Arrhythmia Monitoring Algorithm

Application Note

Introduction

The ST/AR (ST and Arrhythmia) algorithm is an ECG algorithm that the HeartStart MRx and XL+ monitor/defibrillators utilize for basic and cardiotach arrhythmia monitoring. This application note provides a detailed description of the arrhythmia monitoring portion of the algorithm. The capabilities are presented in general terms as they are implemented in Philips defibrillators. Refer to the *HeartStart MRx* or *HeartStart XL+ Instructions for Use* for specific information on the algorithm's capabilities.

PHILIPS

What is an Algorithm?

An algorithm is a set of rules and instructions that computers use to analyze data. The arrhythmia monitoring algorithm analyzes one channel of surface ECG signals, from either paced or non-paced patients. As it does so, the QRS complexes are detected, labeled and classified. Based on the classification, the algorithm then generates alarms for the monitor/defibrillator to communicate.

For your information, the default Pacer setting for the HeartStart MRx is *non-paced* and *unknown* for the HeartStart XL+. To optimize the ST/AR algorithm, the Pacer setting should be set according to the patient's status.

How to Get the Best Performance from Computerized Arrhythmia Monitoring

There are several steps you can take to get the best possible performance during arrhythmia monitoring:

1. Optimize Signal Quality:

– Skin preparation is especially important when using gel electrodes.

– Change electrodes every 24 hours. Increased baseline wander is the first indication that electrodes are dry and need to be changed.

– Support cable and electrode wires. Artifact and wander may increases if the skin under the electrode is stretched. Taping the electrode and lead may reduce this if your patient is active.

2. Choose the Best Lead:

Choose a lead where QRS amplitude is stable and has adequate amplitude (recommended amplitude is greater than 0.5 mV).

3. Ensure the Best QRS Complex:

Size and shape of the QRS are very important for proper beat detection and classification. Use the following guidelines to choose leads which produce the best QRS morphology for analysis by the arrhythmia system:

▶ **The Normal Beat**

– R-wave is tall, not clipped or biphasic.

– T-wave is less than 1/3 the R-wave height.

– P-wave is less than 1/5 the R-wave height.

▶ **The Ectopic Beat**

– Height is at least 1/5 the normal QRS height.

– Beat should not be clipped.

– Shape is distinctly different than the normal.

▶ **The Paced Beat**

– Pace pulse not much larger than the QRS complex.

– Ventricular paced beat is wider than the normal QRS complex.

– Pace pulse has no visible re-polarization.

How the Arrhythmia Monitoring Algorithm Works

The incoming ECG waveform undergoes several distinct processing steps:

▶ First, the algorithm checks the quality of the ECG, to detect noisy signals and other problems.

▶ Then, the actual analysis begins (see "" on page 4). During analysis, the algorithm filters the digitized ECG, detects and classifies the QRS complexes, calculates the heart rate, identifies ectopic events and rhythms, and generates alarms.

Each of these steps is explained in more detail in the sections that follow.

Quality Check of the ECG Signal

Before any analysis begins, the ECG signal quality is checked for electrical noise and for other inoperative (INOP) or technical conditions.

Electrical Noise

"Noise" refers to any degradation of the ECG signal that makes it difficult to accurately detect and classify beats. Causes of noise, such as artifact and electrical interference, should be avoided whenever possible.

Some common causes of noisy ECG signals include:

▶ Poor skin preparation

▶ Dried electrode gel

▶ Muscle artifact caused by shivering, movement, or tremors

▶ Baseline wander caused by excessive chest movement or the electrical differences between two brands of electrodes

▶ Respiration artifact caused by thoracic or abdominal movement of both spontaneous and ventilated breathing patterns

▶ Nearby electrical equipment

Prompt attention by the clinician to any ECG interference increases the accuracy of the algorithm and decreases the incidence of false alarms. Types of noisy signals, their possible causes, and recommended corrective actions are shown in Table 1 on page 3.

INOP (Technical) Conditions

INOP conditions (as classified in the HeartStart MRx) or technical conditions (as classified in the HeartStart XL+) are those most likely involving an equipment issue, such as:

▶ Detached electrodes

▶ Broken lead wires

A "lead off" or "cannot analyze ECG" condition, which results in the loss of ECG monitoring, will also inhibit arrhythmia monitoring until the condition is corrected and the lead has been restored.

You may need to select a different lead or change the electrodes or electrode position if there is excessive noise, unstable voltage, low amplitude QRS, or large P- or T-waves.

Table 1   **Noisy ECG Problem Solving**
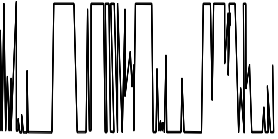
Problem	Appearance	Cause	Corrective Action
Power Line Interference (50 / 60-Cycle Interference)	Regular sawtooth baseline.	Poor electrode placement.	Reapply electrodes.
		Possible non-grounded instrument near patient.	Unplug AC power from electrical equipment near patient, one at a time. Have grounding checked.

