THE VENTRICULAR COMPLEX IN RIGHT VENTRICULAR HYPERTROPHY AS OBTAINED BY UNIPOLAR PRECORDIAL AND LIMB LEADS

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THE dramatic benefits to be obtained from modern cardiac surgical procedures have, among other things, crystallized the need for a more accurate diagnosis of heart disease. One of the most elusive of these conditions is right ventricular hypertrophy, and more definite criteria for its recognition are greatly needed. Roentgenologists and clinicians have attacked the problem, but the roentgenographic diagnosis of right ventricular hypertrophy is notoriously difficult and radiologists differ in their opinions as to the reliability of the criteria thought to be of diagnostic importance.[1-4] Various authors have described the electrocardiographic pattern of marked right ventricular hypertrophy in the standard limb leads[5-10] and in the precordial leads.[11-15,27] The criteria for the diagnosis of the lesser degrees of right ventricular hypertrophy have not been clearly established in either standard or precordial leads, nor has the frequency of the significant findings been accurately defined. It is the purpose of this paper to describe the patterns seen in sixty cases of right ventricular hypertrophy and to differentiate normal right axis deviation (due to position of the heart) from abnormal right axis deviation (due to right ventricular hypertrophy).

SUBJECTS AND METHODS

Sixty patients (of whom twenty-four, or 40 per cent, were 5 years of age or younger) with right ventricular hypertrophy who suffered from cyanotic congenital cardiac disease, tetralogy of Fallot, mitral stenosis, cor pulmonale, or kyphoscoliotic disease were studied. Tables I and II summarize the types of cases and the age and sex distribution. Of the forty-four patients with congenital cardiac disease, in twenty the diagnosis was proved by surgical intervention, in six by autopsy, and in seven by Diodrast angiocardiography (Table I). The diagnosis in the remainder of the group with congenital cardiac anomalies was made by routine clinical and roentgenographic examination. The diagnosis of right ventricular hypertrophy in patients with chronic asthma and emphysema was based on the clinical manifestations of chronic cor pulmonale with dyspnea

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Aided in part by a grant from the Mrs. Albert E. Schwabacher Fund.

Presented in preliminary form before the American Federation of Clinical Research, April, 1947, Chicago, Ill.

and cyanosis, as well as on the demonstration of emphysema by roentgen examination. Clinical and roentgen examination supplemented the physical signs of mitral stenosis in patients with rheumatic disease.

TABLE I. THE CAUSES OF RIGHT VENTRICULAR HYPERTROPHY IN THE PRESENT SERIES OF CASES

Congenital cardiac disease		44
Tetralogy of Fallot	18	
Proved by autopsy	4	
Proved surgically	13	
Proved by Diodrast angiocardiograms	1	
Cor triloculare with right ventricular hypertrophy; autopsy	1	
Overriding aorta or high interventricular septal defect with right ventricular enlargement shown by Diodrast angiocardiogram	6	
Miscellaneous cyanotic congenital cardiac disease with abnormal films of the heart but no Diodrast, surgery, or autopsy	19	
Chronic asthma and emphysema		8
Rheumatic heart disease with mitral stenosis		6
Kyphoscoliosis		1
Pulmonary fibrosis		1
Total cases		60

All of the patients were studied by means of standard limb leads, unipolar limb leads, and unipolar precordial Leads V_1 through V_6. On many of the patients further exploratory leads were taken over the right side of the anterior chest, the right side of the upper abdomen, and the xiphoid. Goldberger's modification[16] of Wilson's central terminal was used for the unipolar leads. On all of the patients routine seven-foot films of the chest were taken and on many of the congenital patients Diodrast angiocardiograms were available.*

TABLE II. RIGHT VENTRICULAR HYPERTROPHY; DISTRIBUTION BY AGE AND SEX IN SIXTY CASES

AGE	MALE	FEMALE
1 mo.–2 yrs.	6	7
2 yrs.–5 yrs.	8	3
5 yrs.–10 yrs.	5	2
10 yrs.–20 yrs.	1	4
20 yrs.–30 yrs.	4	4
30 yrs.–50 yrs.	6	4
50 yrs.–70 yrs.	6	0
Total	36	24

The electrocardiograms were analyzed in tabular form on master sheets, all waves of each record being carefully measured through a magnifying lens, if necessary. The amplitude of upright waves was measured from the upper edge

*An independent study by Dr. E. R. Miller and his associates of the Division of Radiology.

of the base line to the peak of the wave; that of inverted waves, from the lower edge. Calibration corrections were applied, if necessary for standardization (1.0 cm. = 1.0 millivolt). In addition to the usual measurements, particular attention was paid to the voltage of the R and S waves in the precordial and unipolar extremity leads in order to calculate the ratios to be described.

One hundred fifty subjects (healthy nurses, medical students, house staff personnel, and flying personnel of a commercial airline, whose histories, physical examinations, electrocardiograms, and roentgenograms of the chest were within normal limits) were used for comparison. The mean age of the normal subjects was 34.6 years, with a range of 4 to 70 years. Four were under the age of 10 years. A separate group of thirteen normal infants from the well-baby clinic were studied for calculation of the R/S ratios and of the ventricular activation time in view of the observations of Battro and Mendy[18] of an abnormally prominent R wave in Lead V_1 in normal infants.

The differentiation of right ventricular hypertrophy and right bundle branch block was attempted and all cases were excluded from this study in which the electrocardiogram showed an M-shaped complex of the QRS with a prominent R wave and a ventricular activation time exceeding 0.07 second in Lead V_1. This was done to exclude right bundle branch block from the series even though it was appreciated that right ventricular hypertrophy and right bundle branch block could coexist.

RESULTS

Table III summarizes the statistical data obtained in the cases of right ventricular hypertrophy, in the entire normal group, and in subjects with right axis deviation (+80° or more) included in the normal group. Table IV summarizes the criteria obtained from a study of our data for the diagnosis of right ventricular hypertrophy, and Table V summarizes the frequency with which the various electrocardiographic abnormalities were encountered here. It will be seen that abnormalities in voltage and ratios of the R and S waves were the most common abnormalities in the precordial leads.

Voltage of the QRS Complex.—The importance of voltage of the QRS complex is apparent from Table V. No standards of voltage in right ventricular hypertrophy have been published comparable to those of Gubner and Ungerleider[19] in left ventricular hypertrophy.[30] The voltage of the R wave and S wave in the present series can be seen in Table III. The mean height of the R wave in Lead V_1 in the normal subjects was 2.3 mm., whereas the mean height of the R wave in right ventricular hypertrophy in V_1 was 9.6 mm., and thirty-five cases (58 per cent) equalled or exceeded the maximum normal R wave of 7.0 millimeters. The mean depth of the S wave in Lead V_1 was 8.6 mm. in the normal group and 3.1 mm. in the cases of right ventricular hypertrophy, and in thirty of these cases (50 per cent) the S wave was less than 2.0 mm. in V_1. The mean depth of the S wave in V_6 in the normal group was only 0.6 mm. and 6.1 mm. in the cases of right ventricular hypertrophy. In thirty cases (50 per cent) of the latter, the S wave equalled or exceeded the maximum normal of 7.0 mm. in V_5 and/or V_6.

