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.

From the Department of Electrical Engineering and Computer Science, School of Engineering, and School of Medicine, University of Michigan, Ann Arbor, the Michigan Heart and Vascular Institute, and the Cardiac Electrophysiology Laboratory, St. Joseph Mercy Hospital, Ann Arbor, Michigan.

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Reprint requests: Lorenzo DiCarlo, MD, Reichert Health Building R-3003, Catherine McAuley Health Center, P.O. Box 994, Ann Arbor, MI 48106.

The clinical interpretation of cardiac arrhythmias using surface electrocardiography requires an incorporation of the temporal order of atrial and ventricular depolarizations with an analysis of atrioventricular and ventriculoatrial relationships. Historically, the development of automated systems that utilize such methods has had limited success.[1–9]

Arrhythmia diagnosis requires the determination of individual rates and morphologies of serial atrial

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.

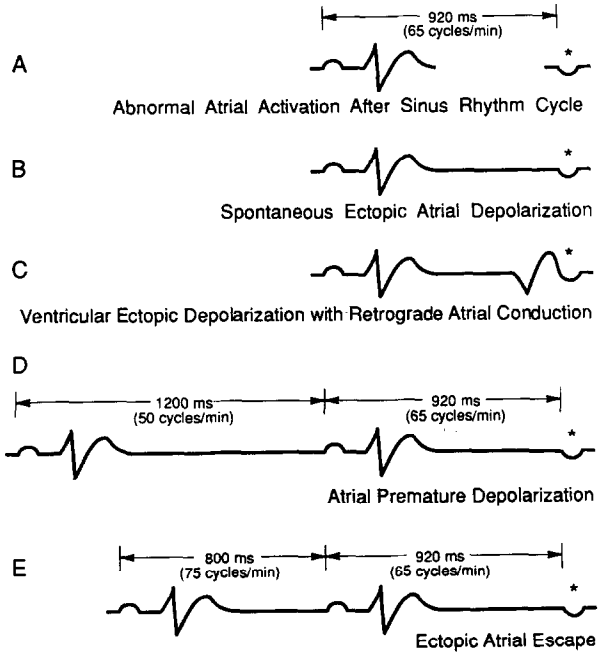


Fig. 1. Interpretation of an atrial depolarization (*) having an abnormal morphology when compared to sinus rythm (A). (B, C) Events intervening since the last sinus rhythm cycle determine whether it is an ectopic atrial depolarization that is spontaneous or due to retrograde conduction. (D, E) Events prior to the last sinus rhythm cycle determine whether the ectopic spontaneous atrial depolarization is premature or represents an escape mechanism.

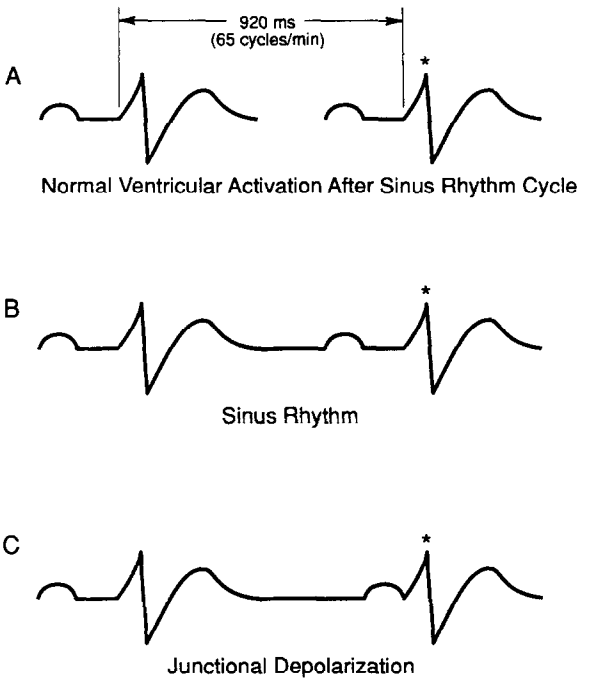


Fig. 2. Interpretation of a ventricular depolarization (*) having a normal morphology when compared to sinus rhythm (B). (B, C) Intervening events since the last sinus rhythm cycle determine whether it is spontaneous or due to anterograde atrial conduction.

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 ventricu-

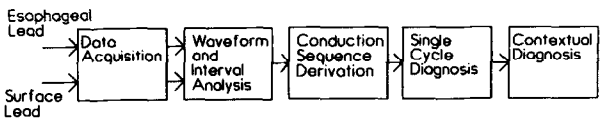


Fig. 3. Block diagram of the system consisting of five subsystems: data acquisition, waveform and interval analysis, conduction sequence derivation, single cycle diagnosis, and contextual diagnosis.

lar waveform and interval analysis; (3) derivation of order of conduction sequence; (4) derivation of a five-digit, single cardiac cycle diagnostic code determined for each cardiac cycle; and (5) integrated interpretation of sequential cardiac cycles (contextual analysis).

Data Acquisition. A two-channel ambulatory or telemetry electrocardiographic system is used for simultaneous recording of atrial electrograms from an esophageal pill electrode and ventricular electrograms from surface electrocardiogram (ECG) lead II using previously described methods.[10–13] After analog-to-digital conversion, the electrograms are analyzed.

Atrial and Ventricular Electrogram Waveform and Interval Analysis. Each cardiac cycle is analyzed for five features: (1) correlation waveform analysis of the atrial electrogram (CC_a); (2) correlation waveform analysis of the ventricular electrogram (CC_v) 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.[11,14,15] This method of analysis has been traditionally applied to surface ECGs,[14,15] and more recently to intracardiac electrograms.[16–20]

The following equation is used to calculate the correlation coefficient:

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

where

M = the number of points in the template;

T_i = the template points;

X_i = signal points to be processed; and

μ = the signal or template average.

