This application note describes principles and uses for continuous ST segment monitoring. It also provides a detailed description of the ST Analysis algorithm implemented in the multi-lead ST/AR (ST and Arrhythmia) algorithm, and an assessment of the ST analysis algorithm’s performance.

Introduction

Routine electrocardiographic monitoring is standard practice in coronary and intensive care units, emergency rooms, ambulatory monitoring settings, and operating rooms. The goals of ECG monitoring have been directed at the measurement of heart rate and the detection of arrhythmia and continuous ST segment monitoring to detect ST changes which may be ischemic episodes.

Ischemia detection has always been an important component in identifying and managing patients with coronary artery disease. Advances in cardiac patient management, such as early reperfusion with thrombolytic therapy and revascularization with PTCA procedure, have made continuous non-invasive detection of ischemia even more important. The emphasis has shifted from detecting and diagnosing coronary artery disease to the on-line monitoring and treatment of evolving ischemia.

Although monitoring ECG for ST segment deviation is not the most sensitive and specific technique for myocardial ischemia detection, it remains the only practical technique for continuous non-invasive monitoring of ischemic episodes.

Myocardial Ischemia

The term “ischemia” refers to a reduction in the supply of oxygenated blood to the cells of an organ. Ischemia occurs when the arterial conduit becomes limited in its ability to feed tissues with sufficient oxygen to meet the metabolic requirements. The impact of ischemia depends upon the duration and location of the tissue cells.

Organs such as the heart and brain are most vulnerable to reduced oxygenation or ischemia due to their high extraction of oxygen. The heart is vulnerable to infarction as it has few collateral
blood vessels to oxygenate tissue if the primary arterial conduits are narrowed or blocked for an extended time.

The main cause of myocardial ischemia is coronary artery disease. More specifically, the principal contributors to reduced myocardial oxygenation are thought to be:

- Reduced vessel size (narrowing) due to increased calcification of plaques within the artery.
- Spasm of the muscular-walled artery.

Situations that cause ischemia, and that without intervention are likely to lead to myocardial infarction are:

- Migration of a blood clot into the coronary artery.
- Rupture of an arterial plaque which releases thrombogenic fluid directly into the coronary artery.

Decreased oxygen supply, either as decreased blood flow or lack of oxygen in the blood, results in delayed or abnormal electrical characteristics during the repolarization phase of the myocardial cells. This is displayed as changes in the level of the ST segment.

The effects of ischemia are reversible if the episode is limited in time. Many ischemic events are self-limiting and are caused by an increased demand for blood from an artery that is unable to respond. For example, if an episode is caused by increased physical or emotional stress, relieving that stress limits its duration. When an episode remains unrelieved, tissue cells begin to die and a myocardial infarction results.

Silent Ischemia

In many cases, myocardial ischemia episodes are accompanied by chest pain (angina). However, ischemia may also be present in many situations in which chest pain is absent (silent ischemia). It has been shown that silent ischemia has the same characteristic changes as those of symptomatic episodes, except that chest pain is not present. Many studies have shown that the majority of ischemic episodes in patients with symptomatic coronary artery disease are actually not associated with angina.

Although several mechanisms have been proposed, the link between pain and transient myocardial ischemia is still not well understood. Data are emerging that show that both painful or silent ischemic episodes in patients, whether with stable angina, unstable angina, or after myocardial infarction, are a major independent sign of increased risk for subsequent major cardiac events.

Therefore, myocardial ischemia is now considered as an entity composed of both painful and silent episodes (total ischemic burden). It has been advocated that therapy for the patient with coronary artery disease should be the total eradication of all ischemic episodes whether symptomatic (painful) or asymptomatic (painless). Because angina can no longer be considered a reliable indicator of ischemia, noninvasive techniques assume a pivotal role in the detection of ischemic episodes.

Detection of Myocardial Ischemia

Technologic advances have presented clinicians with a diversity of techniques for the detection of myocardial ischemia in both clinical practice and research. Each technique measures some aspect of abnormal function seen during the development of ischemia.

