QT Interval Monitoring

ST/AR Arrhythmia Algorithm
Application Note

This paper:
– Describes principles and uses of QT interval monitoring.
– Describes the QT measurement algorithm implemented in the Philips Patient Monitoring Systems.
– Describes the alarms
– Lists the limitations to QT Monitoring.
– Presents performance results from its evaluation.

Introduction
The goals of ECG monitoring in the hospital setting include:
– The measurement and display of heart rate and detection of arrhythmic events.
– ST segment monitoring of acute myocardial ischemia and the assessment of evolving ischemia.
– QT interval monitoring for the detection of prolonged QT interval syndrome

Philips provides a comprehensive ECG solution to meet both the diagnostic and monitoring needs of patients in a hospital setting.
In addition to the Standard 3, 5 and 6-lead monitoring, there are two types of 12-lead ECGs; diagnostic ECGs directly acquired using a 10-lead wire set, EASI derived from a 5-lead wire set or Hexad derived from a 6-lead wire set.
For QT interval analysis, Philips now provides three modalities for QT/QTc measurement;
Electronic caliper assisted QT/QTC measurements can be performed manually on any stored ECG waveform.

Figure 1  Electronic caliper assisted manual QT measurement from the Information Center

Electronic calipers assisted manual QT measurements from the Information Center iX

Diagnostic 12-lead ECG captured at the IntelliVue Patient Monitor can be analyzed for a global QT/QTC measurement using the Philips 12-lead analysis algorithm at the Information Center or Information Center iX.

Figure 2  12-Lead ECG capture analyzed for QT/QTC interval by the 12-lead ECG Algorithm

Figure 3  Automated continuous QT/QTC interval analysis using all user specified leads on the IntelliVue Patient Monitor and Information Center
What is the QT interval?
The QT interval is one part of the heart’s electrical signature as recorded by an electrocardiogram (ECG). The QT interval measures the total duration of depolarization (QRS duration) and repolarization phases (ST-T) of the ventricular action potential. The QT interval is measured from the beginning of QRS to the end of T-wave, as shown in Fig. 5.
The beginning of the QRS complex can usually be relatively easily identified, however the end of the T-wave can be difficult to determine. One commonly used method is to draw a tangent from the steepest downslope of the T-wave to the intersection of the baseline which is considered the end of the T-wave.

Figure 4  PQRST Intervals and Segment Measurements

Figure 5  One method for finding the end of T-wave

QT intervals will vary with age, sex and heart rate. Normally the QT interval should be less than 50% of the preceding R-R interval.

QT Adjustment for Heart Rate
The QT interval has an inverse relationship to heart rate. Faster heart rates shorten the QT interval and slower heart rates prolong the QT interval. Based on population studies, researchers have generated correction formulas to normalize the effects of heart rate. Heart rate corrected QT interval is abbreviated as “QTc”. It should be noted that since all correction formulas are population based, they may not be representative for a particular patient. In addition, drugs may also change the relationship between QT and heart rate.

Several commonly used heart rate correction formulas are Bazett, Fridericia, Hodges, and Framingham as shown in Table 1. Where QTc on the left hand side of the formula indicates heart rate corrected QT. The QT on the right hand side is the directly measured QT. Both are measured in milliseconds. RR is the time in seconds between two QRS complexes. HR is the heart rate measured in beats per minute. Regardless which correction formula is used, a QTc value of < 460 ms in women and < 450 ms in men is considered normal.

Table 1: Correction Formulas

<table>
<thead>
<tr>
<th>Correction Method</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bazett</td>
<td>QTc = QT / (RR)(^{1/2})</td>
</tr>
<tr>
<td>Fridericia</td>
<td>QTc = QT / (RR)(^{1/3})</td>
</tr>
<tr>
<td>Hodges</td>
<td>QTc = QT + 0.175 (HR - 60))</td>
</tr>
<tr>
<td>Framingham</td>
<td>QTc = QT + 154 (1 – RR)</td>
</tr>
</tbody>
</table>

In clinical practice, the most commonly used formula is Bazett. However, this formula has been shown to over-correct (i.e. the resultant QTc is too short) for low heart rate and to under-correct (i.e. the resultant QTc is too long) for high heart rate. The same limitation, although to a lesser degree, also applies to Fridericia’s formula. In a recent study of 14,548 healthy black and white middle-aged men and woman, there were only minor differences in the risk stratification of predicting coronary heart disease provided by three formulas with Bazett’s formula provided slightly better separation. This finding supports the continuous use of the Bazett in clinical practice.