The correlation coefficient (ρ) 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 VV intervals were set at ±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

Sequence	A		V		AV					VA	
Coding	CC_a	AA	CC_v	VV	CC_a	CC_v	AA	AV	VV	CC_v	VV
values	0	0	0	0	0	0	0	0	0	0	0
	1	1	1	1	1	1	1	1	1	1	1
		2					2	2	2		

Fig. 4. The coding method for all sequences. Correlation waveform analysis of the atrium (CC_a) and the ventricle (CC_v) can be 0 (abnormal) or 1 (normal). Consecutive atrial depolarizations (AA) and the atrioventricular interval (AV) can be 0 (short), 1 (normal), or 2 (long). Two consecutive ventricular depolarizations (VV) can be 0 (short), 1 (normal), or 2 (long) for the AV sequence; and 0 (short) or 1 (long) for the ventricular (V) and ventriculoatrial (VA) sequences.

by a ventricular depolarization, CC_v and AV and VV intervals cannot be determined. The single cardiac cycle diagnostic code contains digits for only two diagnostic features (CC_a 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 nonconducted atrial depolarization, even though all five diagnostic features can be derived from such a cardiac cycle.

If two consecutive atrial depolarizations occur and a ventricular depolarization does not precede the second atrial depolarization, determination of atrioventricular 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 preceded by an atrial depolarization, a sixth feature for the single cardiac cycle is utilized: the ventriculoatrial (VA) interval. It is measured from the ventricular depolarization to the next atrial depolarization which occurs. Ventriculoatrial conduction is defined to have occurred if the CC_a 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 consecutively 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_a of the subsequent atrial depolarization 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 construction 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 ectopic depolarization, atrial escape, sinus slowing (bradycardia depolarization), normal ventricular premature depolarization, junctional escape, ectopic ventricular premature depolarization, ventricular escape, and ventricular fusion. Each atrial depolarization is further characterized as conducted or nonconducted, conducted with AV delay (first-degree AV block), and/or conducted with normal or aberrant ventricular depolarization. Each normal or ventricular ectopic depolarization that is not preceded but followed by an atrial depolarization is further characterized as occurring with or without retrograde atrial activation. (Table 2.)

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

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

AA_1 Interval*	A_1A_2 Interval*	CC_{A1}	A_2V	A_1
Normal	Normal	—	—	Nonconducted
Normal	Short	Normal	Unchanged or Long	Conducted
		Abnormal	Short, unchanged, or long	Conducted
Normal	Long	—	—	Nonconducted
Short	Normal	—	—	Nonconducted
Short	Short	Normal	Unchanged or long	Conducted
		Abnormal	Short, unchanged, or long	Conducted
Short	Long	—	—	Nonconducted
Long	Normal	—	—	Nonconducted
Long	Short	Normal	Unchanged or long	Conducted
		Abnormal	Short, unchanged, or long	Conducted
Long	Long	—	—	Nonconducted

A = atrial depolarization with ventricular depolarization preceding A_1; A_1 = first of two consecutive premature depolarizations without an intervening ventricular depolarization; A_2 = second of the two consecutive premature depolarizations; CC_{A1} = atrial morphology of A_1 when compared to the preprocessed atrial template determined during sinus rhythm; A_1V = the measured atrioventricular interval from A_1 to the next observed ventricular depolarization. *When compared to the last AA interval that occurred during sinus rhythm.

Table 2. Table of Single Cardiac Cycle Classes

Class	Type	Characteristics
1	Normal	CC_a, CC_v, and at least two normal intervals
2	Aberrant	Sinus depolarization with aberrant conduction
3	AV delay	Sinus depolarization with AV delay
4	Blocked	Blocked sinus depolarization
5	APD	Atrial premature depolarization with or without conduction
6	JP	Junctional premature depolarization with or without retrograde
7	VPD	Ventricular premature depolarization with or without retrograde
8	SS	Sinus slowing with or without conduction
9	AE	Atrial ectopic depolarization with or without conduction
10	JE	Junctional escape with or without retrograde
11	VE	Ventricular escape with or without retrograde
12	NS	Nonspecific abnormal depolarization

CC_a = atrial electrogram morphology; CC_v = ventricular electrogram morphology.

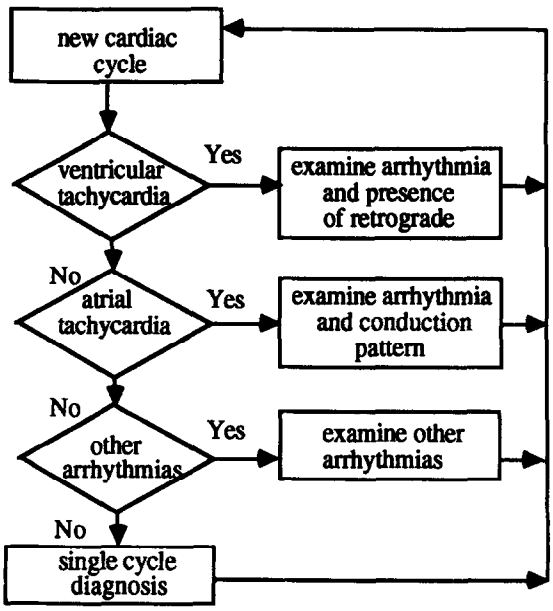


Fig. 5. Flow chart of contextual diagnosis showing the priority of arrhythmia diagnoses.

tricular trigeminy, ventricular couplet, atrial tachycardia, atrial flutter, atrial fibrillation, ventricular tachycardia, ventricular flutter, and ventricular fibrillation.