Inadequate perfusion can be detected by myocardial redistribution scintigraphy. The presence of anaerobic metabolism can be detected using positron emission tomography by detecting a mismatch between myocardial perfusion and metabolism function. Diminished myocardial wall contraction can be detected by either radionuclide ventriculography or two-dimensional echocardiography. The electrophysiologic changes during ischemia can be detected as ST segment changes in the ECG signal.

Continuous ST Segment Monitoring

Although monitoring ECG for ST segment deviation is not the most sensitive and specific technique for myocardial ischemia detection, it has been the most utilized technique for ischemia detection in the operating room and ICU/CCU because of its availability, low cost, and ease of use. It is also the only detection technique that enables the detection and documentation of all episodes of ischemia as reflected by ST segment changes, whether painful or silent.

When monitoring of the ST segment indicates ischemic activity, a 12-lead ECG is commonly performed to confirm the episode.

The ST Segment

After ventricular depolarization, normal myocardial cells are at nearly the same potential. Therefore in the absence of any cardiac pathology, the end of depolarization and the beginning of repolarization are normally isoelectric; this region is called the ST segment. On the ECG signal, the ST segment is defined as the region between the end of the S-wave, also called the J-point, and the beginning of the T-wave.

Ischemic and damaged tissue causes the cells of the myocardium to become either more or less excitable. This change is most apparent in the ECG during the repolarization phase. The ST segment of the ECG primarily reflects ventricular repolarization, and therefore ST depression or elevation reflects this ischemia or damage.
The location of the monitoring electrodes and the direction and magnitude of the ST change indicate the area of the heart at risk, and the possible extent of the damage. The probability of detecting ischemic episodes, and locating them, increases with the number of leads employed, the appropriate choice of ECG leads, and correct lead placement.

**Measuring ST Segment**

The current standard of determining the ST segment measurement is by measuring the voltage difference between the value at a point 60 or 80 milliseconds after the J-point and the isoelectric baseline. The isoelectric baseline is either between the P- and Q-waves (the P-R interval) or in front of the P-wave (the T-P interval).

ST segment measurement values are reported in either millivolts, microvolts or millimeters, because the standard diagnostic ECG strips are plotted at a scale of ten millimeters per millivolt. Thus one millimeter represents 0.1 millivolt. A positive value represents an ST elevation (Figure 3), and a negative value represents an ST depression (Figure 4).

Although there is no standard for ECG diagnosis of myocardial ischemia, ST segment changes of greater than one millimeter are generally considered significant.

When the ST segment is measured at or near the J-point, it is important to differentiate between changes that are significant and those that may be affected by the heart rate. It is therefore necessary to give a description of the ST segment slope.

The slope of the ST segment is often described as “horizontal,” or “downsloping,” both of which are significant, or “upsloping” which is not significant and is possibly influenced by heart rate. (Figure 5)
Indications For Continuous ST Segment Monitoring

There are several areas where continuous ST segment monitoring is clearly indicated. The following are the Class I and II AHA recommendations:

Class I
- Patients in the Early Phase of Acute Coronary Syndromes (ST-Elevation or Non-ST-Elevation MI, Unstable Angina/“Rule-Out” MI)
- Patients Who Present to the ED With Chest Pain or Anginal Equivalent Symptoms
- Patients Who Have Undergone Nonurgent Percutaneous Coronary Intervention With Suboptimal Angiographic Results
- Patients With Possible Variant Angina Resulting From Coronary Vasospasm

Class II
- Patients with post-acute MI.
- Patients Who Have Undergone Nonurgent Uncomplicated Percutaneous Coronary Intervention
- Patients at High Risk for Ischemia After Cardiac or Noncardiac Surgery.
- Evaluating intra- and post-operative ischemia for cardiac and high risk surgical procedures.

ST Segment Changes That Are Not Ischemic Related

Low specificity is a major limitation of ECG as an ischemia monitor. Multiple non-ischemic causes of ECG changes can mimic ischemia, such as:
- Body position changes
- Drug effects (such as digitalis and diuretics)
- Electrolyte imbalances (such as hypokalemia)
- Conduction disturbances (including LBBB and WPW syndrome)
- Hypothermia
- Left ventricular hypertrophy
- Ventricular pacing
- Old infarcts

Note: Because ST segments may be altered by many different conditions, it is imperative that clinicians interpret the ST information in the context of other clinical information.

