ARRHYTHMIA DIAGNOSIS USING MORPHOLOGY AND TIMING FROM ATRIAL AND VENTRICULAR LEADS

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Abstract

Reliable computer arrhythmia diagnosis is mostly restricted to ventricular arrhythmias because information about atrial activation cannot be reliably obtained from surface lead electrocardiograms (ECGs) [1,2,3]. A two channel computer arrhythmia detection system has been designed and successfully tested on a data base of a simultaneous esophageal electrograms and surface lead ECGs. The system has the unique feature of examining the morphology of atrial depolarizations on the esophageal electrogram as well as QRS morphology on the surface ECG. This allows recognition of both ectopic and retrograde atrial activation. The system measures the interval between two consecutive atrial depolarizations (AA interval), the interval between two consecutive ventricular depolarizations (VV interval), and the interval between the atrial and ventricular depolarizations (AV interval).

The system has been tested on twenty-nine passages from twenty-one patients. Test results yielded 99.2% accuracy for single beat diagnosis and 99.5% accuracy for underlying arrhythmia diagnosis. There were no false positives or false negatives.

Introduction

A new computer arrhythmia detection algorithm has been designed and tested. The system examines both timing and morphology of atrial activation on an esophageal lead and ventricular activation on a surface lead, allowing it to detect retrograde atrial activation, ectopic atrial activation, and other arrhythmias which cannot be detected by other systems.

In designing this system, the application of correlation waveform analysis [4,5] is used for the first time on esophageal electrograms [6,7] for detection of abnormal activation. The conduction sequence between a patient's atria and ventricles can now be examined and derived using *timing* and *morphology* of the atrial and ventricular signals.

This system differs from earlier arrhythmia monitors using an esophageal lead [8,9] in that it examines normality of the atrial activation and conduction sequences which were not examined in the old system. Atrial activation and conduction are often vital clues to the underlying rhythm.

The conduction sequence of atrial and ventricular depolarization is no longer assumed to proceed only from the atria to the ventricles. The actual sequence is determined by the timing and morphological information of the patient's atrial and ventricular activation. Four conduction sequences are considered: atria to ventricles, blocked atrial activation, retrograde activation (ventricles to atria), and blocked ventricular activation.

Arrhythmias that can be diagnosed are: sinus beats with aberrant conduction; sinus beats with atrioventricular (AV) delay; atrial premature depolarizations (APDs) with or without conduction; ventricular premature depolarizations (VPDs) with or without retrograde activation; atrial ectopic beats with normal, abnormal, or no conduction; atrial bigeminy; atrial trigeminy; atrial couplets; first degree AV block; second degree AV block; ventricular bigeminy; ventricular trigeminy; ventricular couplets; supraventricular tachycardia (SVT) and atrial flutter with 1:1 or multi-to-one conduction; atrial fibrillation; bradycardia; ventricular tachycardia (VT) and ventricular flutter (VFlut) without retrograde; VT and VFlut with 1:1 or multi-to-one retrograde; and ventricular fibrillation.

Methods and Materials

The structural design is shown in figure 1 which is the block diagram of the system. The system consists of four major subsystems: data acquisition, waveform and interval analysis, single beat diagnosis, and contextual diagnosis.

Tape recorded data, acquired from patients in the coronary intensive care unit, are used for processing. The

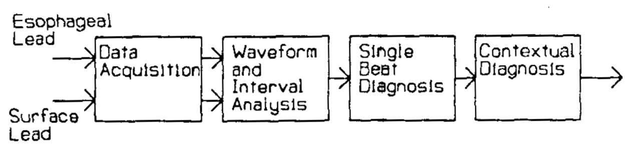


Figure 1. *Block diagram of the two-channel arrhythmia analysis system.*

esophageal/surface data base includes patient data exhibiting the following rhythms: normal sinus rhythm (NSR); sinus beats with aberrant conduction; sinus beats without conduction (blocked sinus beats); APDs with normal, aberrant, or no conduction; junctional premature depolarizations with or without retrograde atrial activation; VPDs with or without retrograde atrial activation; sinus slowing with or without conduction; junctional escape with or without retrograde atrial activation; ventricular escape with or without retrograde atrial activation; atrial bigeminy; atrial trigeminy; atrial couplets; ventricular bigeminy; ventricular trigeminy; ventricular couplets; SVT; atrial flutter; VT; first degree AV conduction block; and second degree AV conduction block.