Table 1   **Noisy ECG Problem Solving** *(Continued)*

Problem	Appearance	Cause	Corrective Action
Muscle Artifact	Fuzzy, irregular baseline.	Tense, uncomfortable patient.	Make sure patient is comfortable and still.
		Tremors. Diaphoresis.	Check that electrodes are applied on flat, non-muscular areas of the torso.
		Poor electrode placement.	Reapply electrodes if necessary.
Irregular Baseline	Rough, jagged baseline.	Poor electrical contact.	Reapply electrodes, using proper technique. Check for loose connections on leads/cable.
		Respiratory interference.	Move electrodes away from areas with greatest movement during respiration.
		Faulty or dry electrodes.	Apply new electrodes.
Baseline Wander	Rhythmic up-and-down movement of the ECG baseline.	Movement of the patient.	Make sure patient is comfortable and still.
		Improperly applied electrodes.	Reapply electrodes. Check that patient cable is not pulling on electrodes.
		Electrical differences between two different brands or types of electrodes.	Make sure electrodes are all from the same manufacturer, and of the same type.
		Respiratory interference.	Move electrodes away from areas with greatest movement during respiration.
Poor Electrical Contact	Trace switching from high to low in steps.	Loose electrodes.	Change all electrodes, using good skin prep.
		Defective leads/cables.	Replace leads/cables.

ECG Analysis

The algorithm now begins to analyze the ECG signal. Following a five step sequence, it:

1. Prepares the digitized ECG for analysis. See "Step 1: Digital Sampling".

2. Detects and processes pacemaker pulses (if the Pacer setting is *paced*), and filters the ECG to compensate for muscle artifact and baseline wander. See "Step 2: ECG Signal Filtering".

3. Detects beats by detecting P waves, T waves, and QRS complexes. See "Step 3: Beat Detection".

4. Measures features of the detected beat, classifies its morphology, and applies a label to the detected beat. Meanwhile, it continuously checks for ventricular fibrillation. See "Step 4: Feature Measurement and Labeling".

5. Measures the heart rate, determines the underlying rhythm, and identifies ectopic events. Alarms are then generated as needed. See "Step 5: Rhythm and Alarm Detection".

Step 1: Digital Sampling

The patient's incoming ECG waveform is digitally sampled at 8000 samples/second. This high ECG sampling rate is used to preserve the narrow pacemaker pulses (spikes) for accurate pacing analysis. After some initial analyses, the signal is passed to the arrhythmia monitoring algorithm at a rate of 500 samples/second. Full diagnostic bandwidth is used for signals from ECG leads even if another bandwidth is selected for display or recording. Monitoring bandwidth is used for signals from hands-free pads because of signal limitations from the size of the pads. Within the arrhythmia monitoring algorithm, a lower sampling rate of 125 samples/second is used for QRS detection, QRS classification, and ventricular fibrillation detection, where high sampling rates are not needed.

Step 2: ECG Signal Filtering

Pacemaker Pulse Processing

Pace pulse artifact is eliminated before the ECG waveforms are processed by the QRS detector. In this way the accidental detection of the pace pulse as a QRS is prevented.

NOTE: The removal of pace pulses is done only on the signal that is used by the algorithm for arrhythmia analysis. The pace pulses remain available for viewing on the display or printed strips.

Filtering

Next, the digitized ECG waveform(s) are processed by two digital filters: a detection filter and a classification filter. These filters are optimized individually to enhance the performance of QRS detection and classification. They operate simultaneously on the ECG.

The *detection filter* removes low frequency noise (baseline wander) and muscle artifact, and accentuates the QRS complexes. P-waves and T-waves are diminished. This filter makes it easier to accurately detect the QRS and helps avoid erroneously detecting tall T-waves or artifact as beats. Since it distorts the true shape of the QRS, the output from the detection filter is used only for beat detection.

The *classification filter* also removes signal irregularities, but it preserves the important features of the QRS. Since this filter does not distort the complex, the resulting ECG output can be used for feature measurements and beat classification.

Step 3: Beat Detection

The algorithm's challenge in QRS detection is to first locate R-wave peaks that become "candidate peaks" and then to make sure that they are not actually noise, or P- or T-wave peaks.

The Effect of ECG Amplitude and Gain

AAMI Standard EC-13 requires that the detection threshold for the QRS cannot be less than 0.15 mV. This specification is aimed at preventing the detection of P-waves or baseline noise as QRS complexes during complete heart block or asystole.

To conform with these requirements, ST/AR analyzes the ECG of the patient before any size adjustments are made to enhance the display of the wave. **Thus, keep in mind that increasing or decreasing the ECG size displayed on the defibrillator has no effect on the ECG used for QRS detection and classification.** For optimal beat detection, ensure good lead placement and contact, and select the lead with the best signal.