The ST Segment Algorithm

ST analysis algorithm is designed to provide continuous ST measurement, while providing continuous patient surveillance and alarm generation for all available ECG leads. The total number of ST measurements generated by the ST/AR algorithm depends on the ECG lead-set and the type of monitoring device used for monitoring. Please refer to the Instructions for Use for the monitoring device for the specific number of ST measurements supported by the monitor and the lead set.

When a 5-wire leadset is used in standard lead placement, a maximum of 8 ST values are generated. These include 6 limb leads, 1 unipolar chest lead (V) and 1 bipolar chest lead (MCL).

When a 6-wire lead set is used in standard electrode placement, a maximum of 8 ST values can be generated. These include 6 limb leads and 2 unipolar chest leads Vₐ and V₉. The two chest leads for the 6-lead placement can be positioned at any two of the V₃ to V₆ positions and labelled according to their position. For the Information Center you can also position and choose V₃R, V₄R, V₅R, V₇, V₈ and V₉.

When EASITM lead placement is used, the direct ST measurements are performed first on the three directly acquired EASITM leads. Subsequently, ST values are determined for all derived 12 leads.

Note: EASITM derived 12-Lead ECG’s and their measurements are approximations to conventional 12-Lead ECG’s, and should not be used for diagnostic interpretations.

For conventional 12-lead ECG, direct ST measurements are performed on two limb leads and all six chest leads first. The limb leads that are not directly measured, are derived.

The ST algorithm uses the beat detection and classification information provided by the arrhythmia algorithm and performs several additional actions on the ECG waveforms, including filtering the signals, measuring ST values, producing a representative QRS complex, and generating ST alarms if necessary.

Basic Algorithm Concept

The ST segment is a signal of low amplitude and low frequency content. It is a parameter that is difficult to measure accurately due to distortion introduced by muscle noise and baseline wander. However, since ST segment values do not change very rapidly, not every single beat needs to be measured. Therefore, reliable ST measurements can be extracted using signal averaging techniques.

One common approach is to derive a single representative beat through waveform averaging. The ST segment value is then measured from this representative beat. One potential problem with this
technique is that noisy or abnormal beats, if not rejected completely from the averaging process, can corrupt the final averaged waveform and thus cause inaccurate ST measurement.

In order to reduce the impact of an undesired beat, some products use an averaging technique called incremental updating to compute the averaged beat. Only a pre-defined fixed amount of changes to the averaged beat is allowed for every new beat to be averaged. One disadvantage of this approach is that the resulting averaged waveform may not resemble any of the original QRS complexes.

**ST/AR ST Algorithm Approach**

In order to overcome these problems, ST/AR takes a different approach. Rather than trying to derive an averaged beat with each new beat for measuring ST values, all complexes detected in a discrete time period, 15 seconds, are saved. A representative beat is then derived from these beats using a statistical technique. The ST value associated with the representative complex is used as the final ST value.

The 15-second time interval used for ST segment measurement has been selected to ensure that it is long enough to include a sufficient number of beats at various heart rates to produce a stable ST measurement, yet short enough so that ST segment changes of short duration will not be missed.

**ST Segment Analysis**

**Step 1: ECG Signal Filtering**

The patient’s incoming ECG waveforms are digitally sampled at 500 samples per second. For ST segment analysis where a high sampling rate is not needed, a lower sampling rate of 250 (125 for M3001A Measurement Server) samples per second is used.

To ensure that the ST segment can be measured accurately, the incoming ECG signals must have a low-end bandwidth of 0.05 Hz. This low bandwidth is necessary to ensure that no signal distortion is introduced to the ST segment. ST segment measurement will not be performed if this condition is not met.

An additional ST filter with a higher low-end bandwidth of 0.67 Hz is used to further remove unwanted baseline noise. Although this filter has a bandwidth higher than 0.05 Hz, it is designed not to introduce any distortion to the ST segment.

**Step 2: Saving QRS Complexes**

Next, all QRS complexes detected by the beat detection algorithm within a discrete 15-second period are saved for subsequent ST segment analysis.