TABLE III. THE VENTRICULAR DEFLECTIONS IN THE UNIPOLAR LIMB AND PRECORDIAL LEADS (MEASUREMENTS IN MILLIMETERS)

LEAD	RIGHT VENTRICULAR HYPERTROPHY (60 CASES)				NORMAL (150 CASES)				NORMAL—RIGHT AXIS DEVIATION (19 CASES)			
	MEAN	ST. DEV.	MIN.	MAX.	MEAN	ST. DEV.	MIN.	MAX.	MEAN	ST. DEV.	MIN.	MAX.
V_1												
Q	0.07	0.25	(0.0	1.0)	0.0	0.0	(0.0	0.0)	0.0	0.0	(0.0	0.0)
R	9.6	7.6	(0.0	28.0)	2.3	1.5	(0.0	7.0)	2.1	1.6	(0.0	7.0)
S	3.1	4.1	(0.0	19.0)	8.6	4.3	(2.0	25.0)	8.4	4.3	(1.5	17.0)
T	−1.09	7.77	(−5.0	+ 5.5)	0.15	1.58	(−4.0	+4.0)	−0.26	1.06	(−1.5	+3.0)
VAT*	0.04	0.06	(0.0	0.08)	0.02	0.007	(0.0	0.03)	0.02	0.008	(0.0	0.03)
V_2												
Q	0.0	0.0	(0.0	0.0)	0.0	0.0	(0.0	0.0)	0.0	0.0	(0.0	0.0)
R	9.4	7.1	(0.5	25.0)	5.9	3.1	(0.0	16.0)	5.9	2.8	(2.0	11.0)
S	10.0	6.5	(0.5	24.0)	12.7	5.3	(0.0	29.0)	15.4	5.0	(4.0	29.0)
T	2.2	6.78	(−6.0	+8.0)	5.2	3.32	(−3.0	+18.0)	4.6	2.34	(+1.5	+11.0)
VAT*	0.03	0.01	(0.0	0.08)	0.025	0.006	(0.0	0.04)	0.024	0.008	(0.015	0.04)
V_3												
Q	0.01	0.07	(0.0	0.5)	0.01	0.06	(0.0	0.5)	0.0	0.0	(0.0	0.0)
R	10.1	7.2	(1.0	33.0)	8.9	4.3	(1.5	26.0)	7.4	2.6	(3.0	13.0)
S	10.2	6.0	(0.5	22.0)	8.8	5.3	(0.0	25.0)	11.3	5.7	(2.0	25.0)
T	2.6	6.85	(−7.0	+10.0)	5.38	2.96	(−2.0	+16.0)	5.18	2.21	(+2.0	+10.0)
VAT*	0.03	0.01	(0.0	0.07)	0.03	0.007	(0.02	0.04)	0.029	0.007	(0.015	0.04)
V_4												
Q	0.15	0.92	(0.0	6.5)	0.1	0.4	(0.0	3.0)	0.03	0.02	(0.0	0.5)
R	10.0	7.8	(1.0	35.0)	14.2	5.5	(4.0	27.0)	13.4	4.4	(4.0	23.0)
S	10.4	6.3	(1.0	23.0)	5.2	4.0	(0.0	20.0)	6.5	5.0	(0.0	19.0)
T	2.7	6.84	(−9.5	+11.0)	4.8	2.76	(0.0	+17.0)	4.18	1.79	(+1.0	+8.0)
VAT*	0.03	0.01	(0.0	0.05)	0.034	0.007	(0.02	0.05)	0.032	0.007	(0.02	0.04)

V_5												
	Q	0.31	0.98	(0.0	6.0)	0.3	0.6	(0.0	3.0)	0.2	0.1	(0.0	1.0)
	R	7.9	6.1	(5.0	31.0)	12.1	4.4	(4.0	26.0)	10.2	3.7	(4.0	20.0)
	S	8.5	5.6	(0.5	30.0)	1.5	1.5	(0.0	6.0)	2.0	1.8	(0.0	6.0)
	T	2.4	7.33	(−9.0	+10.0)	3.43	1.62	(0.0	+9.0)	3.29	1.49	(+2.0	+8.0)
	VAT*	0.03	0.01	(0.0	0.05)	0.04	0.01	(0.0	0.05)	0.033	0.008	(0.02	0.04)
V_6													
	Q	0.4	1.1	(0.0	6.5)	0.4	0.5	(0.0	2.0)	0.3	0.2	(0.0	2.0)
	R	6.6	6.1	(0.5	32.0)	9.2	3.6	(4.0	22.0)	8.1	3.6	(2.5	16.0)
	S	6.1	4.8	(0.0	28.0)	0.6	1.0	(0.0	7.0)	0.8	0.9	(0.0	3.5)
	T	2.2	7.89	(−1.0	+12.0)	2.43	1.11	(−0.5	+5.0)	2.37	1.01	(+1.5	+5.0)
	VAT*	0.03	0.01	(0.0	0.05)	0.04	0.01	(0.02	0.05)	0.03	0.01	(0.02	0.05)
aV_L													
	Q	0.28	0.81	(0.0	4.0)	0.2	0.5	(0.0	3.5)	0.1	0.2	(0.0	3.5)
	R	2.7	2.7	(0.0	10.0)	2.1	2.1	(0.0	10.0)	0.9	0.8	(0.0	3.0)
	S	6.0	3.6	(0.0	14.0)	0.4	3.9	(0.0	18.0)	0.5	3.6	(0.0	18.0)
	T	0.3	8.73	(−3.0	+2.5)	0.53	1.26	(−4.0	+6.0)	0.45	1.0	(−2.0	+2.0)
aV_R													
	Q	2.1	2.5	(0.0	9.0)	2.0	3.7	(0.0	8.0)	1.8	2.7	(0.0	8.0)
	R	3.9	2.9	(0.0	14.0)	0.8	0.9	(0.0	5.0)	0.8	0.8	(0.0	3.5)
	S	1.5	2.8	(0.0	12.0)	4.3	4.0	(0.0	13.0)	4.3	4.6	(0.0	13.0)
	T	−1.8	8.78	(−4.0	0.0)	−2.31	0.92	(−5.0	+1.5)	−2.08	0.84	(−4.0	−1.0)
aV_F													
	Q	0.36	0.66	(0.0	3.0)	0.5	1.4	(0.0	3.0)	0.7	0.2	(0.0	2.0)
	R	3.9	2.9	(0.0	14.0)	1.3	8.3	(0.0	20.0)	10.5	4.2	(0.7	20.0)
	S	1.5	2.8	(0.0	12.0)	0.2	1.3	(0.0	8.0)	0.4	2.1	(0.0	2.0)
	T	1.3	8.47	(−2.5	+5.0)	1.86	1.1	(−0.5	+5.0)	1.84	0.96	(+0.5	+4.0)

*Ventricular activation time in seconds; measured from the beginning of the QRS complex to the peak of the R wave.

TABLE IV. THE CRITERIA FOR THE DIAGNOSIS OF RIGHT VENTRICULAR HYPERTROPHY AS OBTAINED BY A STUDY OF SIXTY CASES

I. Voltage of the R and S waves and various ratios:
   1. The R wave in V_1 is 7.0 mm. or more.
   2. The S wave in V_1 is less than 2.0 millimeters.
   3. The S wave in V_5 or V_6 is 7.0 mm. or more.
   4. The sum of the amplitudes of the R wave in V_1 and the S wave in V_5 and V_6 exceeds 10.5 mm. in individuals over 5 years of age.
   5. The R wave in V_5 or V_6 is less than 5.0 millimeters.
   6. The ratio of the R to the S wave in V_5 or V_6 is 1.0 or less.
   7. The R wave in aV_R is 5.0 mm. or more.
   8. The ratio of $\frac{R/S \text{ in } V_5}{R/S \text{ in } V_1}$ is 0.4 or less.
   9. The ratio of the R wave in V_1 to the S wave in V_1 exceeds 4.0 in individuals under the age of 5.
   10. The ratio of the R wave to the S wave in V_1 exceeds 1.0 in individuals over the age of 5 years.

II. Delayed onset of the intrinsicoid deflection (delayed ventricular activation time) 0.04 to 0.07 second in V_1 and/or V_2.

III. Depression of the RS-T segment and inversion of the T wave in:
   a. V_1, less often V_2 and V_3 when the R wave equals or exceeds 5.0 millimeters.
   b. aV_L or aV_F when the R wave equals or exceeds 5.0 millimeters.

IV. Marked right axis deviation, greater than +110° suggests, but is not in itself diagnostic of, right ventricular hypertrophy.

The mean height of the R wave in V_5 in the normal group was 12.1 mm., as contrasted to 7.9 mm. in the cases of right ventricular hypertrophy, and in twenty-one cases (36 per cent), the R wave was 4.0 mm. or less. The mean height of the R wave in aV_R was 0.8 mm. in the normal subjects and 3.9 mm. in the cases of right ventricular hypertrophy. Of the latter, the voltage of the R wave in aV_R equalled or exceeded the maximum normal of 5.0 mm. in eighteen cases (30 per cent).