Therefore, for optimal performance and to prevent false alarms such as pause or asystole, it is important that the lead selected for monitoring has adequate amplitude. The defibrillator display, as well as its printed strips, will show

a waveform with the gain adjustments applied. Consequently the clinician can be looking at a waveform which appears large until compared to the reference, as shown in Figure 1:

Figure 1   **Waveform as Printed (with gain adjustment applied)**
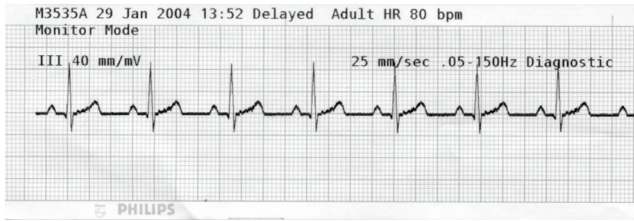
However, the ST/AR algorithm sees a smaller waveform, which it attempts to analyze (Figure 2).

Figure 2   **Waveform as Presented to Algorithm (with gain adjustment removed)**
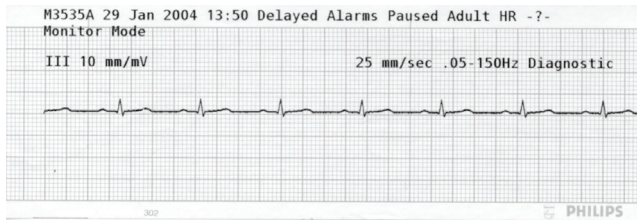
Locating Candidate R-Wave Peaks

The QRS detector checks the QRS detection signal for the presence of the peak of an R-wave. Searching begins after an absolute refractory period from the previously identified QRS complex. This helps prevent a T-wave from being identified as an R-wave. The value used for the absolute refractory period is 192 ms for adult and pediatric (on the HeartStart MRx) or infant/child (on the HeartStart XL+) patients.

A moving search region is established at the end of the refractory period. For each search region, a new threshold is established based on:

▸ Noise around the search region.

▸ Distance from the previously detected R-wave.

▸ Averaged R-wave height.

The largest peak within the search region is considered a candidate R-wave.

Minimum Detection Threshold

To prevent the detection of P-waves or noise as QRS complexes during complete heart block or asystole, the detection threshold will never go below the larger of 1/5 of the average R-wave height or 0.15 mV. Any peak smaller than this value is not detected.

QRS detection is done on the primary lead.

Noise Rejection

After a candidate peak is detected, it is checked against a noise threshold to make sure that it is not a noise artifact or a QRS complex surrounded by noise. If the ECG lead(s) are determined to be noisy then a beat label "A" is assigned to the candidate peak and no classification is performed.

P- and T-Wave Peak Rejection

Before accepting the detected peak as a potential R-wave, there are two further tests which are carried out.

P-Wave: To prevent a P-wave that is associated with a QRS from being counted as a QRS, it is checked against what is known about the previously identified P-waves. If it is found to be similar, the peak is rejected. In addition, to prevent P-waves from being erroneously counted as QRS complexes during complete heart block, three consecutive candidate peaks are further tested to see if they are actually consecutive P-waves. These peaks are rejected if they are found to be P-waves.

T-Wave: If a candidate peak is found in close proximity to the preceding beat, it is tested to see if it might be a late T-wave. After a series of height and timing tests, the peak may be determined to be a T-wave and rejected.

If it is determined that the candidate peak is neither a P-wave or a T-wave, it is identified as a QRS complex and saved.

P-Wave Detection

After a QRS complex is located, a search is made in the area prior to the beat to determine if there is an associated P-wave. This area is 200 ms wide and ends 120 ms before the R-wave peak. To be considered a P-wave, it must be at least 1/32 of the R-wave height and the P-R interval must be close to the average P-R interval. In other words, the candidate P-wave must represent average characteristics in its relationship to the QRS.

Figure 3 **P-Wave Detection for Adult/Pedi**
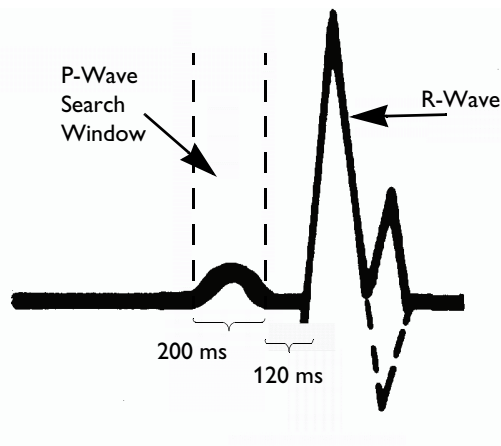
Step 4: Feature Measurement and Labeling

After a beat is detected, it is measured in a number of ways to determine its features. These features represent beat characteristics which can be used to discriminate between different types of beats.

The features measured are: height, width, area, and timing (a series of R-R interval measurements).

The end result of this analysis is that the algorithm assigns a label to each detected complex using one of the following labels:

N Normal

V Ventricular Ectopic

P Paced

? Questionable

L Learning

If the signal quality is not good, the algorithm assigns one of the following labels to the waveform:

I Inoperative

A Artifact

If a beat does not occur within the expected time interval from the last beat, the label below is assigned:

M No QRS

Beat labeling involves two major concepts:

▸ The use of *learning* of the patient's ECG morphology (including ventricular and/or paced morphology if the patient is paced).

▸ The use of *template families* to represent recurring morphologies and to aid classification of QRS complexes.

These concepts are discussed in more detail in the sections that follow.

