Normal measurements of modified Frank corrected orthogonal electrocardiograms and their importance in an on-line computer-aided electrocardiographic system

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We have used a computer-aided 15-lead hybrid electrocardiographic system to obtain normal measurements throughout life for men and women in different age groups.

Amplitude and duration of the P, QRS, and T wave in the modified Frank orthogonal leads were determined. The range of many of these observations was greater than that usually accepted; in particular, the PR interval could be as low as 100 msec and the QRS as long as 115 msec. The QRS and QT intervals were significantly correlated with increasing age. There was a decrease of both the QT interval and the QRS duration with increasing heart rate. Within the limits of 50 to 120 a minute, there was a significant inverse correlation between QRS duration and heart rate. The QRS width affects the QT interval. To eliminate this variable, a new measurement, the ST interval (from the end of the S wave to the end of the T wave), is proposed. The ST interval is significantly inversely related to heart rate and, like the QT interval, is linearly related to age and slightly longer in women than in men. Normal limits of the ST interval are presented for heart rate and age, and it is suggested that actual measurements are expressed as a ratio of these normal limits. A multiple regression equation for computer use has been determined. For men: $ST = 402.2 - 1.678 (\text{heart rate}) + 0.263 (\text{age in years})$; and for women: $ST = 401.5 - 1.400 (\text{heart rate}) + 1.983 (\text{age in years})$.

Normal measurements of the P wave and PR interval were similar in the two sexes and not significantly affected by age or heart rate. Amplitude of Q, R, S, and T waves were lower in women than in men, and generally decreased with age. The variation of these observations and the Q/R and R/S ratios was pronounced, and Q/R ratios suggestive of myocardial infarction were found in 14 per cent of both normal men and women.

The limits of normal electrocardiographic measurements have become increasingly important since the advent of computer-aided electrocardiographic systems. Limits have been previously published for the 12-lead electrocardiogram (Simonson, 1961), and for the Frank corrected orthogonal system (Draper *et al.*, 1964). However, the limits of this orthogonal system have been based only on observations in men over a limited age range.

We have found it necessary to determine our limits for normal electrocardiographic measurements in order to improve our computer programme, and therefore present our normal ortho-

gonal limits in relation to age, sex, and heart rate, since these variables have important effects on many measurements. The QT interval is a composite measurement related to both depolarization and repolarization. It is affected by conduction defects (Talbot, 1973), and consequently we have introduced a new measurement from the end of the S wave to the end of the T wave, termed the ST interval, which we have found more useful. (This should not be confused with the ST segment, which is measured from the end of the S wave to the beginning of the T wave.) The normal limits according to age, sex, heart rate, and QRS duration are presented.

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Subjects and methods

Observations with respect to 542 electrocardiograms reported as normal by a computer-aided 15-lead electrocardiographic system previously described (Sheinok *et al.*, 1972), and checked by a physician, as well as observations from the modified Frank corrected orthogonal leads, form the basis of this report. Measurements of the PR interval, P wave, and QRS duration, QT, ST interval (QRS duration subtracted from the QT interval), age, and heart rate were determined. Measurements for each sex were separated. Age groups were determined and the mean and standard deviation (SD) of each group were calculated. We also grouped these measurements in relation to heart rate, and the mean and SD of each group were calculated. Correlation coefficients were determined when there appeared to be a significant association between any measurements. All measurements were made in the three XYZ leads, using the earliest onset to the latest offset in any lead. In addition, the QRS width in the limb leads I, II, and III were measured separately and the mean determined.

Measurements of amplitude and duration of the individual Q, R, S, and T waves were also calculated. The mean measurements and range have not been presented in the interest of brevity but are available from the authors on request. The time from the onset of the QRS to its peak, often called intrinsic deflection time, was measured in lead X and the mean and range of these observations are presented. Normal computer statements are generally correct (Macfarlane, Lorimer, and Lawrie, 1971) but, when possible, medical records were examined to confirm the finding that these patients had no evidence of cardiac disease.

