Linear Relationship Between Electrical Systole, Mechanical Systole, and Heart Rate*

Harisios Boudoulas, M.D.; Parashos Geleris, M.D.; Richard P. Lewis, M.D.; and Stanley E. Rittgers, Ph.D.

The relationship between the duration of electrical systole (QT) and heart rate (HR) and the relationship between the QT interval and total electromechanical systole (QS₂) were studied in the resting state in 200 patients (100 males and 100 females) without evidence of cardiovascular disease. A linear relationship was found between the QT and HR in males and females (males, QT = 521 msec – 2.0 HR, r = .91; females, QT = 511 msec – 1.8 HR, r = .90). In 20 male and 20 female subjects, the relationship between QT and QS₂ was studied. The QT was slightly shorter but paralleled the QS₂ (males QT = 529 msec – 2.1 HR, QS₂ = 541 msec – 2.2 HR; females QT = 511 msec – 1.9 HR, QS₂ = 540 msec – 2.0 HR). Thus, over the physiologic range of resting HR, a linear relationship exists between QT and HR. The QT interval is slightly shorter but parallels the QS₂ in patients without heart disease. These linear relationships permit a direct comparison of the duration of electrical and mechanical systole.

For more than half a century, investigators have attempted to relate the duration of electrical systole (QT interval) to cardiac cycle length (R-R interval). In the resting state, total electromechanical systole (QS₂) obtained from the systolic time intervals has a linear relationship with the heart rate. On this basis, we hypothesized that the relationship between QT and heart rate (HR) at rest might be linear as well. Accordingly, this study was undertaken to determine the relationship between QT and HR and the relationship between QT and QS₂ in normal resting subjects.

**MATERIALS AND METHODS**

Two hundred hospitalized patients undergoing minimally stressful diagnostic tests were studied. One hundred were males (mean age 40 ± 13, SD, range 19 to 77) and one hundred were females (mean age 39.5 ± 15, range 18 to 79). None of the patients had evidence of cardiovascular disease by history, physical examination, chest x-ray film, ECG. Patients with obvious physical or emotional stress were excluded. None of the patients received any pharmacologic agents during the study period.

The QT interval was measured, from the beginning of the Q wave to the end of the T wave, from a high fidelity ECG recorded at a speed of 25 mm/sec. In cases where

![Graph showing relationship between QT interval and heart rate in normal males](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21256/)

**Figure 1.** Relationship between electrical systole (QT) and HR in males. The 95 percent confidence level is indicated by solid diagonal lines.
the end of T wave was not precise (very rarely), the end of the T wave was taken at the point where a line of most rapid descent of the T wave transected the baseline. Three leads were recorded simultaneously. All the ECGs were performed in the morning with the patient in the supine position. The electrocardiographic lead most clearly demonstrating the onset of ventricular depolarization and the end of T wave was used. The duration of QT interval of ten successive beats was measured and the results were averaged. The HR was calculated from the same leads. All the measurements were performed by the same individual.

In 40 of the patients (20 males and 20 females), systolic time intervals were also measured according to the standard techniques. The QS₂ interval was measured from the onset of the ventricular depolarization to the first high frequency vibration of the aortic component of the second heart sound. The QT intervals obtained from the systolic time intervals recording (paper speed 100 mm/sec) were compared with the QT intervals measured from the ECG, paper speed 25 mm/sec. Statistical evaluation was performed using regression analysis and the Student’s t-test.

**Figure 2.** Relationship between electrical systole (QT) and HR in females. The 95 percent confidence level is indicated by solid lines.

**RESULTS**

Figures 1 and 2 show the relationship between QT interval and HR in males and in females. A regression model with sex included reveals that sex is an important variable in this relationship. The individual regression lines for males and females showed that the slope was the same but the intercepts were different (P < 0.05).

Figures 3 and 4 show the relationship between QS₂ interval and HR according to the equations of Weissler et al. and the relationships between QT interval and HR according to equations of the present study. It can be seen that the QT is shorter but parallels the QS₂. The equations for the QT and QS₂ are shown in Table 1.

Figure 5 shows the relationship between QT, QS₂, and HR in the 40 subjects in whom the systolic time intervals were performed. The regression equations for the QS₂ were identical to that reported by Weissler et al. and for the QT were identical with

---

**614 BOUDOULAS ET AL**

CHEST, 80: 5, NOVEMBER, 1981

---

Downloaded From: http://journal.publications.chestnet.org/pdaccess.ashx?url=/data/journals/chest/21256/ on 04/04/2017
Table 1—Calculation of the QS₂ and QT Indexes

