Wave Amplitude Relationships in the Normal Electrocardiogram

LEON MICHAELS AND JOHN E. KLOVAN

From the Department of Medicine, University of Manitoba, Winnipeg, Canada

The characteristics of the standard 12-lead electrocardiogram have been determined by studies based on large numbers of apparently normal subjects (Kossmann and Johnston, 1935; Myers *et al.*, 1947; Sokolow and Friedlander, 1949; Hiss, Lamb, and Allen, 1960). Means, standard deviations, and percentile distributions have been calculated for all waves. Relationships between amplitudes of waves appearing in different leads have been described qualitatively (Kossmann and Johnston, 1935), and used quantitatively to determine the mean frontal plane QRS axis (Wilson *et al.*, 1944) and to establish criteria for diagnosis of left or right ventricular hypertrophy (Sokolow and Lyon, 1949a, b). However, with one notable exception (Simonson, Cady, and LaRiviere, 1964), no systematic quantitative studies have been made of amplitude relationships between different waves in the normal electrocardiogram. The present study was undertaken in an attempt to delineate such relationships and to determine their clinical usefulness. Criteria are suggested whereby waves that are within currently accepted limits of normal may be identified as abnormal on the basis of abnormal relationships to other waves.

SUBJECTS AND METHODS

The electrocardiograms used in the present study were recorded in 36 men and 22 women aged 30 to 70 years as part of a study of the normal day-to-day variability of the electrocardiogram. In no subject was there any clinical or radiological evidence of cardiovascular disease and the electrocardiograms were individually normal by current criteria. Details of patient selection and recording techniques have been described earlier (Michaels and Cadoret, 1967). In all subjects, R, S, and T wave amplitudes were measured on each of four consecutive days under standardized conditions, and their means were determined. These were used to

calculate coefficients of correlation r between each wave amplitude and each other wave amplitude, an I.B.M. 1620 computer being used for this purpose.* For reasons to be discussed later, the relationships between the voltages of the following pairs of waves were selected for subsequent further study: (1) R and T in all leads; and (2) R, S, and T in each chest lead and the corresponding R, S, and T in each of the remaining 5 chest leads.

When the coefficients of correlation between any of these exceeded $+0.60$ ($p < 0.0005$), graphs were constructed in which mean amplitude values for the waves in each pair were plotted for all subjects (Fig. 1-3). For example, all 58 values for RV1 were plotted along the x-axis of one such graph and the corresponding values for RV2 along the y-axis (Fig. 2a). Regression equations relating amplitudes in each pair of waves were calculated by the method of least squares and standard errors of estimate computed. The 95 per cent confidence limits were calculated using the formula

$$y' = \bar{y}_x \pm 2.0 \times \text{SE of estimate} \times \sqrt{1 + \frac{1}{n} + \frac{(\bar{x} - \bar{x})^2}{(n-1)(\text{var. of } x)}}$$

when n is the number of subjects, $\bar{x}$ the mean of x , and $\bar{y}_x$ and y' denote, respectively, the mean estimate and the 95 per cent confidence limits of y for any given value of x (see also Fig. 2e). Regression lines and 95 per cent confidence limits were drawn for each pair of waves.

The range of normal thus delineated by the 95 per cent confidence limits has been termed the "relative normal range", in contrast to the "absolute normal range", derived from previous measurements of the amplitude of individual waves (Kossmann and Johnston, 1935; Myers *et al.*, 1947; Sokolow and Friedlander, 1949).

RESULTS

Inspection of the tracings showed that RV2 was invariably larger than RV1. TV2 was invariably

* A complete table of these coefficients is available from the authors on request.

Received August 25, 1967.

FIG. 1.—Relationships between amplitudes (in tenths of a millivolt) of R and T waves in (a) lead I and (b) lead aVL.

less negative or more positive than TV_1 . The site of the transition zone showed normal variability, but in no case was it characterized by QRS complexes that were much smaller than those recorded to its right and left. With one exception, RV_6 was invariably smaller than RV_5 .

Among the pairs of waves selected for further study, coefficients of correlation of +0.60 or more were found in the following: (1) R and T in leads I and aVL; (2) R in all adjacent chest leads, e.g. V_3 and V_4 ; (3) S in V_2 and V_3 , V_3 and V_4 , V_4 and V_5 ; and (4) T in all adjacent chest leads; T in V_2 and V_4 .

The coefficients of correlation between R, S, and T wave amplitudes of "separated" chest leads such as V_3 and V_5 were consistently less than the coefficients relating to adjacent leads such as V_3 and V_4 .