Results

The range of measurement (± 2 SD) of the QRS duration, the ST interval, and PR interval for men and women in different age groups are presented in Tables 1, 2, and 3, respectively. There was a significant association of the ST interval ($r=0.55$, $P<0.01$) and QRS duration ($r=0.16$, $P<0.01$) (and therefore of the QT interval) with age. There was a slight but insignificant association of the PR interval with age. The heart rates were similar in different age groups, but if only observations at heart rates between 70 and 79 beats a minute were used, the associations with age presented above persisted: these associations were similar for men and women.

There was a slight but insignificant inverse relation of the PR interval to heart rate. The ST intervals are represented in heart rate groups in Table 4. There was a decrease of ST interval (as well as the QT) with increasing heart rate. The ST interval (but not the QT) was significantly correlated with cycle length ($r=0.8$, $P<0.01$). The relation of the ST interval to heart rate and age has been expressed by the following multiple regression equations.

TABLE 1 Measurements of QRS width in relation to age in years for men and women*

Age group	No. of records	Mean (XYZ)	± 2 SD	Mean leads (I, II, III)	± 2 SD
<i>Women</i>					
2-19	10	85.9	73.7-98.1	78.0	57.6-98.4
20-29	22	85.8	67.7-103.8	80.0	58.2-91.8
30-39	43	86.9	68.5-105.2	76.8	47.8-105.8
40-49	47	86.6	71.6-101.6	76.8	51.4-102.2
50-59	52	87.5	79.7-105.4	78.2	52.2-104.2
60-69	38	87.6	71.7-104.5	80.6	47.8-113.4
70+	20	86.8	63.5-110.1	83.3	59.3-107.3
(Mean 76.6 yr)					
Total:	232	86.9	(SD 8.18)		
<i>Men</i>					
2-19	7	90.9	65.4-116.3	84.1	52.3-115.9
20-29	25	93.2	73.7-113.6	90.4	64.8-115.0
30-39	50	90.3	73.5-107.2	86.4	61.2-111.6
40-49	59	91.7	73.7-109.7	85.3	60.5-110.1
50-59	75	91.5	71.4-111.5	85.2	59.0-111.4
60-69	58	92.1	71.3-113.8	83.8	53.2-114.4
70+	36	93.9	76.7-111.2	86.2	58.8-113.6
(Mean 73.4 yr)					
Total:	310	91.9	(SD 9.7)		

* 95 per cent confidence limits for orthogonal and limb leads in msec.

TABLE 2 Measurement of ST interval in relation to age and sex*

Age group (yr)	No.	Mean (msec)	Range = Mean ± 2 SD
<i>Women</i>			
2-19	10	274.8	208.6-341.0
20-29	22	280.8	210.9-350.7
30-39	43	280.6	203.5-357.6
40-49	47	297.5	226.6-358.5
50-59	52	297.3	225.2-369.5
60-69	38	290.9	227.7-354.1
70+	20	269.9	201.1-338.7
(Mean 76.6 yr)			
Total:	232	288.3	(SD 35.6)
<i>Men</i>			
2-19	7	296.8	216.6-377.1
20-29	25	267.8	193.9-341.7
30-39	50	274.4	208.0-341.4
40-49	59	278.8	223.4-322.2
50-59	75	278.1	218.8-337.4
60-69	58	286.5	213.4-359.6
70+	36	307.1	218.2-396.0
(Mean 73.4 yr)			
Total:	310	280.6	(SD 35.3)

* 95 per cent limits (± 2 SD) for men and women.