In addition to the absolute value of the height of the R wave and depth of the S wave, the relationship of the R wave to the S wave in V_1 and in V_5 and V_6 was found to be quite different in the group with right ventricular hypertrophy, as compared with the normal subjects (Table VI). Calculations of the R/S ratio in Lead V_5 from data on nine cases of chronic pulmonary heart disease from the paper by Salazar and Sodi-Pallares[20] revealed a mean R/S ratio of 0.94. In six of the nine cases, the R/S ratio in V_5 was less than 0.6, in contrast to the minimum normal in our series of 1.0. The difference between the two groups was more strikingly evident when the ratio of $\frac{R/S \text{ in } V_5}{R/S \text{ in } V_1}$ was determined (Table VII). The mean figure for this latter ratio was 1.6 in the cases of right ventricular hypertrophy, as compared with 32 in the normal subjects. In fifteen (48 per cent)

of the thirty-one cases of right ventricular hypertrophy in which the ratio could be calculated, the ratio $\frac{R/S \text{ in } V_5}{R/S \text{ in } V_1}$ equalled or was less than the minimum normal value of 0.4. The sum of the total right ventricular potentials R wave in V_1

TABLE V. THE FREQUENCY OF VARIOUS ABNORMALITIES OF THE VENTRICULAR COMPLEX IN RIGHT VENTRICULAR HYPERTROPHY

I.	Voltage of the R and S waves	53
	R wave in V_1, 7.0 mm. or more	35
	S wave in V_1, less than 2.0 mm.	30
	S wave in V_5 or V_6, 7.0 mm. or more	30
	R in V_1 + S in V_5 exceeds 10.5 mm. in individuals over 5 years	26
	R wave in V_5 or V_6, 4.0 mm. or less	21
	R/S ratio, 1.0 or less in V_5 or V_6	19
	R wave in aV_R is 5.0 mm. or more	18
	The ratio* $\frac{R/S \text{ in } V_5}{R/S \text{ in } V_1}$ is 0.04 or less	15
	The R/S ratio* exceeds 4.0 in patients under 5 years	9
	The R/S ratio* exceeds 1.0 in patients over 5 years	8
II.	Delayed onset of the intrinsicoid deflection (right ventricular activation time), 0.04 second to 0.07 second	42
III.	Axis deviation between +110° and −80°	37
IV.	Abnormalities of the RS-T segment and T wave	30
	Inverted T wave in V_1 with R wave 5.0 mm. or more	26
	Inverted T wave in V_1, V_2, and V_3	9
	Inverted T wave in V_1 and V_2	6
	Inverted T wave in standard Leads II and III	6
	Inverted T wave in Lead aV_L when associated with R wave greater than 5.0 mm.	4
V.	Tall P waves (greater than 2.5 mm.) in standard Leads II and III or unipolar Leads V_5, V_6, or aV_F	9

*These ratios can be calculated only when R and S waves are both present.

TABLE VI. THE R/S RATIO IN RIGHT VENTRICULAR HYPERTROPHY AS COMPARED WITH NORMAL SUBJECTS

LEAD	NORMAL				RIGHT VENTRICULAR HYPERTROPHY			
	MEAN	ST. DEV.	MIN.	MAX.	MEAN	ST. DEV.	MIN.	MAX.
V_1	0.3	0.3	(0.0	1.0)	3.1	6.3	(0.0	28.0)
V_2	0.2	1.2	(0.1	13.0)	2.1	3.1	(0.0	16.0)
V_3	1.4	1.4	(0.1	10.0)	1.9	2.4	(0.0	12.0)
V_4	4.1	3.8	(0.2	19.0)	1.6	1.7	(0.1	7.0)
V_5	7.3	4.7	(1.0	24.0)	1.4	2.4	(0.1	16.0)
V_6	9.0	5.0	(2.3	22.0)	2.1	4.5	(0.0	28.0)

TABLE VII. THE R/S IN V_5 DIVIDED BY THE R/S RATIO IN V_1 IN CASES OF RIGHT VENTRICULAR HYPERTROPHY AS COMPARED WITH NORMAL SUBJECTS

	$\frac{\text{R/S IN } V_5}{\text{R/S IN } V_1}$			
	MEAN	ST. DEV.	MIN.	MAX.
Right ventricular hypertrophy	1.61	2.26	(0.01	8.5)
Normal subjects	32.0	26.9	(0.4	100.0)

+ S wave in V_5 or S wave in V_6 proved to be significant (Table VIII). The mean sum of the amplitude of R in V_1 + S in V_5 or S in V_6 in the cases of right ventricular hypertrophy was 16.1 mm., as compared with a value of 3.7 mm. in the normal adult subjects. In twenty-six cases (out of thirty-six) of right ventricular hypertrophy over the age of five years, the sum exceeded the maximum normal value of 10.5 millimeters. In two normal children, both 5 years of age, the sum of R in V_1 plus S in V_5 equalled 15 millimeters. In only three normal subjects over the age of 5 did the sum of R in V_1 plus S in V_5 exceed 7.0 millimeters.

TABLE VIII. THE SUM OF THE AMPLITUDES OF THE R WAVE IN S_1 AND THE S WAVE IN S_5 OR V_6 (WHICHEVER IS GREATER) IN CASES OF RIGHT VENTRICULAR HYPERTROPHY AS COMPARED WITH NORMAL SUBJECTS

	R WAVE IN V_1 + S WAVE IN V_5 OR S WAVE IN V_6			
	MEAN	ST. DEV.	MIN.	MAX.
Right ventricular hypertrophy	16.1	9.0	(4.0	37.0)
Normal subjects	3.7	2.4	(0.0	10.5)

In four cases of chronic cor pulmonale with normal voltage of the R wave and normal ventricular activation time in V_1, but with an abnormal R/S ratio in V_5, the sums equalled 11, 12, 13, and 14 mm., respectively (Fig. 7). A calculation of the total right ventricular potential from the data presented on twelve cases of chronic cor pulmonale published by Salazar and Sodi-Pallares[20] revealed that in four (30 per cent) the sum of R in V_1 and S in V_5 exceeded our maximum normal value of 10.5 millimeters. These data suggest that the voltage of the right ventricular potentials may be an important associated criterion of right ventricular hypertrophy and may be especially valuable in borderline cases.

The R/S ratio in V_1 in thirteen normal infants under the age of 2 years was determined and found to be conspicuously greater than that seen in the group of older normal subjects, but was never greater than 4. In these normal infants,

the ventricular activation time* in V_1 did not exceed 0.02 second, despite an R/S ratio of 3 or 4. As will be seen later, this is in distinct contrast to the cases of right ventricular hypertrophy, in which an increased ventricular activation time was found in V_1 when the R/S ratio was of this magnitude. The R/S ratio in V_5 and V_6 in the normal infants did not differ significantly from that seen in the normal adults, again in contrast to what was found in the cases of right ventricular hypertrophy.

*Ventricular Activation Time** (time of onset of the intrinsicoid deflection).—The data in Table III indicate that the time of onset of the intrinsicoid deflection in relation to the onset of the QRS complex in Lead V_1 (ventricular activation time) is occasionally of definite value in the diagnosis of right ventricular hypertrophy. In four different series of normal subjects comprising 332 cases,[17,21,22,29] the onset of the intrinsicoid deflection (ventricular activation time) in V_1 was less than 0.04 second. Kossmann and Johnston[21] stated that the time of onset of the intrinsicoid deflection in the normal individual averages 0.02 second in V_1. In the present control series of normal subjects the upper limit of normal found in Lead V_1 was 0.03 second. This is in contrast to the cases of right ventricular hypertrophy of which 42 per cent of the total revealed a ventricular activation time of 0.04 second or more, but less than 0.07 second in V_1. Delay in the ventricular activation time was found in practically all of the proved cases of pulmonary stenosis (Figs. 1, 2, and 4), in some of the cases of mitral stenosis (Fig. 5), but rarely in the cases of chronic cor pulmonale (Fig. 7). In some instances of right ventricular hypertrophy, notching of the upstroke of the R wave occurred in V_1 (Fig. 2) and suggested the presence of an associated conduction defect, but in these cases, the ventricular activation time in V_1 was less than 0.06 second, and broad, slurred S waves in the left precordial leads were absent. The possibility of an associated right bundle branch block was considered when the ventricular activation time in V_1 exceeded 0.07 second; cases of this type have been excluded from this study. The right ventricular activation time may not be delayed in the marked right ventricular hypertrophy of pulmonary stenosis or related lesions if dextrocardia is also present (Fig. 3). In the cyanotic child whose tracing is shown in this figure, the bizarre axis, the abnormalities in the unipolar extremity leads, and the RS ratio in V_6 lead to the correct ante-mortem diagnosis of right ventricular hypertrophy.