Because the average heart rates in pediatric and neonatal population are higher than those in the adult population, a study comparing heart rate correction using the above four formulas in children have shown that none of the four formulas provided an optimum QT correction. The Fridericia and Framingham corrections may be superior in the assessment of congenital Long QT syndrome compared with the Bazett and Hodges formulas.

In 2005, ICH (The International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use) issued a guidance-for-industry document (E14) titled “Clinical Evaluation of QT/QTc Interval Prolongation and Proarrhythmic Potential for Non-anti-arrhythmic Drugs.” In this guidance document it is required that both Bazett and Fridericia formulas be included in all drug study submissions.

The Philips monitoring system default uses the Bazett correction formula. The user has the ability to configure either the Bazett or Fridericia formula. The configured formula will be used for all three methods of QT measurements – continuous, electronic caliper assisted manual, and diagnostic 12-lead analysis.
QT-RR Hysteresis
While higher heart rates shorten the QT interval and slower heart rates prolong the QT interval, there is a delay for the QT interval to adapt to the new heart rate following a rate change. This lag in QT adaptation is described as “hysteresis”. A change of heart rate may require 1 to 2 minutes (the time delay varies from patient to patient) for a new QT interval to become stable. Therefore, for reliable QTc calculation, it is important to avoid a region where the heart rate is changing.

QTc Prolongation & Long QT Syndrome
Lengthening of the repolarization phase of the ventricular action potential results in so-called “long QT syndrome” (LQTS). LQTS is a disorder of cardiac repolarization and is characterized by the prolongation of the QT interval. Prolonged QT is associated with sudden cardiac death. LQTS can be congenital or acquired.

Congenital LQTS
The congenital LQT is a heritable ion channel disease caused by one of several mutations in the genes coding for the sodium or potassium ion channel proteins. Several subsets of congenital LQT (LQT1 – LQT8) have been identified. Clinical presentation varies with the specific gene affected and the specific mutation. Each of these forms has its own triggers, ECG characteristics, and outcomes. The genetic disorder is most often seen in children and adolescents with otherwise healthy hearts.

Acquired LQTS
The acquired LQT is almost always associated with drugs that prolong the QT interval, although other causes have been reported. Both cardiac and non-cardiac drugs may cause QT prolongation. It may occur gradually or rapidly in a variety of clinical situations such as adverse cardiac responses to the administration, increased dosage, or overdose of QT prolonging drugs.
A variety of drugs, such as procainamide and quinidine, have been shown to prolong the duration of the action potential and thus increase the QT interval. Some drugs (at higher dosage) may increase the heterogeneity of action potential durations by selectively shortening action potential duration in some myocardial regions. Drugs with such action include lidocaine, mexiletine, tocainide, and phenytoin.
A number of antiarrhythmic and antipsychotic drugs and some antibiotics may initiate serious arrhythmic events. The anti-arrhythmic quinidine, procainamide, disopyramide, sotalol, dofetilide, and the antibiotics erythromycin and clarithromycin are most likely to cause severe arrhythmias. The list of arrhythmogenic antipsychotic drugs includes chlorpromazine, haloperidol, mesoridazine, pimozide and thioridazine.
Researchers have also reported lengthening of QT when using cisapride and doxapram in neonates and preterm infants and recommended ECG follow-up when using cisapride and doxapram.
An extensive list of these drugs can be found at the web site provided by the University of Arizona Center for Education and Research on Therapeutics, (http://www.torsades.org).