TABLE 3 Measurement of PR in relation to age and sex*

Women Age group (+ mean age)	No.	Mean (msec)	± 2 SD range	Men Age group (+ mean age)	No.	Mean (msec)	± 2 SD range
2-19 (15.8)	10	129.2	111.1-147.3	2-19 (13.7)	7	149.6	112.4-186.8
20-29 (23.9)	22	147.3	106.8-187.8	20-29 (24.9)	25	134.5	110.0-159.0
30-39 (35.0)	43	139.2	101.6-176.8	30-39 (35.0)	50	139.3	104.3-174.2
40-49 (45.2)	47	143.9	105.6-182.3	40-49 (44.7)	59	144.1	110.9-177.3
50-59 (54.6)	52	147.6	99.3-195.9	50-59 (53.9)	75	146.3	103.3-189.3
60-69 (64.6)	38	148.4	96.6-200.2	60-69 (63.9)	58	151.2	99.6-202.8
70+ (76.6)	20	138.9	111.8-166.2	70+ (73.4)	36	145.1	109.9-180.3
Total:	232	144.6 (SD 21.3)		Total:	310	144.4 (SD 20.5)	

* Mean age in years for each group is presented in parentheses. 95 per cent confidence limits (± 2 SD) for men and women.

TABLE 4 Measurement of ST interval in milliseconds in relation to heart rate*

Heart rate	Women No. Mean	± 2 SD range	Men No. Mean	± 2 SD range
40-49	0		7 370.3	336.8-403.8
50-59	14 327.4	254.9-399.9	20 321.4	271.2-371.6
60-69	41 310.0	258.9-361.1	55 302.9	240.4-365.4
70-79	61 299.1	236.1-362.1	75 292.9	269.4-326.4
80-89	57 288.4	233.5-343.3	74 273.7	237.8-309.5
90-99	29 273.4	228.6-318.2	38 259.2	238.6-279.8
100-109	13 260.3	201.3-319.3	34 237.3	192.7-281.9
110+	17 221.5	174.7-268.3	7 220.1	198.3-241.9
(Mean 124.4)			(Mean 116.9)	

* 95 per cent limits (± 2 SD) for men and women.

Men: $ST = 402.2 - 1.678$ (heart rate) $+ 0.263$ (age in years)

Women: $ST = 401.5 - 1.400$ (heart rate) $+ 1.983$ (age in years)

The QRS duration was inversely related to heart rate in both sexes and significantly correlated for the entire group ($r = -0.22$, $P < 0.01$). Sex differences were not significant for any measurement, but both the QT and ST intervals were longer for women than for men, and the QRS width and P wave duration and PR intervals were greater in men. The pronounced variation of the P wave duration may have increased the variation of the PR interval. From these measurements the upper and lower limits of normal have been defined for the entire group (Table 5).

The results of the Q, R, S, and T wave amplitudes were not significantly affected by age, though there was a slight decrease with age. Women usually had lower values than men. These measurements did not show normal distributions, and though logarithmic transformations using natural logarithms reduced skewing it was still not possible to determine 95 per cent confidence limits without computing the actual 95 per cent limits. Separation of normal and abnormal tracings was unsatisfactory using logarithms. The Q/R and R/S amplitude ratios were also calculated. These ratios were less dependent on the variables of age and sex. However the ratios preserved the pronounced variation of the amplitude measurements. The Q/R ratios are used for diagnosis of myocardial infarction and therefore the results for these calculations are presented in

Table 6, together with the number of patients showing ratios exceeding the normal limits of Draper *et al.* (1964), which are used for the diagnosis of myocardial infarction. These exceptions increase with age.

Q wave duration and intrinsic deflection were not apparently affected by heart rate or age, but were slightly less in women. The normal range of intrinsic deflection is presented in Table 5.