Learning

When arrhythmia monitoring starts, a "learning" process is initiated. The goal is to learn the patient's normal complexes and/or paced complexes (if the patient with a pacemaker is in paced rhythm). The learning process involves the first 15 valid (non-noisy) beats encountered during the learning phase.

The family selected to represent the "normal" includes the beat that is the most frequently seen, narrowest, on-time beat. For this reason, learning should not be initiated when the patient's rhythm is primarily ventricular. It should be initiated only when the ECG signal is noise-free.

A manual relearning should be initiated if the beat detection is not occurring or if beat classification is incorrect and results in a false alarm. Remember, however, that if the same signal condition that caused the algorithm to perform poorly still persists, relearning will not be able to correct the problem. The problem can only be corrected by improving the quality of the signal (e.g., by selecting a different lead).

The algorithm learns the primary ECG lead whenever:

▸ ECG monitoring is initiated.

▸ the HeartStart MRx and XL+ therapy knob is turned to Monitor, Pacer, or Manual Defibrillation Mode (and AED Mode on the XL+).

▸ The relearn function is activated.

▸ Patient's Paced status is changed.

▸ A leads or pads off condition lasting longer than 60 seconds is corrected.

▸ The ECG Lead or Lead Label is changed.

Grouping into Template Families

To aid the algorithm in labeling a new beat, previously detected beats that have similar shapes are grouped into "template families" (see Figure 4).

Figure 4   **Example of Template Families**

ECG to Be Analyzed

Existing
Template Families
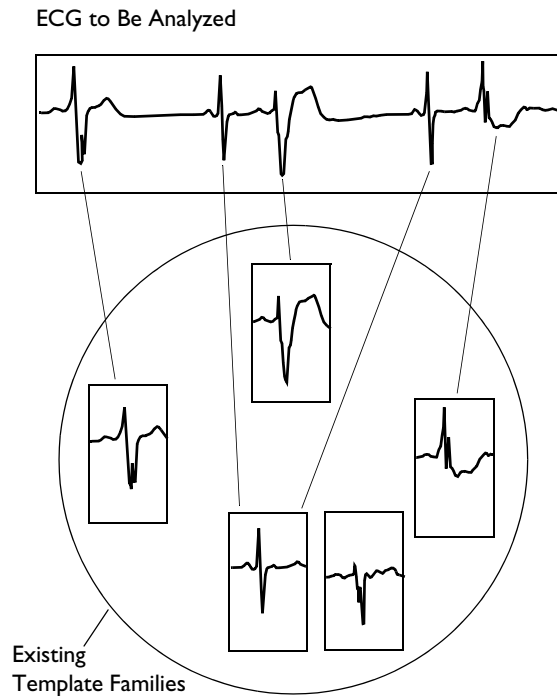
Each template family contains the following information:

▸ Template family classification: Normal, Ventricular, Paced, or Unclassified.

▸ Waveform template, generated by averaging all the beats that are considered similar enough to be included.

▸ The number of complexes having this shape.

▸ The length of time since this shape was last seen.

▸ Statistical information on the beats' feature measurements.

▸ If the patient is paced, pace pulse information associated with the beats.

For each patient, up to 8 different active template families can be created for each individual lead. To keep the template family information current, they are dynamically created and replaced as the patient's beat shapes change.

If the patient begins to display a new beat morphology, a new template family is created. Older template families from beats the patient is no longer experiencing are automatically deleted.

Template Matching: When a beat is detected, it is matched against the stored waveform templates for that patient. Matching means comparing the beat shape with a waveform template. This process involves overlaying the beat on the template and using a mathematical procedure to measure the differences between the two shapes (see Figure 5).

Figure 5   **Matching a New Beat to a Template Family**

New Beat

Stored Template 1   Stored Template 2

Poor Match   Good Match
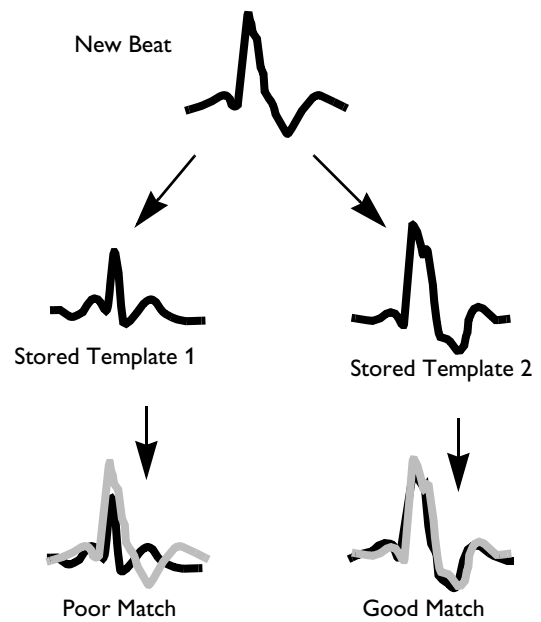
Beat Labeling

Once the initial learning process is over and a normal template family is established, each newly detected beat is labeled:

▸ If the beat matches a waveform template of a family which has already been classified:

– The beat is labeled the same as the template family.