QRS complexes that are classified by the arrhythmia algorithm as PVC, questionable, ventricularly paced, or AV sequentially paced are excluded from the ST segment analysis. If arrhythmia analysis is not selected, beats that are premature or display a ventricular pacer spike are excluded.

In addition, for each lead saved, checks are made to make sure that any measurement points, lead, and bandwidth changes did not occur during this 15-second period. If any of these conditions is present, ST measurement for that lead will not be performed.

**Step 3: Pre-processing of Measurement Points**

The ST segment value is measured based on two user-adjustable measurement points: the isoelectric point and the J-point or the isoelectric point and the ST point depending on the user configuration (ST point only available for bedside monitors). If J-point is configured the ST segment is measured at either 60 or 80 milliseconds after the J-point for the IntelliVue Patient Monitor or 0, 20, 40, 60 or 80 milliseconds for the Information Center.

Rather than using the same isoelectric and ST measurement points to perform ST measurement for each beat, the points are shifted left or right as necessary to avoid noise in the measurement regions. The maximum amount of shifting allowed is limited to 20 milliseconds.

**Step 4: Rejecting Beats with Unstable Isoelectric Baseline**

In order for accurate ST values to be derived, beats with unstable isoelectric baseline are also excluded from subsequent ST segment analysis.

For each lead, the median isoelectric value for all the beats in the 15-second period is derived. The median value for a group of measurements is defined as the value selected from the group such that half of the measurements are larger than this value and half of the measurements are smaller.

The isoelectric value for each beat is then compared to the median value. Any beat with an isoelectric value that deviates more than 2.5 millimeters from the median value is excluded from further ST analysis. This additional step further eliminates beats with noise that could corrupt the final ST measurement.
Step 5: Statistical Analysis of ST Measurement

The ST algorithm then performs a statistical analysis of the distribution of all the individual ST segment values from the remaining beats. If the ECG signal being monitored is stable and ST can be reliably measured, these individual ST segment measurements will form a bell-shaped normal distribution and an ST value and a representative complex will be generated.

The advantage of this technique is that noisy beats and incorrectly classified PVCs will not contaminate the representative beat for ST measurement. Thus, the algorithm discards statistically irrelevant data while focusing on the beat and associated ST value which is clinically relevant.

The median value for all the individual ST segment measurements is determined. In order to make sure that the selected median value is not just an isolated point in the distribution, the algorithm further examines a group of five beats. These five beats include the beat with the median value, two beats with the smallest ST measurements greater than the median value, and two beats with the largest ST measurements less than the median value. In order to produce a valid ST value, the difference between the highest and the lowest ST values within the group must be less than or equal to 0.5 millimeters, and at least three out of these five beats must have very similar morphology.

Finally, all beats with similar morphology from this group are averaged to produce a representative ST waveform. The ST segment measurement associated with this representative beat is used as the ST value for this 15-second time period.

Step 6: Computing Derived ST Values and Waveforms

When a 5-wire or 6-wire leadset in standard placement or conventional 12 lead placement is used, ST values and waveforms for two limb leads are directly measured. A total of four additional limb leads can be derived. The V-leads are directly measured - one for 5-wire, two for 6-wire and six for 10-wire leadset.

When monitoring with EASI™ lead placement, all 12 leads are derived.

In addition to the ST measurements, the ST Index (STIndex) is calculated when possible. The ST index is a summation of the absolute values of three ST segment measurements, using leads that can best indicate ST changes in the different locations of the heart:

- Anterior lead - V2
- Lateral lead - V5
- Inferior lead - aVF

Since the ST index is based on absolute values, it is always a positive number.

Step 7: Generating One-Minute ST Values and Waveforms

In addition to the 15-second ST values and associated waveforms for real-time display, the ST algorithm also provides ST values and associated ST waveforms at one-minute intervals for database storage and recall. The one-minute ST value and waveform are selected from the four 15-second ST values and waveforms within that minute. The value which shows the largest deviation from the previous one-minute ST values is selected.

Alarm Detection

The ST monitoring algorithm supports the detection of ST alarm conditions for each lead separately. However the generation of ST segment alarms can vary between monitoring product. Please refer to the Instructions For Use manual for specific information about how ST alarms are generated on your system.

For individual ST lead alarms, the ST high and low alarm limits can also be set independently for each lead.

