Automated Interpretation of Cardiac Arrhythmias
Design and Evaluation of a Computerized Model

Lorenzo A. DiCarlo, MD, Dongping Lin, PhD, and Janice M. Jenkins, PhD

Abstract: Historically, the development of computerized models that utilize the deductive methods used by clinicians for the interpretation of cardiac arrhythmias have been limited by the absence of a consistently reliable means of detecting atrial activation. In this study, a theoretical model was developed with a hierarchical organization of problem-solving strategies utilizing automated analysis of atrial activation from a commercially available esophageal pill electrode and ventricular activation from a simultaneously recorded surface electrocardiographic lead. The theoretical model was then tested in 21 patients with 1 or more of 28 distinct supraventricular and ventricular arrhythmias. Of the 641 individual cardiac cycles analyzed, 636 (99.2%) were correctly identified. The accuracy of a contextual, that is, more comprehensive interpretation of consecutive cardiac cycles was 638/641 (99.5%). The following cardiac arrhythmias were identified: sinus rhythm, sinus bradycardia, atrial premature depolarizations, atrial flutter, and supraventricular tachycardias with normal and aberrant ventricular conduction, first-degree and second-degree heart block; junctional escape, junctional rhythm, idioventricular rhythm, ventricular premature depolarization, and ventricular tachycardia with and without retrograde activation; atrial bigeminy, atrial trigeminy, atrial couplets, ventricular bigeminy, ventricular trigeminy, and ventricular couplets. This study represents the first computerized model ever developed to incorporate the morphology and timing of atrial activation with the morphology and timing of ventricular activation for arrhythmia diagnosis. Such modeling appears to be capable of achieving accurate interpretation of spontaneous, complex clinical cardiac arrhythmias and atrioventricular relationships. Key words: computer-assisted diagnosis, arrhythmia, esophageal electrode.
and serial ventricular activations, the sequence of atrial and ventricular activation, and the comparisons of the interval between atrial and ventricular depolarization with the interval between ventricular and atrial depolarization to infer atrioventricular and ventriculoatrial relationships. Arriving at a diagnosis, however, may not necessarily mandate a systematic assessment of all available variables in a consistent and unbiased manner. For example, analysis of an isolated atrial or ventricular event might require integration of its occurrence with intervening events since the last sinus rhythm cycle alone. In other cases, analysis of a similar event may depend upon events prior to the last sinus rhythm cycle (Figs. 1 and 2).

A theoretical model was designed that, for the first time, examines and interprets the morphology and timing of atrial as well as ventricular events in the cardiac cycle. At the initial level of data organization, atrial-atrial, ventricular-ventricular, atrial-ventricular, and ventricular-atrial intervals and atrial and ventricular morphologies were identified and classified, providing a single cardiac cycle diagnosis. In a second level of more complex organization, a hierarchy was developed to determine the relationship of the individual cardiac cycle to the cardiac cycles that preceded it. In this second level of hierarchical organization, the diagnosis ascribed to the single cardiac cycle under analysis was incorporated with those of the eight preceding cardiac cycles to derive a contextual, that is, more comprehensive, diagnosis. This theoretical model was then tested in 21 patients with 1 or more of 28 different supraventricular or ventricular arrhythmias.

Materials and Methods

Theoretical Model

A block diagram of the five major components of the model is presented in Figure 3. The components include: (1) data acquisition; (2) atrial and ventricular activation analysis; (3) conduction sequence derivation; (4) single cycle diagnosis; and (5) contextual diagnosis. Fig. 1. Interpretation of an atrial depolarization (*) having an abnormal morphology when compared to sinus rhythm (A). (B, C) Events intervening since the last sinus rhythm cycle determine whether it is an ectopic atrial depolarization that is spontaneous or due to retrograde conduction. (D, E) Events prior to the last sinus rhythm cycle determine whether the ectopic spontaneous atrial depolarization is premature or represents an escape mechanism.
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(1) correlation waveform analysis of the atrial electrogram (CCa); (2) correlation waveform analysis of the ventricular electrogram (CCv) and interval determination between (3) two consecutive atrial depolarizations (AA); (4) atrial and subsequent ventricular depolarization (AV); and (5) two consecutive ventricular depolarizations (VV).