Long QT and Torsade de Pointes (TdP)
QTc prolongation has been associated with serious arrhythmic episodes with an increased risk of syncope and sudden death from Torsade de Pointes. Both congenital and acquired long QTc syndrome may lead to Torsade de Pointes.
The term “Torsade de Pointes” (TdP), a French term meaning “twisting of points”, is used to describe a particular form of ventricular tachycardia. The arrhythmia is characterized by a continuous alteration in morphology, amplitude, and polarity of the QRS complexes, whose peaks twist around the isoelectric baseline. The rhythm may range from 100 to 250 beats/min, and usually terminates spontaneously but may degenerate into ventricular fibrillation or more rarely monomorphic ventricular tachycardia. When this rhythm occurs, no blood is pumped out from the heart, and the brain quickly becomes deprived of blood, causing the usual symptoms of sudden loss of consciousness and sudden death if the rhythm persists.

Figure 6  Torsade de Pointes
Torsade de Pointes typically occurs after a prolonged QT in the preceding sinus beats. Especially in acquired LQTS, TdP is usually triggered by a typical short-long-short QRS complex interval initiation sequence.

**Indication for use of QT Interval Monitoring**

Of special concern in QT monitoring is the administration of QT prolonging drugs to patients identified with risk factors for TdP. Females, older patients and patients with bradycardia, impaired left ventricular function (ischemia, left ventricular hypertrophy), hypokalemia and hypomagnesemia are in this increased risk category. Current AHA Scientific Statement on Practice Standards for Electrocardiographic Monitoring in Hospital Settings listed the following as indications for QT monitoring:

- **Class I**
  - Patients administered an antiarrhythmic drug known to cause torsade de points
  - Patients who overdose from a potentially proarrhythmic agent
  - Patients with new-onset brady arrhythmias
  - Patients with severe hypokalemia or hypomagnesemia

- **Class II**
  - Patients who require treatment with anti psychotics or other drugs with possible risk of Torsade de Pointes
  - Patients with acute neurological events

- **Class III**
  - Healthy patients administered drugs that pose other risk for Torsade de Pointes

**Automated QT Measurement Algorithm**

When measuring the QT interval, two points must be determined: the onset of the QRS complex and the end of the T-wave. The onset (Q wave) is abrupt and fairly easy to detect. It is very close to the same time point on different ECG leads. The end of the T-wave is gradual and usually differs from one lead to another. So the main difficulty in measuring the QT interval is finding the end of T-wave. This measurement is even more difficult to measure in a monitoring environment where ECG signals are often contain muscle noise and baseline wander. However, since QT intervals do not change very rapidly not every single beat needs to be measured. Therefore, reliable QT measurements can be made by using signal averaging techniques.

**End of T-wave Measurement Technique**

Although QT interval is routinely measured in many clinical applications, there is no agreed upon method on how the end of the T-wave should be measured. The ST/AR algorithm uses a novel technique to measure the end of the T-wave. The measurement algorithm is shown in Fig. 9.

**Figure 8 End of T-wave Determination**

The end of the T-wave is determined using the following steps; 1) draw a line segment from the top of the T-wave forward in time to a heart rate adjusted point on the baseline, 2) measure the vertical distance between each sample point on the waveform to the line segment, 3) identify the location of the maximum vertical distance as the location of
the T-wave end. This measurement technique has been used in both the Philips’ cardiograph and Holter system with highly accurate results.

**QT Interval Monitoring Mode**

For QT interval monitoring, the user has the ability to select one of the following three modes (Default is All leads Mode):
- **All Leads Mode** - All available leads, excluding the augment leads and the right and posterior chest leads, are used to produce a global QT measurement. With EASI lead configuration, the directly acquired EASI leads ES, AS and AI are used to produce a global QT measurement.
- **Primary-Lead Mode** - The primary lead will be used for QT measurement. If the original primary lead becomes unavailable, QT measurement will continue with the new primary lead.
- **Single-Lead Mode** - A single lead selected from any available lead, excluding the augmented leads and the right and posterior chest leads, will be used for QT measurement. QT measurement will stop if the selected single lead becomes unavailable.

