Day to day and beat to beat variation in normal 3 orthogonal lead electrocardiograms

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Beat to beat and day to day variation in computer calculated electrocardiographic measurements is described on the basis of a study of normal serial 3 orthogonal lead electrocardiograms recorded on 25 patients. The variation of scalar amplitudes and vector orientations was investigated for both the QRS complex and the ST-T segment. The 96 per cent ranges of beat to beat and day to day variation are presented together with other statistical measurements. The beat to beat variation was always less than the day to day variation for the QRS complex but this was not always the case for ST-T segment data which are more prone to measurement error. The results derived are of value in the formulation of criteria for the detection of abnormal day to day changes in the electrocardiogram by computer.

Interpretation of electrocardiograms by digital computer is tending to become a routine procedure and several programmes for analysis of 12 lead electrocardiograms (Caceres, 1963; Pordy *et al.*, 1968; Wartak, Milliken, and Karchmar, 1971; Bonner *et al.*, 1972) and 3 orthogonal lead electrocardiograms (Pipberger, 1965; Arvedson, 1967; Smith and Hyde, 1969; Pryor *et al.*, 1969; Macfarlane, 1971; Wolf and Rautaharju, 1971) have been developed. On the other hand, reports on the use of a digital computer for the detection of day to day changes of clinical importance in serially recorded electrocardiograms have only recently appeared (Macfarlane *et al.*, 1972b; Pryor, Lindsay, and England, 1972). A more detailed description of methods used by the authors for interpretation of serial electrocardiograms as part of a routine automated electrocardiogram reporting service is presented elsewhere (Macfarlane, Cawood, and Lawrie, 1974).

Detection of sequential electrocardiographic changes is of considerable value in certain patients where the clinical diagnosis is in doubt, e.g. cases of acute myocardial infarction or pulmonary embolism. In conventional methods of electrocardiographic interpretation, a cardiologist or physician subjectively evaluates the appearances to decide whether or not a change has taken place between successive recordings. Often there may be a gross alteration in T wave appearances from an upright to an inverted pattern. Occasionally these changes may be less pronounced and would not

normally be quantified by a physician. Nevertheless they could be interpreted as sequential changes indicative of myocardial infarction. For a digital computer to report day to day changes in electrocardiogram voltage measurements as clinically significant, precise data on the extent of variation which can be regarded as normal must be determined. Therefore, in parallel with the development of computer techniques for routinely comparing electrocardiograms recorded serially from the same patient, it was necessary to determine in the first instance the normal ranges of day to day and beat to beat variation of selected electrocardiogram parameters in order that criteria for abnormal day to day changes could ultimately be developed (Cawood *et al.*, 1974).

The 3 orthogonal lead electrocardiogram, as derived from the modified axial lead system (Macfarlane, 1969), was used for this study. It has previously been shown that this system was of equal clinical value compared with the 12 lead electrocardiogram in the computer interpretation of electrocardiograms (Macfarlane, Lorimer, and Lawrie, 1971). Only a limited amount of information is available on the beat to beat variation (Fischmann, Cosma, and Pipberger, 1968) and on the day to day variation (Willems, Pobleto, and Pipberger, 1972) of the 3 orthogonal lead electrocardiogram. These data, however, were derived from the Frank (1956) system and since measurements made using one lead system cannot readily be translated to another (e.g. Lawrie and Macfarlane,

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1968), it was necessary to obtain additional measurements on normal electrocardiographic variation using the modified axial lead system.

Subjects and methods

Serial electrocardiograms were recorded during the period August 1971 to September 1972 on 92 patients, who formed two groups. The first group consisted of 25 patients without any evidence of cardiovascular disease. There were 21 men, with ages ranging from 13 to 75 years (mean age 46 ± 19), and 4 women, with ages ranging from 16 to 53 years (mean age 40 ± 16). Each had a normal 3 and 12 lead electrocardiogram and a normal chest x-ray. In addition, no patient was receiving drug therapy which would affect the cardiovascular system.

The remaining patients had clinical, electrocardiographic, and biochemical evidence of acute myocardial infarction and were studied to obtain data on sequential 3 lead electrocardiographic changes. Results from these patients are presented in an accompanying paper (Cawood *et al.*, 1974). For the remainder of this paper, only the first group of patients is discussed.

On three different days, during the course of a week, a 3 lead electrocardiogram was taken on each patient. Various cardiographers recorded the electrocardiograms using unmarked electrode positions. Each electrocardiogram was recorded on magnetic tape and then replayed to a PDP8 computing system for analysis using methods which have been discussed previously (Macfarlane, 1971; Macfarlane *et al.*, 1972a). Certain additions to the basic programme were made in view of their possible significance in the detection of serial electrocardiographic changes.