Waveform Analysis. In preprocessing prior to automated analysis, an atrial depolarization is selected from a normal sinus rhythm cycle as a normal atrial template. A ventricular depolarization from the same cardiac cycle is selected as a normal ventricular template. The method of waveform analysis of subsequent cardiac cycles is a comparison of each subsequent atrial depolarization with the atrial template and each subsequent ventricular depolarization with the ventricular template, respectively, using correlation waveform analysis. This method of analysis has been traditionally applied to surface ECGs, and more recently to intracardiac electrograms.

The following equation is used to calculate the correlation coefficient:

\[ \rho = \frac{\sum_{i=1}^{M} (T_i - \mu_T)(X_i - \mu_X)}{\sqrt{\sum_{i=1}^{M} (T_i - \mu_T)^2 \sum_{i=1}^{M} (X_i - \mu_X)^2}} \]

where

- \( M \) = the number of points in the template;
- \( T_i \) = the template points;
- \( X_i \) = signal points to be processed; and
- \( \mu \) = the signal or template average.

The correlation coefficient (\( \rho \)) represents a measure of similarity between a signal and a template in the range \(-1 < \rho < +1\). Where +1 indicates a perfect match. In this system, a depolarization with \( \rho \geq 0.95 \) is considered a match, that is, normal; those falling below this value are classified as abnormal.

Interval Analysis. Interval analysis is performed by comparing each incoming AA, AV, and VV interval with the AA, AV, and VV intervals determined during the normal sinus rhythm cycle. In this study, the upper and lower limits of the AA and AV intervals were set at \( \pm 15\% \) of the template normal sinus rhythm cycle. Intervals of the cardiac cycle being analyzed are classified into three categories. If an interval falls below the lower limit of its normal range, it is classified as short; if above, it is classified as long. If the interval is between the lower and upper limits, it is classified as normal.

Single Cardiac Cycle Code. For each cardiac cycle, a five-digit single cardiac cycle code is determined for the five analyzed features (Fig. 4). The digits assigned for atrial morphology and ventricular morphology are either 0 (abnormal) or 1 (normal). The digits assigned for the AA, AV, and VV intervals are 0 (short), 1 (normal), or 2 (long).

Definitions of Normal AA, AV, and VV Intervals During Sinus Rhythm. During sinus rhythm at rates of 60–100 cycles/min, the upper and lower limits of a normal AA and a normal VV interval are 1.15 and 0.85 times the template sinus cycle AA and VV intervals. The lower limit of a normal AV interval is 0.8 times the template sinus cycle AV interval or 100 ms if the latter value is greater. The upper limit of a normal AV interval is 1.2 times the last sinus cycle AV interval or 220 ms if the latter value is greater.

Definitions of Atrioventricular Conduction. In cardiac cycles where an atrial depolarization is not followed
by a ventricular depolarization, CC, and AV and VV
intervals cannot be determined. The single cardiac
cycle diagnostic code contains digits for only two di-
agnostic features (CC, and AA interval), and the
atrial depolarization is defined as nonconducted.

In this theoretical model, an atrial depolarization
followed by a ventricular depolarization with an AV
interval greater than 360 ms is also defined as a non-
conducted atrial depolarization, even though all five
diagnostic features can be derived from such a car-
diac cycle.

If two consecutive atrial depolarizations occur and
a ventricular depolarization does not precede the sec-
ond atrial depolarization, determination of atriovent-
ricular conduction is defined by four features and is
summarized in Table 1.

**Definitions of Ventriculoatrial Conduction.** In cardiac
cycles where a ventricular depolarization is not pre-
ceded by an atrial depolarization, a sixth feature for
the single cardiac cycle is utilized: the ventriculoatrial
(VA) interval. It is measured from the ventricular de-
polarization to the next atrial depolarization which
occurs. Ventriculoatrial conduction is defined to
have occurred if the CC, of the atrial depolarization
is 0 (abnormal) and the measured VA interval is at
least 100 ms but <400 ms.

