Automated Analysis of Spontaneously Occurring Arrhythmias by Implantable Devices

Limitations of Using Rate and Timing Features Alone

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Abstract: Real-time automated systems for arrhythmia analysis by implantable antitachycardia devices have been designed to incorporate two-channel rate criteria with intracavitary atrial and ventricular electrogram morphology. Because the power requirements for morphologic analysis substantially limit antitachycardia device longevity, the authors sought to develop an alternative algorithm that relies solely on rate and three newly developed timing features: onset (median ventricular rate filtering to detect abrupt onset), loss of atrioventricular (AV) sequency (premature ventricular depolarizations), and regularity-multiplicity (minimal median cycle length variation concurrent with integral [n:1] AV periodicity). This system was assessed using spontaneously occurring arrhythmias in patients undergoing electrophysiology studies. Electrograms were captured on FM tape (1–500 Hz) using bipolar catheters in the high right atrium and the left ventricular apex. In 11 patients, 25 distinct arrhythmias were analyzed, which included sinus tachycardia (ST) (1 passage), supraventricular tachycardia (SVT) (6 passages), ventricular tachycardia (VT) with concurrent sinus rhythm (16 passages), VT with concurrent atrial flutter (VT/AFl) (2 passages), and ventricular fibrillation (VF) (1 passage). The algorithm correctly diagnosed 1 of 1 episode of ST, 4 of 6 episodes of SVT, 15 of 16 episodes of VT with concurrent sinus rhythm, 0 of 2 episodes of VT/AFl, and 1 of 1 episode of VF. Ventricular tachycardia episodes were misdiagnosed as SVT because of absence of loss of AV sequency in VT onset (1 episode), presence of multiplicity between VT and AFl (1 episode), and absence of VT regularity during AFl (1 episode). Algorithms that are confined to rate and timing features alone are capable of correctly diagnosing most spontaneously occurring tachyarrhythmias. Misdiagnosis of VT may occur, however, despite the integration of multiple timing features. **Key words:** antitachycardia devices, ventricular tachycardia, atrioventricular sequency, electrophysiology studies, rate analysis, timing features.

Implantable cardioverter defibrillators, restricted at present to one-chamber (ventricular) rate analysis, are capable of ventricular tachycardia (VT) and ventricular fibrillation detection with high sensitivity. However, distinction of VT and ventricular fibrillation from nonthreatening supraventricular rhythms still has limited specificity. Dual-sensing systems that use rates of both atrial and ventricular depolarizations have been shown in investigative studies to in-

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crease specificity dramatically.[1] In particular, dual-chamber sensing has the potential of suppressing inappropriate therapy in the event of sinus tachycardia (ST) and most supraventricular tachycardias (SVT) with fast ventricular response, the most common causes of erroneous VT diagnoses.[2,3] Dual-chamber sensing circuits have long been used by antibradycardia pacemakers. Analogous sensing should be feasible for antitachycardia devices.

A real-time automated system was previously developed to incorporate two-channel rate criteria combined with analysis of intracardiac atrial and ventricular morphology.[4] It was found, however, that the morphologic addition improved specificity but at a cost of considerable computation. At present, such a burden is not feasible in battery-operated devices. In this study, dual-chamber rate sensing was used in an alternative algorithm: relationship of atrial and ventricular events/two-channel arrhythmia detection (RAVE2CAD).

RAVE2CAD replaces morphology with additional features used to segregate arrhythmias such as those with 1:1 atrioventricular or ventriculoatrial relationship or simultaneously occurring independent atrial and ventricular arrhythmias. The three newly developed timing features contained within this algorithm include onset delineation, atrioventricular sequency, and regularity–multiplicity criteria. This algorithm has been designed to reduce computation when compared with morphology-based algorithms and to increase specificity over rate-only algorithms. The three separate timing criteria have been reported previously as individual studies, and results are given in the algorithm description in the next section.[5-7] RAVE2CAD was tested exclusively on spontaneously occurring arrhythmias recorded from intracardiac electrodes.