The variation of 32 measurements was studied. These parameters were

(a) for the QRS complex:

- i) the amplitudes of the R wave in leads X and Y and of the S wave in lead Z, which is directed positively to the anterior, cf. I, aVF, V₂ (Fig. 1)
- ii) the amplitude of the maximum spatial QRS vector
- iii) the orientation of the projection of maximum spatial QRS vector onto the frontal (XY), right sagittal (ZY), and transverse (XZ) planes (Fig. 2)

(b) for the T wave:

- i) the amplitude of the 5/8, 6/8 time normalized ST-T vector components in leads X, Y, and Z (Fig. 3)
- ii) the maximum T wave amplitude in leads X, Y, and Z
- iii) the amplitude of the maximum spatial T vector
- iv) the orientation of the projection of the maximum spatial T vector, the 5/8 and 6/8 ST-T time normalized vectors onto the frontal (XY), right sagittal (ZY), and transverse (XZ) planes.

Beat to beat variation

To evaluate beat to beat variation, each electrocardiogram was analysed by the computer three times with a

FIG. 1 The directions of the 3 leads X, Y, and Z. (Cf I, aVF, and V₂, respectively.)

FIG. 2 The three reference planes on to which spatial vectors were projected.

FIG. 3 The 5/8 and 6/8 time normalized ST-T segment amplitudes. These are obtained from division of the ST-T segment into 8 equal time intervals and measuring the amplitude at the end of each (Draper *et al.*, 1964).

FIG. 4 An illustration of the 96 per cent range of a set of measurements. Two per cent of values are excluded at either end. This method of estimating ranges is of value where the distribution is skew as shown here. Note that in practice such a curve need not be constructed. It is only necessary to sort data in numerical order to find the extreme values required.

different complex being selected on each occasion. For each of the 32 parameters, the difference between the smallest and largest of the measurements from each electrocardiogram was computed. An estimate of the maximum beat to beat variation of each parameter was thus obtained from each patient. Since each of the 25 patients had an electrocardiogram recorded on three different days, it was possible to repeat this procedure for the other two electrocardiograms and so obtain three estimates from each patient of the maximum beat to beat variation for each of the 32 parameters. From each set of 75 measurements, the approximate 96 per cent range of beat to beat variation was obtained, i.e. the extreme 2 per cent of values at either end of the range were excluded (Fig. 4), in keeping with the suggestion of Simonson (1961) to use percentiles in the establishment of limits. Where a small group is studied, as in this case, the mean ± 2 SD could alternatively be used to estimate the range, but for compatibility with the results of others, this was not done, though these data are presented. No other data on beat to beat variation are given because of their limited value in the detection of serial electrocardiographic changes.

Day to day variation

For each electrocardiogram, which was interpreted three times by the computer programme, a mean value of a set of three measurements was obtained for each of the 32 parameters. These mean values were used to estimate the day to day variation of the three serial electrocardiograms by making the following comparisons:

- i) mean values from the first electrocardiogram with corresponding values from the second electrocardiogram.
- ii) mean values from the first electrocardiogram with those of the third electrocardiogram.
- iii) mean values from the second electrocardiogram with those of the third electrocardiogram.

With this technique of comparison, the change of each scalar amplitude was calculated for each of the 25 patients. The nature of the change, i.e. whether there was an increase or decrease in amplitude, was noted. Likewise, the change in vector orientations was measured, with the direction of the change taken into account.

After the day to day variations for the 25 sets of serial electrocardiograms were obtained, all results for individual parameters were pooled, with the distinction between increase and decrease in amplitude or clockwise and counterclockwise rotation being preserved. The mean, standard deviation, and 96 per cent ranges of the day to day variations were then computed for each parameter.

To obtain an estimate of the amount of variation, the percentage variation, defined as (mean variation/MEAN) $\times 100$, was evaluated for each parameter. MEAN is the average of the 75 corresponding values of mean values, defined previously, i.e. one value from each of the three serial electrocardiograms recorded from 25 patients. The percentage variation should not be confused with the coefficient of variation.

Maximal variation

By combining the 96 per cent ranges obtained from the day to day variation with those of the beat to beat variation, the maximal variation was obtained. This represents the maximum of the 96 per cent ranges from each set of data and is the value used as the upper limit of normal variation.

Results

The day to day and beat to beat variations of the selected P, QRS, and ST-T measurements are presented in Tables 1 to 6. The mean, standard deviation, and 96 per cent ranges of day to day variation are presented together with the 96 per cent range only of beat to beat variation. Only the value at the upper end of the 96 per cent ranges is presented because of its diagnostic interest. The maximal variation is also presented in each Table.