RST-T Abnormalities.—In contrast to their frequency in left ventricular hypertrophy, abnormalities of the RS-T segment and T waves in the unipolar precordial and extremity leads were seen less frequently and were of less diagnostic value in right ventricular hypertrophy than the abnormalities of voltage and ventricular activation time. Earlier workers emphasized the importance of a depression of the RS-T segments with inversion of the T waves in Leads II and III in the diagnosis of right ventricular hypertrophy.[5-10] In the cases of the present series, these RST-T changes were seen inconsistently in Leads II and III (Table III). Depression of the RS-T segment and inversion of the T

*The time in seconds from the onset of the QRS complex to the beginning of the abrupt downstroke of the R wave.

waves, when present in the extremity leads, was seen more frequently in the left leg lead (aV_F) and more rarely found in the left arm lead (aV_L) (Figs. 4 and 7). The characteristic RST-T contour of ventricular hypertrophy with depressed convex RS-T segment and asymmetrically inverted T wave was seen more frequently in the right precordial leads than in the extremity leads. When the

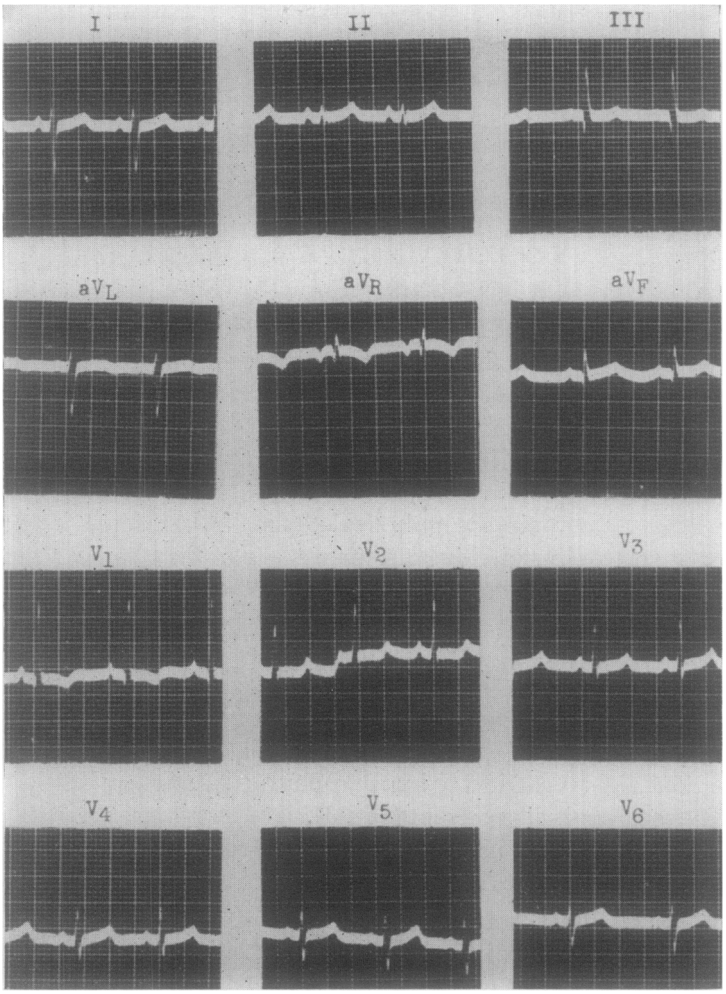

Fig. 1.—S. Z., boy, age 7, U133502. Tetralogy of Fallot. Blalock operation with excellent results. Tracing shows typical finding of right ventricular hypertrophy with marked right axis deviation, tall R wave, absent S wave, delayed ventricular activation time, slightly depressed R-ST segment and inverted T wave in V_1, and small R and deep S wave with short ventricular activation time in V_5 and V_6.

RST-T complex was normal in the standard and extremity leads (Figs. 1 and 2), characteristically tall R waves with delayed ventricular activation time and abnormal RST-T findings occasionally were seen in Leads V_1 and V_2. Inverted T waves in V_1 through V_3 appeared occasionally as the sole electrocardiographic manifestation of acute cor pulmonale (acute pulmonary embolism).

The RST-T abnormalities were first seen either in Lead V_1 or in the unipolar extremity leads. When the left leg lead was abnormal, RST-T abnormalities were usually found in standard Leads II and III (Figs. 4 and 7).

Table IX summarizes the relationship of the T wave to the height of the R wave in patients with right ventricular hypertrophy as compared with the normal subjects.

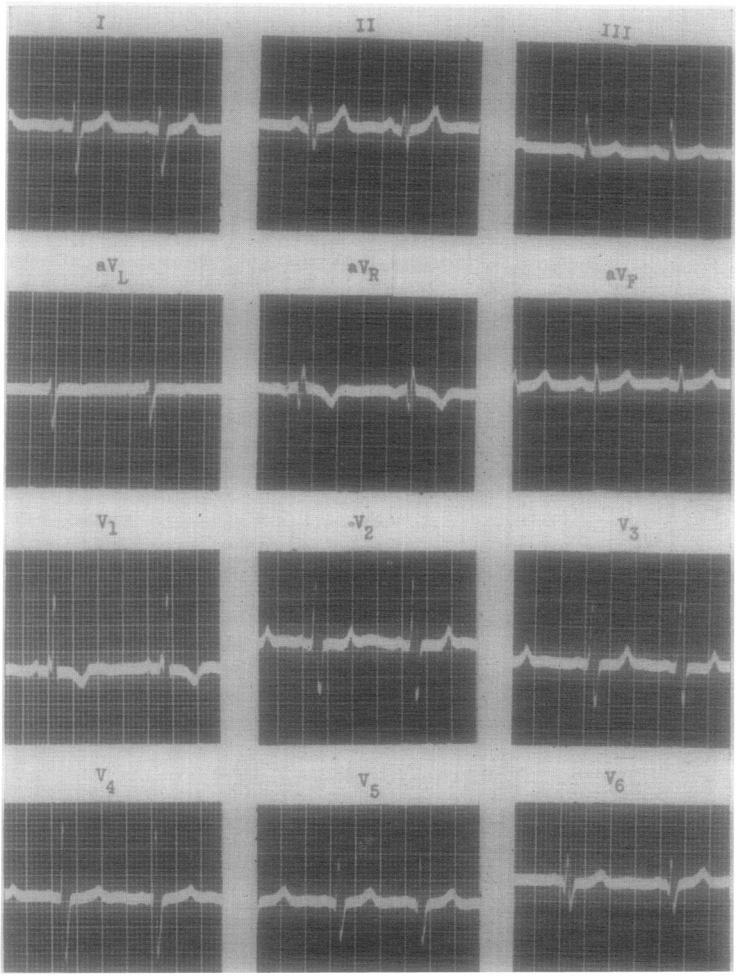

Fig. 2.—F. L., boy, age 7, U132040. Pulmonary atresia with marked right ventricular hypertrophy proved at autopsy. Note the typical findings of right ventricular hypertrophy. Lead V_1 reveals the typical abnormalities, whereas V_2 is not abnormal.