Materials and Methods

Data Acquisition

Atrial and ventricular electrograms were simultaneously recorded during elective clinical cardiac electrophysiology studies. Distal bipolar endocardial electrodes were positioned in the right ventricular apex and in the high right atrium. Electrograms were amplified at a bandwidth of 1–500 Hz (Electronics for Medicine VR12, Lenaxa, KS) and recorded on FM magnetic tape (Hewlett-Packard 3698A, San Diego, CA) with a tape speed of $3\frac{3}{4}$-in/s. Eleven patients demonstrated 25 spontaneously occurring arrhythmias during electrophysiologic studies.
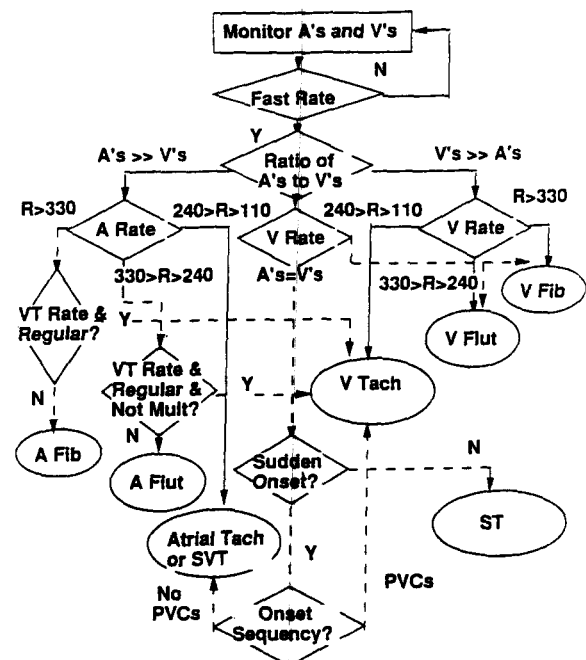
The real-time algorithm was developed on Intel X486/50E (Intel Corp, Hillsboro, OR) personal computer. The two-channel electrograms are digitized by an analog-to-digital converter (Tecmar Labmaster, Scientific Solutions, Solon, OH) at 1,000 samples/s for each channel and processed in real time. A software trigger with autoadapting threshold determined atrial and ventricular depolariza-

tions. Automated arrhythmia analysis yielded a contextual diagnosis that is reported on each cardiac cycle.

Algorithm Description

The proposed algorithm, RAVE2CAD, uses two intracardiac signals, atrial and ventricular. A flowchart of the overall logic is shown in Figure 1. Initially, rate is monitored until the rate of one or both signals accelerates. Eight consecutive short intervals determined by a selectable threshold cycle length (default value of 500 ms) must be detected before diagnosis is invoked. Once that criterion has been met, there are three main branches to the flowchart: more atrial events than ventricular, more ventricular events than atrial, and the 1:1 (atrial:ventricular) branch. This initial logic corresponds to an earlier algorithm developed by one of these authors,[1] but departs in a unique way to solve confounding rhythms. More atrial events than ventricular events (A > V) are seen on the left branch of the figure, more ventricular events than atrial events (V > A) on the right, and the 1:1 branch is in the center. By calculating the ratio of atrial cycles to ventricular cycles, the intrinsic fast rhythm can be attributed to the atria if atrial cycles predominate and to the ventricle if the ventricular cycles predominate. To be classified as A > V or V > A, the ratio must be equal to or greater than 9:7.

The separation of arrhythmias into three main classes (A > V, V > A, and 1:1) has been extensively tested and is considered robust. Preliminary data from 22 patients was published in 1984,[1] and more recently in 56 patients containing a variety of complex arrhythmias.[4]

Fig. 1. Flowchart of detection algorithm, relationship of atrial and ventricular events/two-channel arrhythmia detection (RAVE2CAD).

