to-Left Shunt Even with Exercise (19 Patients)

AQRS was directed inferiorly and to the left in 10 patients and either vertically or toward the right in nine patients. The mean AQRS in the frontal plane projection was located at 90° and its magnitude was 29.9 μv. s. (fig. 7). AQRS was located more to the right than normal in five patients (26 per cent).

A_T was located inferiorly and to the left in most of the patients. The mean direction of A_T in the frontal plane was 64°, the mean magnitude being 32.5 μv. s. (fig. 7). The ventricular gradient was directed inferiorly and to the left in 16 patients and inferiorly and to the right in three patients. The mean direction of G in the frontal plane was 75° and the mean magnitude, 57.0 μv. s. (fig. 7). The G was deviated more to the right than normal in 11 patients. In four patients the angle between AQRS and G was abnormally wide, whereas the angle between G and A_T was abnormally wide in one patient (table 2).

The Spatial Vectorcardiogram

Spatial vectorcardiograms (sVCG) were obtained for 33 of the 140 patients with tetralogy of Fallot. The results are summarized in figures 1-6 and 8.

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<th>Position of A_T relative to G</th>
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Group I: Patients with Right-to-Left Intracardiac Shunt at Rest (25 Patients)

In all of the patients with type A electrocardiograms (17 patients), the maximal instantaneous vectors of the QRS sE-loops were directed inferiorly, to the right, and anteriorly. The mean direction of the QRS sE-loop in the frontal plane projection was 129° (range, 101° to 133°). In every instance the QRS sE-loop was inscribed in a clockwise direction in the frontal plane. The loops were generally wide, elliptical, and tended to display little if any distortion. In most of the patients the major portion of the QRS sE-loop was oriented to the right of the 90° axis. The anterior displacement of the QRS sE-loop in the left sagittal plane projection was marked in most of the sVCG (mean, 128°) (fig. 1). The maximal mean instantaneous vector of the T sE-loops was directed inferiorly, to the left, and anteriorly (fig. 8).

In types B and C (four patients) the QRS and T sE-loops were similar to those described for type A except that there tended to be less rightward orientation of the QRS sE-loop in the frontal plane projection (mean, 116°). As a result, a greater portion of the loop was oriented to the left of the 90° axis than in type A (fig. 3). There was also less anterior displacement of the QRS sE-loop in the left sagittal plane projection (mean, 115°) than for that in type A. One patient with type

lead V_s and the equiphasic complexes (Katz-Wachtel) in leads V_s through V_6. Also, there is a terminal projection in the sVCG directed superiorly, to the right, and posteriorly. The ECG and sVCG from these patients closely resemble those from patients with uncomplicated ventricular septal defect.

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B had a QRS sE-loop that was inscribed in a counterclockwise direction (fig. 2).

In three of the four patients with type D electrocardiograms, the maximal mean instantaneous vectors of the QRS sE-loops were directed inferiorly, to the left, and anteriorly (fig. 4). The fourth patient had a QRS sE-loop which was similar to that described for type A.

Group II: Patients with Right-to-Left Shunt on Exercise Only (Three Patients)

The maximal mean instantaneous vectors of the QRS sE-loops in the three patients in this group were directed inferiorly and vertically in the frontal plane projection with as much of the loop being oriented to the left of the 90° axis as to the right (figs. 5 and 8). The QRS sE-loop in the left sagittal plane projection was oriented anteriorly. All of the loops were inscribed in a clockwise direction.

In one of the patients the maximal mean instantaneous vector of the T sE-loop was directed to the right (fig. 8).

Group III: Patients without Right-to-Left Shunt Even with Exercise (Five Patients)

The maximal mean instantaneous vectors of the QRS sE-loops of this group of patients were directed inferiorly and to the left in the frontal plane projection (fig. 8). In four patients the loop was directed anteriorly and, in one patient, slightly posteriorly to the isopotential point. All but one of the loops rotated in a clockwise direction. In three patients a prominent terminal projection of the QRS sE-loop was directed to the right, posteriorly and superiorly to the isopotential point (fig. 6).

The maximal mean instantaneous vectors of the T sE-loops were directed inferiorly to the left, and in two patients were projected posteriorly and in one patient anteriorly to the isopotential point (fig. 8).

