ORIGINAL ARTICLES

Computer Diagnosis of Supraventricular and Ventricular Arrhythmias

A New Esophageal Technique

JANICE M. JENKINS, PH.D., DELON WU, M.D., AND ROBERT C. ARZBAECHER, PH.D.

SUMMARY Computerized arrhythmia monitors recognize only a few of the significant arrhythmias and generally fail to detect arrhythmias of supraventricular origin. This is because conventional surface leads, which are sufficient for QRS recognition, are highly inadequate for automated P-wave detection. A new two-lead system, which includes a swallowable capsule-electrode for esophageal monitoring of atrial activity, is used in an on-line arrhythmia monitor. Three interval measurements (AA, AR and RR) and a QRS shape measurement provide the foundation for a detailed interpretation of each beat. Building on the single-beat analysis, a contextual diagnostic algorithm then recognizes and reports on-line the following arrhythmias: couples, bigeminy, trigeminy, ventricular tachycardia, supraventricular tachycardia, atrial flutter, atrial fibrillation, ventricular tachycardia with retrograde conduction to the atria, first-degree block, second-degree block, Wenckebach periodicity, advanced block, third-degree block and sinus bradycardia.

INTEREST IN THE DETECTION and management of cardiac arrhythmias has grown in recent years and with it has grown the volume of electrocardiographic data to be processed. Computer techniques for detection of ventricular arrhythmias have naturally emerged. By using a swallowable capsule-electrode for esophageal recording of atrial activity, we have developed a computerized arrhythmia analyzer that yields reliable P-wave identification and thus provides recognition of supraventricular arrhythmias as well.

Previous authors1-10 have called attention to the difficulties in computer detection of P waves from surface leads. The problem is twofold: 1) Normal P waves are slow and of small amplitude and therefore difficult to separate from baseline shifts and noise; 2) abnormal P waves are often coincident with QRS complexes or T waves and cannot be separated, even by an experienced electrocardiographer. The only fundamentally new approach to this problem before our study is a system11 that uses an intra-atrial electrode. Unfortunately, venous catheterization is required.

Esophageal electrocardiography with enhanced registration of atrial activity has been used for years in special circumstances for analysis of cardiac arrhythmias,12-21 but has failed to become a routine clinical procedure largely because of the nuisance and discomfort of nasal or oral intubation. To eliminate this problem, we developed an easily swallowed capsule-electrode that enabled us to design and implement a computer system for automatic processing of simultaneous esophageal and surface ECGs. We studied both normal and abnormal subjects with the objective of computer diagnosis of ventricular and supraventricular arrhythmias as seen in coronary care, exercise testing, ambulatory monitoring and routine electrocardiography. In recent reports from this laboratory in the technical literature we described the electrode22 and the details of the initial computer programs for arrhythmia analysis.23, 24 In the present paper, we summarize the final computer implementation and present the clinical results of this work.

Materials and Methods

Esophageal Electrode

We devised a small bipolar electrode in the shape of a slender rod suspended from a pair of thin, extremely flexible wires (fig. 1). The electrode (Consolidated Medical Equipment, Inc., Utica, New York) is enclosed in a gelatin capsule and placed in the esophagus simply by having the patient swallow the capsule in the usual way with water, while the nurse or ECG technician holds the wire loosely, allowing the electrode to descend to a level below the left atrium. After a few minutes the capsule has dissolved, and the electrode is slowly withdrawn a few centimeters until its electrocardiographic registration shows a P-to-QRS ratio of 3:1 or more. Then the wire is taped to the patient’s chin to prevent further peristaltic lower-
ing. The procedure is painless and because the wire is so lightweight and flexible, the electrode is tolerated comfortably for extended periods of time without restricting normal activity, eating and sleeping. Figure 2 shows a two-channel ECG in which the esophageal signal is seen on the top channel and the signal from a standard surface lead appears on the lower channel.