For QT interval monitoring to be effective, basic or enhanced arrhythmia should be active.

**The ST/AR QT Measurement Algorithm**

The ECG signal from patients being monitored in the critical care setting contains significant amounts of muscle and motion artifacts, and the location and number of electrodes varies. The ST/AR QT/QTc real-time analysis algorithm is designed to address these challenges. The algorithm provides continuous QT and QTc interval measurement, while providing continuous patient surveillance and alarm generation.

Based on the ECG leads selected the QT interval measurement algorithm generates a QT and QTc value once every 15 seconds.

The algorithm consists of the following steps.

**Step 1: Saving QRS complexes**

All QRS complexes detected by the beat detection algorithm within a discrete 15 second time period are saved for subsequent QT analysis. Only beats that are classified as normal or atrial paced will be included in the subsequent analysis. Beats followed by a premature QRS or PVC will also be excluded from the measurements to prevent the premature beat from obscuring the end of the T-wave if the beat is occurs is less than 20 percent of the R-R interval.

**Step 2: Form Averaged Beat**

For each beat clustering and outlier rejection is performed first to reduce the impact of a noisy signal. Beats with similar morphology are then averaged to form the representative waveform.

In addition, an isoelectric point in the P-Q waveform region is identified. The offset to the isoelectric point is subtracted from the waveform to further remove any residual baseline offset.

**Step 3: Form RMS Signal**

The representative waveforms from all selected leads are then combined into one root-mean-squared (RMS) ECG. The RMS ECG is calculated by summing the squares of all representative complexes from all selected leads and taking the square root of the summation excluding leads with low T-wave amplitude. This has the effect of converting all waves to their positive form and combining the information present.

The QT interval is measured on this RMS ECG rather than on individual leads. A QT interval measured on this RMS ECG represents the earliest Q onset to the latest T offset of all leads. Measuring QT on a combined RMS ECG is particularly beneficial when one lead has the best-defined Q onset while another lead has the best T offset. Measuring the RMS ECG can also reduce variations in measurements from positional and respiratory changes. This is particularly important in the patient monitoring environment.

**Step 4: R-Wave Amplitude Check**

To ensure reliable QT measurement, the R wave amplitude is first checked. If the R wave amplitude of the RMS waveform is less than 200 μV, no QT interval measurement will be performed.

**Step 5: T-wave End Determination**

Using the technique describe above, the T-wave end is determined. First, the peak of the T-wave is detected from a heart rate dependent search window. If the peak of the T-wave is less than a predefined threshold, no QT measurement will be performed. To determine the T-wave offset, a line is drawn from the peak of the T-wave forward in time to a heart-rate adjusted point on the baseline. The point along the ECG waveform with the maximum vertical distance from this line is determined to be the T offset.

**Step 6: Q-Wave Onset Determination**

Q-wave onset is determined using the same technique used for finding the end of the T-wave. For Q onset, a line is drawn from the midpoint of the rising edge of the R wave to a heart rate adjusted point prior to the QRS complex. Starting from the point with the maximum vertical distance from this line to the signal being analyzed, a search is made to locate the Q-wave onset.
Step 7: QT Interval Calculation

Once the Q onset and the end of the T-wave are determined, the QT interval is computed as the difference between the two. The QT interval is measured in milliseconds.

Step 8: QTc Interval Calculation

In order to calculate the QTc interval, an averaged heart rate (QT-HR) is generated. QT-HR is computed using all the valid beats in the 15 second window used for the QT interval measurement. QTc is then calculated using the rate correction formula selected. The QTc interval is also measured in milliseconds.

Step 9: 15 second QT/QTc Measurement

The above steps are repeated for each new 15 second interval. At the end of 15 seconds, the last 15 second QTc interval measurements are made available from the ST/AR algorithm to the host device. Depending on the device and revision values updated on the display every 15 seconds, every one minute or every five minutes. In addition, ST/AR will also make available a ECG snippet for display.