– The number of beats in the family is increased, and the new beat features are added to the family's statistics.

▸ If the beat matches a waveform template of a family which has not been classified:

- The beat is labeled using the beat labeling rules (described below).

- The template family is updated, and when enough beats matching the template occur, the template family is classified using the template family classification rules (described below)

▶ If the beat does not match any of the existing waveform templates:

- The beat is labeled using the beat labeling rules.

- A new template family is created with this beat as its first member.

Beat Labeling Rules: Every beat is analyzed using the "beat labeling rules." These rules determine a preliminary label for each beat:

N	Normal
V	Ventricular Ectopic
P	Paced
?	Questionable

To help avoid artifact being labeled V, a new beat shape may be labeled as "?" when initially seen.

The beat labeling rules use a combination of the following information:

▶ Feature measurements.

▶ Timing/Rhythm.

▶ Template matching.

▶ Morphology similarity to neighboring beats.

▶ Pace pulses associated with the beat (if patient is paced).
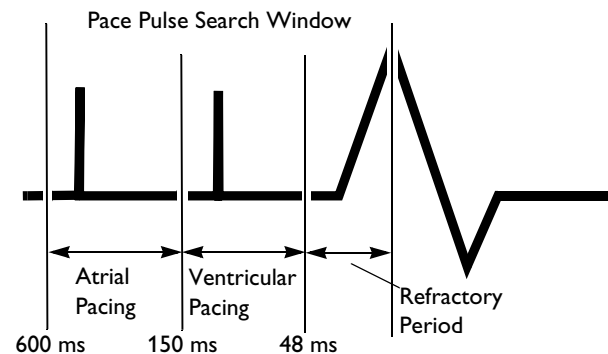
Paced Beat Classification

First, the algorithm searches for both atrial and ventricular pacemaker pulses. To accomplish this, a "search window" is established prior to the QRS complex. Then, as pace pulses are seen in the search window, their distances from the beat are tracked.

For the algorithm to consider the new beat paced, the distance (time interval) from the pace pulses to the QRS must be similar to that of pace pulses associated with the
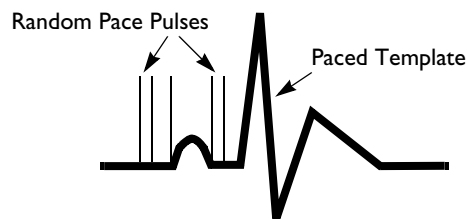
paced template. If the pace pulses fall at random distances from the QRS they are considered to be independent of the beat.

The distance that the pulses are found from the beat determines the type of pacing—atrial, ventricular or AV (atrial/ventricular) paced. See Figure 6.
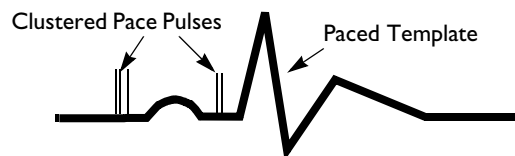
Figure 6 **Paced Beat Analysis**

Pace Pulse Search Window

Atrial Pacing

Ventricular Pacing

Refractory Period

600 ms   150 ms   48 ms

Random Pace Pulses Around QRS

Random Pace Pulses

Paced Template

Clustered Pace Pulses Around QRS

Clustered Pace Pulses

Paced Template

Template Family Classification Rules

After the normal family is initially learned, each newly created family remains unclassified until enough similar beats, usually less than five, are seen to classify it accurately.

Template families are classified as:

N	Normal
V	Ventricular Ectopic
P	Paced

The labels given to the beats using the beat labeling rules are used to determine the family classification.

A normal template family can include N and S beats. For a template to be classified V, at least five of the first nine members must be labeled V. By the ninth beat, if there are not five Vs, the template is classified N.

A paced template is determined by statistical analysis of all the pace pulses detected within 600 ms of the QRS complexes that are included in the template family. In order for the algorithm to consider the template paced, pace pulses must fall at a consistent distance from the QRS. Based on the number of consistent distances found and their values, the paced template is classified as atrially paced, ventricular paced or AV paced.

The template family classifications are continuously checked against labels given to the individual beats using the beat labeling rules. If many discrepancies are found, the template family is reclassified. In this way, the algorithm has a mechanism to correct inaccuracies made during template classification.

Beat labeling rules use current information to analyze ectopic activity, while template matching provides long term memory to the algorithm. By using this combination of beat features, timing, and template matching techniques, the algorithm flexibly manages a variety of conditions with a high degree of accuracy.

Ventricular Fibrillation Detection

Working in parallel with beat detection and labeling, a separate detector continuously examines the in-coming ECG signal(s) for ventricular fibrillation and flutter. If a flutter or sinusoidal wave pattern persists for more than four seconds, the defibrillator alarms for ventricular fibrillation/tachycardia.

Step 5: Rhythm and Alarm Detection

The results from beat labeling and ventricular fibrillation detection are used by the rhythm and alarm detector as it measures the heart rate, determines the patient's underlying rhythm, and identifies ectopic events.