Patient Selection

The patients were selected according to the quantity and variety of their arrhythmias, not sequentially or according to a randomization schedule. The patients were from a coronary intensive care unit, and the precise nature of the arrhythmias was not always known in advance. Fifty-three patients were asked to swallow the capsule-electrode. One patient refused, one could not swallow the electrode, and a third required endotrachial intubation for a recurrence of frequent ventricular fibrillation and no recording was made before the electrode was removed. The remaining 50 patients who swallowed the electrode required 1–5 minutes for esophageal placement. None of the 50 patients experienced difficulty, except for slight initial gagging in three patients that subsided when the electrode descended well into the esophagus. All patients described the swallowing procedure, recording period and removal as being free of discomfort.

Two patients had no visible P waves on the esophageal (and 12-lead) ECG; both had severe mitral

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**Table 1. Rhythm Classes and Computer Contextual Diagnoses**

<table>
<thead>
<tr>
<th>Rhythm class</th>
<th>Contextual diagnostic statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Normal sinus beats</td>
<td>a. Normal sinus rhythm</td>
</tr>
<tr>
<td>II. Occasional abnormal beats</td>
<td>None</td>
</tr>
<tr>
<td>III. Frequent premature ventricular beats</td>
<td>a. Couplet</td>
</tr>
<tr>
<td></td>
<td>b. Bigeminy</td>
</tr>
<tr>
<td></td>
<td>c. Trigeminy</td>
</tr>
<tr>
<td></td>
<td>d. Ventricular tachycardia</td>
</tr>
<tr>
<td>IV. Frequent premature atrial beats</td>
<td>a. Supraventricular tachycardia</td>
</tr>
<tr>
<td></td>
<td>b. Atrial fibrillation</td>
</tr>
<tr>
<td></td>
<td>b. Atrial flutter</td>
</tr>
<tr>
<td></td>
<td>c. Supraventricular tachycardia</td>
</tr>
<tr>
<td></td>
<td>d. Ventricular tachycardia</td>
</tr>
<tr>
<td></td>
<td>e. Ventricular tachycardia</td>
</tr>
<tr>
<td></td>
<td>f. Ventricular tachycardia</td>
</tr>
<tr>
<td></td>
<td>g. Ventricular tachycardia</td>
</tr>
<tr>
<td>V. Delayed or dropped beats</td>
<td>a. First-degree block</td>
</tr>
<tr>
<td></td>
<td>b. Second-degree block</td>
</tr>
<tr>
<td></td>
<td>c. Third-degree block</td>
</tr>
<tr>
<td>VI. Bradycardic beats</td>
<td>a. Bradycardia</td>
</tr>
<tr>
<td>VII. Junctional or ventricular escape beats</td>
<td>a. Third-degree block</td>
</tr>
</tbody>
</table>

*Sequences of beats belonging to the rhythm class shown in the left column may lead to contextual diagnostic statements shown on the right, provided other criteria are met.

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**Figure 1.** Drawing of the swallowable esophageal electrode encased in a gelatin capsule. The pill-electrode is a closely spaced bipolar pair, as shown in the inset, suspended from a pair of thin flexible wires. The electrode passes into the esophagus with a swallow of water followed by additional swallowing until it is positioned immediately posterior to the left atrium.

**Figure 2.** A two-channel ECG with the esophageal tracing on the top channel and the surface lead on the lower channel. "A" represents atrial depolarization recorded from esophageal lead, and "R" represents the QRS complex recorded from surface lead (see text for discussion).
stensosis and radiographically documented enlarged left atrium. In the remaining 48 patients, esophageal recordings with clearly defined P waves and minimal artifact and noise were obtained for periods up to 30 hours. In 34 patients, the two channels were also recorded on magnetic tape to be used for development of the computer system.

Hardware

The esophageal ECG is amplified two to four times and bandlimited from 5–100 Hz to eliminate low-frequency artifact due to respiration, peristalsis and cardiac contraction. The signal is differentiated and passed to a threshold detector that produces a trigger signal followed by a blanking period sufficient to prevent multiple detection during multiphasic waveforms. The surface lead ECG is recorded at the standard bandwidth of 0.05–100 Hz, rectified to produce its absolute value, differentiated and applied to a threshold detector for a trigger output with suitable blanking. The two trigger signals are delivered to a PDP-11/45 computer with 48K memory and appropriate analog-to-digital channels.