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 hierarchial 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 CC_a) 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.

Couplets. Two consecutive atrial premature depolarizations or two atrial premature depolarizations with an intervening ventricular depolarization without 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

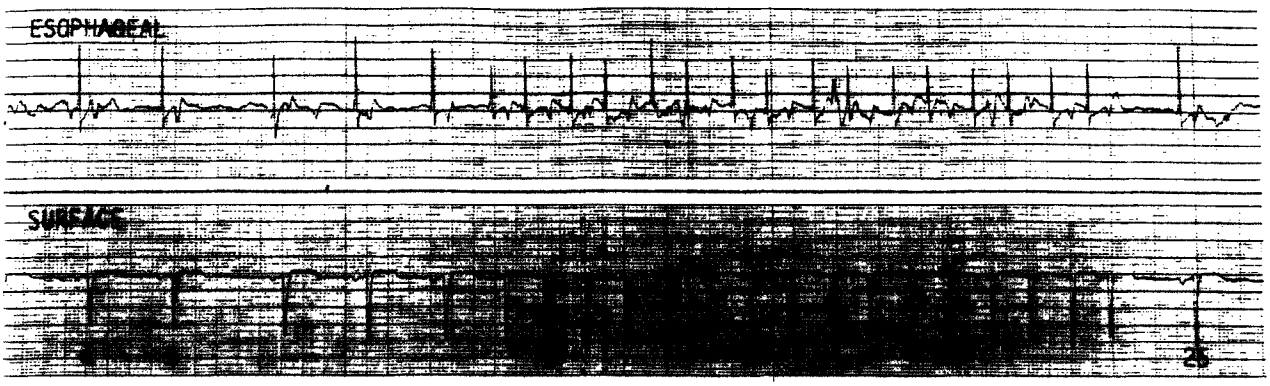
Data Acquisition

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.[10–13] 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 artifact 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

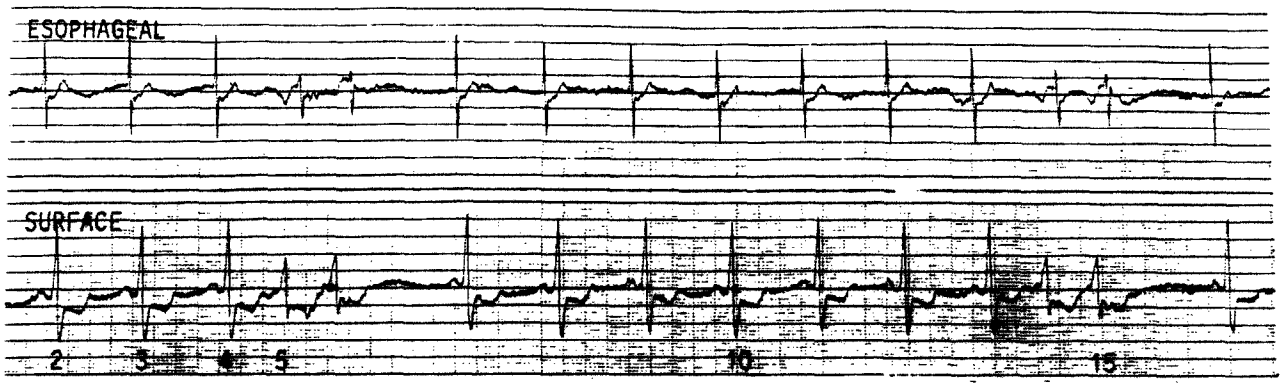


Cycle	Seq	Code	Cycle Diagnosis	Contextual Diagnosis
4	AV	11111	Normal	NSR
5	AV	11111	Normal	NSR
6	AV	11212	Sinus slowing with cond.	Sinus slowing with cond.
7	AV	11111	Normal	
8	AV	11111	Normal	
9	AV	11010	APD with cond	APD with cond.
10	AV	11010	APD with cond	1:1 Atrial couplet
11	AV	11010	APD with cond	3 APDs with 1:1 cond.
12	AV	11010	APD with cond	4 APDs with 1:1 cond.
13	AV	01010	APD with cond	5 APDs with 1:1 cond.
14	AV	11010	APD with cond	1:1 SVT
15	AV	11010	APD with cond	1:1 SVT
16	AV	11010	APD with cond	1:1 SVT
17	AV	11010	APD with cond	1:1 SVT
18	AV	11010	APD with cond	1:1 SVT
19	AV	11010	APD with cond	1:1 SVT
20	AV	11010	APD with cond	1:1 SVT
21	AV	11010	APD with cond	1:1 SVT
22	AV	11010	APD with cond	1:1 SVT
23	AV	11010	APD with cond	1:1 SVT
24	AV	11010	APD with cond	1:1 SVT
25	AV	11111	Normal	

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



Cycle	Seq	Code	Cycle Diagnosis	Contextual Diagnosis
2	AV	11111	Normal	
3	AV	11111	Normal	
4	AV	11111	Normal	NSR
5	VA	00	VPD with retrograde	VPD with retrograde
6	VA	00	VPD with retrograde	V couplet with 1:1 retro.
7	AV	11212	Sinus slowing with cond.	Sinus slowing with cond.
8	AV	11111	Normal	
9	AV	11111	Normal	
10	AV	11111	Normal	NSR
11	AV	11111	Normal	NSR
12	AV	11111	Normal	NSR
13	AV	11111	Normal	NSR
14	VA	00	VPD with retrograde	VPD with retrograde
15	VA	00	VPD with retrograde	V couplet with 1:1 retro.
16	AV	11212	Sinus slowing with cond.	Sinus slowing with cond.

