Electrocardiographic Quantitation of Ventricular Repolarization

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Quantification of the electrocardiographic ventricular repolarization involving the T-U wave complex is usually performed with reference to the axis of the T wave and the QT interval duration. A novel quantitative approach to improve the description of ventricular repolarization was applied to the digitized electrocardiograms of 423 normal subjects. Six electrocardiographic repolarization characteristics were identified: duration, rate, area, symmetry, late phenomena, and interlead heterogeneity. A computer algorithm was designed to automatically interpret the electrocardiographic repolarization segment and measure 11 variables that quantified these repolarization characteristics. The application of redundancy-reduction techniques selected a final set of seven variables that were used in the statistical analysis. The QT interval, which was included in the initial group of variables, was replaced by the time interval between S wave offset and T wave maximum. All selected electrocardiographic variables were independent of age ($r^2<0.11$) and body surface area ($r^2<0.03$); all except the early duration variable were heart rate– and QT interval–independent ($r^2<0.2$, $r^2<0.13$, respectively); and most were uncorrelated to each other. A comparison of repolarization characteristics by gender revealed that repolarization duration was significantly more prolonged ($p<0.0001$) in women than in men. This multidimensional quantitative approach conveys a new and more complete description of the repolarization process and provides an electrocardiographic repolarization database in normal subjects as a reference standard for identifying patients with disordered repolarization. (*Circulation* 1989;80:1301–1308)

Ventricular repolarization is a complex electrical phenomenon that has been studied theoretically and experimentally.1–5 The T-U wave complex on the surface electrocardiogram (ECG) is the integrated signal of this repolarization process, and it has several distinct morphologic features. Conventionally, the ECG repolarization duration is quantified by measuring the QT interval or the heart rate–corrected form (QTc), both of which are used clinically to assess the propensity to ventricular arrhythmias in certain subsets of patients.6–13 Other repolarization features, however, have not been quantified. Since the advent of digital ECG recordings, accurate quantification of different repolarization features has been possible.

The purpose of our study is to identify and quantify several descriptive ECG features of ventricular repolarization using a validated computer algorithm for the analysis of digitized surface ECGs. This morphologic database of ECG ventricular repolarization parameters obtained in a large normal population can be a reference standard for identifying patients with disordered repolarization.

**Methods**

**Population**

The study population comprised respondents to local advertisements offering free physical examinations and 12-lead ECG recordings to healthy individuals. Individuals were excluded if they had one or more of the following: 1) medical history suggesting any organic heart disease, atrial flutter or fibrillation, sustained ventricular tachycardia, black-out spells, diabetes, hypertension, hypercholesterolemia (>250 mg/dl), peripheral vascular disease, thromboembolic phenomena, organic brain disease, chronic or recent (within the past 2 weeks) pulmonary disease, chronic kidney or liver disease, any...
malignancy, thyroid disease, recent peptic disease, anemia, alcoholism, or previous cardiac, lung, or breast surgery; 2) regular or current use of any medication, except an occasional use of acetaminophen or aspirin; 3) family history (first-degree relatives) of premature coronary disease, diabetes, or hypertension; 4) any cardiovascular abnormality on physical examination; or 5) any abnormal finding (including technical errors) on a 12-lead ECG reviewed by two experienced observers (the QT interval was not used as a selection criterion). All recordings showed normal sinus rhythm with normal QRS axis and duration (<0.10 seconds). The study population consisted of 423 normal individuals (200 women and 223 men; age, 10–81 years; median age, 35 years) of an original cohort of 454 respondents who fulfilled the previously listed criteria.

Digital Electrocardiographic Recording

ECGs were recorded on a MAC-12 system (Marquette Electronics, Milwaukee, Wisconsin) that simultaneously acquires and digitizes two limb leads (L1, L2) and six precordial leads (V1 through V6) for 10 seconds, at a sampling frequency of 250 Hz and with a resolution of 5 μV. After removal of the 60-Hz noise, samples of the sinus beats recorded in each lead were medianized to construct lead-specific median beats. Earliest P wave onset, earliest Q wave onset, latest S wave offset, and latest T wave offset in 12 leads (eight acquired and four reconstructed) were measured. Twelve median beats per ECG were stored in a compressed form on a floppy disk. The floppy disk data were copied onto a magnetic tape and transferred to a VAX/VMS 8350 Digital Equipment Computer for interactive use.