Computer Arrhythmia Detection

Upon receiving the trigger signals corresponding to P waves (A) from the esophageal channel and QRS complexes (R) from the surface channel, the computer automatically measures the AA, AR and RR intervals. The surface ECG is digitized at 500 Hz for analysis of the shape of the QRS.23 Because the shape of the A wave is not used in this scheme, the esophageal channel is not digitized. Arrhythmia analysis is done in real time by detecting each incoming QRS complex as it occurs and comparing it and its three associated intervals with a previously stored normal beat. If the QRS complex has abnormal morphology, the shape index is assigned a code of 0 for purposes of computer analysis; if it has a normal shape, it is assigned a code of 1. The AA, AR and RR intervals associated with the beat are graded short, normal or long and assigned a code of 0, 1 or 2, respectively. The codes for these four features are combined into a four-digit number with the following format: AA-AR-RR-CC, where CC represents the coefficient of correlation, or shape index (fig. 2). The four-digit code for each beat is computed upon the appearance of the QRS complex. Therefore, if the ventricular impulse precedes the expected A wave, the AA and AR intervals cannot be calculated for that beat and the first two digits of the code are set to 3, indicating the measurements are indeterminate. With this scheme for coding the four features, 60 distinct four-digit combinations exist. We constructed ladder diagrams that explicate the conduction sequence described by each beat code and devised a single-beat diagnostic statement for the code. The appendix contains these ladder diagrams for 49 sequences that appear clinically possible and the computer diagnostic statement for each.

Contextual Arrhythmia Analysis

The individual beat codes provide the foundation for the contextual recognition of more complex arrhythmias. The contextual arrhythmia diagnostic algorithm examines beat-code sequences for patterns that reflect specific arrhythmias. Rhythm patterns that can be identified by the program are normal sinus rhythm (NSR), couplets, bigeminy, trigeminy, ventricular tachycardia, supraventricular tachycardia, atrial flutter, atrial fibrillation, ventricular tachycardia with retrograde conduction to the atria, first-degree block, second-degree block, Wenckebach periodicity, advanced block, third-degree block and sinus bradycardia. As each QRS is detected, the computer delivers a one-line report to a display terminal: The first entry is the beat number; the second entry is the four-digit individual beat code; the third entry is the single-beat diagnostic report for that code; the fourth entry, a contextual diagnosis derived from a serial evaluation of recent beats, appears only when one of the previously listed arrhythmias is recognized.

Computer Logic and Decision Rules

Each beat is classified according to one of the following categories: conducted; premature ventricular and aberrant ventricular; premature atrial; conducted with atrioventricular delay; ventricular and junctional escape; bradycardic. We created a rhythm class for each beat category, plus one additional rhythm class that reflects isolated abnormal beats with no specific underlying arrhythmia identified. We also developed a hierarchical pattern recognition scheme that examines a recent sequence of beat codes and assigns a tentative rhythm class, within which certain contextual diagnoses are possible, provided certain other tests are met (table 1). We have also implemented the technique with actual two-channel recordings of all the arrhythmias included in the rhythm classes.

Results

In 48 patients recorded, we found NSR in two, isolated abnormal beats in 13, multiple ventricular beats and runs in 15, supraventricular arrhythmias in 15, atrioventricular block in seven, and bradycardia in two. (Some patients had more than one arrhythmia.) Thirty-five different arrhythmia episodes have been computer processed on-line. These constitute the most interesting arrhythmias of the 48 patients studied and include at least one example of each of the arrhythmias in table 1. Of the 22 patients not computer processed, four were studied before completion of the computer program, two were in NSR during the recording, and 16 are the subject of a future study. None of these patients had arrhythmias that were significantly different from the 26 patients who were processed.

The following examples of the results of analysis are grouped according to the rhythm classes specified in table 1 and provide a description of the logic used in the computer diagnosis.
Rhythm Type I — Normal Sinus Beats

If the QRS complex has normal morphology and the AA, AR and RR intervals fall within specified normal ranges, a contextual diagnostic statement of NSR is delivered after the individual beat diagnosis. If an abnormal beat interrupts the NSR report, 10 consecutive normal beats are required before the NSR diagnosis resumes.