Ventricular > Atrial and Atrial > Ventricular Branches

If the origin of the fast rhythm is ventricular (V > A branch), the rhythm is easily classified as ventricular fibrillation, ventricular flutter, and VT by rate, determined by a running average, as described in the earlier algorithm.[1] A tachycardia zone is defined as having a cycle length between 250 and 500 ms, flutter between 180 and 250 ms, and fibrillation less than 180 ms. Similarly, if the origin is atrial (A > V), the leftmost branch classifies atrial tachycardia, flutter, or fibrillation, respectively, by rate as well. In this branch, the new algorithm performs additional diagnostic logic, as described in the Competing Rhythms section, to recognize competing fast ventricular rhythms that are present concurrently with a fast atrial rhythm.

1:1 Branch

Tachycardias with a 1:1 relationship are the most difficult to interpret by automated analysis. Earlier algorithms applied onset criteria,[8,9] but they were used on ventricular electrograms only. In this new algorithm, onset criterion and other timing criteria use rate and the initiating events. If the rate falls within the tachycardia range and contains a 1:1 relationship, a distinction is made by these criteria between ST, SVT, or VT. However, if the 1:1 rate exceeds fibrillation or the flutter rate in both chambers, there is a competing atrial flutter/fibrillation with ventricular flutter/fibrillation. The program diagnoses ventricular fibrillation or flutter by default because of safety factors.

Separating ST From SVT and VT. A sudden onset criterion is first applied to separate ST from both VT or SVT. In general, ST has been found to have a slow and gradual onset while paroxysmal VTs and SVTs have abrupt beginnings. A median filter is used to detect sudden onset. To be considered a sudden onset, the following ratio must be greater than 25%:

$$(1) \quad Onset = \frac{(\text{Median of current and last six cycles}) - (\text{Median of last seven cycles})}{(\text{Median of last seven cycles})}$$

This ratio is calculated every cardiac cycle. When the algorithm enters the diagnostic state on discovery of a fast rate, the recognition of a 1:1 rhythm will require the algorithm to look back 12 cycles for determination of a sudden onset.

In an earlier study from our laboratory, 50 cases of onsets from ST and VT were tested with the median sudden onset criteria using fixed intervals and percentage change for threshold determination. These results were compared with a previously published study of sudden onset methods using fixed interval and percentage change in individual cycle lengths.[10] Results demonstrated that median ventricular rate filtering (threshold of 25%) was superior to other onset methods with sensitivity of 92% and specificity of 96%.[5] This threshold is used in the present study.

Distinguishing SVT and VT. If the onset is abrupt, examining the onset sequence of atrial and ventricular events is used to distinguish VT from SVT. Such a sequence analysis is based on the hypothesis that VT commonly begins with one or more ventricular premature depolarizations. The algorithm recognizes a ventricular premature depolarization if the event sequence is AVVA. Once in the diagnostic state of a 1:1 fast rhythm, the algorithm looks back 12 cycles for a ventricular premature depolarization. The use of the AV sequence for separation of paroxysmal SVT from paroxysmal VT was tested separate from the overall algorithm on 25 patients with spontaneous arrhythmic events. Results showed 100% sensitivity and 83% specificity in diagnosing VT.[6]

Competing Rhythms

The most difficult problem in arrhythmia detection is the occurrence of competing rhythms such as VT during atrial flutter or atrial fibrillation in the A > V branch. Recent studies have reported that atrial fibrillation with fast ventricular response is the main cause of false shocks.[2,3] An earlier simplistic method simply examined relative atrial or ventricular rate,[1] and whichever predominated was given attention. However, algorithms that concentrate on the faster chamber do not address VT occurring concurrently (competing) with atrial flutter/fibrillation. The addition of a competing rhythm diagnostic algorithm is perhaps the main advantage of this new method (RAVE2CAD). A flowchart of the competing rhythm analysis is shown in Figure 2.