P-Wave Abnormalities.—Abnormalities of the P wave have been noted frequently in right ventricular hypertrophy. Katz[10] has referred to the so-called "P pulmonale pattern" in which large P waves occur in Leads II and III. Salazar and Sodi-Pallares[20] also emphasized the importance of abnormal P waves in Leads II, III, and aV_F in chronic cor pulmonale. Our data (Table V) show the occasional presence of these findings, although we have not diagnosed right ventricular

TABLE IX. THE RATIO OF THE R WAVE TO THE T WAVE (R/T RATIO) IN CASES OF RIGHT VENTRICULAR HYPERTROPHY AS COMPARED WITH NORMAL SUBJECTS

LEAD	NORMAL				RIGHT VENTRICULAR HYPERTROPHY			
	MEAN	ST. DEV.	MIN.	MAX.	MEAN	ST. DEV.	MIN.	MAX.
V_1	1.4	0.9	(0.3	7.0)	3.9	3.1	(0.5	11.0)
V_2	1.4	1.4	(0.2	12.0)	3.3	2.9	(0.2	11.0)
V_3	1.9	1.6	(0.3	13.0)	3.1	2.9	(0.1	15.0)
V_4	2.9	1.7	(0.3	9.0)	3.4	3.3	(0.1	17.5)
V_5	3.5	1.6	(1.0	9.0)	3.0	2.2	(0.6	10.0)
V_6	4.1	1.9	(1.7	10.0)	2.6	1.6	(0.8	7.0)
VL	2.6	1.9	(0.1	10.0)	2.6	2.1	(0.5	8.0)
VF	4.6	3.2	(0.3	14.0)	4.2	2.7	(0.7	10.0)

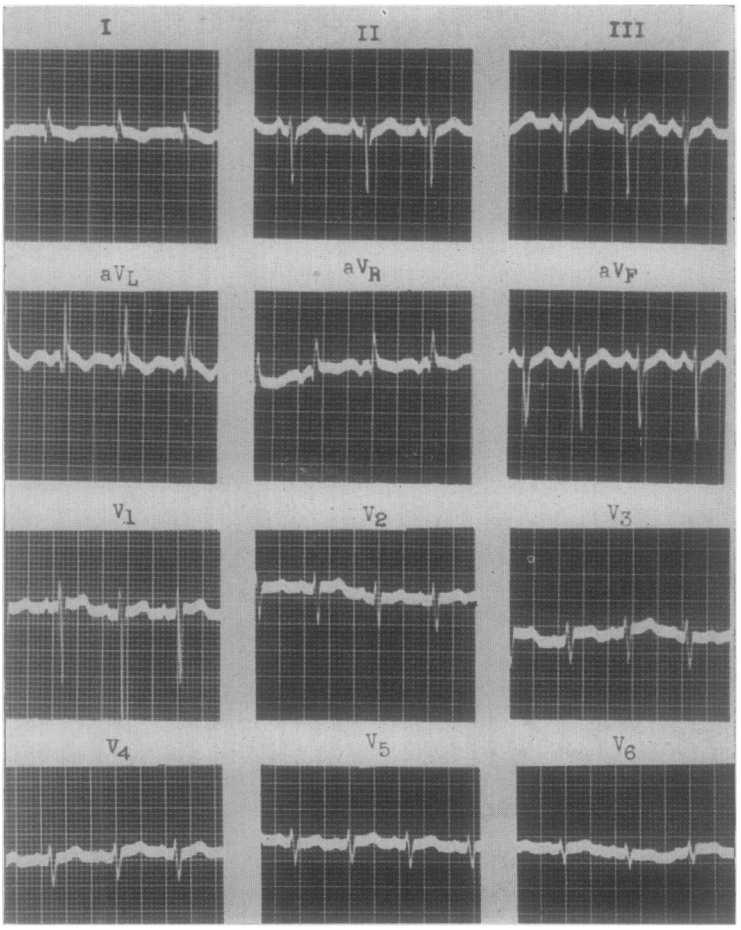

Fig. 3.—R. C., boy, age 10 months, U133966. Hypoplastic pulmonary artery, interauricular septal defect, dextrocardia, and marked right ventricular hypertrophy proved at autopsy. The dextrocardia explains the bizarre axis and absence of typical findings in Lead V_1.

hypertrophy solely on the basis of the P-wave abnormalities, nor do we recommend such a procedure. Tall, peaked P waves, rather than broad, notched P waves were the usual variation from normal seen in both the chronic cor pulmonale group (Figs. 6 and 7) and in the patients with congenital cardiac disease. In mitral stenosis, however, broad or notched P waves were the usual finding (Fig. 5).

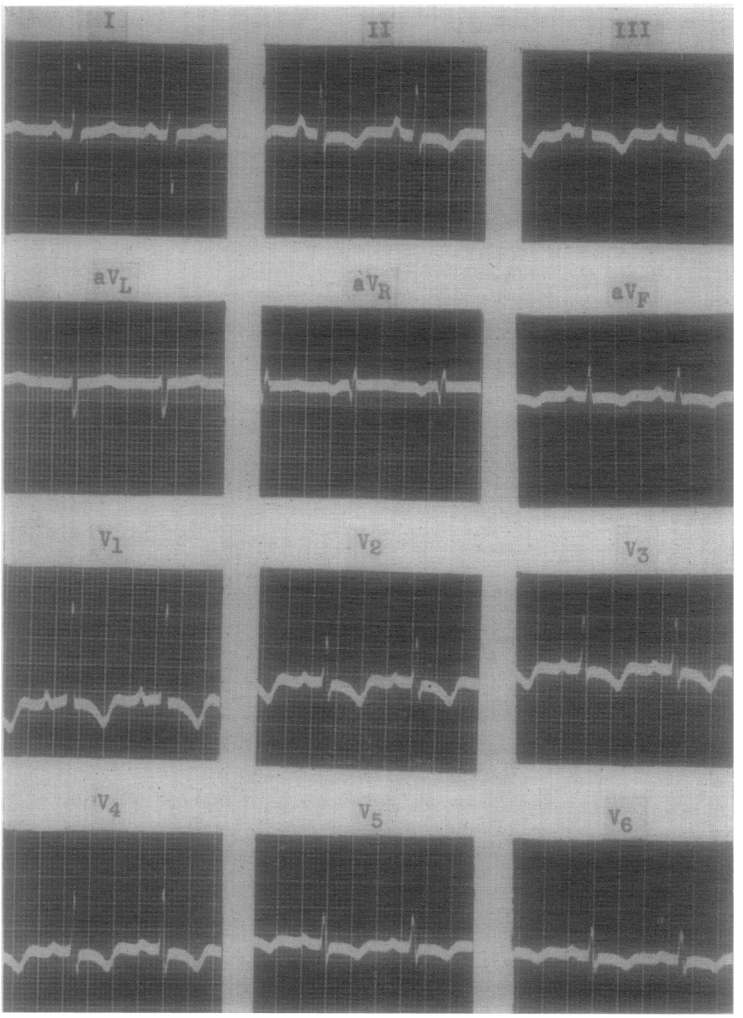

Fig. 4.—L. C., woman, age 25, U134697. Pulmonary stenosis and patent interauricular septal defect with right ventricular hypertrophy proved at autopsy. Right ventricular thickness, 1.5 cm.; left ventricular thickness 1.1 cm. Normal coronary arteries.

Electrocardiographic Position of the Heart.—The electrocardiographic position of the heart, using the criteria of Wilson and his associates,[12] was frequently indeterminate. A horizontal position was noted on occasion, but often neither the right nor the left precordial leads in any way resembled the electrocardiographic patterns of the left leg or the left arm leads. At times, the right pre-

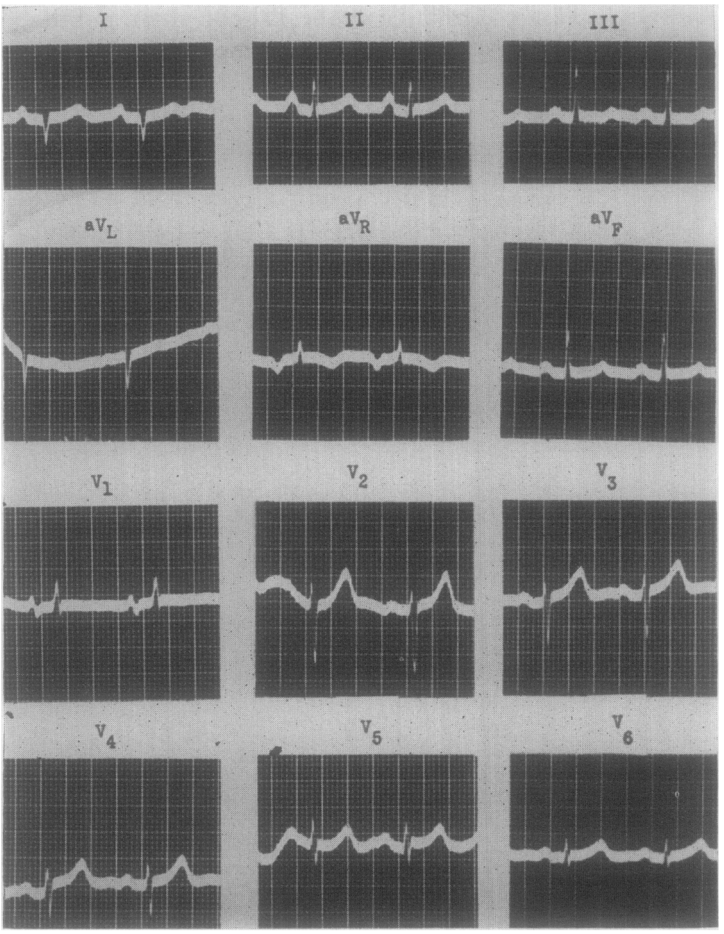

Fig. 5.—G. T., woman, age 29. Mitral stenosis. Note the abnormal P waves in Leads II, III, and aV_F, the monophasic upright R wave in aV_R, the broad negative phase of the P wave in V_1, and the R/S ratio in V_1 with a ventricular activation time of 0.04 second. The R/S ratio in V_1 is definitely abnormal, whereas that in V_2 is quite normal.