Rhythm Type II — Occasional Abnormal Beats

Isolated or repeated abnormal beats that do not meet the criteria for other rhythm types cause this rhythm class to be entered. No contextual analysis is given and only the single-beat diagnosis appears. Figure 3 shows the computer processing of a patient with atrial bigeminy. The ectopic A wave, hidden in the T wave on the surface ECG (lower tracing), is easily detected by computer from the esophageal ECG (upper tracing). The beat code, which is computed upon the appearance of the QRS complex, reports a normal AA interval (first digit = 1), a normal AR (second digit = 1), a long RR (third digit = 2) and normal shape (fourth digit = 1). This beat code reflects a normal sinus beat following a premature beat (atrial, junctional, or ventricular). Because the code of the beat describes intervals that precede it, the preceding beat is examined to determine the exact diagnosis. In this case, the computer infers premature
atrial beats (PABs) and the appropriate report is given. Computer monitoring systems using surface leads alone for wave form and interval recognition would misdiagnose this arrhythmia as sinus bradycardia.

Rhythm Type III — Frequent
Premature Ventricular Beats (PVBs)

This rhythm type is designated if premature ventricular beats occur with a frequency of two or more within the last five beats. Four possible diagnostic statements can be delivered: couplet, bigeminy, trigeminy or ventricular tachycardia. The algorithm tests for specific patterns of PVBs and normal beats within the past four beats. The appearance of two consecutive PVBs elicits a couplet diagnosis that is modified to ventricular tachycardia if a third consecutive PVB appears. If repeated, an alternation of a PVB with a normally conducted sinus beat elicits a diagnosis of bigeminy, and a trigeminal pattern is recognized as well. Figure 4 shows a bigeminal rhythm that continues until the appearance of a second sinus beat at beat 15. The sequential pattern at beat 16 is recognized as trigeminy, and the diagnostic statement is modified accordingly.

**Figure 5.** A sequence of premature ventricular beats (PVBs) that elicits a diagnosis of ventricular tachycardia (V-TACH). The PVBs occur in a 2:1 ratio with respect to atrial activation. Thus, the types of beat codes are affected by the relationship of the QRS to the preceding A wave. In one case, the QRS follows an earlier A wave, while in the second, there is no associated A wave. The best codes oscillate between the two representations. Both cases are recognized as PVB types, however, and three consecutive such beats produce a diagnosis of V-TACH.

**Figure 6.** Atrial flutter registered from the esophageal lead. A string of beats recognized as premature atrial beats (PABs) is further examined for atrial rate to distinguish specific atrial arrhythmias. This patient's atrial rate of 320 beats/min is recognized by the contextual analyzer as atrial flutter; this diagnosis is reported upon the appearance of each QRS complex.
The ventricular tachycardia seen in figure 5 reveals a 2:1 ventricular-to-atrial ratio. Because A waves occur only half as frequently as R waves, an alternation of beat codes results. Codes of 3300 and 1000 are in the PVB category, and the continuous sequence of these codes generates a contextual diagnosis of ventricular tachycardia.

Rhythm Type IV — Frequent Premature Atrial Beats

Supraventricular arrhythmias are sorted into one of four possible diagnoses that the algorithm can deliver from this rhythm class: supraventricular tachycardia, atrial flutter, atrial fibrillation, and a joint diagnosis of supraventricular tachycardia with aberrancy or ventricular tachycardia with retrograde conduction to the atria. The initial criterion for diagnosing rhythm type IV is a run of beats whose codes contain a zero in the first digit, reflecting short AA intervals. In default of a more specific refinement, the diagnosis is supraventricular tachycardia. If the majority of AA intervals fall into the range of 170–240 msec, the tachycardia is recognized as atrial flutter; if they repeatedly fall below 170 msec, atrial fibrillation is reported. Figure 6 shows an atrial rate in excess of 300 beats/min and a 2:1 atrioventricular response. All beats have a code of 0101, each of which is diagnosed as a premature atrial beat (PAB). The contextual analyzer examines the length of the AA intervals and reports atrial flutter.