<table>
<thead>
<tr>
<th>Sex</th>
<th>Equation</th>
<th>Mean ± 2 SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>QS₂I = 2.1 HR + QS₂</td>
<td>546 ± 28</td>
<td>518-574</td>
</tr>
<tr>
<td></td>
<td>QT = 2.0 HR + QT</td>
<td>521 ± 22</td>
<td>499-543</td>
</tr>
<tr>
<td>Female</td>
<td>QS₂I = 2.0 HR + QS₂</td>
<td>549 ± 28</td>
<td>521-577</td>
</tr>
<tr>
<td></td>
<td>QT = 1.8 HR + QT</td>
<td>511 ± 21</td>
<td>490-532</td>
</tr>
</tbody>
</table>

Table 2—Relationship Between QT and Cardiac Cycle*

<table>
<thead>
<tr>
<th></th>
<th>Equation</th>
<th>Slope (r²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bazetti¹ and Fenn²</td>
<td>QT = K (RR)²/s</td>
<td>r²</td>
</tr>
<tr>
<td>Fridericia³</td>
<td>QT = K (RR)²/s</td>
<td>−</td>
</tr>
<tr>
<td>Shipley and Hallaran⁴</td>
<td>(RR)²/s is better for slow HR</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>(RR)²/s is better for fast HR</td>
<td>−</td>
</tr>
<tr>
<td>Ashman⁵</td>
<td>QT = K log (10 (RR+K))</td>
<td>−</td>
</tr>
<tr>
<td>Present study:</td>
<td>M QT = 521 − 2.0 HR</td>
<td>0.8293</td>
</tr>
<tr>
<td></td>
<td>log QT = 7.63 − 0.308 log HR</td>
<td>0.8380</td>
</tr>
<tr>
<td></td>
<td>F QT = 511 − 1.8 HR</td>
<td>0.8074</td>
</tr>
<tr>
<td></td>
<td>log QT = 7.58 − 0.384 log HR</td>
<td>0.7872</td>
</tr>
</tbody>
</table>

*K = constant; RR, cardiac cycle length; r², correlation coefficient.

the entire group of 200 subjects studied. The QT was shorter than the QS₂ by 23 ± 4 msec in males and by 29 ± 2.5 msec in females.

The mean normal QT value for each heart rate is shown in nomogram (Fig 6). Deviations from the mean value greater than 22 msec for males and 21 msec for females must be considered abnormal.

An excellent correlation was found between the QT interval measured from the ECG (speed 25 mm/sec) and the QT measured from the systolic time intervals (speed 100 mm/sec) r = .97, P < 0.01. The QT measured with a speed of 25 mm/sec was found to be slightly longer than the QT measured with a speed of 100 mm/sec (+2 ± 1.0 msec).

Regression analysis between log HR and log QT are shown in Table 2. Sex is still an important variable. In determining which regression is better (QT vs HR or log QT vs HR), we found that the residual analysis of the log regression was not better than the linear. Thus, such a transformation is not necessary with these data. Logarithmic analysis of our data reveals the equation log QT = log K₁ + n log RR where n equals 0.398 for males and 0.384 for females and K₁ equals 10⁷.6533 for males and 10⁷.5864 for females. This equation may also be stated as log QT = log K₂ − n log HR since heart rate (HR) = 60,000/RR where K₂ = K₁ (60,000).*

**DISCUSSION**

The results of this study show that over the resting range of HR in patients with no evidence of heart disease, a linear relationship exists between the QT interval and HR. In addition, the data indicate that the QT interval is slightly shorter but parallels the QS₂. The fact that changes in both mechanical systole and electrical systole with the HR were parallel is of interest but not explained by our data. This is currently under investigation in our laboratory.¹⁰

In the range of HR from 40 to 110 beats per minute, the duration of QS₂ is related linearly with HR.⁴¹ This relationship in normal subjects has been expressed with the equation of Weissler et al.⁸ Comparison of the slopes of the QT and QS₂ showed that the two slopes are parallel in this HR range and that there is no significant difference between the slopes. In the smaller groups of patients in whom both systolic time intervals and QT were measured, the identical relationships between QT, QS₂, and HR were demonstrated. The QS₂ is slightly longer than the QT. This could, in part, be related to the mechanical properties of blood flow, since it is known that there is a 5 to 10 msec delay between aortic-left ventricular pressure cross over and aortic valve closure.⁶⁰

![Figure 5. Regression lines of electrical systole (QT) and electromechanical systole (QS₂) in 20 males and 20 females in whom systolic time intervals were performed.](http://journal.publications.chestnet.org/pfaccess.ashx?url=/data/journals/chest/21256/ on 04/04/2017)
the formula of Fridericia (RR)44 (Table 3). Finally, Ashman6 proposed that data more exactly fit a logarithmic relation. The logarithmic relation of our data showed that \( \log QT = \log K_1 + n \log RR \), (\( n = 0.398 \) in males and 0.384 in females). Since \( n \) is greater than one-third and less than one-half, we can infer a fit between Fridericia and Bazett and Fenn as would also have been expected from equations of Ashman. Lepeschkin6 comprehensively reviewed the problem by analyzing approximately 6,000 cases. He showed that good agreement exists among all the formulas when the range of HR is narrow (between 60 to 80 beats per minute), but at high or low heart rates, considerable deviation is seen. However, a less rigorous linear relation employing HR rather than RR does not decrease the closeness of fit, is applicable over the entire resting range of HR, is a more manageable relationship, and substantially decreases the standard deviation. Further, it allows direct comparison with the QS interval.