Data Processing

Median beats of leads V1 through V6 were analyzed by a dedicated wave-detection algorithm (Figure 1) that uses the P wave onset, Q wave onset, and S wave offset markings made on the original data by the MAC-12 software and determines T wave maximum, T wave offset, and U wave offset in individual leads.14 The repolarization segment was defined as the interval between S wave offset and the next P wave onset or the end of the median-beat signal (whichever occurred earlier). Low-pass filtering was accomplished by a finite impulse-response (FIR) filter with 11 coefficients (Hamming window, α=0.54) using a cutoff frequency of 15 Hz. The filtered median beat—repolarization segment was digitally integrated and derivated using two FIR filters, a trapezoid integrator and a regression filter, respectively. The trapezoid integrator computed the integral of the signal amplitude using the trapezoid approximation. The value of the cumulated integral was then normalized to the total absolute-integrated signal in the repolarization segment. The regression filter (a derivative estimator) used the value of the slope of the least-squares regression line fitting five consecutive signal samples to determine the first derivative at the central sample. Zero-amplitude baseline was defined as the mean amplitude of the last five samples preceding the previous P onset. ECG waves within the repolarization segment were defined as relative positive maxima or negative minima with an absolute amplitude of more than 15 μV. Wave detection was accomplished by identifying the major deflections of the filtered signal using changes in sign of the first derivative. Wave classification was accomplished by defining the absolute-maximal deflection as the T wave, and the occurrence of the next sample in time when a specific combination of signal, derivative, and integral values was met as T wave offset. U wave maximum and U wave offset were determined using similar definitions applied to the post-T offset portion of the median beat. Once T wave maximum, T offset, and U offset were identified, preselected variables were measured.

Variables

Variables were preselected to describe the following morphological characteristics of ventricular repolarization on the surface ECG: 1) duration, 2) rate, 3) area, 4) symmetry; 5) late phenomena, and 6) heterogeneity. All variables were measured in precordial-lead V6 except heterogeneity variables, which were measured in all six precordial leads. The QT interval was measured as the time interval from the earliest Q onset to the latest T offset in any of the 12 leads. Lead V1 was chosen for measuring most variables because of its stable repolarization signal and its partial spatial similarity to lead II that is conventionally used to assess repolarization dura-
The following ECG variables were selected to quantify the aforementioned repolarization characteristics (Figure 2).

**Duration.** 1) QT or total duration (time interval between the Q wave onset and the T wave offset \([T_q] \text{ m sec}\)), 2) S,T, or total-repolarization duration (time interval between the S wave onset \([S_o]\) and T offset \(T_{of}\), m sec), 3) S,T, or early duration (time interval between S and the T wave maximum \([T_m]\), m sec), 4) T, T, or late duration (msec), and 5) \(t_{ASO}\) (time interval to accumulate the first 50% of the total absolute repolarization area \([A_{tot}] \text{ [A+B+C areas in Figure 2, msec]}\).

**Rate.** 6) \(t_{ASO}\) or rise time (time interval to accumulate the mid-50% of \(A_{tot}\) from 25% to 75%, m sec).

**Area.** 7) \(A_{tot}\) or total absolute repolarization area (mV • msec).

**Symmetry.** 8) SR or T wave–area symmetry ratio (ratio between area A and B in Figure 2, dimensionless).

**Late phenomena.** 9) \%A@T, (percent absolute area at \(T_{of}\), percentage).

**Heterogeneity.** 10) \(S_oT_m\)-SD (SD of \(S_oT_m\) in the precordial leads, msec); 11) \(t_{ASO}\)-SD (SD of \(t_{ASO}\) in the precordial leads, msec).