Discussion

Tetralogy of Fallot was considered in this discussion as a congenital cardiac defect in which the predominant lesions were pulmonary stenosis and ventricular septal defect. The three basic hemodynamic variants depend upon the relative degree of pulmonary stenosis and the size of the ventricular septal defect. In the patients with right-to-left shunt at rest the left ventricle receives only a portion of the total systemic venous return (as little as 20 to 30 per cent in severe defects). The "underloading" of the left ventricle results in hypoplasia of this chamber. Angiocardiographic studies have demonstrated that the lumen of the left ventricle is much smaller than that of the right ventricle, and autopsies have repeatedly shown hypoplasia of the left ventricle. Brinton and Campbell, in a necropsy study of 25 patients with tetralogy of Fallot, found that the right ventricle was generally 50 per cent thicker than the left ventricle. The anterior surface of
the heart is formed entirely by the right atrium and right ventricle, the left ventricle being displaced behind the right ventricle.\textsuperscript{10} Owing to the hypoplasia of the left ventricle, the degree of clockwise rotation of the heart is probably greater in tetralogy of Fallot than in any other congenital cardiac defect. The apex of the heart, composed of the right ventricle, is lifted upward and forward.\textsuperscript{11, 12}

The electrocardiograms from the patients with right-to-left shunt at rest reflect a marked degree of right ventricular hypertrophy as well as hypoplasia of the left ventricle and extreme clockwise rotation of the heart. Because of the presence of the interventricular septal defect, the highest level that the right ventricular pressure can reach is that of the arterial blood pressure. Therefore, in tetralogy of Fallot the right ventricular systolic pressure is usually between 95 and 125 mm. Hg.
The configuration of the QRS complex in V1 is similar to that seen in pulmonary stenosis with a normal aortic root and right ventricular pressure in the range of 95 to 125 mm Hg.13 Clockwise rotation of the forward-lifted heart causes the early vectors of ventricular activation to be directed superiorly and to the left in the frontal plane. This results in a prominent Q wave in lead III and the absence of a Q wave in lead V6. Because of the clockwise rotation of the heart and the hypoplasia of the left ventricle, an unusually small R wave is present in leads I, V5, and V6.

Certain aspects of the Q wave in lead III are of interest. According to Ziegler,14 a Q wave in lead III is common in children and decreases in incidence with age. Weisbart and Simonson15 found a prominent Q wave in lead III in 12 per cent of normal young men studied. These investigators measured the amplitude rather than the area of the Q wave.

A report from this laboratory16 of the electrocardiograms of 172 normal children from birth to 16 years of age, in which the area of the Q wave rather than its amplitude was measured, indicated that a Q wave was present in lead III in 61 per cent of the subjects studied and the mean area of the Q wave was 0.55 μv.s. ±0.45 μv.s. No statistical relationship was found between the area of the Q wave in lead III and the patient's age. In the present study, a Q wave was found in lead III in 75 per cent of the patients in group I, and in 28 per cent of these patients it was two standard deviations or more from the mean for the normal children.

The absence of a Q wave in lead V6 deserves comment. A Q wave is present in lead V6 in well over 90 per cent of normal infants and children after the age of 1 month.14 The youngest patient in the present series was 2 months old. The presence of a Q wave in lead V6 in only 13 per cent of the patients in group I supports the idea that in tetralogy of Fallot there is marked clockwise rotation of the heart. Slightly more than half of the patients with uncomplicated pulmonary stenosis or pulmonary stenosis and interatrial shunt display a Q wave in lead V6. Furthermore, when a Q wave is present in lead III, in these latter defects it rarely exceeds the normal limits for area.

The electrocardiograms (type D) of the older patients with tetralogy of Fallot tended to show more evidence of left ventricular activity electrically than did those of the younger patients. It is not known if this is due simply to the duration or physiologic mildness of the disease or if it is because only those patients who have a strong left ventricle survive into middle life.

AQRS, A7, and G in the patients with right-to-left shunts at rest had fairly uniform characteristics. AQRS was directed inferiorly and toward the right (mean, 134°). In patients with uncomplicated pulmonary stenosis with right ventricular systolic pressures in the range of 95 to 125 mm Hg, AQRS tends to be located at 135° in the frontal plane projection.13 Thus, it would appear that in the tetralogy of Fallot as well as in isolated pulmonary stenosis the location of AQRS in the frontal plane depends at least to some extent upon the right ventricular pressure.