cordial leads most closely resembled the pattern seen in the right arm lead, suggesting that rotation of the heart had occurred in such a manner as to allow the right ventricle to face the right arm. Variations in the pattern of right ventricular hypertrophy in the standard leads due to variable position of the heart were seen less frequently than in left ventricular hypertrophy.[30] The electrical axis was calculated according to the method of Carter and his associates[23] and the findings tabulated. It was found that practically all patients with congenital cardiac disease with marked right ventricular hypertrophy had a marked right axis deviation, usually greater than $+120°$, and at times ranging into bizarre axes such as -160 degrees. The axes obtained in the lesser degrees of right ventricular hypertrophy, such as were found in mitral stenosis and chronic cor pulmonale, fell into the range of the upper limits of normal, so that axis deviations of $+80°$ to $+110°$ were noted frequently in these cases.

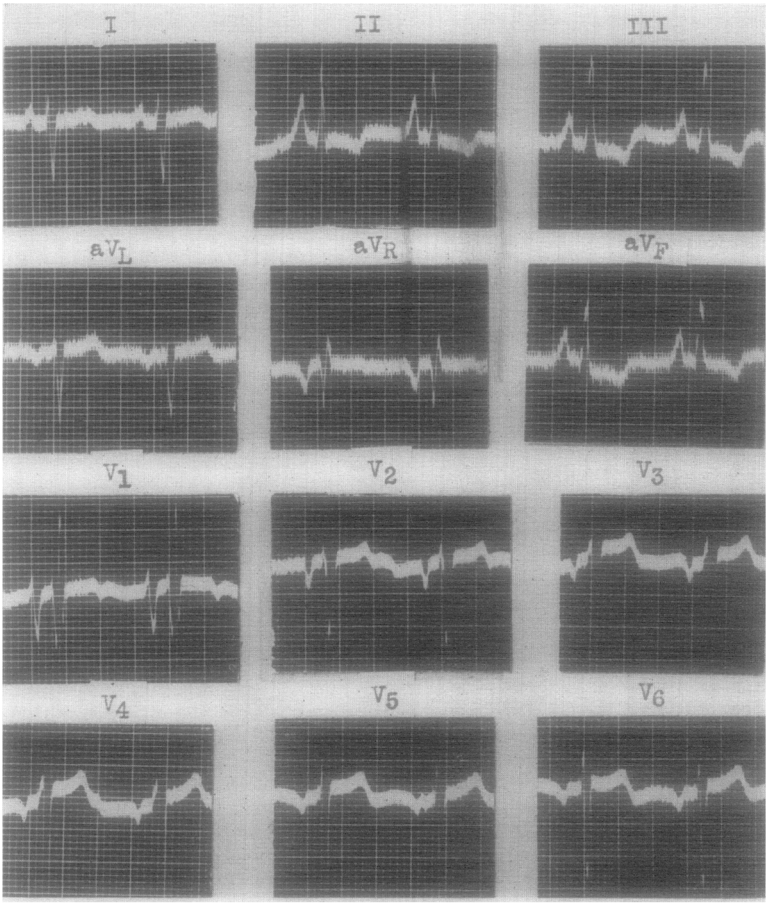

Fig. 6 (Courtesy of Dr. Mervin J. Goldman, Veterans Administration Hospital, Oakland, Calif.).—V. H. S., a man, age 60. Increasing cough, sputum, and dyspnea for twelve years. On admission, right heart failure. Autopsy showed diffuse pulmonary fibrosis, emphysema, and bronchiolectasis. Right ventricular wall, 10 mm; left ventricular wall, 10 mm.; heart weight, 460 grams.

DISCUSSION

It is apparent that the electrocardiographic findings are reliable and consistent in the well-marked case of right ventricular hypertrophy such as occurs in pulmonary stenosis or tetralogy of Fallot (Figs. 1, 2, and 4). Such hypertrophy can be strongly suspected if the electrical axis in the standard limb leads is greater than +110 degrees. Definitive criteria, however, required a study of Leads V_1, V_5, and occasionally aV_R. Abnormal findings in Lead aV_R were rarely observed unless diagnostic changes were also seen in Leads V_1 and/or V_5. In the eighteen cases of congenital cardiac disease verified at surgery or autopsy, all had the typical findings of right ventricular hypertrophy in Leads V_1, V_5, and aV_R (Figs. 1, 2, and 5).

The differentiation of normal from abnormal right axis deviation is of clinical importance and cannot reliably be made from the standard leads alone, even

though the electrical axis is greater than +110°, and abnormalities of the RS-T segment and T waves occur in Leads II and III. The unipolar extremity leads have proved of value in this differentiation by indicating a normal vertical position of the heart to explain the right axis deviation (Fig. 8). However, when individuals with cardiac lesions, such as mitral stenosis, were found to have vertically placed hearts and right axis deviation, further study was required with unipolar precordial and limb leads to determine whether the axis deviation was

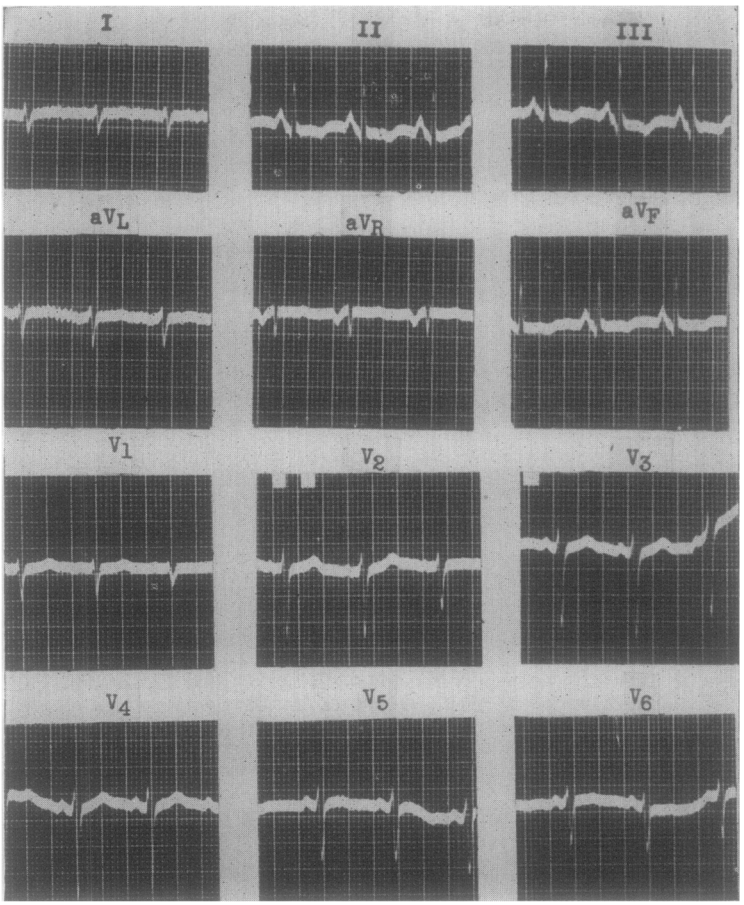

Fig. 7.—W. D., man, age 34, U134878. Chronic asthma, emphysema, and cor pulmonale. Note the abnormal RST-T complex in Leads aVF, II, and III with the low, upright T wave in aVR. The very small R in V_5 and V_6 with a deep S wave in these leads is abnormal. The R wave in V_1 plus the S in V_5 equals 11 millimeters.

due to right ventricular hypertrophy or to a vertical heart with a clockwise rotation on its longitudinal axis. The precordial leads were most helpful in this situation since none of the findings characteristic of right ventricular hypertrophy were observed in these leads in normal subjects with vertical hearts and right axis deviation. Leads V_1 and V_5 were of especial value, and from the changes in these leads the diagnosis was made in most cases. The importance of establishing the diagnosis of right ventricular hypertrophy in individuals with cardiac

lesions which put a strain on the right side of the heart is clear. As Katz[10] stated: "The presence of right ventricular hypertrophy indicates that an acoustically evident valvular lesion has become dynamically important." The prognosis is therefore less favorable.

