Normal Electrocardiographic Waveform Characteristics During Treadmill Exercise Testing

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SUMMARY Forty asymptomatic male patients at low risk for cardiovascular disease completed maximal treadmill testing. Electrocardiograms from leads CC', CM', V5, Yh and Z were recorded across multiple pretest, exercise, and recovery conditions. ECG waveforms were subsequently digitized, averaged and processed to provide Q-, R-, S- and T-wave amplitudes, ST-segment means and slopes, and QS- and RT-interval durations. Average R-wave amplitude increased during early exercise and then dramatically decreased to maximum effort. Average S-wave amplitude became greater as exercise progressed. Average J junction was slightly positive before exercise, became negative during exercise (except lead Z) and returned to zero after exercise. The ST-segment slope increased dramatically with progressive exercise. The response of T-wave amplitude, RT and QS intervals are also described.

Separately, 22 asymptomatic male subjects each completed two maximal treadmill tests 2 weeks apart. ECG data acquisition and processing were similar to those noted above. Pooled, within-subject estimates of variability were computed for the ECG leads, ECG measurements and protocol conditions. These variability estimates are useful for interpreting ECG responses to exercise testing.

TREADMILL TESTING is usually performed with frequent recordings of heart rate, systolic and diastolic blood pressures, and the ECG; functional capacity and patient symptoms are also noted. Of these and other measurements, the ECG has the greatest predictive accuracy for diagnosing coronary artery disease (CAD) and for quantifying the extent of disease in patients with known CAD.

An ischemic response in the exercise ECG is typically identified by application of well-known ST-segment criteria, but these criteria have notable shortcomings. For example, as many as 20% of patients with triple-vessel CAD may show a normal ECG response to maximal treadmill testing. Further, in an asymptomatic population, more than 50% of patients with exercise-induced horizontal or downsloping ST depression of 0.1 mV are found to be free of CAD by coronary angiography. Improved ECG interpretive criteria are needed and are being developed.

Exercise ECG findings that seem to have merit include the presence of U waves, ST-segment elevation, ST spatial shifts, infarct patterns, and R- and S-wave amplitudes. However, there are no data on the behavior of exercise ECG components in normal man. The behavior of R-wave amplitude across the range of exercise and recovery protocol conditions is unknown; the same is true for other ECG amplitudes, intervals and the ST-segment slope. Furthermore, we do not know if the behavior of amplitudes, intervals and the ST-segment slope in one exercise ECG lead is indicative of the behavior of these wave form components in other exercise ECG leads; preliminary evidence suggests this may not be so. These problems must be studied to identify new and proposed exercise ECG discriminant criteria.

An earlier report from this laboratory detailed heart rate, blood pressure and functional capacity responses of normal subjects to treadmill testing. This report is the second in a series on normal subjects, and details the response of ECG waveform components -- by ECG lead -- across the range of treadmill exercise protocol conditions (i.e., pretest, exercise and recovery). Further, estimates of within-subject variability are presented for the various ECG components; these variability estimates are useful in interpreting a subject's ECG response to exercise testing.

Methods

The United States Air Force School of Aerospace Medicine (USAFSAM) provides a clinical consultation service for the evaluation of ambulatory aircrewmen with suspected or manifest medical disorders; crewmen with overt disease — thus disqualified from flying — are not referred. In addition to specialized procedures, each patient at USAFSAM routinely completes a battery of clinical laboratory studies, chest-abdominal-sinus radiographs, resting 12-lead electrocardiography and Frank lead vectorcardiography, echocardiography, maximal treadmill testing, and at least 12 hours of ambulatory ECG monitoring. A thorough medical examination and
history is completed, with referral to medical sub-specialties when indicated.

Records of aircrew patients seen at USAFSAM during 1975–1976 were reviewed to identify a subgroup of asymptomatic male patients at very low risk for having coronary artery disease (hereafter called low-risk normals, or LRN). Forty patients were so identified, and all met the risk factor criteria outlined in table 1. As expected, our risk-factor criteria selected out a younger age group (table 2); their height and weight values are a reflection of USAF aircrew selection standards.