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.

diagnosis of ventricular couplet with 1:1 retrograde activation.

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).

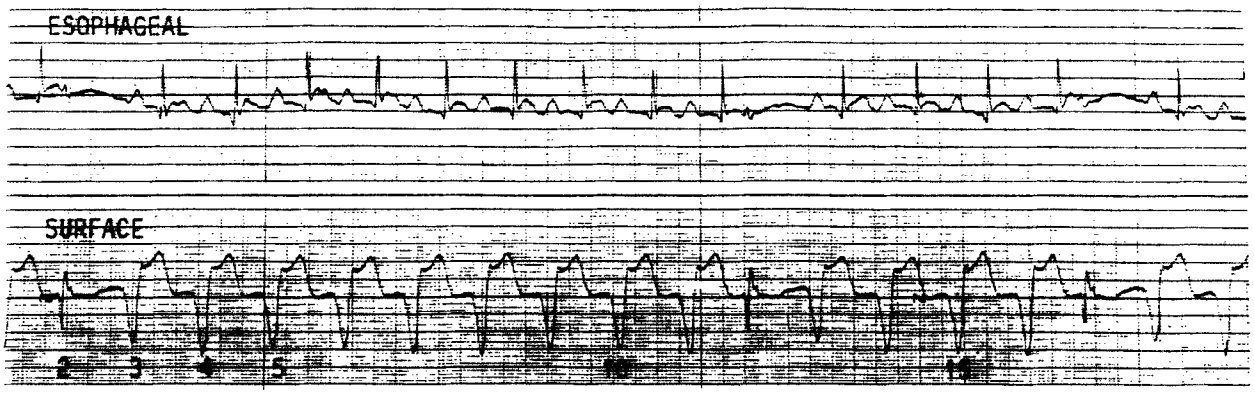
The following types of cardiac arrhythmias were identified: normal sinus rhythm, sinus rhythm with aberrant ventricular activation; sinus rhythm without ventricular activation (blocked sinus cycle); atrial premature depolarizations with normal or aberrant ventricular activation, atrial premature depolarizations 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.[1–9] 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-



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

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.[10–13] 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.[21] Further improvements and implementation of analogous models of arrhythmia analysis into devices such as implantible antitachycardia 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.[22–24]

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.[25,26] 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.

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References

1. Pipberger HV, Fries ED, Taback L et al: Preparation of electrocardiographic data for analysis by digital electronic computer. Circulation 21:413, 1960
2. Staples IF, Gustafson JE, Balm GJ et al: Computer interpretation of electrocardiograms. Am Heart J 72: 351, 1966
3. Bonner RE, Schwetman HD: Computer diagnosis of the electrocardiogram II. Computer program for arrhythmia diagnosis. Comput Biomed Res 1:366, 1968
4. Bonner RE, Crevasse L, Ferrer MI et al: A new computer program for analysis of scalar electrocardiograms. Comput Biomed Res 5:629, 1972
5. Pryor TA, Lindsay AE, England RW: Computer analysis of serial electrocardiograms. Comput Biomed Res 5:709, 1972
6. Pipberger HV, McCaughan D, Littman D et al: Clinical application of a second generation electrocardiographic computer program. Am J Cardiol 35:597, 1975
7. Geddes JS, Warner HR: A PVC detection program. Comput Biomed Res 4:493, 1971
8. Vetter NJ, Julian DG: Comparison of arrhythmia computer and conventional monitoring in coronary-care unit. Lancet 1:1151, 1975
9. Jenkins JM: Automated electrocardiography and arrhythmia monitoring. Prog Cardiovasc Dis XXV:367, 1983

10. Arzbaecher R: A pill electrode for the study of cardiac dysrhythmia. Medical Instrumentation, 12:277, 1978
11. Jenkins J, Wu D, Arzbaecher R: Computer diagnosis of supraventricular and ventricular arrhythmias. Circulation 60:977, 1979
12. Arzbaecher R, Jenkins J, Collins S et al: Atrial electrical activity: the view from the esophagus. p. 314. IEEE/EMBS Conference (Frontiers of Engineering in Health Care), 1979
13. Lin D, Jenkins JM, DiCarlo LA: Analysis of P-wave changes on the esophageal electrogram: a two-lead arrhythmia analysis system using morphology and timing of both atrial and ventricular activation. Computers in cardiology. IEEE Press, New York, 1987
14. Feldman CL, Amazeen PG, Klein MD et al: Computer detection of ventricular ectopic beats. Comput Biomed Res 4:666, 1971
15. Arzbaecher R, Biancalana P, Stibolt T et al: Computer technique for detection of cardiac dysrhythmias. Journal of the Association for the Advancement of Medical Instrumentation 5:104, 197 (Abstr)
16. Lin D, DiCarlo LA, Jenkins JM: Identification of ventricular tachycardia using intracavitary ventricular electrograms: Analysis of time and frequency domain patterns. PACE 11:1592, 1988
17. Throne R, Jenkins J, Winston S et al: Discrimination of retrograde from anterograde atrial actrivation using intracardiac electrogram waveform analysis. PACE 12: 1622, 1989
18. Throne R, DiCarlo LA, Jenkins J et al: Paroxysmal bundle branch block of supraventricular origin: a possible source of misdiagnosis in detecting ventricular tachycardia using time domain analyses of intraventricular electrograms. PACE 13:453, 1990
19. Finelli CJ, DiCarlo LA, Jenkins JM et al: Effects of heart rate and sympathetic tone on intraventricular electrogram morphology. Am J Cardiol 68:1321, 1991
20. DiCarlo LA, Jenkins JM, Winston SA, Kriegler C: Differentiation of ventricular tachycardia from ventricular fibrillation using intraventricular electrogram morphology. Am J Cardiol 70:820, 1992
21. Arzbaecher R, Collins S, Jenkins J et al: Feasibility of long-term esophageal electrocardiography in the study of transient arrhythmias. Biomed Sci Instrum 14:1, 1978
22. Manz M, Gerckens U, Luderitz B: Erroneous discharge from an implanted automatic cardioverter/defibrillator during supraventricular tachyarrhythmia-induced ventricular fibrillation. Am J Cardiol 7:343, 1986
23. Platia EV, Griffith LSC, Reid PR et al: Complications with the automatic implantable cardioverter defibrillator. J Am Col Card 2:200, 1986 (Abstr)
24. Steinberg JS, Sugalski JS, Haratonic K: Cardiac rhythm precipitating automatic-implantable cardioverter defibrillator discharge in outpatients. Am J Cardiol 67:95, 1991
25. DiCarlo LA, Throne RD, Jenkins JM: A time-domain analysis of intracardiac analysis electrograms for arrhythmia detection. PACE 14:329, 1991
26. Throne RD, Jenkins JM, DiCarlo LA: A comparison of four new time-domain techniques for discriminating ventricular tachycardia from sinus rhythm using ventricular waveform morphology. IEEE Trans Biomed Eng 38:561, 1991