Step 10: Calculate QTc Change (dQTc)

Finally, QTc change (dQTc or ΔQTc) is calculated by subtracting the baseline QTc value from the current QTc value. The measurement unit for dQTc is also in msec. The initial QT baseline is automatically set by the algorithm using the 1st valid five-minute QT and QTc measurements. The user can select a new baseline anytime during QT monitoring. Note: depending on the monitoring product, ΔQTc may also be used instead of dQTc for QTc change.

QT View Window

The QT View Window is available on the IntelliVue Patient Monitors Release G.0 and higher, and the Philips IntelliVue Information Center iX. In this window (Figure 8 IntelliVue Monitor or 9 Information Center iX) is displayed representative waveform for each lead. The waveform or snippet is the averaged waveform for each lead. During “QT Startup” this waveform is updated every minute. After the startup period the waveform is updated depending on the host device. Data in these windows are updated every 15 seconds. Data is updated on the main display of the IntelliVue Monitor every 1 minute and on the Philips IntelliVue Information Center iX every 15 seconds.

Figure 9 QT View Window at the IntelliVue Patient Monitor automatically update every minute.

Figure 10 QT View at the Philips IntelliVue Information Center iX - If the source of ECG is Patient Worn Device and Patient Worn Monitors the data is updated every 15 seconds and if the source is IntelliVue Monitors data is updated every one minute when requested.
There are two QT alarms, QTc high limit alarm and QTc change alarm. The QTc limit alarm has higher priority than the QTc change alarm. Both alarms are long yellow alarms.

**Long QTc Alarm**
The QTc high limit alarm is a continuous yellow alarm sound which is generated when 60% of the 15-sec QT measurements exceed the QT alarm limit over a period of 5 minutes. The visual alarm message will appear in one of two formats depending on the configuration of the monitor. The QTc high limit alarm is defaulted to 500 milliseconds for adults patients (480 for pediatric and 460 for neonatal patients) but can range from 200 to 800 milliseconds in increments of 10 millisecond.

**QTc Change alarm**
The delta QTc alarm or QTc change alarm is generated as a yellow level continuous alarm when the difference between the current value and the baseline value exceeds the set limit for 60 percent during a five-minute period. The QTc change alarm is defaulted at 60 milliseconds but can be changed to from 30 to 200 milliseconds in 10 milliseconds increments.

| ΔQTc  nnn>hhh | nnn is current value  
|--------------|-----------------------
|               | hhh is the set high limit |

**Table 2: QT INOP Messages**

<table>
<thead>
<tr>
<th>Additional Messages</th>
<th>Cause of Invalid QT Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>QT Startup</td>
<td>QT monitoring was just turned on or has been reset</td>
</tr>
<tr>
<td>Leads Off or Asystole</td>
<td>Not all specified leads needed to perform QT analysis are available, or Asystole condition is detected</td>
</tr>
<tr>
<td>Insufficient Valid Leads</td>
<td>Not enough valid QRS complexes to generate a QT measurement</td>
</tr>
<tr>
<td>Invalid rhythm for QTc</td>
<td>Not enough valid RR intervals to generate QT-HR, the averaged HR used for QTc calculation</td>
</tr>
<tr>
<td>High QT-HR</td>
<td>QT-HR exceeds the specified upper limit of 150 bpm (for adults) or 180 bpm (for neonates and pediatrics)</td>
</tr>
<tr>
<td>Small R Wave</td>
<td>R-wave of the signal is too small</td>
</tr>
<tr>
<td>Small T Wave</td>
<td>T-wave of the signal is too small</td>
</tr>
<tr>
<td>End of T Not detected</td>
<td>End of the T-Wave cannot be accurately detected</td>
</tr>
<tr>
<td>QT Out Of Range</td>
<td>QT measurement is outside the specified range of valid QT values (200 - 800 msec)</td>
</tr>
<tr>
<td>QTc Out Of Range</td>
<td>QTc measurement is outside the specified range of valid QTc values (200 - 800 msec)</td>
</tr>
<tr>
<td>QTc Erratic</td>
<td>QTc measurements are not stable</td>
</tr>
</tbody>
</table>
Limitations QTc Monitoring

Conditions that can cause difficulty for continuous QT monitoring are described below.