In addition, the following demographic and physiologic variables were included: 1) age (years), 2) gender, 3) BSA (body surface area, calculated according to Mosteller\(^15\), m\(^2\)), and 4) RR (average RR interval over the 10-second original recording, msec).

**Quality Control**

Four hundred twenty-three recordings of limb leads L1 and L2 and precordial leads V\(_1\) through V\(_6\) (a total of 3,384 leads) with the algorithm-computed T maximum, T offset, and U offset markings were visually overread using a graphic computer output; the signal-amplitude scale was maximized according to the T wave amplitude (regardless of the R wave amplitude) to allow optimal visual assessment of T and U wave offset markings (Figure 3). Manual measurements of \(S_oT_m\) interval in a random sample of 60 ECG leads were made on hard-copy ECGs by two experienced observers and correlated well \((r^2=0.92)\) with the corresponding computer measurements done on the same leads. Due to inadequate technical quality of a minority of tracings, a subroutine in the algorithm was designed to automatically execute the following exclusion criteria: 1) baseline shift, malalignment of the signal with the zero baseline at the end of the repolarization segment; 2) unidentified T offset; and 3) U offset misidentification (in cases with a U wave). Visual overreading verified that all algorithm-excluded leads were actually excluded for appropriate reasons. A total of 471 individual ECG leads (13.9%) were excluded from the analysis, and their corresponding variables values were labeled as missing. Out of these excluded leads, 350 leads (74%) were originally excluded by the algorithm, mainly due to baseline shift (76%), whereas only 121 additional leads were excluded after visual overreading (3.6% of all original leads). Variables measured in lead V\(_1\) were missing in 59 (14%) cases, and heterogeneity variables were miss-
ing in the 33 cases (8%) in which more than any two precordial leads were excluded.

Statistical Analysis

All analyses were done by gender. All variables (except age) were symmetrized by the base-10 logarithm transformation to avoid outliers influence in cross correlations. Pearson’s correlation coefficients were obtained for each pair of transformed variables (14×14 cross-correlation matrix). Evaluation of these coefficients by the Hierarchical Dimensionality Reduction\textsuperscript{16} and the Karhunen-Loeve expansion\textsuperscript{17} techniques allowed primary redundancy reduction and the generation of a secondary list of seven variables that best described the various independent repolarization characteristics identified.\textsuperscript{18} The Karhunen-Loeve expansion technique is usually used to create an optimal set of new variables (principal components) obtained from a linear transformation of the original variables. The principal components are uncorrelated (orthogonal) to each other and are determined according to the original variability of the data. The expansion associates one eigenvector and one eigenvalue to each principal component. The principal component corresponding to the largest eigenvalue accounts for the largest proportion of the original variability and is called the first principal component. Additional principal components account for decreasing proportions of the data variability. Our analysis aimed at redundancy reduction among the original variables. For this reason, and to get interpretable three-dimensional graphic representations, two subsets of variables were treated separately. In both subsets, the Karhunen-Loeve expansion was applied to the cross-correlation matrix of the log-transformed variables to allow comparison of the principal components coefficients. Values of selected variables in the total population were summarized by standard descriptive statistics. Differences between mean values in gender subsets were tested for statistical significance by the Student’s t test using Bonferroni’s correction for multiple comparisons. A p value of less than 0.0036 (0.05/14) was considered statistically significant. Significance levels were verified by a Wilcoxon test and a median test for each comparison.