If two ventricular depolarizations occur consecu-
tively without an intervening atrial depolarization,
retrograde atrial conduction by the first ventricular
depolarization is defined by five features: (1) the VV
interval of the first ventricular depolarization is 0
(shorter than the normal VV interval during sinus
rhythm), (2) the CC, of the subsequent atrial depo-
larization is 0 (abnormal), (3) the AA interval of the
atrial depolarization is 1 (unchanged) or 0 (shorter
than the normal AA interval during sinus rhythm),
(4) the VA interval measured from the first of the
two consecutive ventricular depolarizations may be
0, 1, or 2 (within 100–400 ms), (5) the VA interval
measured from the second of the two consecutive
ventricular depolarizations is <100 ms. Figure 4
shows the coding scheme for each of the possible
sequences (A, V, AV, or VA).

**Single Cardiac Cycle Diagnosis.** The construc-
tion of cardiac cycle codes from these rules results in
122 possible diagnostic statements for single cardiac
cycle classification. Ladder diagrams for all 122 codes
are given in the Appendix. Single cycle diagnoses
include: atrial premature depolarization, atrial ec-
topic depolarization, atrial escape, sinus slowing
(bradycardia depolarization), normal ventricular
premature depolarization, junctional escape, ectopic
ventricular premature depolarization, ventricular es-
cape, and ventricular fusion. Each atrial depolariza-
tion is further characterized as conducted or noncon-
ducted, conducted with AV delay (first-degree AV
block), and/or conducted with normal or aberrant
ventricular depolarization. Each normal or ventricu-
lar ectopic depolarization that is not preceded but
followed by an atrial depolarization is further charac-
terized as occurring with or without retrograde atrial
activation. (Table 2.)

**Integrated Interpretation of Sequential Car-
diac Cycles (Contextual Diagnosis).** Single cycle
diagnoses of the eight most current cardiac cycles are
incorporated to derive a contextual diagnosis. Possi-
bile contextual diagnoses include sinus, atrial, junc-
tional, or idioventricular bradycardias; first-degree
and second-degree AV block; atrial bigeminy, atrial
trigeminy, atrial couplet, ventricular bigeminy, ven-

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**Table 1. Definitions of Atrioventricular Conduction and Block of the First of Two Consecutive Atrial Depolarizations Without an Intervening Ventricular Depolarization**

<table>
<thead>
<tr>
<th>AA Interval</th>
<th>A1 A2 Interval</th>
<th>CC A1</th>
<th>A2 V</th>
<th>A1</th>
</tr>
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<tbody>
<tr>
<td>Normal</td>
<td>Normal</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Normal</td>
<td>Short</td>
<td>Normal</td>
<td>Unchanged or Long</td>
<td>Conducted</td>
</tr>
<tr>
<td>Normal</td>
<td>Long</td>
<td>Normal</td>
<td>Abnormal</td>
<td>Conducted</td>
</tr>
<tr>
<td>Short</td>
<td>Normal</td>
<td>—</td>
<td>—</td>
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<td>Short</td>
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<td>Short, unchanged, or long</td>
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</tr>
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<td>Short</td>
<td>Long</td>
<td>Normal</td>
<td>—</td>
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</tr>
<tr>
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<td>Long</td>
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</table>

A = atrial depolarization with ventricular depolarization preceding A1; A1 = first of two consecutive premature depolarizations without an intervening ventricular depolarization; A2 = second of the two consecutive premature depolarizations; CC A1 = atrial morphology of A1 when compared to the preprocessed atrial template determined during sinus rhythm; A2V = the measured atrioventricular interval from A1 to the next observed ventricular depolarization. *When compared to the last AA interval that occurred during sinus rhythm.
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Table 2. Table of Single Cardiac Cycle Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normal</td>
<td>CCₐ, CCᵥ, and at least two normal intervals</td>
</tr>
<tr>
<td>2</td>
<td>Aberrant</td>
<td>Sinus depolarization with aberrant conduction</td>
</tr>
<tr>
<td>3</td>
<td>AV delay</td>
<td>Sinus depolarization with AV delay</td>
</tr>
<tr>
<td>4</td>
<td>Blocked</td>
<td>Blocked sinus depolarization</td>
</tr>
<tr>
<td>5</td>
<td>APD</td>
<td>Atrial premature depolarization with or without conduction</td>
</tr>
<tr>
<td>6</td>
<td>JP</td>
<td>Junctional premature depolarization with or without retrograde</td>
</tr>
<tr>
<td>7</td>
<td>VPD</td>
<td>Ventricular premature depolarization with or without retrograde</td>
</tr>
<tr>
<td>8</td>
<td>SS</td>
<td>Sinus slowing with or without conduction</td>
</tr>
<tr>
<td>9</td>
<td>AE</td>
<td>Atrial ectopic depolarization with or without conduction</td>
</tr>
<tr>
<td>10</td>
<td>JE</td>
<td>Junctional escape with or without retrograde</td>
</tr>
<tr>
<td>11</td>
<td>VE</td>
<td>Ventricular escape with or without retrograde</td>
</tr>
<tr>
<td>12</td>
<td>NS</td>
<td>Nonspecific abnormal depolarization</td>
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CCₐ = atrial electrogram morphology; CCᵥ = ventricular electrogram morphology.