It is not clear why the predominant features of right ventricular hypertrophy should often be seen solely in Lead V_1 and less often in V_2 as well (Figs. 1, 2, and 5) since the clockwise rotation of the heart in right ventricular hypertrophy

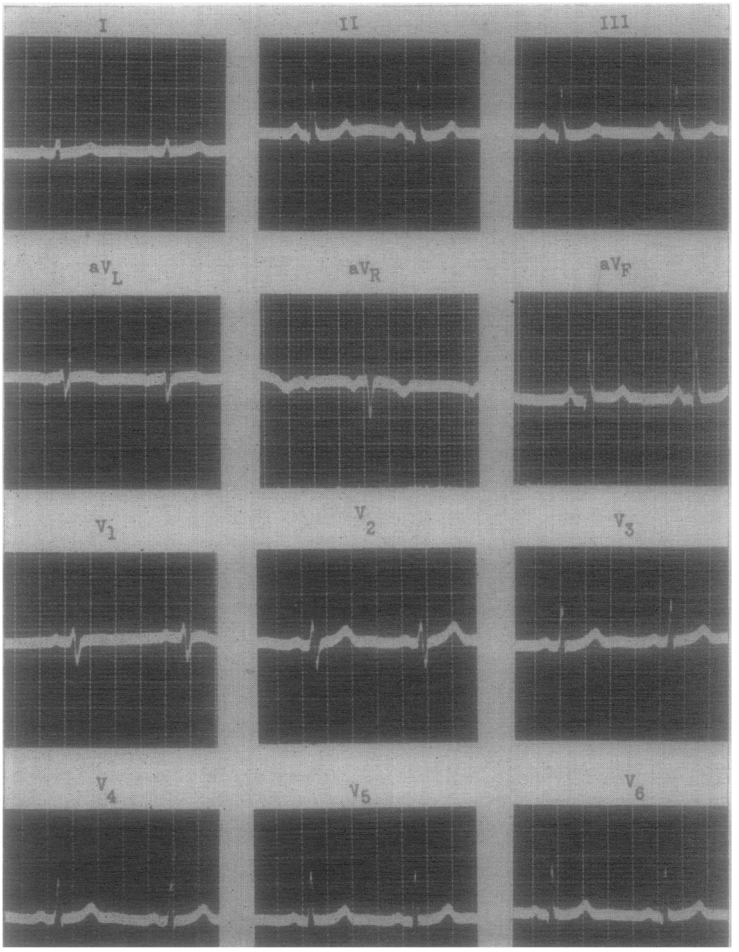

Fig. 8.—B. P., woman, age 22, U111442. Axis +85. Normal vertical heart.

allows the right ventricle to present as the major portion of the anterior cardiac surface. But in precordial Positions 3 and 4, despite the fact that the exploring electrode is presumably over the right ventricle, patterns similar to those from the left ventricle have been obtained (Fig. 2). This is of practical importance because some clinics utilize Position 2 as the site for recording the routine right precordial lead. If right ventricular hypertrophy is suspected, Lead V_1 should

be taken, because often V_2 is not abnormal (Fig. 2) and the diagnosis of right ventricular hypertrophy would then be dependent largely on the changes in V_5 and V_6, leads which give signs of lesser reliability (Figs. 6 and 7).

A study of the electrocardiographic position of the heart has revealed errors in the diagnosis of ventricular hypertrophy. Earlier authors have described the combination of right axis deviation and inverted T wave in standard Leads II and III as typical of right ventricular hypertrophy.[5-10] However, we have noted cases of *left* ventricular hypertrophy in vertical hearts, where the same combination of findings may be present in the standard limb leads (Fig. 9). This fact has been described clearly by Wilson and his associates,[12] but apparently has not been sufficiently appreciated. Study of the precordial leads in these cases will reveal the changes in V_5 and V_6 as being the result of left and not right ventricular hypertrophy, and the left leg lead will show the findings seen in left ventricular hypertrophy. Since the abnormal RST-T changes appear in Lead aV_F, they usually also appear in Leads II and III. In occasional cases, the RS-T abnormalities may appear only in Lead aV_F. The right axis deviation is due to the vertical position of the heart. Left ventricular hypertrophy can be suspected in these circumstances because the S wave in Lead I may be small or absent and the R wave is usually tall in Leads II and III (Fig. 9). The precordial leads, however, are required for the definitive diagnosis.[30]

The frequency of right ventricular hypertrophy in chronic pulmonary disease (as determined by autopsy) has been stressed,[24,25,26] and yet the clinical diagnosis of right ventricular hypertrophy has been difficult to establish. Our results suggest that calculation of the various ratios and reference to the data on voltage presented may be helpful in diagnosis. Salazar and Sodi-Pallares[20] in a recent study of fourteen cases of chronic pulmonary heart disease have commented on the frequency of normal findings in Leads V_1 and V_2 in this group of cases and the fact that reliance for diagnosis must be placed on abnormalities found in Leads V_5 and V_6 and on the abnormal P-wave pattern. Care must be taken that precordial leads are taken sufficiently far to the left in order to be well past the transitional zone before a small R and prominent S wave in Leads V_5 or V_6 are interpreted as supportive evidence for right ventricular hypertrophy. In patients with marked clockwise rotation of the heart, a prominent S wave may be present over a transitional zone which occasionally is displaced as far to the left as Position 6 or rarely 7. A small R wave may be found over the fringes of a myocardial infarct, but here a deep S wave is rarely seen.

Further study is required in infants and in cases of early right ventricular hypertrophy due to cor pulmonale and mitral stenosis in order to establish the reliability of these criteria when the variations from normal occur solely in the left precordial leads.

Myers and his associates[28] have published very recently an excellent paper on the electrocardiographic criteria of right ventricular hypertrophy based on forty autopsied cases. This paper appeared just as the final draft on our paper was being prepared. Myers and his associates emphasized the importance of the R/S ratios in the right and left precordial leads, the ventricular activation time,

the inversion of the T wave in Lead V_1, and the fact that incomplete or complete right bundle branch block may be associated with right ventricular hypertrophy. They noted the need for considering the possibility of abnormal displacement of the transitional zone to the right or to the left before attributing the findings to hypertrophy of the right ventricle. They also emphasized the relative diagnostic inadequacy of the pattern of a depressed RS-T segment in Leads II and III and inversion of the T wave in these leads, findings that for so long have been considered the basic pattern for right ventricular hypertrophy.