Clinical records pertaining to 151 electrocardiograms were obtained and no evidence of cardiovascular disease was found in relation to 138 (117

TABLE 5 Proposed normal limits of modified Frank orthogonal electrocardiogram

Measurement	Women (msec)	Men (msec)
P wave	60-130	70-130
PR interval	95-200	100-200
QRS interval	65-110	65-115
QT interval	280-460	250-490
ST interval	200-370	205-400
Intrinsic deflection in lead X	31-74	34-74

TABLE 6 Number of normal people with Q/R ratios compatible with myocardial infarction

Men	Q/R ratio in lead X > 17 per cent	Q/R ratio in lead Y > 25 per cent	Q/R ratio in lead Z < 10 per cent	Women	Q/R ratio in lead X > 17 per cent	Q/R ratio in lead Y > 25 per cent	Q/R ratio in lead Z < 10 per cent
2-19	1	0	0	2-19	1	1	0
20-29	1	0	0	20-29	1	0	1
30-39	0	3	3	30-39	0	2	1
40-49	3	0	5	40-49	1	1	1
50-59	1	7	3	50-59	0	1	5
60-69	6	7	2	60-69	1	1	5
70+	4	5	1	70+	0	0	2
Total:	16	22	14	Total:	4	6	15
Mean (Q/R ratio)	4.98	7.91	62.23		3.92	6.19	71.14
SD	(5.41)	(12.11)	(58.93)		(4.09)	(9.27)	(92.38)

patients). Thirteen electrocardiograms (11 patients) were associated with either hypertension (6) or coronary artery disease (7). Results from these normal records did not differ from the entire group.

Discussion

The normal range of the 12-lead electrocardiogram in 649 men and 311 women between 20 and 60 years of age was reported by Simonson (1961). Pipberger and Tanenbaum (1958) studied the orthogonal electrocardiogram using 3 simultaneous XYZ leads of the SVEC III system in 133 normal men and women. This method of measurement has the advantage that the variation of the time of onset and the time of offset in different leads can be eliminated (White, Leach, and Foote, 1941) and a true measurement of the maximum QRS duration obtained. The broader QRS in our orthogonal compared with our three lead measurements confirms the importance of measuring simultaneous orthogonal leads. Further analysis by this method using the Frank corrected orthogonal system on 518 normal subjects was confined to men (Draper *et al.*, 1964; Pipberger *et al.*, 1967). Other results using the Mcfee-Parungao

system (Copeland *et al.*, 1973) and a modified Mcfee system (Macfarlane *et al.*, 1971) may not be comparable to our results using a modified Frank orthogonal system.

The limits recorded by Draper *et al.* (1964) differ slightly from our results. The lower limits of PR interval and P wave duration are greater, and both upper and lower limits of the QT and QRS are slightly greater for our population. This may be due to differences in the sample studied. In general, figures for the normal time intervals of the orthogonal electrocardiogram have been similar to those recorded for the 12-lead electrocardiogram (Stewart and Manning, 1944; Caceres and Kelsner, 1958). Simonson (1961) confirmed a difference in the QRS duration between men and women and a significant difference in the QT interval. Though these changes have been consistently observed (Pipberger and Tanenbaum, 1958), they have not usually been statistically significant. Our normal limits for people aged less than 20 years were obtained from a small sample and must be interpreted with care. However, from the results of all age groups, we conclude that the QRS does increase significantly with increasing age. Blackburn and Simonson (1957) showed an in-

crease of the QRS with age but this was not significant. Savilahti (1946) in a more comprehensive study of adolescents and children concluded that the QRS increased with increasing age, though this was not supported by statistical results. The correlation of the QT with age is well established (Simonson, 1961), and we have, in addition, found a similar correlation for the ST interval.

The relation of the QRS to cycle length in normal individuals has not been previously recorded. Limited observations on patients with conduction defects have suggested that this relation is lost in such patients with rates greater than 100 a minute (600 msec cycle length). At faster heart rates the QRS becomes broader.