During their referral, each LRN patient completed a maximal treadmill exercise test using either the Balke or USAFSAM protocol;\textsuperscript{11} testing was completed in the morning with the patient fasting. Silver/silver chloride electrodes were applied to carefully prepared skin sites for recording ECG leads CC\textsubscript{5}, CM\textsubscript{5}, Yh, Z and the Mason-Likar adaptation\textsuperscript{12} of V\textsubscript{5} (fig. 1). Analog ECG data were tape recorded (0.05–100 Hz passband) during the test. Taped ECG data were subsequently recovered, processed and used to characterize ECG amplitude, interval and slope responses to treadmill exercise testing.

Another group of subjects (nonpatients) were recruited from the USAFSAM technical and professional staff. Recruitment and subsequent selection were based in part on sex (male), age, height, weight, activity habits and health status (table 3). The 22 subjects selected were all asymptomatic, with normal resting ECGs and normal ST-segment responses to maximal treadmill exercise testing; other risk factors were not assessed.

Each of the 22 subjects completed two maximal treadmill exercise tests spaced 2 weeks apart. Each test used the USAFSAM protocol\textsuperscript{11} and was conducted in the afternoon with the subject fasting and well rested. Silver/silver chloride electrodes were applied to prepared skin sites — ECG leads CC\textsubscript{5}, Yh and Z (see fig. 1) were tape recorded (0.05–100 Hz passband) during each test; leads CM\textsubscript{5} and V\textsubscript{5} were not recorded. Taped analog ECG data were later recovered, processed and used to compute within-subject variability of ECG amplitude, interval and slope measurements.

All taped ECG data were selectively digitized at 500 samples per second. Twelve-second digital records were obtained for each lead from each of the two pretest conditions (supine rest and quiet standing), from exercise heart rates of 100, 120, 140, 160 and 180 beats/min and maximum, and from supine recovery at the end of minutes 1, 3, 5 and 7 for LRNs or at recovery heart rates of 140, 120 and 100 beats/min for the 22 subjects.

All 12-second digital ECG records were subsequently processed, ECG baselines were straightened and ECG wave forms were averaged using the R-wave maximum downslope for alignment.\textsuperscript{13} Averaged ECG wave forms were then processed by software that identified and marked wave form fiducial points as defined in table 4. Each averaged wave form with marked fiducial points was visually reviewed; Q and S fiducial points associated with excessive wave form coving, ST-segment slopes beginning before or after the J junction, and T-wave fiducial points that missed the maximum or associated with biphasic T-waves were

![ECG waveform diagram](https://example.com/ecg_diagram.png)

**TABLE 1. Risk-factor Levels Used in Identifying a Group of Asymptomatic Patients at Low Risk for Cardiovascular Disease (Low-risk Normals)**

<table>
<thead>
<tr>
<th>Risk factor</th>
<th>Level</th>
</tr>
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<tbody>
<tr>
<td>Serum cholesterol</td>
<td>&lt;250 mg%</td>
</tr>
<tr>
<td>Serum triglycerides</td>
<td>&lt;150 mg%</td>
</tr>
<tr>
<td>Fasting blood sugar</td>
<td>≤110 mg%</td>
</tr>
<tr>
<td>Glucose tolerance test</td>
<td>Normal</td>
</tr>
<tr>
<td>Body fat</td>
<td>&lt;25%</td>
</tr>
<tr>
<td>Blood pressure</td>
<td>&lt;140/90 mm Hg, normotensive history</td>
</tr>
<tr>
<td>Resting ECG</td>
<td>Normal</td>
</tr>
<tr>
<td>Maximal treadmill test</td>
<td>Normal aerobic and ECG responses</td>
</tr>
<tr>
<td>Smoking history</td>
<td>Negative for last 10 years</td>
</tr>
<tr>
<td>Family history</td>
<td>Negative for CVA or CVD before age 60 years</td>
</tr>
</tbody>
</table>

*Abbreviations: CVA = cerebrovascular accident; CVD = cardiovascular disease.*
Mean 2. Range data bases group all eliminated. Wave form amplitude, interval and slope measurements were completed and separate data bases were assembled for each study group.