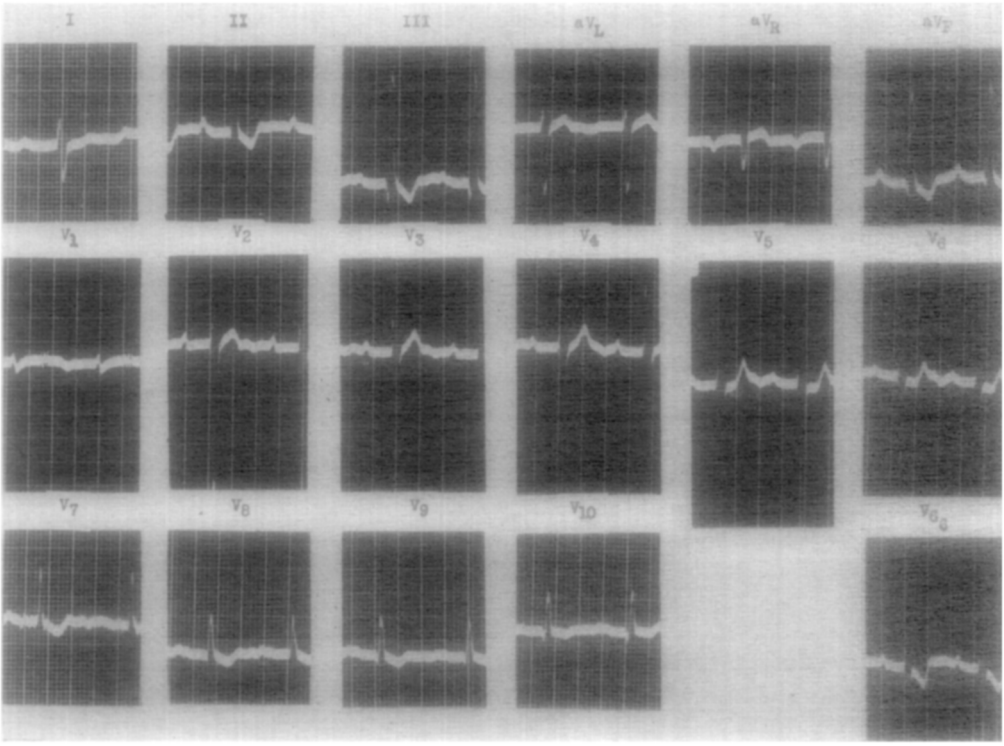

Fig. 9.—M. S., a woman, age 30. Congenital heart disease with large pulmonary artery and left ventricular hypertrophy confirmed by Diodrast angiocardiogram. Right axis deviation with inverted T_2 and T_3 plus the deep S in V_6 suggested right ventricular hypertrophy, but the abnormalities in aV_F indicated the need for further left precordial exploratory leads. Leads V_7 to V_{10} and V_6 in the sixth intercostal space indicated left ventricular hypertrophy with displacement of the transitional zone to Position 7.

The detailed data given by Myers and his associates on forty autopsied cases with right ventricular hypertrophy in Table II of their paper[28] were used to determine the reliability of the criteria which we have compounded from a study of our sixty cases. Of the thirty-three cases in Groups A through E of their classification, all would have been diagnosed as right ventricular hypertrophy by our criteria. Of the seven cases in Group F which were not diagnosed as right ventricular hypertrophy ante mortem by Myers and his associates, Case 37

would have been diagnosed right ventricular hypertrophy according to our criteria. The reliability of our diagnostic criteria when applied to Myers' autopsied cases is demonstrated by the analysis summarized in Table X.

TABLE X. THE FREQUENCY OF VARIOUS ABNORMALITIES OF VOLTAGE OF THE VENTRICULAR COMPLEX IN RIGHT VENTRICULAR HYPERTROPHY CALCULATED FROM DATA PUBLISHED ON FORTY AUTOPSIED CASES BY MYERS AND HIS ASSOCIATES,[28] AND COMPARED WITH THE PRESENT SERIES OF SIXTY CASES

VOLTAGE OF THE R AND S WAVES	FREQUENCY			
	MYERS ET AL. (40 CASES)		SOKOLOW AND LYON (60 CASES)	
	NO.	PER CENT	NO.	PER CENT
R wave in V_5 or V_6 4.0 mm. or less	18	45	21	35
R wave in V_1 7.0 mm. or more	15	38	35	58
S wave in V_1 less than 2.0 mm.	13	33	30	50
S wave in V_5 or V_6 7.0 mm. or more	13	33	30	50
R wave in V_1 + S wave in V_5 exceeds 10.5 mm.	8	20	26	43
R/S ratio 1.0 or less in V_5 or V_6	11	28	19	32
R wave in aV_R 5.0 mm. or more	9	23	18	30
The ratio $\frac{\text{R/S wave in } V_5}{\text{R/S wave in } V_1}$ is less than 0.4	11	28	15	25

CONCLUSION AND SUMMARY

1. An analysis of the electrocardiographic patterns as obtained by unipolar leads in sixty cases of right ventricular hypertrophy is presented and compared with the findings in 150 normal subjects.

2. The typical electrocardiographic pattern of right ventricular hypertrophy, as seen in the tetralogy of Fallot, consists of a tall R wave, a small to absent S wave, and delayed intrinsicoid deflection (delayed ventricular activation time) in the right precordial leads, especially V_1; a small R and prominent S wave with a small R/S ratio in the left precordial Leads V_5 and V_6; a prominent R wave in aV_R; the RS-T segment may be depressed and T wave inverted in Lead V_1 or V_2; similar RST-T changes may occur in Lead aV_L or aV_F and Leads II and III, but these changes are inconsistent; and the standard leads may show right axis deviation or marked left axis deviation if unusual rotation has occurred.

3. Any of the changes noted in (2) may be absent or less strikingly abnormal when seen in the early development of the pattern of right ventricular hypertrophy. This occurs most typically in cases of mitral stenosis and cor pulmonale.

4. The R/S ratio in Lead V_1 exceeded the maximum normal value of 1.0 in adults in forty-three (72 per cent) of the cases of right ventricular hypertrophy; the R/S ratio in Leads V_5 or V_6 was less than the minimum normal value of 1.0 in nineteen (32 per cent) of the cases of right ventricular hypertrophy. Calculation of these ratios was thus very helpful in the diagnosis of right ventricular hypertrophy.

5. The R/S ratio in Lead V_5 divided by the R/S ratio in V_1 was less than the minimum normal value of 0.4 in fifteen (48 per cent) of the cases of right ventricular hypertrophy in which the ratio could be calculated.

6. The maximum normal height of the R wave of 7.0 mm. in V_1 was exceeded in thirty-five (58 per cent) of the cases of right ventricular hypertrophy.

7. The sum of the total right ventricular potentials (the height of the R wave in Lead V_1 plus the depth of the S wave in Lead V_5 or V_6) in twenty-six of thirty-six cases of right ventricular hypertrophy exceeded the maximum normal value of 10.5 mm. in adults.

8. In chronic cor pulmonale, diagnosed clinically, the only electrocardiographic abnormality may be a small R wave in Lead V_5 or V_6 accompanied by a prominent S wave and a small R/S ratio in these leads. The findings in these leads were similar to those obtained in the same leads in definite right ventricular hypertrophy (as in pulmonary stenosis) and differ from the findings in normal vertical hearts. Such findings, therefore, should permit one to suspect, but not definitely diagnose, right ventricular hypertrophy. In four cases of chronic cor pulmonale in which a small R/S ratio in Leads V_5 and V_6 represented the only abnormal findings, the sum of the R wave in V_1 and the S wave in V_5 exceeded the maximum normal of 10.5 mm. and, therefore, the suspicion of the presence of right ventricular hypertrophy was strengthened.

9. Unipolar precordial leads may differentiate normal from abnormal right axis deviation by demonstrating either the normal pattern or that of right ventricular hypertrophy. The patterns obtained in unipolar precordial leads in cases of normal vertical hearts with right axis deviation of $+80°$ or more do not differ from the findings obtained by similar leads in normal intermediate or horizontal hearts.

10. Unipolar precordial leads in infants were characterized by a greater R/S ratio in Leads V_1 and V_2 than is seen in older individuals; these infants do not, in a limited study, show the delayed intrinsic deflection in Leads V_1 and V_2 or the altered R/S ratio in V_5 and V_6 that characterizes right ventricular hypertrophy.

11. The electrocardiographic position of the heart could not be determined accurately in many cases of right ventricular hypertrophy because neither the right nor left arm leads resembled either the right or left precordial leads. At times the right precordial leads resembled most closely the right arm lead, suggesting that in addition to the clockwise rotation on the longitudinal axis of the heart characteristic of right ventricular hypertrophy, the right ventricle and anterior portion of the cardiac surface is rotated clockwise around the anteroposterior axis of the heart.

Grateful acknowledgment is made to Miss Nancy Gelardi, Mrs. Doris Tuttle, Mrs. Angelina Galente, and Mrs. Suzanne Cahill for their technical assistance, and to Dr. John C. Talbot for statistical advice.

ADDENDUM

To date we have had eighteen cases in which the electrocardiographic diagnosis of right ventricular hypertrophy was made on the basis of the criteria presented. In seventeen patients the right ventricle was at least 5 mm. thick and in the remaining patient a single ventricle 7 mm. thick was presented.

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