Anomalous QRS complexes in the presence of repeatedly short AA intervals could reflect ventricular tachycardia with retrograde conduction to the atria. No simple or sure distinction can be made between this arrhythmia and supraventricular tachycardia with aberrancy without evidence of onset or conversion; we report the dual diagnosis of supraventricular tachycardia with aberrancy or ventricular tachycardia with retrograde conduction to the atria in order that a possible life-threatening arrhythmia not go unobserved. Such an event is seen in the short burst of paroxysmal supraventricular tachycardia in figure 7. A contextual diagnosis of NSR is interrupted by a beat of junctional or low atrial origin at beat 14. This impulse is propagated normally, but the three rapidly firing preceding beats conduct aberrantly. Upon the third consecutive such beat, a diagnosis of supraventricular tachycardia with aberrancy or ventricular tachycardia with retrograde atrial conduction appears. The normal morphology of the following beat (fourth digit = 1) changes the diagnosis to the more general report of supraventricular tachycardia.

Rhythm Type V — Delayed or Dropped Beats

This rhythm type reflects long AR intervals and reports first-degree block upon a sequence of such beats or second-degree block if a dropped beat occurs. Two additional refinements are possible. If the dropped beat is preceded by beats showing progressively lengthening AR intervals, a diagnosis of Wenckebach periodicity is delivered. If at least one dropped beat occurs for each conducted beat, advanced block is reported. In figure 8A, the presence of an AR interval consistently exceeding 300 msec generates a context-
Figure 8. First-degree atrioventricular (A-V) block, second-degree block, and Wenckebach episodes. This patient exhibited a wide spectrum of arrhythmias indicative of A-V conduction disturbance. A) AR intervals exceeding 300 msec are evident, and first-degree block is the diagnosis reported with each beat. The appearance of a blocked beat at beat 15 causes the contextual statement to be modified to second-degree block. B) The AR interval progressively grows until a blocked beat appears after beat 15, eliciting a Wenckebach diagnosis at beat 16. This statement reverts to second-degree block, which continues to be reported if a blocked beat was present within the past five beats.

Rhythmic diagnosis of first-degree block. A blocked beat before beat 15 causes modification of the diagnosis to second-degree block. In figure 8B the AR interval gradually grows until a dropped beat appears after beat 15. This elicits a diagnosis of Wenckebach periodicity at beat 16. The diagnostic statement reverts to second-degree block, indicating long AR intervals plus a dropped beat within the past five beats. Advanced block (not shown here) requires the same initial logic and at least one dropped beat for each conducted beat.

Rhythm Type VI — Bradycardic Beats

A sequence of three or more beats with codes reflecting sinus bradycardia generates a diagnostic report of bradycardia. In general, beats with both long AA and RR intervals are considered bradycardic and are reported as such by the program.

Rhythm Type VII — Ventricular and Junctional Escape Beats

Rhythm type VII reflects repeated escape ventricular or junctional beats. If evidence of dissociation is present, the computer can deliver a contextual diagnosis of third-degree block, in addition to the single-beat statements of escape. The logic test for the full contextual diagnosis of third-degree block requires 1) three or more consecutive escape beats, 2) the presence of a regular sinus rate, and 3) abnormal AR intervals, indicating a random relationship between the atrial and ventricular activity.

Accuracy of Detection and Diagnosis

The accuracy of detection of P waves and QRS complexes was evaluated in computer-processed rhythm strips (1–3 minutes long) from 26 patients. Of
the 3059 P waves on the esophageal channel, 11 (0.36%) were not detected and 14 (0.46%) were falsely detected. Of the 3197 QRS complexes on the surface lead channel, four (0.13%) were not detected and 19 (0.59%) were falsely detected. Individual pulses from the trigger during atrial fibrillation could not be directly associated with distinct P waves due to the nature of the atrial activity, but computer diagnosis of atrial fibrillation is nevertheless possible, because the erratic atrial depolarization causes repeated firing of the trigger signal. For this reason, the number of P waves reported does not include P waves for the two patients with atrial fibrillation, although the QRS complexes for these patients are included. In longer recordings we have observed subtle changes in the atrial signal due to posture, and major artifacts during eating. These problems have not been examined in the present study.