Results

Amplitude, Interval and Slope Responses to Treadmill Testing

Amplitude, interval and slope data from 40 LRN group patients were averaged by ECG component, ECG lead and treadmill protocol condition. These averaged data are the basis for results, as presented in figures 1-4. The number of patients represented by any one average value varied from 30-40; the exception was for exercise heart rate 100 beats/min (n = 25-29); many LRN patients began exercise at heart rates above this level.

Q-wave Amplitude

Average Q amplitudes for leads CC₅, Yh, CM₅ and V₅ were -0.1 mV (range -0.03 to -0.2 mV) for pretest conditions, decreased by 0.15 mV as exercise progressed to a heart rate of 180 beats/min, and quickly returned to pretest levels during supine recovery. There was one exception: Q amplitudes in lead Z began near zero and deviated only slightly for subsequent exercise and recovery conditions. Lead CM₅ had the most prominent Q wave (pretest = -0.2 mV) and attained the most negative amplitude (i.e., -0.3 mV) with exercise stress.

R-wave Amplitude

Average R amplitudes are plotted in the upper half of figure 2 by protocol condition and ECG lead. CM₅ has the largest resting amplitude (i.e., 3 mV) and also the greatest decrease in amplitude with progressive exercise (i.e., 0.6 mV). All leads (except Z) show an increase in amplitude across exercise heart rates 100, 120 and 140 beats/min; mean amplitudes begin to fall thereafter and are lowest by the end of supine recovery minute 1. The unique behavior of vertical lead Yh is notable: Its recovery R₁ amplitude is higher than that at "max" exercise, and its rebound substantially overshoots control period values.

Recent studies have indicated that the R wave may be a good discriminator for CAD.¹ Change in R-wave amplitude — pretest stand to exercise "max" — was tabulated by patient and by ECG lead; specificity was computed using the R-wave criterion of Bonoris.² The results of these tabulations are given in table 5. Most LRN patients have reduced R amplitude at exercise "max," and this pattern is most prominent in lead CM₅.

S-wave Amplitude

Average S amplitudes are plotted in the lower half of figure 2. Except for lead Z, the amplitude behavior of all leads is similar: Pretest amplitudes of approximately -0.3 mV become more negative as exercise progresses, changing maximally by 0.3-0.4 mV. S

Table 2. Characteristics of 40 Low-risk Normal Patients

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>33</td>
<td>179.2</td>
</tr>
<tr>
<td>Range</td>
<td>22-45</td>
<td>170-191</td>
</tr>
</tbody>
</table>

Table 3. Physical Data (Mean and Range) on 22 Subjects

<table>
<thead>
<tr>
<th>Age group (years)</th>
<th>No.</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Vital capacity (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-39</td>
<td>6</td>
<td>179 (170-191)</td>
<td>80 (71-90)</td>
<td>5.0 (4.1-6.1)</td>
</tr>
<tr>
<td>40-49</td>
<td>9</td>
<td>173 (165-179)</td>
<td>73 (63-80)</td>
<td>4.5 (3.6-5.4)</td>
</tr>
<tr>
<td>50-59</td>
<td>7</td>
<td>180 (175-183)</td>
<td>82 (71-91)</td>
<td>4.8 (3.9-5.0)</td>
</tr>
</tbody>
</table>

Table 4. Criteria for Defining Fiducial Points within Averaged ECG Wave Forms

 Isoelectric reference—16-msec interval having smallest squared deviation within a window 64-14 msec before the R wave.