To distinguish between VT versus a fast ventricular response in atrial fibrillation or flutter, the algorithm first determines whether the ventricular rhythm is regular. The regularity criterion is as follows:

$$(2) \quad Regularity = \frac{(\text{Median of last seven cycles}) - (\text{Smallest of last seven cycles})}{(\text{Smallest of last seven cycles})}$$
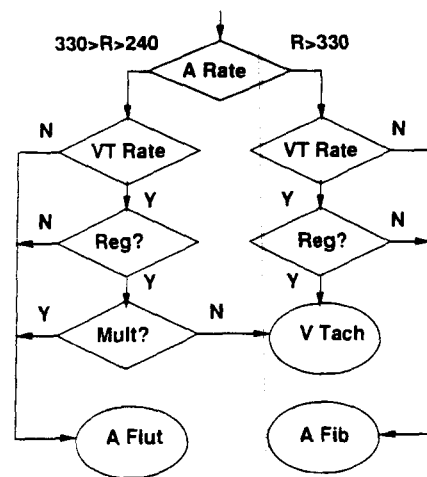

Fig. 2. Flowchart of competing rhythm analysis by relationship of atrial and ventricular events/two-channel arrhythmia detection (RAVE2CAD).

If the regularity measure is less than 0.10, the rhythm is considered regular.

Atrial Fibrillation versus VT. In the case of atrial fibrillation, if the ventricular rate exceeds the VT rate and the ventricular intervals are regular, the ventricular rhythm is defined as VT. Otherwise, the algorithm defaults to atrial fibrillation with fast ventricular response.

Atrial Flutter versus VT. For atrial flutter rates, however, an additional multiplicity criterion needs to be applied because the case of atrial flutter with n:1 response can easily be misinterpreted as a regular VT. During atrial flutter, multiplicity discerns if the conduction pattern is a consistent n:1 conduction in response to the atrium. Multiplicity is only performed when a flutter rate is discerned and ventricular response is regular. The multiplicity criterion is as follows:

(3)

$$\text{Multiplicity} = \frac{\text{(Median of last seven V cycles) MOD}}{\text{(Median of last seven A cycles)}}$$

where MOD is the remainder of the division. Multiplicity is assumed if the ratio is less than 0.1 or greater than 0.9; otherwise it is not classified as a multiple. In summary, if the ventricular rate exceeds the VT rate and satisfies the ventricular regularity criteria and the ventricular rate is not a multiple of the atrial rate, the rhythm is diagnosed as VT. Otherwise, the rhythm is diagnosed as atrial flutter with fast ventricular response. For the competing rhythms of VT in atrial flutter/fibrillation, 20 cases (10 cases of atrial fibrillation or atrial flutter with fast ventricular response and 10 competing VT rhythms in atrial fibrillation or atrial flutter) were tested in an independent study. The algorithm achieved 90% sensitivity and 90% specificity.[7]

Automated Analysis

All analyses are performed automatically by RA-VE2CAD. For each event (A/V), the computer lists the temporal location of each atrial or ventricular event, the most recent AA/VV interval, the AA/VV interval average over
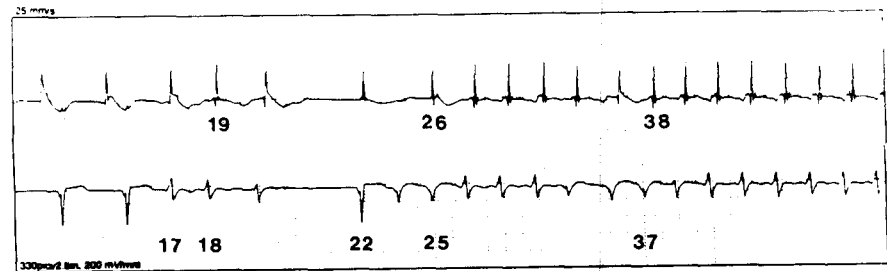

Fig. 3. Example of 1:1 ventricular tachycardia. Strip-chart tracing and corresponding computer listing of arrhythmia analysis is given. The upper tracing is the intracardiac atrial signal and the lower tracing is the intracardiac ventricular signal. The ventricular tachycardia onset satisfies sudden onset criterion and contains ventricular premature depolarizations.