Results

Cross Correlations

Cross correlations were determined among the 14 defined variables (11 repolarization variables plus age, BSA, and RR interval) by gender. The complete cross-correlation matrix by gender is provided in Table 1. All ECG repolarization variables were independent of age ($r^2<0.11$) and body surface area ($r^2<0.03$). Four duration variables (QT, $S_{T_m}$, $S_{T_o}$, and $t_{AT}$), all of which included early repolarization intervals, were RR interval-dependent ($r^2>0.4$), whereas the late repolarization duration variable ($T_{mT_o}$) was RR interval–independent ($r^2<0.07$). The rate, area, symmetry, late phenomena, and heterogeneity variables were all independent of RR interval ($r^2<0.2$). The area, symmetry ratio, and heterogeneity variables were all relatively independent of all other variables, respectively ($r^2<0.20$), whereas the repolarization-rate variable was highly correlated with the late-phenomena variable ($r^2>0.62$) but was independent of all other variables ($r^2<0.27$).

Variables Redundancy Reduction

Because no significant differences were found in the cross correlations by gender, redundancy reduction was done using the pooled results in both genders. Using the Hierarchical Dimensionality Reduction technique,\textsuperscript{15} seven of 11 variables were selected for quantifying different repolarization characteristics: $S_{T_m}$, $T_{mT_o}$, $t_{AT}$, $S_{T_o}$, $t_{T}$, $S_{T_m}$-SD, and $S_{T_m}$-T.

Principal component analyses were carried out separately for the duration and rate variables (group A) and for the area, symmetry, and heterogeneity variables (group B). For group A (Table 2), the first principal component, which included 60% of the data variability, was dominated by repolarization-duration variables. $S_{T_m}$ was selected as representative on the basis of simplicity and accuracy of measurement. The second and third principal components contained information mostly on late-repolarization duration ($T_{mT_o}$) and repolarization rate ($t_{AT}$), respectively. For group B (Table 3), the first three principal components, which included 92% of the variability of the data, provided independent information about heterogeneity ($S_{T_m}$-SD, $t_{AT}$-SD), total-repolarization area ($A_{tot}$), and symmetry (SR), respectively. $S_{T_m}$-SD was selected as the representative variable of heterogeneity for its relative simplicity and its potential applicability to manual measurement. Thus, redundancy reduction resulted in the selection of seven relatively independent ECG variables that quantify different aspects of repolarization: $S_{T_m}$ (early-repolarization duration), $T_{mT_o}$ (late-repolarization duration), $t_{AT}$ (repolarization rate), $A_{tot}$ (total-repolarization area), SR (T wave symmetry ratio), $S_{T_m}$-T (late phenomena), and $S_{T_m}$-SD (repolarization heterogeneity).

Correction for RR Interval Dependency

According to the cross-correlation matrix, the only variable among the seven selected repolarization variables that needed RR interval correction was $S_{T_m}$. The QT interval, which was not selected as one of the final seven variables, required heart-rate correction as well and was kept in its corrected form as a conventionally measured variable for reference. The linear regression equations for the log-transformed QT and $S_{T_m}$ intervals on RR interval by gender are presented in Table 4.
| Male$§ | BSA | 0.135 | RR | -0.135 | 0.078 | QT | -0.007 | 0.106 | 0.906$‡ | S$_{0}$T$_{o}$ | 0.070 | -0.055 | 0.709$§ | 0.770$‡ | S$_{0}$T$_{m}$ | 0.012 | -0.060 | 0.703$‡ | 0.754$‡ | 0.850$‡ | T$_{m}$T$_{o}$ | 0.109 | -0.011 | 0.256 | 0.292 | 0.568$‡ | 0.055 | t$_{A50}$ | 0.040 | -0.016 | 0.651$‡ | 0.709$‡ | 0.800$‡ | 0.935$‡ | 0.057 | t$_{A25-75}$ | -0.053 | 0.120 | 0.333 | 0.350 | 0.311 | 0.328 | 0.065 | 0.518$‡ | A$_{tot}$ | -0.215 | -0.127 | 0.441 | 0.400 | 0.313 | 0.162 | 0.351 | 0.005 | -0.026 | SR | -0.102 | -0.133 | 0.238 | 0.198 | 0.166 | 0.316 | -0.180 | 0.017 | -0.116 | 0.418 | %A@T$_{o}$ | 0.020 | -0.091 | -0.112 | -0.083 | -0.022 | -0.169 | 0.239 | -0.435 | -0.818 | 0.271 | 0.324 | S$_{0}$T$_{m}$-SD | -0.123 | -0.091 | 0.072 | 0.111 | 0.144 | 0.198 | -0.036 | 0.128 | 0.015 | 0.023 | 0.189 | 0.072 | t$_{A25}$-SD | -0.097 | -0.050 | 0.122 | 0.151 | 0.208 | 0.267 | -0.024 | 0.281 | 0.202 | -0.059 | -0.002 | -0.139 | 0.719‡ |

All variables except age transformed with base-10 logarithm.