Alarms are activated by the alarm generator. Higher priority alarms, such as asystole, take precedence and supersede lower priority alarms, such as low heart rate.

Heart Rate Computation

Two different averages are used by the arrhythmia algorithm to determine the heart rate:

▸ Normally, the heart rate is computed by averaging the most recent 12 R-R intervals. Beats N, P, and V are all included in the computation. This average gives a stable estimate of the underlying heart rate even when the rhythm is irregular.

▸ When the heart rate drops below 50 bpm, the number of R-R intervals used in the average is dropped to four to improve the response time for the computed heart rate to reach the correct value during bradycardia.

NOTE: For the ventricular tachycardia alarms which have a user-definable PVC run length limit, the heart rate is computed based on the user selected PVC run length up to nine PVCs maximum (i.e. up to 8 R-R intervals).

For example, if the VT alarm is user-defined as five or more consecutive PVCs and heart rate greater than 100 bpm, then four R-to-R intervals will be used to compute the heart rate to see if the rate exceeds the limit of 100 bpm. Likewise, if the VT alarm is user-defined as ten or more consecutive PVCs and heart rate greater than 100 bpm, then eight R-to-R intervals will be used as that is the maximum possible.

Arrhythmia Monitoring for the Paced Patient

Since the pace pulses are detected and eliminated *before* the ECG waveform is processed by the QRS beat detector, accidental detection of the pace pulse as a QRS is prevented. The pace pulses remain available for viewing on the display or printed strips. The pace pulses appear at the point in the waveform where they actually occurred.

Proper Application of the Paced Patient Algorithm

Careful observation during the arrhythmia system's analysis of the paced patient is vitally important. The clinician must always verify that paced pulse detection is indeed taking place.

First, patient information must be entered, confirming the patient is being paced. With the HeartStart XL+, you activate the pacing status by specifying the appropriate patient category. With the HeartStart MRx, the default pacing status is non-paced or **Pacing Paused**. In any case, pacing detection should always be turned on when monitoring patients with any type of pacemaker. The device then relearns the patient's rhythm using the paced patient algorithm.

While learning, the user should observe the delayed, annotated wave to be certain pace pulse tic marks are properly associated with pace pulses.

Up to two pace pulse tic marks are displayed regardless whether they are associated with the following beat or not. Thus for a dual-chamber paced beat there will be two separate marks (one for each pace pulse).

Paced Alarms

Although not designed to detect pacemaker sensing problems, the alarm system incorporates two specific alarms for paced rhythms:

▸ "Pacer-Not-Capture" is determined when a QRS does not occur for 1.75 times the average R-to-R interval and a pace pulse is detected in the time interval.

▸ "Pacer-Not-Pacing" is initiated if a QRS does not occur for 1.75 times the average R-to R interval and no pace pulse is detected in the time interval.

NOTE: "M" beat label will appear when a QRS does not occur.

NOTE: "Pacer-Not-Capture" and "Pacer-Not-Pacing" alarms are not active during transcutaneous pacing.

The following application points can greatly improve the results of the paced patient algorithm:

▸ Pacing detection should always be turned on when monitoring patients with any type of pacemaker.

▸ Paced complexes should be between 1 and 2 mV in size and taller than the pace pulse.

▸ Cardiac response of ventricularly paced beats should be wider than the normal QRS complex.

▸ Pace pulses should not have visible repolarization tails (overshoot/undershoot). Repolarization causes increased width to the pace pulse and could result in the pace pulse being detected as a beat.

Figure 7   **Repolarization Tails on Pace Pulses**

Repolarization Tails
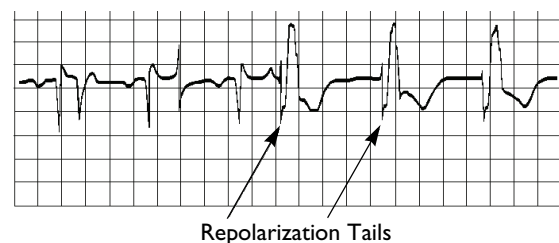
Computerized Arrhythmia Monitoring

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

Tall P- and T-waves

The algorithm is designed to selectively recognize and filter out P- and T-waves to prevent classification as beats. However, if a T-wave is much larger than the R-wave's height, correct classification is difficult. The T-wave might be detected and incorrectly classified as a PVC, and a "High Heart Rate" alarm could be activated.

Large P-waves may also be detected and incorrectly classified as an R-wave, causing the algorithm to generate incorrect high heart rate or PVC-related false alarms.

In most instances, large T- and P-waves can be addressed by selecting different leads. However, in conditions such as extreme atrial hypertrophy, hyperkalemia, or decreased ventricular voltage, the P- and T-waves may be as large as the R-wave despite careful lead selection. In these cases, select the lead that shows the lowest P- and T-wave height.