BEAT	Apos	Vpos	AA	AV/VA	VV	AArate	VVrate	Diagnosis
14	4560		730	558		770		Sinus Rhythm
paroxysmal onset								
15		4772		212	770		742	Sinus Rhythm
16	5294		734	522		764		Sinus Rhythm
17		5297		3	525		684	Sinus Rhythm
18		5713		419	416		665	Fast V: checking
19	5819		525	106		698		Fast V: checking
paroxysmal onset								
20		6272		453	559		567	Sinus Rhythm
21	6387		568	115		669		Sinus Rhythm
paroxysmal onset								
22		7417		1030	1145		661	Sinus Rhythm
23	7499		1112	82		732		Sinus Rhythm
paroxysmal onset								
24		7883		384	466		646	Fast V: checking
25		8266		767	383		638	Fast V: checking
26	8288		789	22		743		Fast V: checking
paroxysmal onset								
27		8664		376	398		598	Fast V: checking
28	8770		482	106		701		Fast Both: checking
29		9061		291	397		411	Fast Both: checking
30	9169		399	108		645		Fast Both: checking
paroxysmal onset								
31		9464		295	403		395	Fast Both: checking
32	9575		406	111		626		Fast Both: checking
33		9830		255	366		391	Fast Both: checking
34	9952		377	122		594		Fast Both: checking
35		10302		350	472		409	Fast Both: checking
36	10442		490	140		490		Fast Both: checking
37		10663		221	361		400	Fast Both: checking
In 1:1 loop								
Sudden Onset = 1 AVVA = 1								
38	10825		383	162		422		Ventricular Tachycardia
In V >> A loop								
39		10904		79	241		360	Ventricular Tachycardia
In V >> A loop								
40		11005		180	101		293	Ventricular Tachycardia
In 1:1 loop								
41	11197		372	192		404		Ventricular Tachycardia

the past six cycles, and the computer-generated diagnosis. Note that a contextual diagnosis is given for each cycle (ie, depends on the previous cycles). Also, the diagnosis "paroxysmal onset" appears when detected, even if it is not necessarily used in the final diagnosis. The citation, "in 1:1," "in V > A," and "in A > V," appears in order to indicate which branch of the algorithm has been invoked. At the first 1:1 event after the diagnostic state is reached, the onset routine is enabled. This routine checks in a backward manner examining 12 cycles for sudden onset and AVVA pattern and sets flags for each to 0 (false) or 1 (true). These values are also shown on the computer listings. An example with a corresponding strip chart of the arrhythmia is shown in Figure 3.

Results

In this study, 25 distinct spontaneous arrhythmias (11 patients) were analyzed that included ST, SVT, VT with concurrent sinus rhythm, VT with concurrent atrial flutter, and ventricular fibrillation. Results are shown in Table 1. A passage was considered correct only if every cycle in that passage was correct. Results given in Table 1 list the number of passages with proper diagnoses in each category. Overall, 21 of 25 passages were correct.

Discussion

The global two-channel algorithm RAVE2CAD includes the initial recognition of a fast rhythm(s) and follows one of three branches (A > V, V > A, 1:1). Logic for distinction of the onset pattern and for the recognition of competing rhythms from previous studies is integrated into the overall logical structure, as described in the Materials and Methods section. This algorithm successfully diagnoses most spontaneous rhythms. However, algorithm misdiagnoses occur despite integration of multiple timing features.