*Pearson's product moment correlation coefficient ($r$).

$\gamma n=200$, age 15–76, median 37 years; except for BSA ($n=196$), S$_{0}$T$_{m}$-SD, and t$_{A50}$-SD ($n=180$), and for S$_{0}$T$_{o}$, S$_{0}$T$_{m}$, T$_{m}$T$_{o}$, t$_{A50}$, t$_{A25-75}$, A$_{tot}$, SR, and %A@T$_{o}$ (n=173).

§$\gamma n=223$, age 10–81, median 33 years; except for BSA ($n=220$), S$_{0}$T$_{m}$-SD, and t$_{A50}$-SD ($n=210$), and for S$_{0}$T$_{o}$, S$_{0}$T$_{m}$, T$_{m}$T$_{o}$, t$_{A50}$, t$_{A25-75}$, A$_{tot}$, SR, and %A@T$_{o}$ (n=191).

BSA, body surface area; RR, mean RR interval; QT, time interval between earliest Q wave onset and latest T wave offset in 12 leads; S$_{0}$T$_{o}$, time interval between S wave offset and T wave offset; S$_{0}$T$_{m}$, time interval between S wave offset and T wave maximum; T$_{m}$T$_{o}$, time interval between T wave maximum and offset; t$_{A50}$, time to accumulate 50% of total repolarization area; t$_{A25-75}$, time to accumulate 25–75% of total repolarization area; A$_{tot}$, total absolute repolarization area; SR, T wave area–symmetry ratio; %A@T$_{o}$, percent absolute area accumulated at T wave offset; S$_{0}$T$_{m}$-SD, standard deviation of S wave offset to T wave maximum interval in precordial leads; t$_{A50}$-SD, standard deviation of time interval to accumulate 50% of total absolute repolarization area in precordial leads.

### TABLE 2. Principal Components (Eigenvectors) of Group A Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
<th>PC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>QT</td>
<td>0.4508</td>
<td>-0.0757</td>
<td>-0.0028</td>
<td>-0.8871</td>
<td>0.0642</td>
<td>0.0059</td>
</tr>
<tr>
<td>S$<em>{0}$T$</em>{m}$</td>
<td>0.4835</td>
<td>0.2198</td>
<td>-0.3044</td>
<td>0.1897</td>
<td>-0.4724</td>
<td>-0.6051</td>
</tr>
<tr>
<td>S$<em>{0}$T$</em>{o}$</td>
<td>0.4886</td>
<td>-0.2879</td>
<td>-0.1095</td>
<td>0.2526</td>
<td>-0.3497</td>
<td>0.6931</td>
</tr>
<tr>
<td>T$<em>{m}$T$</em>{o}$</td>
<td>0.1519</td>
<td>-0.8450</td>
<td>0.2333</td>
<td>0.1588</td>
<td>0.1758</td>
<td>-0.3904</td>
</tr>
<tr>
<td>t$_{A50}$</td>
<td>0.4869</td>
<td>0.2526</td>
<td>-0.1300</td>
<td>0.2826</td>
<td>0.7756</td>
<td>0.0293</td>
</tr>
<tr>
<td>t$_{A25-75}$</td>
<td>0.2531</td>
<td>0.2920</td>
<td>0.9078</td>
<td>0.0911</td>
<td>-0.1345</td>
<td>-0.0148</td>
</tr>
<tr>
<td>Eigenvalue</td>
<td>3.6130</td>
<td>1.2085</td>
<td>0.8033</td>
<td>0.3287</td>
<td>0.0439</td>
<td>0.0026</td>
</tr>
<tr>
<td>PVR</td>
<td>60.2</td>
<td>20.1</td>
<td>13.4</td>
<td>5.5</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>C-PVR</td>
<td>60.2</td>
<td>80.3</td>
<td>93.7</td>
<td>99.2</td>
<td>99.9</td>
<td>100.0</td>
</tr>
</tbody>
</table>