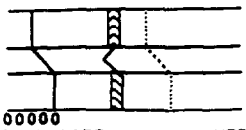
Appendix

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

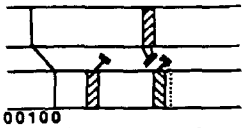
Beat Code Pattern: | CCa | CCv | AA | AV | VV |

CCa, CCv = 0 -- abnormal, 1 -- normal

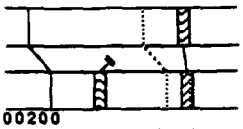
AA, AV, VV = 0 -- short, 1 -- normal, 2 -- long



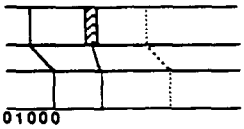
00000
Blocked APD and blocked VPD



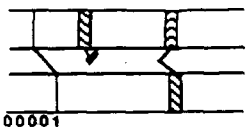
00100
Ventricular escape after 2 blocked APDs



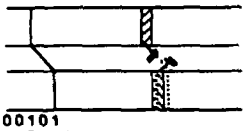
00200
Low atrial ectopic with aberrant conduction after blocked VPD



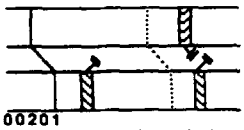
01000
Low atrial premature



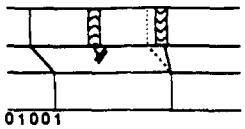
00001
Ventricular escape after 2 blocked APDs



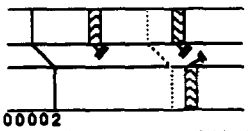
00101
APD with aberrant conduction



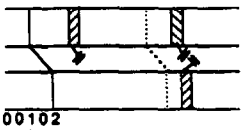
00201
Atrial escape and ventricular escape after blocked VPD



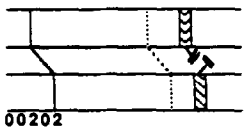
01001
Junctional or low atrial premature after blocked APD



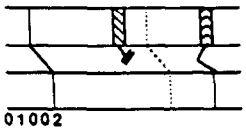
00002
Ventricular escape after 2 blocked APDs



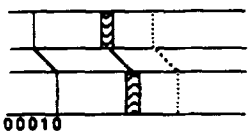
00102
APD with aberrant conduction after blocked APD



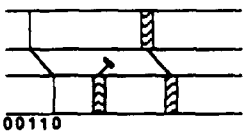
00202
Atrial escape and ventricular escape



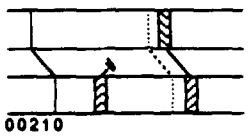
01002
Junctional escape with retrograde after blocked APD



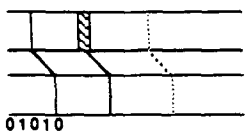
00010
APD with aberrant conduction



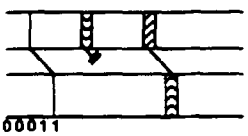
00110
APD with aberrant conduction



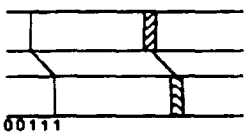
00210
Atrial escape with aberrant conduction after blocked VPD



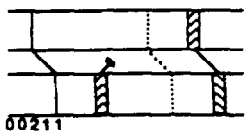
01010
APD with conduction



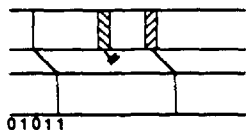
00011
APD with aberrant conduction after blocked APD



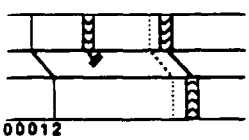
00111
VPD with blocked atrial ectopic after blocked VPD



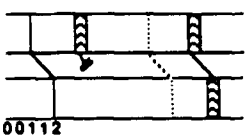
00211
Atrial escape with aberrant conduction after blocked VPD



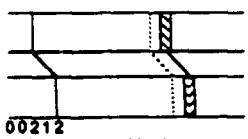
01011
APD with conduction after blocked APD



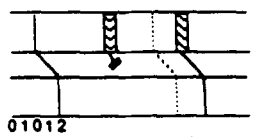
00012
APD with aberrant conduction after blocked APD



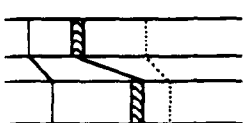
00112
Ventricular escape following blocked APDs