Fig. 5. Flow chart of contextual diagnosis showing the priority of arrhythmia diagnoses.

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CCₐ = atrial electrogram morphology; CCᵥ = ventricular electrogram morphology.

Sustained supraventricular arrhythmias are then further characterized by their blocked or anterograde conduction pattern (1:1, 2:1, 3:1, etc.), and sustained ventricular arrhythmias are characterized by the presence or absence of atrial retrograde conduction and the retrograde conduction pattern (1:1, 2:1, 3:1, etc.).

To achieve this characterization four counters are employed. The first counter (AA) records the number of current sequential atrial depolarizations with short or long AA intervals. The second counter (VV) records the number of current sequential ventricular depolarizations with short or long VV intervals. The third counter (AV) records the number of atrioventricular activations that are recorded during a supraventricular bradycardia or tachycardia. The fourth counter (VA) records the number of ventriculoatrial activations detected during a ventricular bradycardia or tachycardia.

Contextual Diagnostic Definitions. Figure 5 shows a flow chart of the contextual diagnostic scheme. During the contextual diagnosis, a hierarchical priority scheme is employed. In this model, ventricular arrhythmias are sought first.

If the initial depolarization examined is an ectopic ventricular premature depolarization and is followed by five or more consecutive ventricular premature depolarizations, the contextual diagnosis is ventricular tachycardia, ventricular flutter, or ventricular fibrillation. The contextual diagnosis system examines the ventricular rate to classify the arrhythmia into ventricular fibrillation (more than 330 depolarizations per minute), ventricular flutter (240–330 depolarizations per minute), or ventricular tachycardia (100–240 depolarizations per minute). For ventricular fibrillation, the system reports ventricular fibrillation. For ventricular flutter or tachycardia, the system examines for retrograde atrial activation (abnormal CCᵥ) and records each such event using the ventriculoatrial activation counter. If the counter records zero, the system reports ventricular flutter without retrograde or ventricular tachycardia without retrograde. If the counter is not zero, the conduction pattern is calculated by dividing the last complete AA interval by the VV interval. If these intervals are equivalent, the arrhythmia is seen as 1:1 retrograde. If the AA interval is twice the current VV interval, there is 2:1 retrograde. Other retrograde patterns (3:1, 4:1, etc.) are determined in the same manner.

If no ventricular tachycardia is present, the system searches for supraventricular tachycardia. If an atrial premature depolarization is followed by five or more consecutive atrial premature depolarizations, the contextual diagnosis system then examines the type of supraventricular tachycardia pattern present.

Atrial fibrillation is diagnosed if the atrial rate is greater than 330 cycles per minute. Atrial flutter is
diagnosed if the atrial rate is 240–330 cycles per minute. Supraventricular tachycardia is diagnosed if the atrial rate is between 140 and 240 cycles per minute. An atrial conduction counter indicates whether the dysrhythmia conducts to the ventricles. If so, the conduction pattern (1:1, 2:1, 3:1, etc.) is calculated by dividing the last complete VV interval by the current AA interval. The supraventricular tachycardia and its conduction pattern (1:1, 2:1, 3:1, etc.) is then reported.

If there is no atrial or ventricular tachycardia, the system next examines for bradycardia. If the current depolarization is a sinus or atrial slowing depolarization and is followed by five or more such depolarizations in succession, the system reports a contextual diagnosis of bradycardia.