With increasing separation of the leads, the correlations became consistently poorer.

Inspection of the graphs and data plots for each subject suggested an approximately linear relationship between the heights of the waves in each pair. No obvious sex differences in amplitude relationships were detectable, though individual wave size tended to be greater among the men.

Relationships between R_I and T_I and between R_{aVL} and T_{aVL} are shown in Fig. 1, relationships between R waves in adjacent chest leads in Fig. 2, and the corresponding relationships between T waves in Fig. 3. Use of the figures is best illustrated by examples. Consider (Fig. 3c) an electrocardiogram in which TV_3 measures 8 mm. and TV_4 3 mm. (10 mm. $\equiv$ 1 mV). A line drawn upwards from the 8 mm. mark on the x-axis of Fig. 3c

FIG. 3.—Relationships between T wave amplitudes (in tenths of a millivolt) in adjacent chest leads. (a) V1-V2, (b) V2-V3, (c) V3-V4, (d) V4-V5, (e) V5-V6.
 — regression line
 - - - 95 per cent confidence limits
 - - - line of identity
 ○ men
 ● women
 For significance of vertical line and arrow in Fig. 3c see text.

crosses the lower interrupted line at a point (marked by an arrow) corresponding to 5.1 mm. on the y-axis. 5.1 mm. is therefore the lower limit of normal for TV4 in an electrocardiogram in which TV3 measures 8 mm. A 3 mm. T wave in lead V4 would therefore be abnormally small according to the standards now being proposed, despite being within the "absolute normal range". In the same way, inspection of Fig. 1b suggests that when RaVL exceeds 7 mm., inversion of TaVL is to be considered abnormal, in so far as falling outside the 95 per cent confidence limits may be equated with abnormality.

DISCUSSION

According to vector theory, the voltages recorded in any limb lead are derived from potentials generated by the heart, these being modified by the conducting properties of the body and the solid angle between the cardiac vector and the lead axis (Lamb, 1965). Were these conducting properties and geometrical relationships identical in all subjects, correlations between wave amplitudes in any two leads, e.g. RI and RaVL, would invariably be perfect. The voltages recorded would vary from subject to subject but, to cite the example given, the relationship between the voltages of RI and RaVL would be constant for all subjects in a population. In any person, if the voltage of RI were known, that of RaVL would be accurately predictable. (For theoretical purposes the absence of any errors of measurement is assumed.) In practice, people are not identical either in tissue conductivity or in geometrical relationships between cardiac vectors and limb lead axes. The extent to which they resemble each other or differ is reflected in the proximity or otherwise to unity of coefficients of correlation between wave amplitudes in different limb leads. In a population, the coefficient of correlation between the amplitudes of, say, RI and RaVL reflects the extent to which these amplitudes are related and, secondarily, the closeness of the limits within which the voltage of RaVL in any one person is predictable from a knowledge of the voltage of RI. In the present study, correlations between waves in pairs of limb leads were often highly significant. Regression lines similar to those illustrated could therefore have been constructed and confidence limits established. These, however, would have been without clinical value as they would not have contributed to interpretation of electrical events within the heart. Values outside the confidence limits would only have indicated unusual relationships of cardiac vectors and lead axes to each other, or exceptional conditions determining electrical conductivity between heart and recording electrodes.

No attempt was made, therefore, to define the "relative normal ranges" of the limb lead amplitudes.

In the case of the chest leads, too, the proximity or otherwise of the coefficients of correlation to unity reflects largely the extent to which people resemble each other or differ with respect to (1) the geometrical relationships between cardiac vectors and lead axes, and (2) the conducting properties of the tissues between the surface of the heart and the electrodes. However, wave amplitude relationships in the chest leads may also be influenced by local electrical forces arising in the myocardium underlying a recording electrode and affecting a single lead. Factor analysis of the electrocardiogram indicates that over 95 per cent of all electrocardiographic information can be ascribed to three "internal generators" (Scher, Young, and Meredith, 1960). On the other hand, Helm (1953) found significant differences between actual recordings of unipolar chest leads and corresponding scalar leads derived electrically from three component leads of a spatial electrocardiogram. This suggests that the electrical activity recorded by electrodes on the chest cannot be accounted for by vector forces alone. The results of cancellation studies have been similar (Levine, Schmitt, and Simonson, 1953). Local forces have been used by Grant, Estes, and Doyle (1951) to explain T wave inversion occurring in a single chest lead. Such forces could be insufficient to raise or reduce wave size above or below accepted limits of normal, yet be sufficient to disturb relationships between wave amplitudes, determination of which has consequent potential clinical value in chest as opposed to limb leads.