**Flat T-wave**
T-wave amplitude in some ECGs may be too low for identification of the end of the T-wave. For reliable QT monitoring, select a lead with sufficient T-wave amplitude.

**U wave**
A discrete and separate U-wave is not considered as part of the QT interval. U waves often overlap the T-wave and the midpoint of the overlap is taken as the end of the T-wave. ST/AR QT algorithm will usually measure the end of the T-wave correctly in the presence of a U-wave. However, if the presence of U-wave is causing the algorithm to produce erroneous measurements, select a lead without a predominant U-wave.

**High Heart Rate**
When the heart rate is high, the P wave of the subsequent P-QRS-T complex may approach the end of the T-wave and produce an effect similar to that of a U wave. The midpoint will be taken as the end of the T-wave. If the heart rate is above 150 bpm for adults or 180 bpm for pediatric and neonates no measurement will be made. If P-wave is causing the algorithm to produce erroneous measurements, select a lead without a predominant P-wave.

**Wide QRS Complex**
Increases in QRS duration contribute to a long QTc interval. Patients with left or right bundle branch block, Wolff-Parkinson-White or hypertrophy may have widened QRS durations. If a long QTc is observed it should be verified to ensure that it is not caused by QRS widening.

**Atrial Fibrillation & Atrial Flutter**
Patients with atrial fibrillation or atrial flutter often do not have clear T-waves because of the interference due to atrial activity. In addition, the marked variation of rate usually makes correction more problematic. QTc measurements are difficult to interpret. Some of these problems may be reduced by choosing leads with no visible flutter activity.

**Leads Used for QT Measurement**
As previously mentioned, the apparent end of T-wave varies from lead to lead. The biggest problem comes from small T-waves and from respiratory variation in the morphology. If a single lead is being used for patient monitoring, it is advisable to choose a lead with a large T-wave and no terminal inversion.

**Prolonged PR Intervals**
With rapid heart rates typical in neonates and young pediatric patients, the P wave and T-wave may overlap. Some extreme cases of prolonged PR intervals may result in the P wave occurring before the end of the T-wave. In such cases, the end of the T-wave should still be measurable. If P-wave is causing the algorithm to produce erroneous measurements, select a lead without a predominant P-wave.

**Arrhythmia Algorithm Accuracy**
Beat labeling from the arrhythmia algorithm is used in the QT algorithm to reject beats that should not be measured. Incorrect beat labeling by the arrhythmia algorithm can influence the accuracy of the QT measurement algorithm. In order to obtain accurate QT measurements, factors that affect the arrhythmia monitoring performance should be corrected. Because normal beats followed by ventricular beats are not included in the analysis, no QT measurement will be generated in the presence of a bigeminy rhythm if the premature beats occur within 20 percent of the R-R interval.

**Other Issues**

**Computer Measurements versus Manual Measurements**
QT and QTc values measured manually from one or two monitoring leads may not correspond to QT values reported by the automated algorithm that uses multiple leads with averaging. The reason is that the automated algorithm selects multiple similar beats with clean signals, averages these beats, and calculates one complex from multiple channels. Manual measurement can only take one beat on the available leads at one time. In addition, it is a well-known fact that automated QTc measurements are consistent but manual measurements are affected by ECG paper speed and gain and also T-wave amplitude. Manual QTc measurements also differ from one individual to the next.