Although the data base of patient recordings is too small for a statistical analysis of diagnostic accuracy, 29 12-second passages of the episodes analyzed by computer were chosen at random for diagnosis by an electrocardiographer who was not told the computer diagnosis. Of the single-beat diagnoses, 95.5% were confirmed by the cardiologist as correct, 4.5% were found to be false negatives (the abnormality was detected by both the computer and cardiologist, but the diagnostic statements disagreed), and there were no false positives. (The false triggers referred to above were not in the small sample submitted to the cardiologist.) In these same tracings, there were 38 distinct arrhythmic events, consisting of three or more beats, that required contextual analysis for identification. Of these sequences, two of the contextual analyses delivered by the computer (6%) were found to be in error when compared with the diagnosis of the electrocardiographer. One passage was diagnosed as NSR by the computer, while the reader called it low atrial rhythm; in the second instance a computer report of NSR was given for a passage interpreted by the cardiologist as atrial escape rhythm.

Discussion

Accurate computer diagnosis of arrhythmias is severely hampered because surface leads cannot reveal P waves with any reliability or certainty. The reliance on QRS data only by current computer methods limits present diagnoses to a few simple ventricular arrhythmias and poses difficulties in diagnosis of supraventricular arrhythmias. Important distinctions that must be made between ominous and less serious arrhythmias, such as distinguishing PVBs from PABs with aberrancy, are possible only if P-wave information is used in the decision logic. The arrhythmia analysis system described in this study includes a second lead for recording atrial activity from the esophagus. The large, sharp atrial impulse registered from immediately behind the left atrium permits precise P-wave detection by computer, including P waves that occur simultaneously with the QRS complex. The system diagnoses PVBs, couplets, bigeminy and trigeminy, as many single-lead systems do. However, it can also measure PR intervals, and when these are added to the conventional criteria of prematurity and abnormal QRS morphology, PABs with aberrancy are easily distinguished from PVBs. In addition, blocked atrial beats as in atrial bigeminy can be recognized. No other system is able to make this diagnosis. If a wide QRS tachycardia is present, our system can distinguish ventricular tachycardia from supraventricular tachycardia with aberrant conduction by noting the absence of P waves preceding some of the QRS complexes. However, if 1:1 atrioventricular relation occurs with wide QRS tachycardia, our system would report two possibilities: supraventricular tachycardia with aberrancy or ventricular tachycardia with retrograde conduction. An accurate distinction of these arrhythmias can usually be made only with His bundle recording techniques.

Our esophageal/computer technique is capable of differentiating several supraventricular arrhythmias, such as paroxysmal supraventricular tachycardia, atrial flutter and atrial fibrillation, by accurately detecting atrial depolarization and separating these tachycardias according to their atrial rates. Another feature unique to the two-lead monitor is the ability to diagnose first-, second- and third-degree atrioventricular block. The capacity to measure and compare PR intervals and to detect the occurrence of a dropped beat leads to specific identification of first-degree atrioventricular block, second-degree atrioventricular block with Wenckebach periodicity, second-degree atrioventricular block of the Mobitz II variety, and high-grade block (2:1, 3:1 or 4:1). In addition, the ability to perceive both atrial and ventricular impulses and to determine a lack of correspondence between the two makes a diagnosis of third-degree block possible.

The system can now identify sinus rhythm and 14 complex arrhythmias, as well as classify 49 normal and abnormal beats. This is achieved by the precise recognition of P waves recorded from the esophageal electrode. The patients in the present study were monitored from the esophageal electrode for periods ranging from 30 minutes to 30 hours. In all cases, the electrode was swallowed easily and quickly, and the entire procedure was reported by the patients to be simple and completely free of discomfort. The electrode imposes no restriction of normal activity, and our preliminary observations in several patients with prolonged recordings suggest that the electrode is well-tolerated for extended periods of time while maintaining reasonable signal quality. Twenty-four-hour Holter recordings made of six normal subjects have clearly shown the feasibility of the esophageal technique for long term and ambulatory monitoring. Based on this experience, we have begun an in-patient drug-efficacy study that requires a 5-day continual esophageal recording.