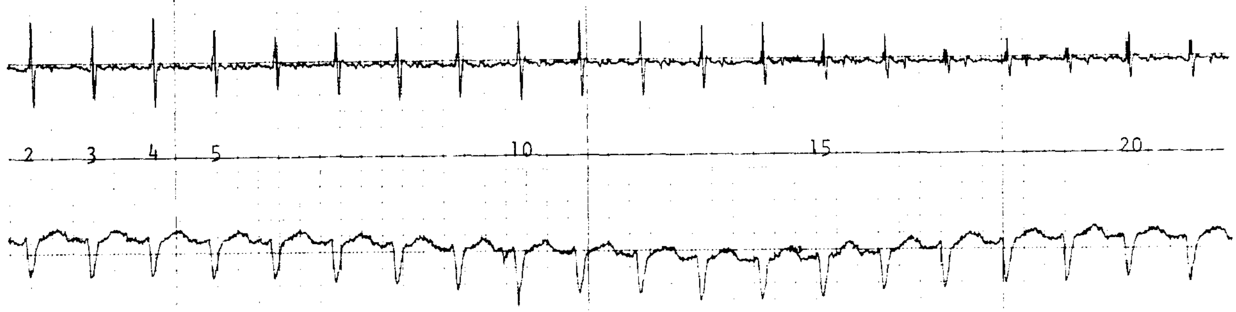
The esophageal electrograms were recorded from a bipolar pill-electrode [10] swallowed by the patient and located posterior to the left atrium. A surface lead ECG was recorded concurrently. Computer data acquisition was done using two-channel concurrent analog-to-digital (A/D) conversion with a sampling rate of 1000 Hz on each channel. The software is implemented on an IBM PC/AT compatible computer. Analog to digital (A/D) and digital to analog (D/A) conversion is done by a Tecmar Lab Master subsystem.

A software trigger (digital differentiator) is used for waveform detection. Correlation waveform analysis is performed on the current atrial and ventricular deflections. Interval analysis is performed by computing the AA interval, the AV interval, and the VV interval, and comparing these with the normal ranges. The combined waveform and interval analysis is a feature extraction procedure which generates five features for further analysis [7].

Normal ranges of the AA and VV intervals are determined by the AA and VV intervals of normal templates with a ±15% tolerance. The lower limit of the normal AV range is determined to be the smaller of the normal AV interval minus a 20% tolerance and 100 ms, i.e. $AV_{low} = \min(100, 0.8 \times AV_{normal})$. The upper limit of the normal AV range is determined to be the larger of the normal AV interval plus a 20% tolerance and 220 ms, i.e. $AV_{up} = \max(220, 1.2 \times AV_{normal})$.

Waveform analysis is performed by correlating the atrial and ventricular depolarizations with atrial and ventricular templates recorded during normal sinus rhythm. The correlation waveform analysis method has been shown to yield excellent performance in distinguishing abnormal from normal depolarizations [7].

Interval analysis is performed by comparing the current AA, AV, and VV intervals with normal AA, AV, and VV intervals to see whether they fall within the normal range.



BEAT	Seq	Code	Beat Diagnosis	Contextual Diagnosis
2	VA	00	VPD with retrograde	VPD with retrograde
3	VA	00	VPD with retrograde	V couplet with 1:1 retro.
4	VA	00	VPD with retrograde	3 VPDs with 1:1 retro.
5	VA	00	VPD with retrograde	4 VPDs with 1:1 retro.
6	VA	00	VPD with retrograde	5 VPDs with 1:1 retro.
7	VA	00	VPD with retrograde	VT 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	VA	00	VPD with retrograde	VT with 1:1 retro.
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.

Figure 2. *An example of ventricular tachycardia with 1:1 retrograde atrial activation. The esophageal lead (atrial) is on the top trace, and the surface lead (ventricular) is on the bottom. All beats after beat 7 were diagnosed identically.*

After the comparison, the intervals are classified into three categories: *short, normal,* and *long.*

Since arrhythmias can alter these two morphologies and three intervals, a five-feature coding system is employed to characterize each beat. The five features consist of a morphology index for atrial depolarization (CC_a), for ventricular depolarization (CC_v), and the three associated intervals, AA, VV, and AV.