**QTc Measurements by Monitoring Algorithm versus by 12-lead Diagnostic Algorithm**
The QTc measured on monitoring ECG and 12-lead diagnostic ECG are likely to be different. Numerous causes exist for such differences. ECG sampling rates and signal bandwidths are different between monitoring ECG and diagnostic ECG. As described above, the monitoring QTc interval measurement algorithm uses 15 seconds of ECG and selected beats with similar morphology to form an average beat and calculates RMS ECG for QTc measurement. The approaches are different in monitoring QTc algorithm and 12-lead diagnostic ECG QTc algorithm. Pharmaceutical studies have generally shown that different QT methods may differ in absolute values but are capable of detecting changes in patients as long as a consistent method is used.
Assessing ST/AR QT Measurement Analysis Algorithm Performance

The performance of the algorithm used to measure QT and QTc intervals is fundamental to the effectiveness of computerized QT/QTc monitoring. It is important that the algorithm enables the system to alert the clinical staff to true QT/QTc changes without unnecessarily distracting them from their duties. Such an algorithm will allow the monitoring system to generate accurate cumulative data that will be useful in supporting therapeutic decision.

Reference Database

For performance evaluation, three sets of ECG data are used. For the adult patients, the publicly available PhysioNet QT database is used. This data set consists of 105 patient records, each 15 minutes long with two ECG channels. The database contains a variety of T-wave morphologies and has been annotated by cardiologists for QT interval. For pediatric patients, 20 2-channel ECGs of ten-minute in duration are recorded from a pediatric intensive care unit (PICU). For the neonate patients, 50 single-channel ECGs of ten-minute duration were recorded from two neonatal intensive care units (NICU). Cardiologist annotations are used as the “gold standard” reference QT values in the performance evaluation. In 103 out of 105 records of the PhysioNet QT data set, QT intervals have been annotated for approximately 30 to 50 beats starting from the 10th minute of the record. For the pediatric and neonatal data sets, two cardiologists annotated QT intervals in a 15-second period starting from the 7th minute of the recording. Table 2 shows the number of records, the number of cases annotated by the cardiologist, and the average heart rate for the three data sets used in the performance evaluation.

Table 3: Summary of Datasets for performance evaluation

<table>
<thead>
<tr>
<th>Database</th>
<th>Number of Records</th>
<th>Number of Annotated</th>
<th>Mean HR (bpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhysioNet (Adult)</td>
<td>105</td>
<td>103</td>
<td>71</td>
</tr>
<tr>
<td>PICU</td>
<td>20</td>
<td>20</td>
<td>123</td>
</tr>
<tr>
<td>NICU</td>
<td>50</td>
<td>50</td>
<td>155</td>
</tr>
</tbody>
</table>

For each record, the mean values of the manual measurements i.e., the average of all beats from the cardiologists, are used as the reference QT interval. The algorithm measurements used in the comparison are the average of the algorithm’s 1-minute QT measurements that fell within a window starting slightly before the first beat of the cardiologist annotation and ending slightly after the last beat of cardiologist annotation.

Performance Measures

The performance measures quantify the extent to which the algorithm QT measurement results agree with the expert annotated QT intervals. The performance measures used to measure QT interval accuracy include the following:

Measurement Correlation Coefficient - Correlation coefficient is a statistical measurement of how well the algorithm’s generated values and the cardiologist annotated values correlate. The value ranges from -1.0 (negatively correlated) to +1.0 (positively correlated). A high positive measurement correlation coefficient indicates that the two sets of values are similar a high percentage of the time.

Linear Regression Line - Relationship between two sets of data can be viewed graphically via scatter plots. The linear regression line is the equation of a straight line that best fits the plotted data. When the two sets of data are similar, the line regression line approaches Y = X (slope of the regression line = 1).

Mean Difference and Standard deviation of the differences - The mean difference is the average of the differences between two sets of data. If the two sets of data are similar the mean difference will be small. Standard deviation (SD) is the most common measure of statistical dispersion. The standard deviation of the differences measures how widely spread the differences are from the mean difference. A large value indicates that the measurement differences are far from the mean difference, and a small value indicates that they are clustered closely around the mean difference.

Bland-Altman Plot - Another way to examine the relationship between two sets of data is to use the Bland-Altman plot. In this graphical method the difference between the two sets of data (Y-axis) is plotted against the mean of the two measurements (X axis). Three horizontal reference lines (mean difference, mean ± 2SD) are also plotted.