Among factors affecting the closeness of correlation between R and T wave amplitudes is individual variability in the mean spatial QRS-T angle. Hiss *et al.* (1960) found that this can vary normally by as much as 70°, and Simonson and Keys (1954) observed even greater variability. Furthermore, R alone does not represent the depolarizing vector, the importance of the S wave being great though varying. In the chest leads, correlations between R and T wave amplitudes tended to be poorer in leads with prominent S waves and better in leads with small or absent S waves; correlation improved steadily with progression from V1 towards V6. Our finding of correlations between R and T wave amplitudes that were frequently significant but usually insufficiently close for prediction in individual tracings is similar to that of Simonson (1961).

To date, the only detailed study of amplitude relationships in different leads has been made by Simonson *et al.* (1964). The present investigation,

though not covering all possible lead combinations, has included a larger number of waves and leads. The charts are simpler to use, with choice of x and y axes based largely on the conventional practice of reading chest leads from right to left. The data now being presented have, however, been based on a population smaller than that studied by Simonson *et al.* (1964), and should, therefore, be considered a preliminary investigation and applicable only to a population similar to that studied. Inaccuracies due to use of wave amplitudes instead of areas are unlikely to have been great, as the relationships between amplitudes and areas are very close in the case of both the QRS complexes and the T waves (Simonson *et al.*, 1954). Pooling the data on both sexes was considered justified as no sex differences in relationships between amplitudes were detectable on inspection of the graphs. The selection of pairs of waves, based on a coefficient of correlation of 0.60 or more, was perhaps a little arbitrary. With 58 subjects, significance at the 5 per cent level is reached when r exceeds 0.25. A coefficient very much greater than this is necessary, however, if confidence limits are to be close and the "relative normal range" narrow enough to be of practical utility when assessing waves in individual electrocardiograms.

When an x-axis wave is near the lower limit of normal, the minimum y-wave amplitude, as delineated by the 95 per cent confidence limits, may be below the "absolute normal range". Conversely, when the x-axis wave is near the upper limit of normal, the maximum y-wave amplitude so delineated may be above the "absolute normal range". This is because the determinants of the normal range shown by the 95 per cent confidence limits are (1) the variances of the x-axis waves and (2) the variances of the relationships between the x- and y-axis waves; the effects of these two factors are additive. The y-axis wave should only be considered normal if within both the "relative" and the "absolute normal range". Furthermore, when using Fig. 2a and 3a, RV2 and TV2 should only be considered normal if above the line of identity; RV2 and TV2 were never algebraically less than RV1 and TV1, respectively.

It is suggested that for any amplitude of an R or T wave in any chest lead, the normality or otherwise of the R or T wave in the next lead to the left may be determined with 95 per cent probability by inspection of the appropriate figure. Similarly, the normality or otherwise of TI or TaVL may be determined for any amplitude of RI and RaVL, respectively. Even if within the "absolute normal range", amplitudes beyond the confidence limits should be suspected of being abnormal. Defining

abnormalities in S wave relationships is similarly possible in the cases of leads V2 and V3, V3 and V4, and V4 and V5. These, however, have limited practical applicability and have not, therefore, been illustrated. In contrast, an ability to detect abnormalities in R and T wave amplitude relationships has several possible clinical applications, providing, of course, that care is taken to site the chest lead electrodes accurately. For example, an anterior myocardial infarction may be characterized by R waves that remain small or diminish in size with progression from V1 towards V6 (Levy and Hyman, 1950). In the absence of Q waves, the individual complexes in such electrocardiograms may all be within the "absolute normal range". Using the criteria now being presented, however, such complexes may be characterized as abnormal on the basis of abnormalities in relations between R wave amplitudes in adjacent chest leads. Another possible application is in recognition of abnormalities in relative amplitudes of RV5 and RV6 in patients suspected of having left ventricular hypertrophy. Abnormal T wave relationships in V1-4, of the type associated with right ventricular "strain", may be similarly detectable. Recognition of primary T wave changes as seen in anterior or lateral myocardial ischaemia may be facilitated by recognition of abnormalities in relationships of T waves in the chest leads or of R and T waves in leads I and aVL. Quantitatively defining the range of normal in wave amplitude relationships may thus facilitate greatly the recognition of minor electrocardiographic abnormalities. As with other non-specific changes, determination of cause must depend on the total clinical picture.