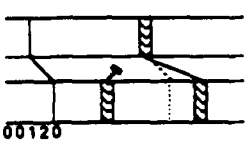
00212
Atrial escape with aberrant conduction



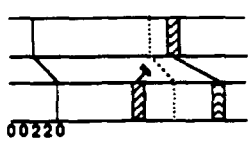
01012
APD with conduction after blocked APD



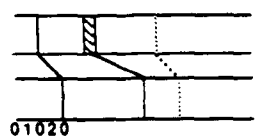
00020
APD with aberrant conduction



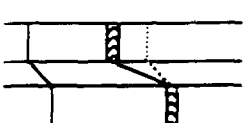
00120
Atrial ectopic with aberrant conduction



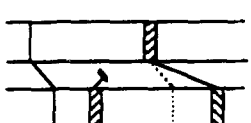
00220
Atrial escape with aberrant conduction after blocked VPD



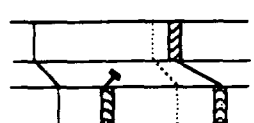
01020
APD with AV delay



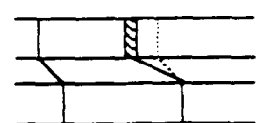
00021
APD with aberrant conduction



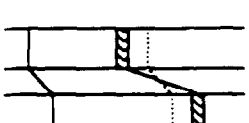
00121
Atrial ectopic with aberrant conduction after blocked VPD



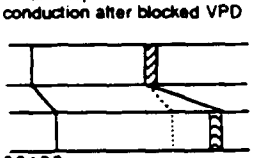
00221
Atrial escape with aberrant conduction after blocked VPD



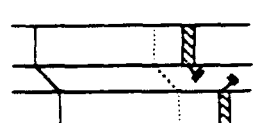
01021
APD with AV delay or with junctional escape



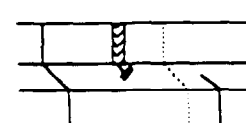
00022
APD with aberrant conduction



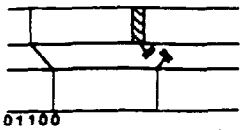
00122
Atrial ectopic with aberrant conduction



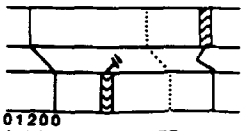
00222
Atrial escape and ventricular escape



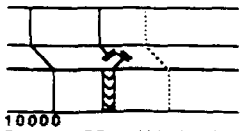
01022
APD with junctional escape or with AV delay



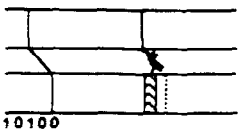
01100
Blocked premature ventricular depolarization with blocked APD



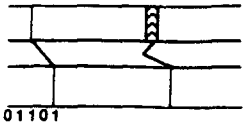
01200
Atrial ectopic with VPD after blocked VPD



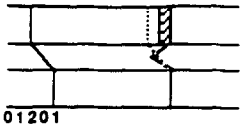
10000
Blocked APD and blocked VPD



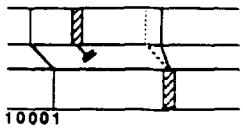
10100
VPD with blocked sinus depolarization



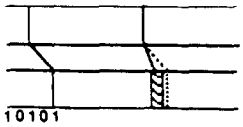
01101
Lower atrial ectopic with normal conduction



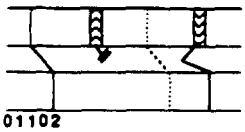
01201
Junctional escape with retrograde



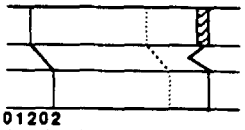
10001
APD with aberrant conduction ater blocked APD



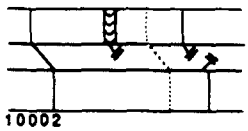
10101
Sinus depolarization with ventricular fusion



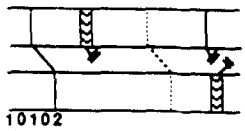
01102
Junctional escape with retrograde after blocked APD



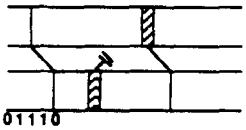
01202
Junctional escape with retrograde



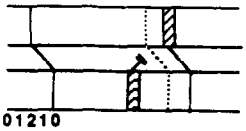
10002
Ventricular escape with blocked APDs



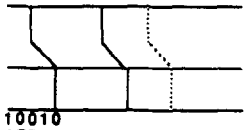
10102
Ventricular escape after blocked APDs



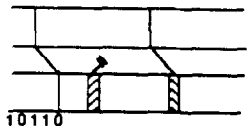
01110
Atrial ectopic depolarization after blocked VPD



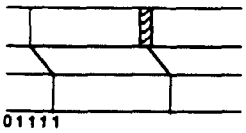
01210
Atrial escape with normal conduction after blocked VPD



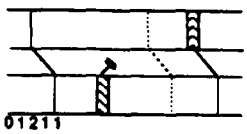
10010
APD with aberrant conduction



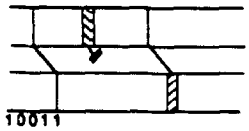
10110
Sinus depolarization with aberrant conduction after blocked VPD



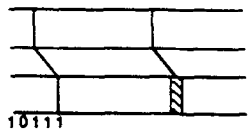
01111
Atrial ectopic depolarization with conduction



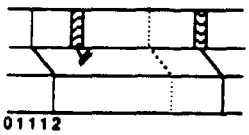
01211
Atrial escape with normal conduction after blocked VPD



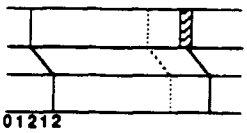
10011
APD with aberrant conduction after blocked APD