Since AQRS and G were both deviated to the right, whereas A7 remained essentially normal in position, the angle between G and A7 was usually wider than that between AQRS and G. Because of clockwise rotation of the heart on its longitudinal axis, AQRS was located to the right of G in most of the patients with right-to-left shunt at rest.

The mean AQRS in the older patients (type D) was only slightly deviated toward the right and in five patients AQRS was actually directed to the left in the frontal plane. These findings are considered further evidence of an increase in left ventricular muscle mass in these older patients. In fact, in five patients the ventricular gradient was normal, probably because of the balancing of electrical forces as the left ventricle hypertrophied.

The spatial vectorcardiograms (sVCG) described for patients with right-to-left shunt at rest were essentially similar in orientation, configuration, and rotation. Donoso et al.,17 using a different method of electrode place-

*Circulation, Volume XXIV, July 1961*
ment have also noticed such consistency in the sVCG of patients with tetralogy of Fallot. The QRS sE-loop was oriented almost completely to the right of the 90° axis in the frontal plane. With this type of QRS sE-loop, an R wave of small magnitude and an S wave of great magnitude is expected in leads I and V6 of the electrocardiogram. The marked anterior displacement of the QRS sE-loop in the left sagittal plane projection is probably a result of lifting of the apex of the heart, one of the characteristic anatomic alterations in the tetralogy of Fallot.

The small magnitude of many of the loops was at times striking, the maximal mean instantaneous vector of the QRS sE-loop in the frontal plane being less than 1 mv. in 60 per cent of the patients. This was presumably due to the hypoplasia of the left ventricle.

In the older patients with tetralogy of Fallot the QRS sE-loops were oriented inferiorly and to the left. The relatively greater degree of orientation of the QRS sE-loop to the left and the lack of anterior displacement of the loop in the older patients would seem to support the idea that with persistence of the anatomic defect there is increasing evidence of left ventricular electrical activity.

It is important to differentiate tetralogy of Fallot from pulmonary stenosis with reversed interatrial shunt. The sVCG of 10 patients with proved pulmonary stenosis and venoarterial interatrial shunt have been studied in this laboratory. In six of these 10 patients the QRS sE-loop was oriented superiorly, to the right, and posteriorly in the frontal plane. This spatial orientation of the QRS sE-loop was not encountered once in tetralogy of Fallot.

When the degree of pulmonary stenosis is less severe, fewer signs of marked right ventricular hypertrophy and extreme clockwise rotation of the heart are evident in the electrocardiogram. Those patients with right-to-left shunt on exercise only tended to have better developed R waves in leads I, V5, and V6 as well as deeper S waves in lead V1 than those patients with right-to-left shunt at rest. In addition, a deep Q wave in lead III was less common and a Q wave in V6 more common in the former group than in the latter.

The influence of the hemodynamic changes on the electrocardiogram in the patients with right-to-left shunt on exercise only deserves comment. Because of the left-to-right shunt at rest, and in spite of the presence of pulmonary stenosis, the pulmonary blood flow is increased. Therefore, the left ventricle is "overloaded" rather than "underloaded" so that it is not underdeveloped. With progression of the disease, some of these patients probably develop a veno-arterial shunt at rest. When a patient of this type becomes cyanotic, his electrocardiogram would be expected to be different from the type of electrocardiogram seen in the typical case of tetralogy of Fallot. In fact, Gasul and co-workers have shown that patients with uncomplicated ventricular septal defects may with time develop infundibular pulmonary stenosis and arterial oxygen desaturation. AQRS and G tended to be directed more to the left in the frontal plane than in the patients with right-to-left shunt at rest. Also, there was less tendency for the QRS sE-loop to be oriented to the right.