Table 1. Analysis Results of 12 Patients and 25 Distinct Arrhythmias by RAVE2CAD

Arrhythmia Type	Correct Results	Misdiagnosed As
Sinus tachycardia	1 of 1	
Supraventricular tachycardia	4 of 6	Ventricular tachycardia
Ventricular tachycardia	15 of 15	
Atrial flutter/ ventricular tachycardia	0 of 2	Atrial flutter/ fast ventricular response
Ventricular fibrillation	1 of 1	

RAVE2CAD, relationship of atrial and ventricular events/two-channel arrhythmia detection.

Spontaneous rhythms are difficult to obtain during clinical cardiac electrophysiology studies because the patient must coincidentally have a spontaneous arrhythmia during recording. Because of the limited data set, the algorithm was trained on two patients only. This dramatically affected the ability to set thresholds that applied to the final test set of 25 episodes.

Misdiagnoses were accounted for as follows. Reentrant SVT was misdiagnosed as VT due to competing SVTs arising in the atrium. In both cases, the two reentrant SVTs initiated a premature ventricular event misdiagnosed by automated analysis as a ventricular premature depolarization. In the era of radiofrequency ablation, it should be anticipated that the incidence of reentrant SVTs misdiagnosed as VTs would be quite rare and would not dramatically decrease specificity in future devices. Ventricular tachycardia with concurrent atrial flutter misdiagnoses occurred for two separate reasons. A coincidental multiplicity between the atrial and ventricular events during VT with atrial flutter caused the misdiagnosis of atrial flutter with fast ventricular response. The other VT in atrial flutter did not meet the threshold for the regularity criterion and was misdiagnosed as atrial flutter with fast ventricular response.

The contextual diagnosis at each cycle was correctly determined for most (84%) arrhythmias. However, the three timing criteria were unable to completely separate all rhythms. Although the algorithm dramatically improves specificity over current devices, sensitivity must be improved. Future refinements of timing algorithms may help to further increase both the sensitivity and specificity of automated VT diagnosis.

References

1. Azbaecher RC, Bump T, Jenkins JM et al: Automatic tachycardia recognition. PACE 7:541, 1984
2. Steinberg J, Sugalski J: Cardiac rhythm precipitating automatic implantable cardioverter-defibrillator discharges in outpatients as detected from transtelephonic electrocardiographic recordings. Am J Cardiol 67:95, 1991
3. Cohen T, Chien W, Lurie K et al: Implantable cardioverter defibrillator proarrhythmia: case report and review of the literature. PACE 14:1326, 1991
4. Chiang C-M: Real-time automatic detection of cardiac arrhythmias by rate and morphology analysis of intracardiac electrograms. PhD dissertation, University of Michigan, Ann Arbor, 1993
5. Chiang CJ, Jenkins JM, Silka MJ, DiCarlo LA: Median filtering as a sudden onset criterion to separate sinus tachycardia from ventricular tachycardia. p. 379. In IEEE Computers in Cardiology. IEEE Press, Los Alamitos, CA, 1992
6. Chiang CJ, Jenkins JM, DiCarlo LA: Value of onset sequence in discriminating ventricular tachycardia from supraventricular tachycardia. p. 173. In IEEE Computers in Cardiology. IEEE Press, Los Alamitos, CA, 1993

7. Chiang CJ, Jenkins JM, DiCarlo LA: Dual chamber analysis for recognition of competing atrial and ventricular tachycardias in antitachycardia devices. PACE 17:768, 1994

8. Pless BD, Sweeney MD: Discrimination supraventricular tachycardia from sinus tachycardia of overlapping cycle length. PACE 7:1318, 1984

9. Olson WH, Bardy GH: Cycle length and morphology pattern at onset of spontaneous ventricular tachycardia and fibrillation. p. 284. In 7th Annual Scientific Session NASPE, 1986

10. Brown J, Gillette P, Goh T, Arzbaecher R:Distinguishing sinus from paroxysmal tachycardia by rate of onset. J Electrocardiol 19:309, 1986