For ST multi-lead alarms, a multi-lead ST alarm is announced when two or more ST leads exceed a defined set of lead limits.

For automatic alarm limits (IntelliVue Patient Monitor), the high low limits can be applied to all leads used for ST segment monitoring and are set around the patient’s current ST value based on a preset offset. See application note: Automatic Alarm Limits Pub# 4522 981 85691.

For smart alarms (Information Center), the high and low limits are set around the patient’s current ST value based on a configured offset. They can be applied when ST monitoring is started and reapplied as necessary.

ST values must exceed the alarm limit for four consecutive 15-second time periods (1 minute) before an alarm is declared.
Special Concerns for Computerized ST Segment Monitoring

It is impossible to design a computerized ST segment analysis algorithm that accurately analyzes 100% of all patients. In the following sections, several conditions that can cause difficulty for the ST segment analysis algorithm are described.

ECG Signal Quality

A clean signal is integral to accurate ST segment monitoring. It is important to minimize or eliminate factors that create electrical noise, baseline wander, muscle artifact, or 60 Hz interference.

Lead Selection

It is mandatory to standardize lead location. Seemingly insignificant errors in lead location can have a profound effect on the resulting ECG which can impact the final interpretation.

The benefit of ST monitoring is the ability of the system to detect episodes of myocardial ischemia independent of patient symptoms. Therefore, it is important to select the leads most likely to detect ST segment changes during the ischemic episode.

Arrhythmia Algorithm Accuracy

When arrhythmia analysis is on, beat labeling from the arrhythmia algorithm is used in the ST algorithm to reject beats that should not be measured. Incorrect beat labeling by the arrhythmia algorithm can influence the accuracy of the ST measurement algorithm. Some of the conditions that can cause the arrhythmia algorithm to perform poorly include: large P- and T-waves, changing QRS morphology, and noisy signal. In order to obtain accurate ST measurement, factors that affect the arrhythmia monitoring performance should be corrected.

Even when arrhythmia analysis is off, the ST algorithm is able to maintain its measurement accuracy by rejecting short runs of ventricular beats and isolated PVC’s. However, the presence of sustained runs of ventricular beats will influence the accuracy of the ST measurement algorithm. This is easily identified in the ST trends as a step change as opposed to a gradual change for a true ischemic event.

Incorrect Measurement Points

The isoelectric point establishes the baseline against which the ST measurement point is compared. For proper operation, the isoelectric point should be set within the P-R or T-P interval, and the ST measurement point should be set at 60 or 80 milliseconds after the J-point.

Artifactual ST segment depression or elevation occurs when the isoelectric point or the ST measurement point is set incorrectly. It is important that these measurement points be set correctly when monitoring is initiated. In addition, they should also be reassessed periodically and readjusted if necessary.

Heart Rate Changes

While nominal variation of the heart rate should not affect the ST measurement, errors can occur if there is a significant increase in the heart rate. When the heart rate increases, ventricular repolarization, as measured by the QT interval, becomes shorter. Because the algorithm measures the ST segment at a fixed interval from the J-point, QT shortening can cause the ST measurement point to fall within the T-wave. When this occurs, the location of the measurement point should be checked and readjusted if necessary.

Atrial Fibrillation and Flutter

In some cases of atrial dysrhythmias, the erratic baseline caused by fibrillations and flutters makes it difficult to achieve reliable ST measurement. In such cases, leads with the least amount of erratic baseline should be selected. However, this may not eliminate the problem completely. These types of waveforms remain a major challenge for the ST algorithm.
Assessing ST/AR ST Analysis Algorithm Performance

The performance of the algorithm used to detect ST segment deviation is fundamental to the effectiveness of computerized ST segment monitoring. It is important that the algorithm enable the system to alert the clinical staff to true ST segment episodes 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 decisions.

Reference Database

The European Society of Cardiology (ESC ST-T) database is available to the public for the testing of ST segment monitoring algorithms. This database consists of records of adult patient ECG waveforms, together with a set of annotation files in which ST segment changes have been identified by expert cardiologists.

The ESC ST-T database has been used to assess the performance of the ST segment monitoring algorithm. The database consists of data from 90 adult patients and was developed for the purpose of evaluating ST segment analysis algorithms.