Discussion

Various authors have estimated the day to day variation in electrocardiographic parameters using marked electrode positions. This technique allowed Simonson, Brozek, and Keys (1949) to estimate the variation in 11 recordings made over a period of 3 months in 12 young men. More recently, Willems *et al.* (1972) used marked electrode positions to show that the day to day variation of the 3 lead electrocardiogram was reduced compared to using unmarked positions. Since the purpose of our study was to establish normal day to day variation of electrocardiograms obtained routinely, it was thought preferable that electrode positions should not be marked and that several electrocardiographers should be involved in recording electrocardiograms from the same patients.

The greatest variation of all measurements was found in P wave data as might be expected. The reasons for this are several in number. First, where there are low voltage P waves of bifid type, the maximum scalar amplitude can alternate from a positive to a negative value. Secondly, minimal baseline wander can contribute significantly to erroneous P wave amplitude measurements. Thirdly, if the accuracy of electrocardiographic wave measurement by computer is regarded as constant irrespective of the particular electrocardiogram being analysed, then the percentage variations will be highest for the component with the lowest mean amplitude, i.e. the P wave.

The fact that P wave day to day variation was less than beat to beat variation demonstrates that averaging of amplitudes is of value in improving P wave analysis. This suggests that averaged values of P wave measurements should be used in any studies on serial P wave changes.

TABLE 1 Day to day, beat to beat, and percentage variation of QRS amplitude measurements: only upper limit of 96 per cent variation is presented. R_x denotes the R wave amplitude in lead X, etc.

Measurement	Increased amplitude (mV)				Decreased amplitude (mV)				Ranges (mV)	
	Variation (%)	Mean	SD	96 per cent day to day variation	Variation (%)	Mean	SD	96 per cent day to day variation	96 per cent beat to beat variation	Maximal variation
R_x	13	0.16	0.14	0.41	17	0.22	0.17	0.52	0.377	0.52
R_y	18	0.16	0.097	0.36	20	0.17	0.13	0.35	0.257	0.36
R_z	17	0.099	0.082	0.24	14	0.10	0.07	0.23	0.13	0.24
Max spatial QRS vector	12	0.19	0.16	0.46	22	0.25	0.17	0.54	0.26	0.54

TABLE 2 Day to day, beat to beat, and percentage variation of selected ST-T segment amplitude measurements: only upper limit of 96 per cent variation is presented. T_x denotes the amplitude of the T wave in lead X, etc.

Measurement	Increased amplitude (mV)				Decreased amplitude (mV)				Ranges (mV)	
	Variation (%)	Mean	SD	96 per cent day to day variation	Variation (%)	Mean	SD	96 per cent day to day variation	96 per cent beat to beat variation	Maximal variation
T_x	24	0.07	0.06	0.19	27	0.08	0.08	0.25	0.15	0.25
T_y	29	0.09	0.08	0.20	29	0.09	0.08	0.28	0.25	0.28
T_z	23	0.07	0.06	0.18	25	0.07	0.05	0.16	0.13	0.18
5/8 ST- T_x	31	0.07	0.05	0.16	31	0.07	0.06	0.18	0.20	0.20
5/8 ST- T_y	31	0.09	0.10	0.18	28	0.08	0.08	0.19	0.22	0.22
5/8 ST- T_z	22	0.05	0.04	0.13	27	0.06	0.04	0.13	0.11	0.13
6/8 ST- T_x	54	0.04	0.05	0.16	54	0.04	0.03	0.10	0.26	0.26
6/8 ST- T_y	33	0.04	0.03	0.09	50	0.06	0.05	0.16	0.20	0.20
6/8 ST- T_z	45	0.03	0.02	0.08	45	0.03	0.02	0.06	0.14	0.14
Max spatial T vector	28	0.12	0.09	0.24	26	0.12	0.10	0.26	0.20	0.26

TABLE 3 Day to day, beat to beat, and percentage variation of QRS amplitude measurements: only upper limit of 96 per cent variation is presented. P_x denotes the P wave amplitude in lead X, etc.

Measurement	Increased amplitude (mV)				Decreased amplitude (mV)				Ranges (mV)	
	Variation (%)	Mean	SD	96 per cent day to day variation	Variation (%)	Mean	SD	96 per cent day to day variation	96 per cent beat to beat variation	Maximal variation
P_x	73	0.052	0.080	0.13	53	0.037	0.038	0.12	0.167	0.167
P_y	29	0.036	0.027	0.089	32	0.041	0.028	0.094	0.283	0.283
P_z	43	0.020	0.021	0.074	60	0.028	0.021	0.076	0.120	0.120
Max spatial P vector	20	0.031	0.03	0.086	22	0.034	0.025	0.094	0.106	0.106