PC, principal component; PVR, percent of retained variability; C-PVR, cumulative percent of retained variability; QT, time interval between the earliest Q wave onset and latest T wave offset in 12 leads; S$_{0}$T$_{m}$, time interval between S wave offset and T wave maximum; S$_{0}$T$_{o}$, time interval between S wave offset and T wave offset; t$_{A50}$, time to accumulate from 25% to 75% of the total repolarization area; t$_{A25-75}$, time to accumulate 50% of the total repolarization area; T$_{m}$T$_{o}$, time interval between T wave maximum and offset.
TABLE 3. Principal Components (Eigenvectors) of Group B Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>S, T&lt;sub&gt;n&lt;/sub&gt;-SD</td>
<td>0.7024</td>
<td>0.0086</td>
<td>0.0818</td>
<td>0.7071</td>
</tr>
<tr>
<td>t&lt;sub&gt;ASST&lt;/sub&gt;-SD</td>
<td>0.6992</td>
<td>-0.0770</td>
<td>0.0939</td>
<td>-0.7045</td>
</tr>
<tr>
<td>A&lt;sub&gt;tot&lt;/sub&gt;</td>
<td>-0.0522</td>
<td>0.7154</td>
<td>0.6958</td>
<td>-0.0373</td>
</tr>
<tr>
<td>SR</td>
<td>0.1227</td>
<td>0.6944</td>
<td>-0.7074</td>
<td>-0.0484</td>
</tr>
<tr>
<td>Eigenvalue</td>
<td>1.6874</td>
<td>1.1661</td>
<td>0.8224</td>
<td>0.3240</td>
</tr>
</tbody>
</table>

A<sub>tot</sub>, total absolute repolarization area; SR, T wave area symmetry ratio; S, T<sub>n</sub>-SD, SD of S wave offset to T wave maximum interval in the precordial leads; t<sub>ASST</sub>-SD, SD of the time interval to accumulate 50% of the total absolute repolarization area in the precordial leads; PVR, percent of retained variability; C-PVR, cumulative percent of retained variability.

Distributions of Principal Variables and Comparison by Gender

Table 5 summarizes the distributions of the principal ECG variables among the total study population. Table 6 compares both genders with respect to the same variables. Women had significantly (p<0.0001) smaller BSA and faster heart rate than men. In addition, women had longer S, T<sub>n</sub> and smaller A<sub>tot</sub> than men. The rate-corrected early-repolarization duration was significantly (p<0.0001) longer in women than men when using either the Basset correction<sup>19</sup> or the gender-specific rate-correction coefficients for S, T<sub>n</sub> presented in Table 4.

**Discussion**

The findings of our study include the identification of six principal ECG features of ventricular repolarization and their quantification by seven independent variables in a large normal population. All repolarization characteristics identified were independent of age and BSA, whereas all except early duration were independent of heart rate and QT interval. The additional information conveyed by the quantification of these repolarization characteristics to that obtained by the conventionally measured QT interval was further substantiated by the results of the redundancy-reduction techniques used in this study.