If atrial tachycardia, ventricular tachycardia, or bradycardia is not present, the system searches for three or more consecutive ventricular or atrial premature depolarizations by checking ventricular premature or atrial premature counters. If the number in either counter exceeds two, the consecutive ventricular or atrial premature depolarizations are reported along with the retrograde or anterograde conduction pattern.

**Bigeminal and Trigeminal Rhythms.** If none of the above is detected, the system examines the last four depolarizations for atrial and ventricular trigeminy or bigeminy. If there is an atrial premature depolarization (APD) for every two normal ventricular depolarizations in a repeated fashion (Normal-Normal-APD), the system reports atrial trigeminy. If the last atrial premature depolarization is conducted, a diagnosis of atrial trigeminy with conduction is given; otherwise, the diagnosis is atrial trigeminy without conduction. If there is an ectopic ventricular premature depolarization (VPD) for every two sinus depolarizations in a repeated fashion (Normal-Normal-VPD), ventricular trigeminy is diagnosed. A diagnosis of ventricular trigeminy with retrograde conduction, or ventricular trigeminy without retrograde conduction is reported depending on whether or not the last ventricular ectopic depolarization causes retrograde atrial activation. Atrial and ventricular bigeminy are diagnosed in similar fashion. Anterograde and retrograde conduction patterns are also diagnosed for atrial and ventricular bigeminy, respectively.

**Couples.** Two consecutive atrial premature depolarizations or two atrial premature depolarizations with an intervening ventricular depolarization with out retrograde activation will elicit a diagnosis of atrial couplet. The conduction pattern is determined by a counter that records the number of consecutive AV conductions of atrial premature depolarizations. Atrial couplet without conduction will be reported if the counter is zero; atrial couplet with 1:1 conduction if the counter is 2; and atrial couplet with 2:1 conduction if the counter is 1.

### Clinical Evaluation of the Theoretical Model

**Data Acquisition**

After obtaining informed written consent, tape recorded data were acquired from patients in a coronary care unit utilizing an esophageal lead and a standard surface lead II. In this study, the esophageal electrograms were recorded from a bipolar pill electrode (Arzco Medical Electronics, Inc., Chicago, IL) swallowed by the patient and located posterior to the left atrium. The esophageal signal and surface lead were recorded with a bandwidth of 5–100 Hz and 0.05–100 Hz, respectively. The 5 Hz low frequency cut-off applied to the esophageal signal eliminates low-frequency artifacts such as respiration and cardiac motion. Recordings (15 minutes to 2 hours) were made from 21 patients who had 1 or more of 28 distinct arrhythmias. Data were digitized for computer processing using two-channel concurrent analog-to-digital conversion with a sampling rate of 1,000 Hz per channel. The data acquisition subsystem (Tecmar LabMaster, Solon, OH) was interfaced to a personal computer. A software trigger (digital differentiator) was used for P wave and QRS waveform recognition.

A total of 29 passages, each containing 1 or more of 28 distinct arrhythmias, were tested. The passages to be processed were specifically chosen to contain a preponderance of abnormal cardiac cycles in order to assess the robustness of the detection system. Sinus rhythm cycles constituted only 25% of the cardiac cycles analyzed.

Each cardiac cycle and cardiac arrhythmia was evaluated and a diagnosis was given by a clinical cardiac electrophysiologist who was blinded to the results of the computerized analysis. The results were subsequently compared.

Figures 6 and 7 show two examples of computer-processed passages. Figure 6 shows a recording and the results of the analysis from a patient who has a supraventricular tachycardia with 1:1 conduction with both onset of the tachycardia and spontaneous conversion. All ventricular depolarizations have normal morphologies. Cardiac cycles 2–5 are normal. Cycle 6 has long AA and VV intervals and is diagnosed as sinus slowing. Cycles 7 and 8 revert to normal. Subsequently, the patient develops a series of
Fig. 6. Supraventricular tachycardia with 1:1 conduction showing both onset and conversion. This patient has normal sinus rhythm (NSR) at the beginning of the passage (cycles 1–5) followed by a sinus slowing (cycle 6) and an initiation of supraventricular tachycardia at cycle 9. Spontaneous conversion occurs at cycle 25. All ventricular depolarizations are similar. APD = atrial premature depolarization; AV = atrioventricular; cond = conduction; seq = sequence.

atrial premature depolarizations that conduct to the ventricles. At the beginning of the tachycardia (cycles 9 and 10), the system delivers a contextual diagnosis of atrial couplet with 1:1 conduction. For the next three cycles the diagnosis is 3, 4, and 5 consecutive atrial premature depolarizations with 1:1 conduction. After six consecutive conducted atrial premature depolarizations occur, the rhythm diagnosis is 1:1 supraventricular tachycardia, which continues to be reported until conversion occurs (cycle 25).