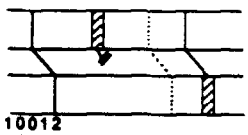
10111
Sinus depolarization with aberrant conduction



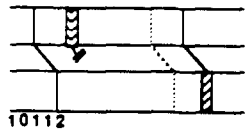
01112
Atrial ectopic depolarization with conduction after blocked APD



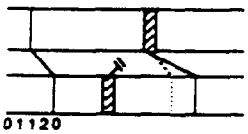
01212
Atrial escape with conduction



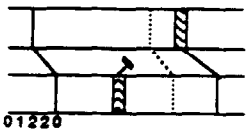
10012
APD with aberrant conduction after blocked APD



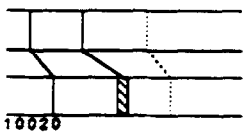
10112
Sinus depolarization with aberrant conduction after blocked APD



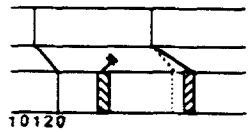
01120
Atrial ectopic depolarization with conduction after blocked VPD



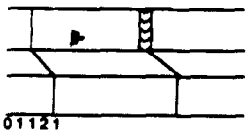
01220
Atrial escape with AV delay after blocked VPD



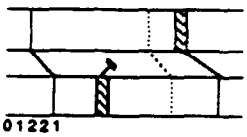
10020
APD with AV delay and aberrant conduction



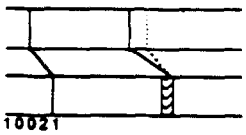
10120
Sinus depolarization with AV delay and aberrant conduction after blocked VPD



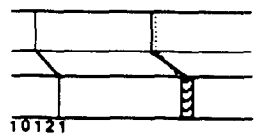
01121
Atrial ectopic depolarization with AV delay



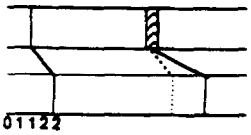
01221
Atrial escape with AV delay after blocked VPD



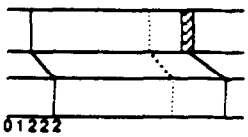
10021
APD with AV delay and aberrant conduction



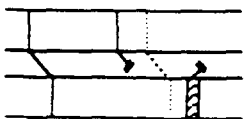
10121
Sinus depolarization with AV delay and aberrant conduction



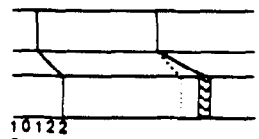
01122
Atrial ectopic depolarization with AV delay



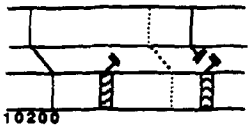
01222
Atrial escape with AV delay



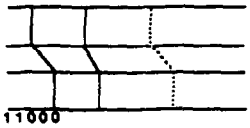
10022
Ventricular escape after blocked APD



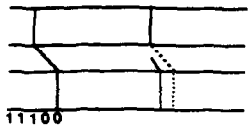
10122
Sinus depolarization with AV delay and aberrant conduction



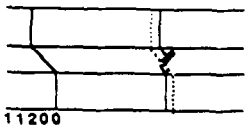
10200
VPD and blocked atrial escape after blocked VPD



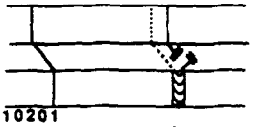
11000
APD with fast conduction



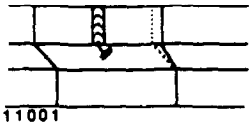
11100
Ventricular premature depolarization



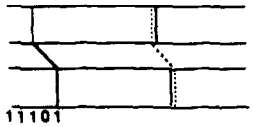
11200
VPD with blocked atrial escape



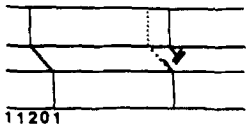
10201
Sinus slowing with VPD without retrograde



11001
APD with fast conduction after blocked APD

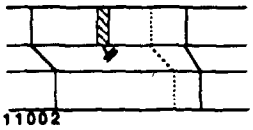


11101
Sinus beat with block and junctional escape or supernormal conduction

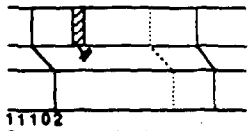


11201
Junctional escape and sinus bradycardia

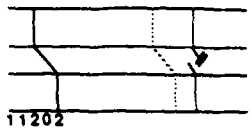
10202
Ventricular escape and sinus slowing with block



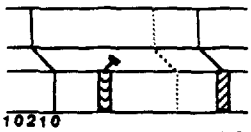
11002
APD with fast conduction after blocked APD



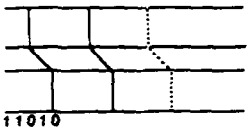
11102
Sinus depolarization with accelerated conduction after blocked APD



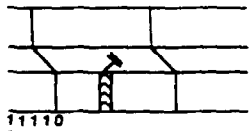
11202
Sinus slowing with junctional escape



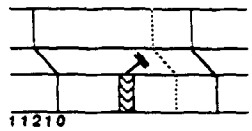
10210
Blocked sinus slowing and VPDs



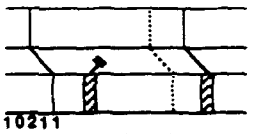
11010
APD with conduction



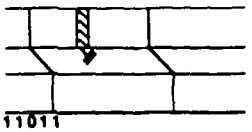
11110
Sinus depolarization with normal conduction after blocked VPD