**Rationale for the Empirc Approach**

Due to the existing gap between surface ECG and direct cardiac recordings, clinical ECG has traditionally used the empiric approach. This approach has made substantial contributions to diagnosis in clinical practice as well as to the inverse solution of the cardiac generator problem. Ventricular electrical recovery is a complex phenomenon that occurs nonuniformly both spatially and temporally and is represented on the surface ECG as the ST-T-U complex, which is an integrated signal of multiple, simultaneous repolarization wave fronts.<sup>1-4</sup> Thus, being aware of the crude and sometimes equivocal relations of surface ECG parameters to basic electrophysiologic concepts and the complexity of the repolarization process, we chose the empiric descrip-

**TABLE 4. Correction for RR Interval Dependency of Log-Transformed QT and S, T<sub>n</sub> Intervals**

<table>
<thead>
<tr>
<th>Regression equation</th>
<th>n</th>
<th>r&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total population</td>
<td></td>
<td></td>
</tr>
<tr>
<td>log (QT) (1.41+0.40 log [RR])</td>
<td>364</td>
<td>0.72</td>
</tr>
<tr>
<td>log (S, T&lt;sub&gt;n&lt;/sub&gt;) (0.97+0.46 log [RR])</td>
<td>364</td>
<td>0.32</td>
</tr>
<tr>
<td>Women</td>
<td></td>
<td></td>
</tr>
<tr>
<td>log (QT) (1.43+0.40 log [RR])</td>
<td>173</td>
<td>0.65</td>
</tr>
<tr>
<td>log (S, T&lt;sub&gt;n&lt;/sub&gt;) (0.63+0.59 log [RR])</td>
<td>173</td>
<td>0.47</td>
</tr>
<tr>
<td>Men</td>
<td></td>
<td></td>
</tr>
<tr>
<td>log (QT) (1.30+0.44 log [RR])</td>
<td>191</td>
<td>0.82</td>
</tr>
<tr>
<td>log (S, T&lt;sub&gt;n&lt;/sub&gt;) (0.73+0.53 log [RR])</td>
<td>191</td>
<td>0.49</td>
</tr>
</tbody>
</table>

log, base-10 logarithm; QT, time interval between earliest Q wave onset and latest T wave offset in 12 leads; RR, mean RR interval; S, T<sub>n</sub>, time interval between S wave offset and T wave maximum.

**TABLE 5. Distribution of Principal ECG Variables Among Total Study Population**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>Q1</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR (msec)</td>
<td>912</td>
<td>899</td>
<td>142</td>
<td>803</td>
<td>999</td>
</tr>
<tr>
<td>QT (msec)</td>
<td>394</td>
<td>392</td>
<td>29</td>
<td>376</td>
<td>412</td>
</tr>
<tr>
<td>QTc (msec&lt;sup&gt;1/2&lt;/sup&gt;)</td>
<td>415</td>
<td>413</td>
<td>17</td>
<td>402</td>
<td>425</td>
</tr>
<tr>
<td>S, T&lt;sub&gt;n&lt;/sub&gt; (msec)</td>
<td>213</td>
<td>212</td>
<td>27</td>
<td>196</td>
<td>228</td>
</tr>
<tr>
<td>S, T&lt;sub&gt;n&lt;/sub&gt; (msec&lt;sup&gt;1/2&lt;/sup&gt;)</td>
<td>224</td>
<td>223</td>
<td>23</td>
<td>207</td>
<td>240</td>
</tr>
<tr>
<td>T&lt;sub&gt;n&lt;/sub&gt;T&lt;sub&gt;o&lt;/sub&gt; (msec)</td>
<td>113</td>
<td>112</td>
<td>19</td>
<td>100</td>
<td>124</td>
</tr>
<tr>
<td>t&lt;sub&gt;ASST-75&lt;/sub&gt; (msec)</td>
<td>82</td>
<td>76</td>
<td>27</td>
<td>64</td>
<td>88</td>
</tr>
<tr>
<td>A&lt;sub&gt;tot&lt;/sub&gt; (mV • msec)</td>
<td>46.6</td>
<td>41.1</td>
<td>21.8</td>
<td>30.8</td>
<td>57.5</td>
</tr>
<tr>
<td>SR</td>
<td>1.5</td>
<td>1.5</td>
<td>0.3</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>%A@T&lt;sub&gt;n&lt;/sub&gt;</td>
<td>88.5</td>
<td>89.6</td>
<td>6.2</td>
<td>85.7</td>
<td>92.9</td>
</tr>
<tr>
<td>S, T&lt;sub&gt;n&lt;/sub&gt;-SD (msec)</td>
<td>17.7</td>
<td>13.5</td>
<td>15</td>
<td>8.7</td>
<td>20.4</td>
</tr>
</tbody>
</table>