Figure 7 shows a recording and the results of the analysis from a patient who has ventricular couplets with retrograde atrial activation. The couplets in this example occur at cycles 5, 6 and 14, 15. All ventricular premature depolarizations in these couplets have retrograde atrial activation with the abnormal atrial depolarizations that follow each ventricular premature depolarization. The system diagnoses pairs of ventricular premature depolarizations in the individual cycle stage and correctly makes the contextual
<table>
<thead>
<tr>
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<th>Cycle Diagnosis</th>
<th>Contextual Diagnosis</th>
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<tr>
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<td>11111</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>4</td>
<td>AV</td>
<td>11111</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>5</td>
<td>VA</td>
<td>00</td>
<td>VPD with retrograde</td>
<td>VPD with retrograde</td>
</tr>
<tr>
<td>6</td>
<td>VA</td>
<td>00</td>
<td>VPD with retrograde</td>
<td>V couplet with 1:1 retro.</td>
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<tr>
<td>7</td>
<td>AV</td>
<td>11212</td>
<td>Sinus slowing with cond.</td>
<td>Sinus slowing with cond.</td>
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<td>AV</td>
<td>11111</td>
<td>Normal</td>
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<td>VA</td>
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<tr>
<td>15</td>
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<td>00</td>
<td>VPD with retrograde</td>
<td>V couplet with 1:1 retro.</td>
</tr>
<tr>
<td>16</td>
<td>AV</td>
<td>11212</td>
<td>Sinus slowing with cond.</td>
<td>Sinus slowing with cond.</td>
</tr>
</tbody>
</table>

Fig. 7. This patient has ventricular premature depolarizations (VPD) and ventricular (V) couplets, (cycles 5 and 6, and 14 and 15) with ventricular atrial (VA) or retrograde (retro) activation. Each VPD is diagnosed in the single cycle stage and the contextual diagnosis of the couplet appears upon the second VPD of each pair. Abbreviations same as in Figure 6.

**Results**

**Single Cardiac Cycle Diagnostic Code**

For the 641 individual cardiac cycles of the 29 passages analyzed, the diagnostic accuracy was 99.2% (636 of 641). There were no false positives (abnormal cardiac cycles classified as normal). All five errors were abnormal cardiac cycles that were misclassified. Two of these five errors were corrected by contextual diagnosis.

**Contextual Diagnosis**

The accuracy of the contextual diagnosis of the recorded cardiac arrhythmias analyzed was 99.5% (638 of 641 diagnostic statements).

The following types of cardiac arrhythmias were identified: normal sinus rhythm, sinus rhythm with aberrant ventricular activation; sinus rhythm without ventricular activation (blocked sinus cycle); atrial premature depolarizations with normal or aberrant ventricular activation, atrial premature depolarizations without ventricular activation (blocked); ventricular premature depolarizations with or without retrograde atrial activation; sinus slowing with or without ventricular activation; junctional escape or junctional rhythm with or without retrograde atrial activation; ectopic ventricular escape or idioventricular rhythm with or without retrograde atrial activa-
tion; atrial bigeminy; atrial trigeminy; atrial couplets; ventricular bigeminy; ventricular trigeminy; ventricular couplets; ventricular tachycardia; supraventricular tachycardia; atrial flutter; first-degree atrioventricular block; and second-degree atrioventricular block.

Discussion

The absence of a consistently reliable means of detecting atrial activation using standard surface electrography has been one of the major obstacles to the implementation of automated methods for accurate arrhythmia diagnosis. Models developed to date have had to rely predominantly upon changes in the timing and morphology of ventricular electrograms to infer relationships between atrial and ventricular activation. As a result, they have had limited diagnostic accuracy. For example, systems used currently for ambulatory, bedside, and intraoperative ECG monitoring are unable to accurately differentiate such elemental arrhythmias as atrial premature depolarizations, or supraventricular tachyarrhythmias with aberrant ventricular conduction from ventricular premature depolarizations or wide-complex tachycardias that are ventricular in origin.