 Q wave—beginning of R-wave upslope, identified by using 4 msec (i.e., 2-point) slope of first derivative; move backward from R-wave peak to find 1) change in sign of 4-msec slope, or 2) first 4-msec slope less than 7% of maximum derivative.

 R wave—maximum R-wave amplitude.

 S wave—end of R-wave downslope, identified by searching past R-wave plus 10 msec for 1) location where next three digital samples all have greater value than current sample, or 2) location where consecutive 4-msec slopes in first derivative are all less than 6% of maximum derivative.

 ST segment—in window 30-120 msec after R wave, the earliest 40-msec segment having 1) a sum squared deviation less than 0.0004 mV or 2) minimum sum squared deviation. An average of the ST-segment location found for supine and early ECG wave forms specified the ST-segment location for all exercise and recovery ECG wave forms.

 T wave—peak amplitude of a monophasic wave form.

Table 5. Number of Low-risk Normal Subjects with Indicated R-wave Response from Pretest Supine to Maximal Exercise. Data from One Subject were Incomplete, Thus n = 39. All Measurements were Made by Computer on Computer-averaged ECG Wave Forms. Specificity was Computed Assuming Normal Individuals Decrease and Abnormal Individuals Increase Their R-wave Amplitudes.

<table>
<thead>
<tr>
<th>Lead</th>
<th>Increase</th>
<th>Decrease</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM₅</td>
<td>1</td>
<td>38</td>
<td>97</td>
</tr>
<tr>
<td>V₅</td>
<td>5</td>
<td>34</td>
<td>87</td>
</tr>
<tr>
<td>CC₅</td>
<td>5</td>
<td>34</td>
<td>87</td>
</tr>
<tr>
<td>Yh</td>
<td>2</td>
<td>37</td>
<td>95</td>
</tr>
<tr>
<td>Z</td>
<td>2</td>
<td>37</td>
<td>95</td>
</tr>
</tbody>
</table>
amplitudes are most prominent at exercise "max" (in contrast to R amplitude behavior), and return toward respective pretest values during supine recovery. S amplitudes in lead Z remain near pretest values for most of exercise and recovery (note that bipolar lead Z is similar in polarity to precordial lead V1).

When considered together, R-amplitude and S-amplitude data have an interesting pattern: R amplitude decreases during exercise in parallel with negative increases in S amplitude; thus, net RS amplitude remains essentially the same. However, R amplitude for supine recovery minute 1 is further decreased in leads CC5, CM5, and V5, while the corresponding S amplitude remains the same or becomes less negative; this results in a net mean decrease of 0.4 mV in RS amplitude at "R1" for these leads.

T-wave Amplitude

Average T amplitudes are plotted in figure 3 by protocol condition and ECG lead. T amplitudes for pretest conditions range from 0.5–0.9 mV. T amplitudes during exercise fall initially and then increase slightly as exercise progresses. The largest T amplitudes were recorded in recovery minute 1. Lead Z had the largest T amplitude within most protocol conditions. T-amplitude measurements were only made where there was a clearly defined, monophasic wave form present.

QS Interval

The QS interval as measured in this study (table 4) is somewhat less than the true duration of ventricular
depolarization. Average QS intervals during pretest conditions ranged from 47–56 msec for the five ECG leads. QS intervals decreased slightly in all leads during exercise, and were maximally reduced by 4–7 msec at an exercise heart rate of 180 beats/min. Intervals during supine recovery returned to or exceeded pretest values. Lead Yh had the largest and lead Z the smallest average QS intervals across all protocol conditions.

**RT Interval**

The RT interval as measured in this study (table 4) is less than the true duration of ventricular depolarization and repolarization. Average RT intervals are plotted in figure 4 by protocol condition and ECG lead. This measurement is similar for all leads at any one protocol condition. Average RT intervals range from approximately 270 msec in the pretest supine condition to approximately 145 msec at exercise “max.” As suggested by these data, RT intervals are very dependent on heart rate.