Results

The ST/AR QT interval measurement accuracy results are summarized in the following scatter plots and Bland-Altman plots. For the scatter plot, the horizontal axis represents the cardiologist’s QT measurement in millisecond. The vertical axis represents the QT measurement, in millisecond, generated by the algorithm. The dotted diagonal line represents the desired goal - the point where the algorithm’s measurement value is equal to the cardiologist’s measurement. The solid line is the linear regression line. QT measurements with no matching algorithm or cardiologist value are shown along the axes. Measurements plotted on the horizontal axis represent QT measurements made by the cardiologist but the
algorithm is not able to generate a QT measurement. Similarly, measurements plotted on the vertical axis are algorithm generated QT measurements but there are no matched cardiologist's measurements. For the Bland-Altman plot, the horizontal axis shows the mean value of the cardiologist and algorithm QT measurements, and the vertical axis shows the measurement difference (Algorithm QT - Cardiologist QT). Both axes are in millisecond. Three dashed horizontal lines are also plotted. The middle one is the mean difference, and the two outer lines are the mean value +/- 2 standard deviations.

Figures 14(a), 15(a), and 16a) are the scatter plots for the adult, pediatric, and neonatal data set respectively. The Bland-Altma plots for the same three data sets are shown in Figures 14(b), 15(b), and 16(b), respectively. Performance results by combing all three data set are shown in Figures 17(a) and (b). The specific performance measures including correlation coefficient, linear regression line slope, mean difference, and standard deviation of the difference are summarized in Table 3 for each data set and all data sets combined. These performance evaluation results show that the automated algorithm has achieved a high level of accuracy in providing QT interval measurements over a large patient population. The algorithm's measurements are highly corrected to the cardiologist's manual QT measurements. In addition to having tested the algorithm using the annotated QT data sets from adult, pediatric, and neonatal populations, we have also stressed the QT algorithm by testing using a variety of ECG signals with arrhythmia, noise artifact, pacing, and long duration. The results obtained show the algorithm's ability to produce stable QT measurement and track changing QT intervals.

Conclusion

The automated QT/QTc interval monitoring is a tool the clinician can use to continuously monitor and evaluate the progress of patients. In order to fully make use of this tool, it is important to understand the algorithm’s capabilities and limitations. If a QTc prolongation is detected, the clinical significance of the change must be determined by a clinician. To ensure peak performance, the staff should be aware of the intervention and adjustments they can implement to enhance the QT algorithm’s performance. From the results presented in the application note, the performance of the QT algorithm is evident. This capability enhances the effective monitoring of QT interval changes in the clinical setting.

Table 4: Performance Summary from all three datasets

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Correlation Coefficient</th>
<th>Regression Line Slope</th>
<th>Mean Diff (ms)</th>
<th>Std Dev of Diff (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhysioNet (Adult)</td>
<td>.94</td>
<td>.90</td>
<td>-5</td>
<td>27</td>
</tr>
<tr>
<td>PICU</td>
<td>.97</td>
<td>1.02</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>NICU</td>
<td>.89</td>
<td>.87</td>
<td>4</td>
<td>13</td>
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<tr>
<td>All</td>
<td>.97</td>
<td>.93</td>
<td>-2</td>
<td>23</td>
</tr>
</tbody>
</table>
Figure 14  (a) Scatter plot of Adult data set performance  
(b) Bland-Altman plot of Adult data set performance

Figure 15  (a) Scatter plot of Pediatric data set performance  
(b) Bland-Altman plot of Pediatric data set performance
Figure 16  (a) Scatter plot of Neonatal data set performance  
(b) Bland-Altman plot of Neonatal data set performance

Figure 17  (a) Scatter plot of All data set performance  
(b) Bland-Altman plot of All data set performance

References

5. Khan IA: Long QT Syndrome: Diagnosis and Management. Am Heart J 2002;143:7-14