11210
Sinus slowing with conduction after blocked VPD

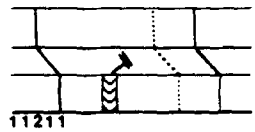


10211
Aberrantly conducted sinus slowing after blocked VPD

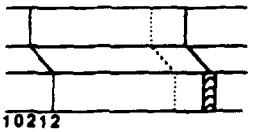


11011
APD with conduction after blocked APD

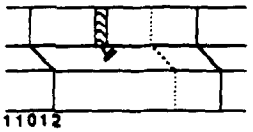
11111
Sinus depolarization with normal conduction



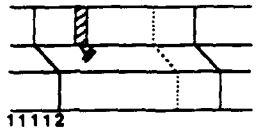
11211
Sinus slowing with conduction after blocked VPD



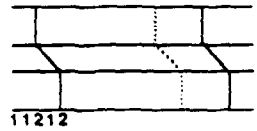
10212
Sinus slowing with aberrant conduction



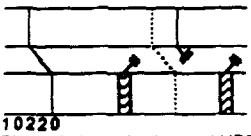
11012
APD with conduction after blocked APD



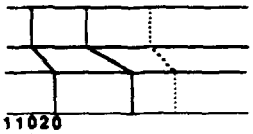
11112
Sinus depolarization with normal conduction after blocked APD



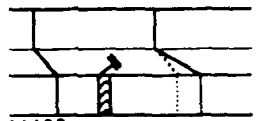
11212
Sinus slowing with conduction



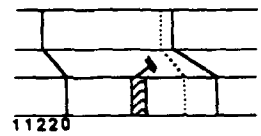
10220
Blocked sinus slowing and VPDs



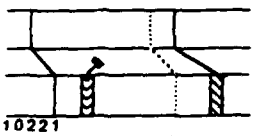
11020
APD with AV delay



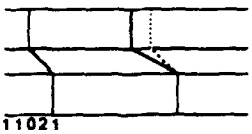
11120
Sinus depolarization with AV delay after blocked VPD



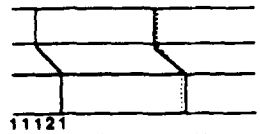
11220
Sinus slowing with AV delay after blocked VPD



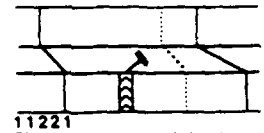
10221
Sinus slowing with AV delay and aberrant conduction after blocked VPD



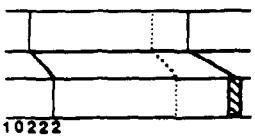
11021
APD with AV delay



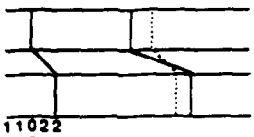
11121
Sinus depolarization with AV delay



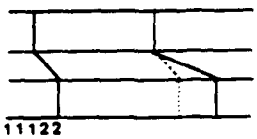
11221
Sinus slowing with AV delay after blocked VPD



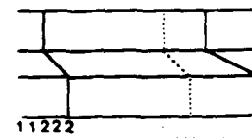
10222
Sinus slowing with AV delay and aberrant conduction



11022
APD with AV delay

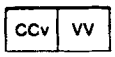


11122
Sinus depolarization with AV delay



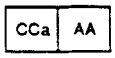
11222
Sinus slowing with AV delay

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



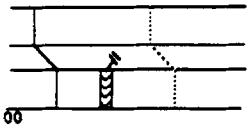
CCv = 0 -- abnormal, 1 -- normal VV = 0 -- short, 1 -- long

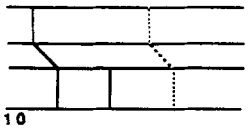
Ladder diagrams, beat codes, and single beat diagnoses of blocked atrial depolarization sequence

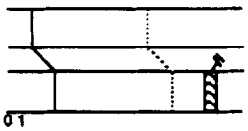


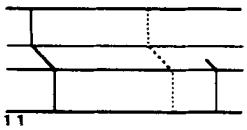
CCa = 0 -- abnormal, 1 -- normal AA = 0 -- short, 1 -- normal, 2 -- long

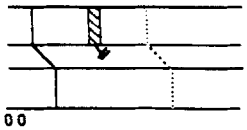
V Sequence

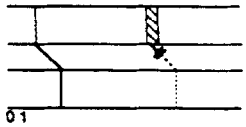

00
VPD without retrograde

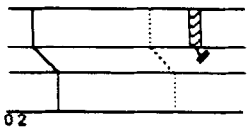

10
VPD without retrograde

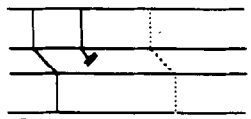

01
Ventricular escape without retrograde


11
Junctional escape without retrograde

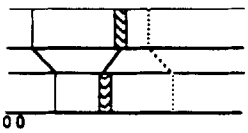

00
Blocked APD

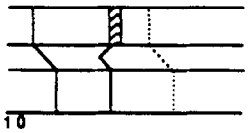

01
Blocked atrial ectopic

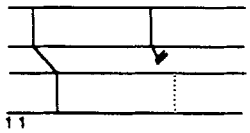

02
Blocked atrial escape

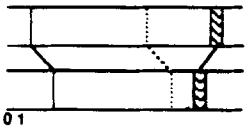

10
Blocked APD

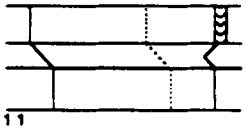
VA Sequence

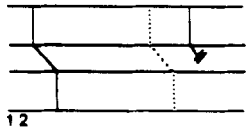

00
VPD with retrograde


10
Premature ventricular depolarization


11
Blocked sinus depolarization


01
Ventricular escape with retrograde


11
Junctional escape with retrograde


12
Blocked sinus slowing