Patients who fail to develop right-to-left shunts even on exercise have only a mild degree of pulmonary stenosis. In this study a pressure gradient of greater than 35 mm. Hg across the infundibular zone or the pulmonary valve was accepted as evidence of an organic stenosis. This was based on the observations of Brotmacher and Campbell in which the lowest pressure gradient across the pulmonary valve found in patients with confirmed pulmonary stenosis at autopsy was 35 mm. Hg. It is realized, however, that patients with functional pulmonary stenosis may occasionally have marked pressure gradients between the right ventricle and pulmonary artery. The electrocardiograms from patients with pulmonary stenosis and ventricular septal defect with left-to-right shunt only resemble those previously described for patients with uncomplicated interventricular septal defect. Since the ventricular septal defect with an
associated left-to-right shunt and not the pulmonary stenosis is the predominant disturbance, there is a tendency for hypertrophy of the crista supraventricularis to develop rather than hypertrophy of the right ventricle generally. The electrocardiograms of these patients often show incomplete right bundle-branch block and an $S_{1}S_{2}S_{3}$ pattern as well as a deep Q wave in lead $V_{6}$. In these patients $\Delta QRS$ was directed inferiorly and vertically in the frontal plane. In uncomplicated ventricular septal defect the mean $\Delta QRS$ is directed toward the left. This difference in the direction of $\Delta QRS$ indicates that, although the patients in this group more closely resemble those with ventricular septal defect than those with tetralogy of Fallot, the presence of the mild pulmonary stenosis is sufficient to alter somewhat the orientation of $\Delta QRS$ in the frontal plane. Again, it would seem that in patients with congenital heart disease the position of $\Delta QRS$ in the frontal plane may reflect right ventricular pressure with some accuracy.

All of the patients without right-to-left shunts had QRS $s\mathbf{E}$-loops that were oriented inferiorly and to the left. In the sVCG from three of these patients the centripetal limb of the QRS $s\mathbf{E}$-loop was projected to the right, posteriorly and superiorly to the isopotential point. This type of terminal orientation of the QRS $s\mathbf{E}$-loop was frequently found in uncomplicated ventricular septal defect and probably represents the late activation of a hypertrophied crista supraventricularis.7

From these data it may be postulated that in the tetralogy of Fallot the electrocardiogram, ventricular gradient and spatial vectorcardiogram vary with the degree of pulmonary stenosis in such a way as to display a progression from hypertrophy of the crista supraventricularis to generalized right ventricular hypertrophy with increasing degrees of pulmonary stenosis.

Summary

The electrocardiogram, ventricular gradient, and spatial vectorcardiogram were studied in 140 patients with proved tetralogy of Fallot. The patients were separated into three groups according to hemodynamic data.

The salient features of the electrocardiogram in patients of group I consisted of diminutive R waves in leads I and $V_{6}$, a deep Q wave and high R wave in lead III, a prominent R wave in lead $V_{1}$, which was not wide, and the absence of Q waves in leads I, $V_{2}$, and $V_{6}$.

The electrocardiogram in patients of group II was similar to that of the patients of group I except for the appearance of more signs of left ventricular electric activity and less clockwise rotation of the heart.

The electrocardiogram of the patients of group III was similar to that previously described for ventricular septal defect.

$\Delta QRS$, $\Delta T$, $\Delta Q$, and sVCG reflected the same general trend as the electrocardiograms.

The electrophysiologic data presented support clinical observations indicating that the tetralogy of Fallot includes patients with a wide range of hemodynamic differences.

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In submitting this to the public I doubt not that I shall be considered, by all those who can justly appreciate medical science, as having thereby rendered a grateful service to our art, inasmuch as it must be allowed to throw no small degree of light upon the obscurer diseases of the chest, of which a more perfect knowledge has hitherto been much wanted.

In drawing up my little work I have omitted many things that were doubtful and not sufficiently digested; to the due perfection of which it will be my endeavour henceforth to apply myself. To conclude, I have not been ambitious of ornament in my mode or style of writing, being contented if I shall be understood.—From On Percussion of the Chest: being a translation of Auenbrugger's original treatise, entitled, Inventum Novum ex Percussione Thoracis Humani, ut Signo, Abstrusos Interni Pectoris Morbos Detectendi. Published in 1761. Translated by John Forbes, M.D. In: Classics of Medicine and Surgery. New York, Dover Publications, Inc., 1959, p. 124.
The Electrocardiogram, Vectorcardiogram, and Ventricular Gradient in the Tetralogy of Fallot
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Circulation. 1961;24:94-109
doi: 10.1161/01.CIR.24.1.94
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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