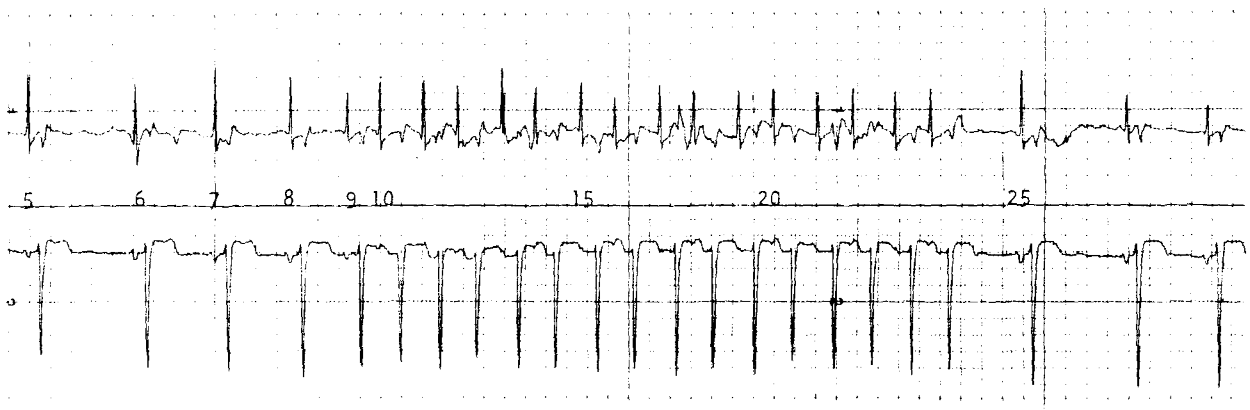
The single beat diagnostic scheme detects whether the current beat is normal or abnormal based on waveform and interval analysis. The diagnostic method includes three steps: 1) assessing the conduction sequence, 2) creating the beat code, and 3) making the single beat diagnosis on each beat [7,8,11].

The contextual diagnosis examines the eight most current beats and diagnoses the underlying arrhythmias. For the atrial arrhythmias, it can precisely determine whether they are conducted and what conduction pattern exists (1:1, 2:1, 3:1, etc.). For ventricular arrhythmias, the system can determine whether they induce retrograde activation or not and what the retrograde pattern is.

Results

A total of twenty-nine passages containing twenty-five distinct arrhythmias were tested. Results demonstrated the effectiveness of the new computer diagnosis system to accurately diagnose these arrhythmias. There was 99.2% accuracy for single beat diagnosis with neither false positives nor false negatives. All errors were a misclassification of abnormals into the wrong abnormal class. The contextual diagnosis produced 99.5% accuracy in recognizing the underlying arrhythmias.

Examples of computer results from 2 of 29 passages are presented. A typical portion of each processed passage and its associated computer diagnosis are shown in figures 2 and 3. Each shows the two-channel tracing of this portion and its computer diagnostic printout. The esophageal electrogram is shown on the upper channel and a simultaneous surface ECG is seen on the lower channel. The sequence number of conduction activation is shown between the two channels. The computer output reports the beat number (first column), followed by the type of



BEAT	Seq	Code	Beat Diagnosis	Contextual Diagnosis
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	

Figure 3. *An example of 1:1 SVT with both onset and conversion. The esophageal lead (atrial) is on the top trace, and the surface lead (ventricular) is on the bottom.*

conduction sequence (second column), the beat code, the single beat diagnosis, and the contextual diagnosis. The first sequence number of conduction reported on the computer output is associated with the left-most beat on the tracing.

Figure 2 shows the test results for ventricular tachycardia with 1:1 retrograde atrial activation. The atrial depolarizations are abnormal and the AA intervals are directly related to the VV intervals which are short. The atrial depolarizations are retrograde activation caused by the ventricular depolarizations. The ventricular depolarizations are abnormal and occur at a rate of about 100 beats per minute. It is slow VT.