SUMMARY

The relationships between amplitudes of different waves were determined in normal 12-lead electrocardiograms. These were recorded in 58 subjects aged 30 to 70 years who were clinically and radiologically free of heart disease. Using a computer, the coefficients of correlation between each R, S, and T wave amplitude and each other R, S, and T wave were determined. Coefficients exceeding 0.60 ($p < 0.0005$) were found, *inter alia*, in the cases of (1) R and T in leads I and aVL, (2) R in all pairs of adjacent chest leads, and (3) T in all pairs of adjacent chest leads. Regression equations and 95 per cent confidence limits were calculated for each of the above pairs of waves and charted. It is suggested that, by reference to the appropriate charts, a "relative normal range" for any of the following may be determined: (1) TI and TaVL for any amplitude of RI and RaVL respectively; (2) R in any one of the leads V2-V6 for any amplitude of

R in the chest lead to its immediate right; and (3) T in any one of the leads V2 to V6 for any amplitude of T in the chest lead to its immediate right.

It is postulated that in electrocardiograms in which the waves are individually normal, an ability to detect abnormalities in R and T wave amplitude relationships may have practical application by facilitating recognition of minor electrocardiographic departures from normal.

REFERENCES

- Grant, R. P., Estes, E. H., Jr., and Doyle, J. T. (1951). Spatial vector electrocardiography. The clinical characteristics of S-T and T vectors. *Circulation*, **3**, 182.
- Helm, R. A. (1953). The vectorcardiographic derivation of scalar leads. *Amer. Heart J.*, **46**, 519.
- Hiss, R. G., Lamb, L. E., and Allen, M. F. (1960). Electrocardiographic findings in 67,375 asymptomatic subjects. X. Normal values. *Amer. J. Cardiol.*, **6**, 200.
- Kossmann, C. E., and Johnston, F. D. (1935). The precordial electrocardiogram. I. The potential variations of the precordium and of the extremities in normal subjects. *Amer. Heart J.*, **10**, 925.
- Lamb, L. E. (1965). *Electrocardiography and Vectorcardiography. Instrumentation, Fundamentals and Clinical Applications*. W. B. Saunders, Philadelphia and London.
- Levine, R. B., Schmitt, O. H., and Simonson, E. (1953). Electrocardiographic mirror pattern studies. II. The statistical and individual validity of the heart dipole concept as applied in electrocardiographic analysis. *Amer. Heart J.*, **45**, 500.
- Levy, L., and Hyman, A. L. (1950). Difficulties in the electrocardiographic diagnosis of myocardial infarction. *Amer. Heart J.*, **39**, 243.
- Michaels, L., and Cadoret, R. J. (1967). Day-to-day variability in the normal electrocardiogram. *Brit. Heart J.*, **29**, 913.
- Myers, G. B., Klein, H. A., Stofer, B. E., and Hiratzka, T. (1947). Normal variations in multiple precordial leads. *Amer. Heart J.*, **34**, 785.
- Scher, A. M., Young, A. C., and Meredith, W. M. (1960). Factor analysis of the electrocardiogram. Test of electrocardiographic theory: normal hearts. *Circulat. Res.*, **8**, 519.
- Simonson, E. (1961). *Differentiation Between Normal and Abnormal in Electrocardiography*. C. V. Mosby, St. Louis.
- , Cady, L. D., and LaRiviere, J. E. (1964). Normal redundancy in chest leads as a basis for recognition of minor abnormalities. *Amer. Heart J.*, **68**, 438.
- , and Keys, A. (1954). Repeat variability of spatial QRS and T vectors. *Circulation*, **10**, 850.
- , Schmitt, O. H., Dahl, J., Fry, D., and Bakken, E. E. (1954). The theoretical and experimental bases of the frontal plane ventricular gradient and its spatial counterpart. *Amer. Heart J.*, **47**, 122.
- Sokolow, M., and Friedlander, R. D. (1949). The normal unipolar precordial and limb lead electrocardiogram. *Amer. Heart J.*, **38**, 665.
- , and Lyon, T. P. (1949a). The ventricular complex in left ventricular hypertrophy as obtained by unipolar precordial and limb leads. *Amer. Heart J.*, **37**, 161.
- , and — (1949b). The ventricular complex in right ventricular hypertrophy as obtained by unipolar precordial and limb leads. *Amer. Heart J.*, **38**, 273.
- Wilson, F. N., Johnston, F. D., Rosenbaum, F. F., Erlanger, H., Kossmann, C. E., Hecht, H., Cotrim, N., de Oliveira, R. M., Scarsi, R., and Barker, P. S. (1944). The precordial electrocardiogram. *Amer. Heart J.*, **27**, 19.