Experience indicates that it is easiest to report the rate-corrected interval as an "index" value. The QT index in milliseconds is obtained by transposition of terms of the regression equation and in fact represents the Y intercepts of the regression at zero rate. By calculation of the index value (for either men or women), an immediate estimate of the deviation from normal is obtained. For example, if a QT index is 490 msec it is immediately clear that it is 31 msec shorter than expected for a normal man (Table 1).

The QT interval can be influenced by several factors.18-19 In this study, patients with such factors present were excluded. Thus, patients on medications, with electrolyte or metabolic abnormalities and/or obvious stress were excluded.16-20 In order to avoid possible respiratory variations, the QT interval was calculated in ten successive beats including inspiratory and expiratory cycles.

Measurements of the QT interval with a speed of 100 mm/sec is probably more accurate than the measurements with a speed of 25 mm/sec.9 In this study, a speed of 25 mm/sec was used since the ECG is usually recorded with this speed in clinical

<table>
<thead>
<tr>
<th>Heart Rate (beats/min)</th>
<th>Bazett1</th>
<th>Fridericia6</th>
<th>Present Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>474</td>
<td>446</td>
<td>443</td>
</tr>
<tr>
<td>100</td>
<td>335</td>
<td>354</td>
<td>343</td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>494</td>
<td>459</td>
<td>442</td>
</tr>
<tr>
<td>100</td>
<td>360</td>
<td>364</td>
<td>362</td>
</tr>
</tbody>
</table>

Figure 6. Nomogram for relationship between HR and electrical systole (QT). Mean normal QT value for each HR is given. Deviations from mean value greater than 22 msec for male and 21 msec for female must be considered abnormal.

The slope which expresses the relationship between the QT and heart rate in males and females is not different. However, the intercepts were significantly different between sexes. Differences in the QT interval between males and females have also been reported previously.14,15 The basis of the rate-dependent changes in the duration of QT is due to the fact that the duration of ventricular action potential is rate dependent.11

The equations most commonly used to correct QT interval for changes in the cardiac cycle length (RR)14 are summarized in Table 2. Bazett and Fenn1,5 proposed that the QT = K(RR)44 where K is constant. Fridericia4 showed that QT varies according to the equation QT = K(RR)44 where K is a constant. Others suggested that (RR)44 is better for slow heart rates and (RR)44 is better for fast heart rates.14,12 At fast heart rates, the QT values obtained from the present study are very close to the values obtained from the formula of Bazett (RR)44, while at slow heart rates, the QT values from the present study are in better agreement with
practice. However, the differences in the QT interval measured with a speed of 25 mm/sec and with a speed of 100 mm/sec were minimal and would not be important for routine clinical use.

In summary, over the physiologic range of HR a linear relationship best describes the relationship between the QT interval and HR during the resting state. The QT interval is slightly shorter but parallels the \( QS_2 \). The proposed linear relation is not only easier to use but also permits a direct comparison of electrical and mechanical systole. These new equations should prove to be of considerable utility in future clinical studies, especially those involving pharmacologic agents.

REFERENCES

1 Bazett HC. An analysis of the time relations of electrocardiograms. Heart 1919; 7:353-70
3 Fenn CK. Studies in variation of length of Q-R-S-T interval. Arch Intern Med 1922; 29:441-48
5 Ashman R. The normal duration of the QT interval. Am Heart J 1942; 23:522-34
6 Lepeschkin E. Modern electrocardiography. Baltimore: Williams and Wilkins, 1951; 180-85
10 Boudoulas H, Geleris P, Lewis RP. Dissociation of electrical and mechanical systole as a manifestation of increased adrenergic activity. Circulation, in press.
12 Shipley RA, Hallaran WR. The four lead electrocardiogram in two hundred normal men and women. Am Heart 1936; 11:325-45
13 Elek SR, Silver AS, Tober JN, Griffith CG. The QT interval in myocardial infarction and left ventricular hypertrophy. Am Heart J 1952; 80:85
14 White RD, Mudd SC. Observations on the effect of various factors on the duration of the electrical systole of the heart as indicated by the length of the Q-T interval of the electrocardiogram. J Clin Invest 1929; 7:367-405
16 Surawicz B. Electrolytes and the electrocardiogram. Mod Concept Cardiovasc Dis 1964; 33:875-80
17 Barker PS, Shrader EL, Ronzoni E. The effects of acidosis and acidosis upon the human electrocardiography. Am Heart J 1939; 17:169-86
20 Autenrieth G, Surawicz B, Kuo CS, Arita M. Primary T wave abnormalities caused by uniform and regional shortening of ventricular monophasic action potential in dog. Circulation 1975; 51:668-76