Recently, the incorporation of surface ECG with the esophageal pill electrodes for the detection of atrial activity has been demonstrated to improve the accuracy of bedside cardiac arrhythmia interpreta-

\[
\begin{array}{cccccc}
\text{Cycle} & \text{Seq} & \text{Code} & \text{Cycle Diagnosis} & \text{Contextual Diagnosis} \\
2 & AV & 01020 & \text{APD with AV delay} & \text{APD with AV delay} \\
3 & VA & 00 & \text{VPD with retrograde} & \text{VPD with retrograde} \\
4 & VA & 00 & \text{VPD with retrograde} & \text{V couplet with 1:1 retro.} \\
5 & VA & 00 & \text{VPD with retrograde} & 3 \text{VPDs with 1:1 retro.} \\
6 & VA & 00 & \text{VPD with retrograde} & 4 \text{VPDs with 1:1 retro.} \\
7 & VA & 00 & \text{VPD with retrograde} & 5 \text{VPDs with 1:1 retro.} \\
8 & VA & 00 & \text{VPD with retrograde} & \text{VT with 1:1 retro.} \\
9 & VA & 00 & \text{VPD with retrograde} & \text{VT with 1:1 retro.} \\
10 & VA & 00 & \text{VPD with retrograde} & \text{VT with 1:1 retro.} \\
11 & VA & 00 & \text{VPD with retrograde} & \text{VT with 1:1 retro.} \\
12 & V & 10 & \text{J premature w/o retro.} & \text{V echo beat} \\
13 & VA & 00 & \text{VPD with retrograde} & \text{VT with 1:1 retro.} \\
14 & VA & 00 & \text{VPD with retrograde} & \text{VT with 1:1 retro.} \\
15 & VA & 00 & \text{VPD with retrograde} & \text{VT with 1:1 retro.} \\
16 & VA & 00 & \text{VPD with retrograde} & \text{VT with 1:1 retro.} \\
17 & V & 10 & \text{J premature w/o retro.} & \text{V echo beat} \\
18 & VA & 00 & \text{VPD with retrograde} & \text{VT with 1:1 retro.} \\
\end{array}
\]

Fig. 8. Ventricular tachycardia (VT) with 1:1 retrograde and echo beats. Cycles 2, 12, and 17 are mistakenly identified in the single cycle diagnostic scheme as junctional (J) premature depolarization without (w/o) retrograde conduction to the atrium. This is due to their normal shape and short VV interval. They are, in fact, ventricular echo beats, and the latter two are recognized as such when examined by the contextual algorithm. Abbreviations same as in Figure 6.
tion by clinicians. The results of this study suggest that the incorporation of similar data can provide a practical means of increasing the complexity and accuracy of automated ECG analysis. The addition of an esophageal atrial signal provides an effective feature for the analysis of the morphology, as well as the timing of atrial activation, thereby permitting the development of an artificial intelligence system for the accurate and comprehensive interpretation of individual cardiac cycles and supraventricular and ventricular arrhythmias.

The importance of contextual diagnosis in accurate arrhythmia analysis is emphasized by one of the limitations of this model. The single cardiac cycle analysis of this model cannot differentiate single atrial depolarizations with normal or prolonged AV conduction or aberrant conduction from single atrial depolarizations followed by a coincidental ventricular ectopic depolarization. There were two such cardiac cycles in a total of 641 analyzed cycles (0.3%) (Fig. 8). In addition, the single cardiac cycle diagnostic code could not detect ventricular echo beats because only the one or two most current depolarizations were considered during cardiac cycle coding. As a consequence, two ventricular "echo" depolarizations were misclassified as junctional depolarizations because of their proximity to the antecedent premature ventricular depolarization that was followed by retrograde atrial activation. The recognition of VA activation (which was accurate) precluded the recognition of the consequent AV conduction that followed. Despite this, the single cardiac cycle errors were corrected by the contextual diagnosis.