TABLE 4 Day to day and beat to beat variation of the maximum spatial QRS vector orientations. Only the upper limit of 96 per cent variation is presented. Max QRS_F, max QRS_{RS}, and max QRS_T denote the projection of the maximum QRS vector onto the frontal, right sagittal, and transverse planes, respectively

Measure- ment	Clockwise rotation (degree)			Counterclockwise rotation (degree)			Ranges	
	Mean	SD	96 per cent day to day variation	Mean	SD	96 per cent day to day variation	96 per cent beat to beat variation	Maximal variation
Max QRS _F	7.5	6.2	19	7.0	4.97	15	7	19
Max QRS _{RS}	16.7	20.7	52	14.8	22.9	60	32	60
Max QRS _T	5.6	4.2	9	12.8	10.3	24	12	24

TABLE 5 Day to day and beat to beat variations of selected ST-T segment vector orientations. Only upper limit of 96 per cent variation is presented. Max T_F, max T_{RS}, and max T_T denote the projection of maximum vector onto frontal, right sagittal, and transverse planes, respectively. Similarly for 5/8 ST-T_F, etc.

Measure- ment	Clockwise rotation (degree)			Counterclockwise rotation (degree)			Ranges	
	Mean	SD	96 per cent day to day variation	Mean	SD	96 per cent day to day variation	96 per cent beat to beat variation	Maximal variation
Max T _F	7.5	6.7	22	8.3	7.3	18	30	30
Max T _{RS}	7.8	8.1	18	10.0	10.3	26	22	26
Max T _T	9.2	8.2	25	6.7	3.6	12	16	25
5/8 ST-T _F	7.9	6.4	22	8.1	5.4	15	24	24
5/8 ST-T _{RS}	9.5	8.1	27	9.1	8.7	29	23	29
5/8 ST-T _T	10.0	9.2	31	8.9	6.7	20	18	31
6/8 ST-T _F	19.0	17.3	51	19.3	19.0	49	79	79
6/8 ST-T _{RS}	17.0	18.4	53	16.0	16.3	34	74	74
6/8 ST-T _T	15.2	11.5	35	19.9	17.5	46	71	71

TABLE 6 Day to day and beat to beat variation of maximum spatial P vector orientations: only upper limit of 96 per cent variation is presented. Max P_F and max P_T denote projection of maximum spatial P vector onto frontal and transverse planes, respectively

Measure- ment	Clockwise rotation (degree)			Counterclockwise rotation (degree)			Ranges	
	Mean	SD	96 per cent day to day variation	Mean	SD	96 per cent day to day variation	96 per cent beat to beat variation	Maximal variation
Max P _F	25.8	22.9	58.3	29.6	31	66.0	179	179
Max P _T	47.5	36.7	107	27.6	29.9	83.0	161	161

Beat to beat variation in the present series is higher than that reported by Fischmann *et al.* (1968), but in general, the 96 per cent ranges of day to day variation of QRS and T wave amplitudes are in close agreement with those obtained using the Frank system (Willems *et al.*, 1972). This was not always the case with angular measurements. For

example, the 96 per cent range of the variation of the counterclockwise rotation of the maximum spatial T vector in the frontal plane using the modified axial lead system was 22° whereas in the Frank (1956) system it was 46° using unmarked recordings (Willems *et al.*, 1972). Even greater differences can be observed in the transverse plane where, with the

modified axial system, the upper limit (96%) of normal spatial T vector variation was 25° compared to over 120° using unmarked recordings with the Frank system.

The main reason for dividing day to day variations according to the direction of change was to obtain data for comparison with electrocardiographic measurements from patients with myocardial infarction. In inferior myocardial infarction, for example, the frontal plane T vector may swing in a counterclockwise direction as sequential changes develop, and it was thought desirable to be able to compare such changes with normal counterclockwise variation. Note, however, that the use of maximal variation as the upper limit of normal variation effectively combines the two sets of changes, e.g. increased or decreased amplitude ranges.

Some of the high variations caused by the occasional technically unsatisfactory tracing could have been lowered by omitting such an electrocardiogram from the series. This was not done since poor quality recordings will sometimes be encountered in a routine operation. The results, therefore, indicate which parameters are least sensitive to day to day and beat to beat variation which may be due in part to technical factors, e.g. the variation of the 6/8 ST-T segment measurements in all leads was generally higher than that of the 5/8 ST-T segment and the maximum T wave.

By using the data presented above, together with those obtained from a series of patients with myocardial infarction (Cawood *et al.*, 1974), diagnostic criteria for the detection of serial ST-T changes by digital computer have been formulated. As a result, techniques for the comparison of serially recorded electrocardiograms have been incorporated into our own electrocardiogram interpretation programme and are now in routine use.

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