Using the ESC ST-T Database

It should be noted that the ESC ST-T database provides only a general idea of the performance of an ST segment monitoring algorithm. The accuracy of the performance measures is limited due to the following characteristics of the database:

- The database annotates only the peak deviation of each ST episode.
- The peak ST value annotations are measured as the difference between the actual value and an initial value selected from the beginning of the record.
- The measurements in the database have a resolution of 0.5 millimeters for values less than 5.0 millimeters, and a resolution of 1.0 millimeters for values greater than 5.0 millimeters.

ST Segment Performance Validation Test

The ST Segment Performance Validation Test quantifies the performance of the ST segment monitoring algorithm.

Performance Measures

The performance measures quantify the extent to which the algorithm results agree with the expert annotation of a given patient record. The measurement of each ST segment in the reference database is called the “true” measurement of that ST segment.

The performance measures used to measure ST segment measurement accuracy include the following:

The Measurement Correlation Coefficient is a statistical measurement of how well the algorithm’s generated values and the true measurement values correlate. A high Measurement Correlation Coefficient indicates that the two sets of values are similar a high percentage of the time.

Relationships 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 Linear Regression Line approaches $Y = X$.

The Mean of Absolute Difference is the average difference between the measurements generated by the algorithm and the true measurements. A low Mean of Absolute Difference indicates that the two sets of values are similar a high percentage of the time.

Results Summary

The ST Segment Measurement Accuracy results are summarized in two scatter plots, one for each ECG channel in the database (Figures 6 and 7).

The horizontal axis in each of the plots represents the range of ST measurement values, in millimeters, generated by the algorithm. The vertical axis represents the ST measurement values, in millimeters, from the ESC ST-T reference database. The middle of the three diagonal lines represents the desired goal - the point where the algorithm’s measurement value is equal to the database’s value. The other two diagonal lines represent an error range of $\pm 1.0$ millimeter.

For each ST segment episode, one point is plotted using the algorithm’s measurement as the horizontal coordinate and the database’s measurement as the vertical coordinate.

![Figure 6 ESC ST–T Database, Channel 1](image)
As shown in the plots, only 10% of the measurements generated by the algorithm exceed the error range of 1.0 millimeter.

The following table summarizes the ST segment measurement accuracy performance measures:

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Correlation Coefficient</td>
<td>0.96</td>
</tr>
<tr>
<td>Linear Regression Line</td>
<td>( Y = 0.94X - 0.06 )</td>
</tr>
<tr>
<td>Mean of Absolute Difference</td>
<td>0.52 mm</td>
</tr>
</tbody>
</table>

The Measurement Correlation Coefficient of 0.96 indicates that the algorithm's value and the ESC ST-T database value are highly correlated. The Linear Regression Line also indicates that the two sets of data are highly correlated because the equation is close to \( Y = X \).

The Mean of Absolute Difference value indicates that the average difference between each of the algorithm’s values and the ESC ST-T database values is 0.52 millimeters. This value is very low when compared with the resolution of the database values (a resolution of 0.5 millimeters for values less than 5.0 millimeters, and a resolution of 1.0 millimeters for values greater than 5.0 millimeters).

From the results presented in the application note, the performance of the ST segment monitoring algorithm is evident. This ability enhances the effective monitoring of ST segment events in the clinical setting.

**References**


**Conclusion**

Computerized ST segment 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 an alarm is triggered due to an ST segment change, only a clinician, not the monitor, can determine the seriousness of the event. To ensure peak performance, the staff should be aware of the interventions and adjustments they can implement to enhance the ST algorithm’s performance and accuracy.
Interested?
Would you like to know more about our imaginative products? Please do not hesitate to contact us. We would be glad to hear from you.

On the web
www.medical.philips.com

Via e-mail
medical@philips.com

By fax
+31 40 27 64 887

By mail
Philips Medical Systems
Global Information Center
P.O Box 1286
5602 BG Eindhoven
The Netherlands

By phone
Asia
Tel: +852 2821 5888

Europe, Middle East, Africa
Tel: +49 7031 463 2254

Latin America
Tel: +55 11 2125 0764

North America
Tel: +1 800 229 6417