**J-junction Amplitude**

Average J-junction amplitudes are plotted in the lower half of figure 5 by protocol condition and ECG lead. J-junction amplitudes were obtained by completing a least-squares fit over the 40-msec ST segment (see table 4), and then noting the amplitude of the best-fit line at the beginning of this 40-msec segment.

J-junction amplitudes in all leads are slightly positive for pretest conditions (average 0.1 mV), become zero in early exercise (except lead Z) and then become more negative as exercise progresses. J-junction amplitude at exercise “max” is depressed most for lead Yh (0.2 mV) and less so for the other three leads (0.1 mV). Lead Z stays slightly positive throughout all protocol conditions, i.e., the ST vector remains anterior.

**ST-segment Slope**

Average ST-segment slopes are plotted in the upper half of figure 5. Most leads show minimally positive ST slopes for pretest conditions. With exercise, however, there is a dramatic increase in slope that peaks at 5.4–8.8 mV/sec in supine recovery minute 1. Slope responses across leads are similar within each of the exercise conditions; slope responses between leads diverge transiently for recovery minute 1 and then tend to merge as recovery progresses. Overall, exercise in LRN patients produces a progressive J-junction depression and a striking increase in ST slope; these changes return toward pretest levels during recovery.

![Figure 3](http://circ.ahajournals.org/). Average T-wave amplitudes for LRN patients are plotted by protocol condition and ECG lead. For exercise heart rate (HR) data at 100 beats/min, n = 25–29; for most other data n = 30–40.

![Figure 4](http://circ.ahajournals.org/). Average R-wave maximum to T-wave maximum intervals for low-risk normal patients are plotted by protocol condition and ECG lead. Averages based on n = 25–40. HR = heart rate.
Within-subject Variability of ECG Waveform Measurements

Estimates of within-subject variability for exercise test ECG components were developed as follows. First, variance was computed for each ECG component by subject, protocol condition and ECG lead. Individual variances were then averaged across subjects to provide pooled estimates of variance for the respective protocol conditions and ECG leads. These pooled estimates were analyzed statistically for trends across the various protocol conditions. In the absence of trends, they were further averaged to provide a single overall estimate of variance for each ECG measurement and lead (table 6). When trends were present, pooled estimates of variability were plotted individually (fig. 6).

Table 6. Within-subject Estimates of Variability Averaged Across Protocol Conditions and Presented For Each Lead as 1 SD Values.

<table>
<thead>
<tr>
<th></th>
<th>CC5</th>
<th>Yh</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q amplitude (mV)</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>R amplitude (mV)</td>
<td>0.23</td>
<td>0.27</td>
<td>0.09</td>
</tr>
<tr>
<td>S amplitude (mV)</td>
<td>0.11</td>
<td>0.18</td>
<td>0.23</td>
</tr>
<tr>
<td>T amplitude (mV)</td>
<td>—</td>
<td>See figure 5</td>
<td>—</td>
</tr>
<tr>
<td>QS interval (msec)</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>RT interval (msec)</td>
<td>—</td>
<td>See figure 5</td>
<td>—</td>
</tr>
<tr>
<td>J-point amplitude (mV)</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>ST-segment slope (mV/sec)</td>
<td>—</td>
<td>See figure 5</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 5. (top) Average ST-segment slopes (40 msec) for low-risk normal (LRN) patients are plotted by protocol condition and ECG lead. (bottom) Average J-point amplitudes for LRN patients are plotted by protocol condition and ECG lead. For exercise heart rate (HR) data at 100 beats/min, n = 25–29; for all other data n = 31–40.

Figure 6. Pooled estimates of within-subject variability are given as 1 standard deviation for the indicated ECG measurements, by protocol condition and ECG lead. With few exceptions, all points plotted are based on n = 13–22.
The variability of several measurements differed significantly across the protocol conditions (fig. 6). Estimates of variability for T amplitude were relatively constant for pretest and exercise conditions, and then increased dramatically for the lower heart rates in supine recovery. On the other hand, estimates of variability for ST slope increased almost linearly across the test protocol. Thus, of all possible ST-slope measurements, we have least confidence that recovery condition ST slopes accurately represent the subject's typical response. Finally, variability of the RT-interval measurement decreased dramatically during exercise and returned to pretest levels during recovery; it is clear that variability is proportional to absolute magnitude of the measurement.