Q1, first quartile; Q3, third quartile; QTc, heart rate corrected QT interval; S, T<sub>n</sub>, heart rate corrected S, T<sub>n</sub> interval; RR, mean RR interval; QT, time interval between earliest Q wave onset and latest T wave offset in 12 leads; S, T<sub>n</sub>, time interval between S wave offset and T wave maximum; T<sub>n</sub>T<sub>o</sub>, time interval between T wave maximum and offset; t<sub>ASST-75</sub>, time to accumulate 25–75% of total repolarization area; A<sub>tot</sub>, total absolute repolarization area; SR, T wave area–symmetry ratio; %A@T<sub>n</sub>, percent absolute area accumulated at T wave offset.
tive approach. Our purpose was to accurately quantify by a validated computer algorithm distinct morphologic features of the ST-T-U wave complex to create a detailed descriptive normal database that will eventually serve as a baseline for comparison with recordings from subsets of patients with clinical manifestations attributed to known or suspected repolarization abnormalities.

Early and Late Repolarization Duration

Total duration (as measured by the QT interval) is the sum of three subintervals: QRS, SoTm, and TmTo. The SoTm variable was dependent on heart rate (as was total duration), whereas TmTo was independent of heart rate and SoTm. Because SoTm retains the heart-rate dependency of the QT interval and because the identification of T max is much more accurate than that of T offset (manually, as well as by a computer algorithm), we decided to replace the QT interval with SoTm and TmTo in our analysis. SoTm interval does not include the activation time (QRS duration). Because SoTm was recorded from a specific location on the body surface and was measured from a uniform starting point (the latest S offset in 12 leads per patient), we assume it is directly related to the average repolarization duration. The gender differences in SoTm interval, its heart-rate-corrected value (SoTmc) and QTc were highly significant (p<0.0001); these findings suggest the need for gender-related electrophysiologic research.

Repolarization Rate and Total Repolarization Area

Repolarization rate was quantified by tA25.75, a parameter that is often referred to as the “rise-time” when used in other disciplines to measure the velocity of a time-dependent process. The gender differences in total absolute-repolarization area was unexpected, and it may relate to many confounding variables such as adipose tissue distribution, lung tissue attenuation, and left ventricular mass that were not available for this analysis. It is noteworthy that repolarization area was not correlated with BSA, age, or heart rate.

T Wave Area–Symmetry Ratio, Late Phenomena, and Heterogeneity

T wave area–symmetry ratio (SR) was used as a simple morphologic feature, and percent area accumulated at T wave offset (%A@Tm) was the selected variable that is directly dependent on the presence of a U wave (mean %A@Tm was 87% in the pres-
ence of a U wave \( [n=286] \) and 93\% in the absence of a U wave \( [n=78, p<0.0001] \). \%A\( @T_m \) was independent of all other selected variables \( (r^2<0.11) \) except \( t_{A25-75} (r^2<0.63) \). The variability of \( S_0T_m \) interval across the precordial leads as a crude measure of repolarization heterogeneity was quantified by its SD. The identification of more specific directional gradients of \( S_0T_m \) across the precordium was beyond the scope of this analysis.

**Implications**

The results of our study are based on a validated computer analysis algorithm of digitized surface ECGs. Using this algorithm we were able to quantify several ECG features of ventricular repolarization in normal subjects in greater and more accurate detail than can be done manually. In addition, according to the redundancy reduction techniques used in this analysis, the seven repolarization characteristics identified were relatively independent of each other. Although the exact electrophysiologic counterparts of these characteristics are not clear, they do convey more morphologic information than the conventionally measured QT interval.

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