Figure 8   **Tall P- and T-waves**

Detects as R
Detects as R
Large T-waves

Detects as R
Detects as R
Atrial Hypertrophy
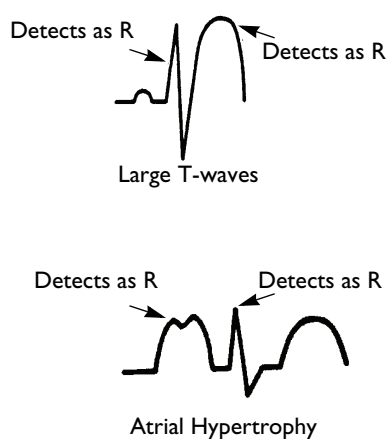
Aberrantly Conducted Beats

Since P-waves are not analyzed, it is difficult and sometimes impossible for a monitoring system to distinguish between an aberrantly conducted

supraventricular beat and a ventricular beat. If the aberrant beat resembles a ventricular morphology, it is classified as ventricular.

Figure 9   **Aberrantly Conducted Beat**
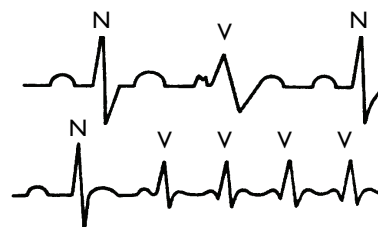
Atrial Fibrillation and Flutter

Since P-wave morphology is not analyzed, there is no method to discriminate atrial rhythms. In some cases of atrial dysrhythmias, the erratic baseline fibrillations and flutters may be greater than the algorithm's detection threshold, causing erroneous detection and false alarms.

Figure 10   **Atrial Fibrillation**

Intermittent Bundle Branch Block

The phenomenon of bundle branch or any of the other fascicular blocks creates a challenge for the arrhythmia algorithm. If the QRS during the block changes considerably from the learned normal, the blocked beat may be incorrectly classified as ventricular, causing false PVC alarms.

Figure 11   **Intermittent Bundle Branch Block**

The Arrhythmia System's Alarm Structure

Alarm Detection

The ST/AR Basic arrhythmia monitoring algorithm is designed to analyze up to 10 rhythm disturbances and irregularities. Each of these must pass a set of tests before an alarm is generated. The system generates ten alarms.

After an alarm sounds and a more serious alarm is detected, the lesser alarm message is superseded and the higher priority alarm is activated.

Tables 2 and 3 describe each alarm and the conditions required to generate the alarm.

Table 2   ***** Red (High Priority) Alarms**

Alarm	Condition Required to Generate Alarm
Asystole	No QRS detected for 4 seconds.
Ventricular Fibrillation/ Ventricular Tachycardia	Fibrillatory wave (sinusoidal wave between 2-10 Hz) for 4 consecutive seconds
Ventricular Tachycardia	Consecutive PVCs ≥ V-Tach Run limit *and* HR > V-Tach HR limit
Extreme Tachycardia	Heart Rate greater than the Extreme Tachy limit, per device configuration.
Extreme Bradycardia	Heart Rate less than the Extreme Brady limit, per device configuration

Table 3   **** Yellow (Medium Priority) Alarms**

Alarm	Condition Required to Generate Alarm
Pacer Not Capture	No QRS for 1.75 x the average R-R interval with Pace Pulse (internally paced patient only)
Pacer Not Pacing	No QRS and Pace Pulse for 1.75 x the average R-R interval (internally paced patient only)
PVCs > Limit	PVCs within one minute exceeded the PVCs /min limit
Heart Rate > Limit	Heart Rate greater than the upper HR limit
Heart Rate < Limit	Heart Rate lower than the lower HR limit

Alarm Activation and Structure

The ST/AR arrhythmia system's alarm structure is based on priorities, with a system of *** Red, ** Yellow, and INOP alarms for the Heartstart MRx and high, medium, and low priority physiological and technical alarms for the HeartStart XL+. See the tables for red (high priority) and yellow (medium priority) descriptions. Each type has a distinctive visual and audible alarm, enabling quick recognition of the severity of the alarm event.

Once an alarm is detected, it is immediately activated. An alarm message appears on the display, and a distinctive audible alarm is annunciated.

*** Red (High Priority) Alarms

Red alarms, the most critical and life-threatening, always take priority over lesser arrhythmia alarms. They can never be individually turned off. All red and yellow alarms will be turned off if:

▶ Alarms are suspended.

▶ ECG alarms are turned off (HR alarms off).

** Yellow (Medium Priority) Alarms

Yellow alarms are considered lower in priority than red alarms, but still may indicate serious rhythm or rate disturbance. A yellow alarm can be superseded by a more serious yellow alarm event, or a red alarm.

INOP (Technical) Alarms

INOP (or technical) alarms occur whenever the ECG signal cannot be properly analyzed due to noise or INOP (or technical) conditions. If more than 2/3 of the time over the last 30 seconds beats are classified as either noisy or questionable, a *Cannot Analyze* INOP (or technical) alarm is generated. When active, the INOP (or technical) alarm continues, visually and audibly, as long as the condition exists, and stops automatically when the condition terminates.

Since the INOP (or technical) alarm is a lower priority alarm, it will not override a red or yellow alarm should it occur during the same time a red or yellow alarm is occurring. Similarly, if an arrhythmia event is detected while the INOP (or technical) alarm is active, the red or yellow arrhythmia alarm will override the INOP (or technical) alarm.