Discussion

A principal goal of this study was the presentation of normal ECG component behavior in response to exercise testing. Selection of these ECG components was based on convention and on other considerations. For example, Q-, R-, S- and T-wave amplitudes were chosen because they are conventional landmarks of the ECG wave form and they have received more attention in recent exercise studies. Similarly, ST-segment components (i.e., slope and J junction) were chosen because of their widespread use in exercise ECG interpretation. The duration of our ST-segment slope (40 msec) is intermediate to that reportedly used by others,14 and is, in our experience, the maximum slope duration that can be used without infringing on the T-wave upstroke at higher exercise heart rates. The QS and RT intervals are new and were chosen, in part, because respective fiducial points were already available as a by-product of Q-, R-, S- and T-wave amplitude identification.

ECG Amplitude, Interval and Slope Responses to Exercise Testing

Our data clarify the subject of R-wave amplitude measurements during exercise testing. In figure 2, note that R-wave amplitude is unchanged (leads CMr and Z) or is increased (CCs and V5) for exercise heart rates lower than 150 beats/min; above this heart rate there is a decrease of R-wave amplitude in all five leads. Hence, the behavior of R-wave amplitude in normal subjects depends greatly on heart rate. In fact, one might speculate that all subjects have a similar R-wave response, and that the reported increase in R-wave amplitude of CAD patients6,7 really reflects their having stopped exercise at submaximal heart rate levels.

While LRN S-wave amplitudes increased with exercise, a similar response has been reported for coronary artery disease patients with exercise-induced left ventricular dysfunction.19 Hence, S-wave amplitude by itself is of dubious value in discriminating for CAD. The J-junction response to exercise in the lateral and inferior leads seems clear: Beginning with early repolarization pretest, the J junction sinks to zero and then becomes negative with progressive exercise. The J-junction response has been reported for coronary artery disease patients with exercise-induced left ventricular dysfunction.19 Hence, S-wave amplitude by itself is of dubious value in discriminating for CAD. The J-junction response to exercise in the lateral and inferior leads seems clear: Beginning with early repolarization pretest, the J junction sinks to zero and then becomes negative with progressive exercise.
has been on diagnostic reproducibility, i.e., given repeat exercise tests on the same person, how consistent was the test-to-test diagnosis based exclusively on ST-segment analysis? Grayboys et al. reported that of 34 patients with marked ST depression (>2 mm) in one treadmill test, 20 had a subsequent test with a completely normal ST response. Most et al. studied 186 patients yearly and reported that 11% of these patients had a subsequent treadmill test whose ST-segment analysis differed from that of the original treadmill test. Mason et al. performed two or three repeat treadmill tests on 25 subjects and noted that the test was not reproducible (based on ST criteria) for five of these subjects. Finally, Doan et al. reported that of 15 patients with an initial positive treadmill test, two patients later had a normal test; in 100 patients with a normal initial test, five patients had a positive second test. The interpretation of these and similar studies is uncertain, since the minimum elapsed time between sequential treadmill tests was usually at least 1 year. Indeed, much of the test inconsistency reported above could be attributed to changes in patient status during the intervening year or more.

The present data indicate that treadmill ECG wave form components vary from test to test, and this variation has now been quantified. The reader is cautioned, however, in the application of our data, since our estimates are an average of the actual variability in each subject. Hence, the actual variability for a given subject could be different from this average value. Furthermore, our data are based on a group of healthy, asymptomatic men with a normal response to treadmill testing; the applicability of our within-subject estimates of variance to patients with a positive treadmill test, patients with known CAD, or to women is assumed but unproven.

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References

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