There is an increase of the QT interval with increasing cycle length, but because of the variation of QT intervals a significant correlation could not be demonstrated by us or Pipberger and Tanenbaum (1958). There is a linear correlation of the QRS with the QT, which is more obvious in the presence of conduction defects than normal intraventricular conduction. There is an association of the ST interval like the QT with the QRS duration, but this is because of a common increase with age and cycle length. If this is eliminated, there is no significant correlation of the ST interval with QRS duration, though the QT is still correlated with the QRS duration. Therefore, variables may influence the QT through the QRS; if this effect is eliminated by using the ST interval, variation may be reduced. This may explain why the ST interval and not the QT has a significant linear correlation with cycle length.

There is also a slight association of the P wave duration and PR interval, but this is due to a common slight association with age and heart rate. If these are eliminated, the PR interval and P wave duration are probably independent. Corrections of the PR interval and P wave duration for heart rate are not required in the usual range (Bertrand *et al.*, 1972). A correction for age does not seem necessary from our results though Simonson (1961) found a significant association of the PR interval with age.

The ST interval is particularly useful in the presence of bundle-branch block. In left bundle-branch block, it remains normal and it is reduced in the presence of right bundle-branch block (Talbot, 1973). The upper limit of the ST interval is the most pertinent and hence this measurement is satisfactory. We have confirmed normal ST intervals in the presence of nonspecific ventricular conduction defects in which the QT interval is usually slightly prolonged. The ST interval can be used in the presence of a normal QRS and is within normal limits like the QT in ischaemia, myocardial infarction,

and left ventricular hypertrophy or their combination.

The relation of the ST and the QT interval to heart rate is probably curvilinear (Ashman, 1942). However, because of the paucity of normal observations at heart rates below 50 a minute and above 120 a minute, the exact relation is obscure. Values at heart rates below 40 a minute are less than expected by a linear relation (Klakeg, Berry, and Burchell, 1954) and the QT probably approaches a minimum of 240 msec at cycle lengths of <0.40 sec. The QTc as determined by Kissin, Schwarzschild, and Bakst (1948) is a poor measurement but far easier to apply in practice than the multiple regression equation of Cady and Woodbury (Simonson, 1961) which also takes age into consideration.

The similar equations for the ST interval presented here are of value for computer use, and do allow for the longer QT interval and ST interval in women (Ashman and Hull, 1941).

The correlation of the ST interval with the cycle length was determined in different age groups. The effects were similar, as were the effects of age in different heart rate groups, suggesting that the effect of age and heart rate are independent and additive.

Since the standard deviation of the ST interval increases with cycle length and age, it is proposed that the easiest way of checking the normality of the ST interval is to determine whether it exceeds the limits shown in Tables 2 and 4. If required, the degree of prolongation can be assessed by relating the actual figure to that expected just as the QT ratio is calculated.

The regression equations described below for the ST interval may be used to compare the observed with the expected ST interval if the age is unknown, but no allowance is made for different standard deviations at different heart rates.

Men: $ST = 151.04 + 166.75(\text{cycle length in seconds})$

Women: $ST = 135.89 + 199.47(\text{cycle length in seconds})$

The measurements of orthogonal wave amplitude for women were slightly lower than those for men. The measurements for men were similar to those of Borun, Chapman, and Massey (1966). They found that in men the voltage of the R wave decreased with age. The measurements of Draper *et al.* (1964) for men were slightly higher though variation was as pronounced. Variation in the observations was the most pronounced feature for men and women, particularly of the Q/R and R/S ratios. Q/R ratios which are used for the diagnosis of myocardial infarction, therefore, lack specificity, and must be

used with care particularly in the older age groups with decreasing voltage of the R wave. In view of the skew distributions, percentile distributions must be used to describe these normal limits.

In view of the known variation of electrocardiographic measurements with constitutional variables (Pipberger *et al.*, 1967), it is likely that normal limits will vary in different populations. We have had to increase our limits of normal for all time intervals (Table 5). The variation of electrocardiographic measurements has had to be taken into consideration in the construction of algorithms for contour and rhythm analysis by computer. Hand measurements may differ slightly from automated measurements, but the normal limits presented in this paper may also be a useful guide in the routine interpretation of electrocardiograms.

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