In conclusion, we have described a new technique for esophageal electrocardiography and a computerized analysis system capable of accurately detecting and differentiating most supraventricular and ventricular arrhythmias. This system should be useful for
identifying prodromal arrhythmias in coronary care monitoring, for evaluating the antiarrhythmic effect of therapeutic regimens, and for automated analysis of data produced during such procedures as exercise laboratory studies and Holter monitoring.

References
Appendix

This appendix contains ladder diagrams that give an electrophysiologic explanation of the activation sequence associated with each of our beat codes. In each diagram, the top, middle and bottom rows represent the atria, atrioventricular junction and ventricles, respectively. Propagation through each of these structures is represented as a line drawn in a generally vertical sense, but in the atrioventricular junction, the rightward horizontal component corresponds to time of conduction. If electrical activation is blocked due to conduction defect or to the refractory period of the previous depolarization, the line is terminated in a short “tee.” If ventricular activation is abnormal, the ventricular segment is marked with an “x.”

As a reference for comparison with short, normal and long intervals, a normally-conducted sequence is shown at the top left in figures A1–A3. In all diagrams, the preceding normal beat is on the left and the beat being classified is on the right. There are 46 beat codes that yield a specific single-beat diagnosis, and one other code (1121) that has three possible interpretations, depending on context.

**FIGURE A1.** Ladder diagrams for beat codes 0000–1001 and the associated computer-generated, single-beat diagnosis. AV = atrioventricular; PAB = premature atrial beat; PVB = premature ventricular beat.

**FIGURE A2.** Ladder diagrams for beat codes 1010–1221 and the associated computer-generated, single-beat diagnosis. AV = atrioventricular; PAB = premature atrial beat; PVB = premature ventricular beat; BBB = bundle branch block.

**FIGURE A3.** Ladder diagrams for beat codes 2010–3321 and the associated computer-generated, single-beat diagnosis. AV = atrioventricular; PVB = premature ventricular beat; BBB = bundle branch block.
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A2

Laddergram of normal rhythm, shown for ease of reference.

1010 Fusion of ventricular beat with sinus beat.

1011 Junctional or low atrial beat.

1020 Ventricular escape following a blocked sinus beat.

1021 Junctional or low atrial escape following a blocked PAB.

1100 Aberrant beat following an interpolated PVB.

1101 Sinus beat following beat with AV delay.

1110 Fusion or sinus beat with ventricular aberrancy.

1111 Sinus beat.

1120 Bradycardic BBB following blocked PAB (full sinus reset).

1121A Sinus beat following a PVB (after a compensatory pause).

1121B Sinus beat following a blocked PAB (full sinus reset).

1200 PVB (or aberrant with delay) after interpolated PVB.

1201 Sinus beat with AV delay following interpolated PVB.

1202 Sinus beat with AV delay.

1210 Junctional premature beat with compensatory pause.

1211 Sinus beat with AV delay following blocked beat.

1220 Ventricular escape following blocked beat.

1221 Sinus beat with AV delay following blocked beat.

A3

Laddergram of normal rhythm, shown for ease of reference.

2010 Ventricular escape in sinus bradycardia.

2020 Ventricular escape in sinus bradycardia.

2021 Junctional escape in sinus bradycardia.

2100 Sinus beat following beat with AV delay.

2101 Sinus bradycardia following PVB.

2110 Sinus beat following beat with AV delay.

2111 Sinus beat after beat with AV delay.

2120 Bradycardic BBB or fusion beat in sinus bradycardia.

2121 Sinus beat in sinus bradycardia, or atrial escape.

2220 Ventricular escape in sinus bradycardia with AV block.

2221 Sinus beat with AV delay in sinus bradycardia.

3100 PVB.

3110 Ventricular escape in sinus bradycardia, pause or arrest.

3300 PVB.

3301 Junctional premature beat.

3310 Ventricular escape in sinus bradycardia, pause or arrest.

3311 Junctional escape in sinus bradycardia, pause or arrest.

3320 Ventricular escape in sinus bradycardia, pause or arrest.

3321 Junctional escape in sinus bradycardia, pause or arrest.
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