All of the single beat diagnoses are reported as VPDs with retrograde. Initially, at beat 3, the system diagnoses ventricular couplet with 1:1 retrograde as a contextual diagnosis. After the sixth consecutive VPD appears, the system diagnoses the rhythm as VT with 1:1 retrograde. For the remainder of consecutive VPDs the system continues the same diagnosis.

Figure 3 shows a supraventricular tachycardia with 1:1 conduction with both the onset of the tachycardia and spontaneous conversion. All ventricular depolarizations are normal which indicates that the conduction is transmitted through the normal pathway.

For beats 2 to 5, the system diagnoses them singly as normal. The contextual diagnosis is normal sinus rhythm at beats 4 and 5. This normal sinus rhythm is interrupted by a sinus slowing beat (beat 6). The next two beats (7 and 8) are diagnosed as normal but no contextual diagnosis is given because they do not meet the 3-beat criteria for a NSR diagnosis. At the beginning of the tachycardia (beats 9 and 10), the system delivers a contextual diagnosis of *atrial couplet with 1:1 conduction.* For the next three beats, the diagnosis is 3, 4, and 5 *consecutive APDs with 1:1 conduction.* After six consecutive conducted APDs appear, the rhythm diagnosis is 1:1 SVT which continues until conversion occurs.

At beat 25, the system makes a single beat diagnosis of *normal* indicating the interruption of SVT. The system can detect both onset of SVT and conversion. The system also has the ability of detecting onset and offset of atrial flutter with or without conduction, atrial fibrillation, ventricular tachycardia with or without retrograde, ventricular flutter with or without retrograde, and ventricular fibrillation.

The system successfully distinguishes 1:1 SVT from VT with 1:1 retrograde. This distinction is extremely important in automated arrhythmia analysis since the two arrhythmias should be treated with different therapy.

The distinction of 1:1 SVT from VT with 1:1 retrograde is not possible for systems with conventional leads. In our system, the esophageal lead makes it possible to detect abnormal atrial activation, which provides a reliable feature for distinguishing the two rhythms.

References

[1] Rey W, Laird JD, Hugenholtz PG: P-wave detection by digital computer. *Computers and Biomedical Research* **4**:509, 1971.

[2] Jenkins J, Swiryn S: Accuracy of rhythm diagnosis: Reasons for the errors. *Computerized Interpretation of the Electrocardiogram VII* pp. 35–44, 1983.

[3] Zhu Y-S and Thakor NV: P-wave detection by an adaptive QRS-T cancellation technique. *Computers in Cardiology*, pp. 249–252, IEEE Press, New York, 1986.

[4] Arzbaecher R, Biancalana P, Stibolt T, Masek G, Dean R: Computer technique for detection of cardiac arrhythmias. *Journal of the Association for the Advancement of Medical Instrumentation* **5**:104, 1971.

[5] Feldman CL, Amazeen PG, Klein MD, et al: Computer detection of ventricular ectopic beats. *Computers and Biomedical Research* **4**:666–674, 1971.

[6] Lin D, Jenkins JM, Wiesmeyer MD, Jadvar H, DiCarlo LA: Analysis of time and frequency domain patterns of endocardial electrograms to distinguish ventricular tachycardia from sinus rhythm. *Computers in Cardiology*, pp. 171–174, IEEE Press, New York, 1986.

[7] Lin D, Jenkins JM, DiCarlo LA: Analysis of P-wave changes on the electrogram: A two-lead arrhythmia analysis system using morphology and timing of both atrial and ventricular activation. *Computers in Cardiology*, 83–86, IEEE Press, New York, 1987.

[8] Jenkins JM, Wu D, Arzbaecher R: Computer diagnosis of supraventricular and ventricular arrhythmias. *Circulation* **60** No. 5, November 1979.

[9] Jenkins JM, MacDonald RS: Arrhythmia analysis from atrial and ventricular leads Holter recorded during coronary care monitoring. *3rd International Symposium on Holter Monitoring*, Vienna, April 1988.

[10] Arzbaecher R: A pill-electrode for the study of cardiac arrhythmia. *Medical Instrumentation* **12**:277, 1978.

[11] Lin D: Computer recognition of complex cardiac arrhythmias by waveform and interval analysis of atrial and ventricular leads. Doctoral thesis, University of Michigan, 1988.

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