Present and Future Applications

Among the potential, practical applications of the type of model developed in this study are accurate automated interpretation of ambulatory ECG (Holter Monitor) recordings and improved automated analysis during intensive care or intraoperative ECG monitoring. Prolonged monitoring with esophageal electrodes has already demonstrated to be feasible. Further improvements and implementation of analogous models of arrhythmia analysis into devices such as implantable antiarrhythmia pacemakers and automatic cardioverter-defibrillators might provide more reliable discrimination of ventricular tachycardia and ventricular fibrillation from other, supraventricular tachyarrhythmias, and help prevent inappropriate device-patient interactions.

Among possible improvements to be made in further models of arrhythmia analysis is the development of more streamlined analysis methods in order to decrease computational time. The possibility of decreasing computational demands for electrogram morphology analysis while maintaining the diagnostic accuracy of morphologic evaluation has been recently demonstrated. Further refinement of the contextual diagnosis system will be another important step in the development of efficient computerized dysrhythmia analysis. For example, future computerized modeling that incorporates strategies such as probability could increase the efficiency of the existing system. By limiting the total number of hypotheses that must be considered when individual cardiac cycles are incorporated into a contextual diagnosis, the total number of variables requiring analysis could also be decreased.

Acknowledgment

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References

10. Arzbaecher R: A pill electrode for the study of cardiac dysrhythmia. Medical Instrumentation, 12:277, 1978
Appendix

Ladder diagrams, beat codes, and single beat diagnoses of AV sequence

<table>
<thead>
<tr>
<th>Beat Code Pattern</th>
<th>CCa</th>
<th>CCv</th>
<th>AA</th>
<th>AV</th>
<th>VV</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blocked APD and blocked VPD</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>00100</td>
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<tr>
<td>Ventricular escape after 2 blocked APDs</td>
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<tr>
<td>00200</td>
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</tr>
<tr>
<td>Low atrial ectopic with aberrant conduction after blocked VPD</td>
<td></td>
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<tr>
<td>01000</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low atrial premature</td>
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</tr>
</tbody>
</table>

0 -- abnormal
1 -- normal
2 -- long

00001
Ventricular escape after 2 blocked APDs

00011
APD with aberrant conduction after blocked APD

00012
APD with aberrant conduction after blocked APD

00020
APD with aberrant conduction

00032
APD with aberrant conduction

00050
Blocked APD and blocked VPD

00101
APD with aberrant conduction

00102
APD with aberrant conduction following blocked APDs

00110
APD with aberrant conduction

00120
APD with aberrant conduction

00121
APD with aberrant conduction

00122
APD with aberrant conduction

00201
Atrial escape and ventricular escape after blocked VPD

00202
Atrial escape and ventricular escape after blocked VPD

00210
Atrial escape with aberrant conduction after blocked VPD

00211
Atrial escape with aberrant conduction after blocked VPD

01010
Atrial escape with AV delay

01011
Atrial escape with AV delay

01012
APD with AV delay

01020
APD with AV delay or with junctional escape

01022
APD with junctional escape or with AV delay
Ladder diagrams, beat codes, and single beat diagnoses of VA sequence and blocked atrial depolarization sequence

\[
\text{CCv} = 0 \rightarrow \text{abnormal} \quad \text{VV} = 0 \rightarrow \text{short}
\]
\[
\text{CCv} = 1 \rightarrow \text{normal} \quad \text{VV} = 1 \rightarrow \text{long}
\]

VA Sequence

00 VPD without retrograde

01 Ventricular escape without retrograde

10 VPD without retrograde

11 Junctional escape without retrograde

Ladder diagrams, beat codes, and single beat diagnoses of blocked atrial depolarization sequence

\[
\text{CCA} = 0 \rightarrow \text{abnormal} \quad \text{AA} = 0 \rightarrow \text{short}
\]
\[
\text{CCA} = 1 \rightarrow \text{normal} \quad \text{AA} = 1 \rightarrow \text{normal}
\]
\[
\text{CCA} = 2 \rightarrow \text{long}
\]

00 Blocked APD

01 Blocked atrial ectopic

02 Blocked atrial escape

10 Blocked APD

11 Blocked sinus depolarization

12 Blocked sinus slowing