Since the *Cannot Analyze* INOP (or technical) alarm indicates that the effectiveness of the arrhythmia monitoring for the patient is compromised, a quick response to this high priority alarm is recommended.

Alarm Chaining

To prevent the confusion of redundant alarms or the activation of less important alarms while acknowledging serious alarms, the arrhythmia algorithm sets alarm priorities through an "alarm chaining" system.

Related events, such as ventricular alarms, are grouped in a "chain." The most critical alarms occupy the top of the chain and are followed by events in logical, descending order (see Figure 12).

The HeartStart XL+ uses the basic arrhythmia monitoring alarm chain for Monitor, Manual Defibrillation, Synchronized Cardioversion, and Pacer Modes but uses the cardiotach mode arrhythmia alarm chain for AED Mode (see Figure 13).

The manner in which the alarms are grouped and prioritized define how the alarms are announced:

▶ *** Red alarms having the highest priority are announced first if present.

▶ If there are no *** Red alarms detected, then the highest priority ** Yellow alarm detected in any given alarm chain is announced.

▶ If alarms of the same priority in different alarm chains are detected, the most recent alarm is announced.

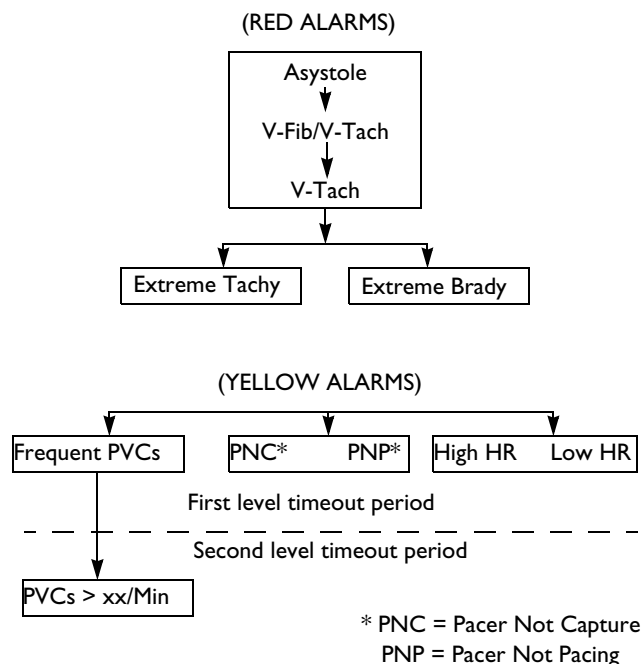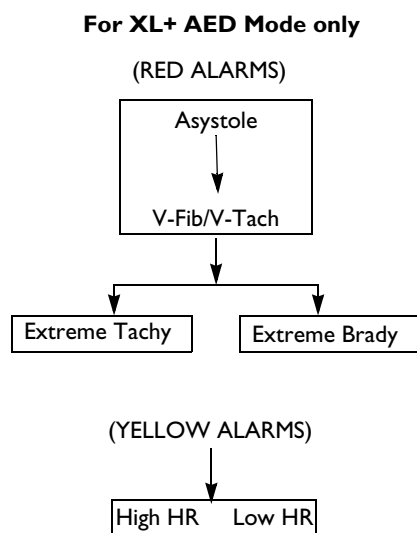Figure 12 **Alarm Chain for Basic Arrhythmia Monitoring**

(RED ALARMS)

Asystole
↓
V-Fib/V-Tach
↓
V-Tach

Extreme Tachy   Extreme Brady

(YELLOW ALARMS)

Frequent PVCs   PNC*   PNP*   High HR   Low HR

First level timeout period
- -
Second level timeout period

PVCs > xx/Min

* PNC = Pacer Not Capture
PNP = Pacer Not Pacing

Figure 13 **Cardiotach Mode Arrhythmia Alarm Priority Chain**

For XL+ AED Mode only

(RED ALARMS)

Asystole
↓
V-Fib/V-Tach
↓
Extreme Tachy   Extreme Brady

(YELLOW ALARMS)

High HR   Low HR

Points to Remember About Alarms

After a red or yellow alarm is acknowledged, the same alarm will be re-announced if the alarm condition persists after a two-minute timeout period. When the alarm reminder is triggered, the alarm sound associated with the alarm is sounded, however the visual alarm

indicator always remains present while the alarm condition exists. The alarm reminder will repeat every two minutes as long as the alarm condition persists.

▶ If an alarm condition exists, it is always announced unless it is turned off, there is a higher priority alarm in effect, or the two-minute timeout period is in effect.

▶ *** Red ECG/arrhythmia alarms never automatically reset.

▶ *All* arrhythmia alarm audio tones and visual messages are disabled on the HeartStart MRx if alarms are paused or HR/ECG alarms are off, whereas only the audio tones are disabled on the XL+ (i.e., visual messages are enabled).

Conclusion

Computerized arrhythmia monitoring is a tool the clinician can use to continuously monitor and evaluate the patient. In order to fully make use of this tool, it is important to understand the computer algorithm's capabilities and limitations.

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