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A new algorithm for rhythm discrimination in cardioverter defibrillators based on the initial voltage changes of the ventricular electrogram

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Aims Ventricular activation onset is faster in supraventricular beats than in ventricular rhythms. The aim of this study was to evaluate a criterion to differentiate supraventricular (SVT) from ventricular tachycardia (VT) based on the analysis of the initial voltage changes in ICD-stored morphology electrograms.

Methods Far field ICD-stored EGMs were obtained from 68 VT and 38 SVT episodes in 16 patients. The first EGM peak was detected, three consecutive time epochs were defined within the preceding 80 ms window and the voltage changes with respect to a sinus template were analysed during each time period and combined into a single parameter for rhythm discrimination.

Results The algorithm was tested in an independent validation group of 442 VT and 97 SVT spontaneous episodes obtained from 22 patients with a dual chamber ICD. The area under the receiver-operator characteristics (ROC) curve indicated that the arrhythmia separability with this method was 0·95 (tolerance interval: 0·85–0·99) and 0·98 (0·87–0·99) for the control and validation groups respectively. A specificity of 0·91 was obtained at 95% sensitivity in the validation group.

Conclusion The analysis of voltage changes during the initial ventricular activation process is feasible using the far field stored electrograms of an ICD system and yields a high sensitivity and specificity for arrhythmia discrimination.
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Key Words: Implantable cardioverter defibrillator, supraventricular tachycardia, ventricular tachycardia, electrogram morphology, tachyarrhythmia detection algorithms.

Introduction

The ICD is becoming one of the most powerful therapeutic tools in the treatment of sustained ventricular arrhythmias and prevention of sudden death[1]. The recognition of rapid ventricular rhythms by these devices is based on the measurement of heart rate. However, rate-only detection algorithms may fail to differentiate between supraventricular and ventricular arrhythmias with overlapping rates, leading to spurious and potentially dangerous ICD therapies[2,3]. Several detection enhancements based on the analysis of the arrhythmia onset and stability[4–6], electrogram (EGM) characteristics[7–10] and atrioventricular association[11,12] have been implemented to overcome this problem in current generation ICD devices. However, inappropriate shocks for supraventricular arrhythmias still remain a common clinical problem. The duration of the initial QRS deflection in the 12-lead ECG has been considered a useful diagnostic criterion to differentiate supraventricular (SVT) from ventricular tachycardia (VT)[13], based on the fact that the initial ventricular activation is slower in VT complexes, even if the total duration of the QRS complex is similar. During SVT the impulse travels through the specialized conduction system, reaching several areas of myocardium almost simultaneously. In

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contrast, the initial activation of VT complexes spreads more slowly through non-specialized myocardial fibres. Thus, the initial deflection of a far-field EGM is expected to be steeper in supraventricular than in ventricular arrhythmias. The aim of the study was to build and evaluate a new criterion to differentiate SVT from VT based on the analysis of the initial voltage changes in ICD-stored morphology EGMs.

Methods

Acquisition of arrhythmic episodes

Two independent groups of ICD-stored EGMs were analysed in this study. The devices were programmed in both groups to store far field EGMs using the subpectoral can and the defibrillation coil as recording electrodes. This lead configuration was chosen to obtain information on the global ventricular activation process. The sampling rate was 128 Hz with 8-bit resolution.

Induced episodes (Group 1)
This was the control group, intended to build and estimate the parameters of the discrimination algorithm. Sixteen patients, with inducible monomorphic VT and an implanted third generation-ICD (Micro-Jewel 7221 and 7223, Medtronic, Minneapolis, MN, U.S.A.) were included in this group. A pre-discharge electrophysiological study was performed at least 3 days after the implant and the EGMs during induced VT were stored by the device. Several sinus beats preceding the VT induction were also recorded and used to generate the template for a normal beat as described below. A treadmill test using a modified Bruce protocol was also performed, setting the cycle length for VT detection to 600 ms, thus allowing the device to detect and store sinus tachycardia episodes. Spontaneous arrhythmias detected during the follow-up of these patients were included in the study and classified as ventricular or supraventricular only if the ICD-stored EGM was morphologically identical to the recorded during an induced VT or during the exercise-induced sinus tachycardia respectively.

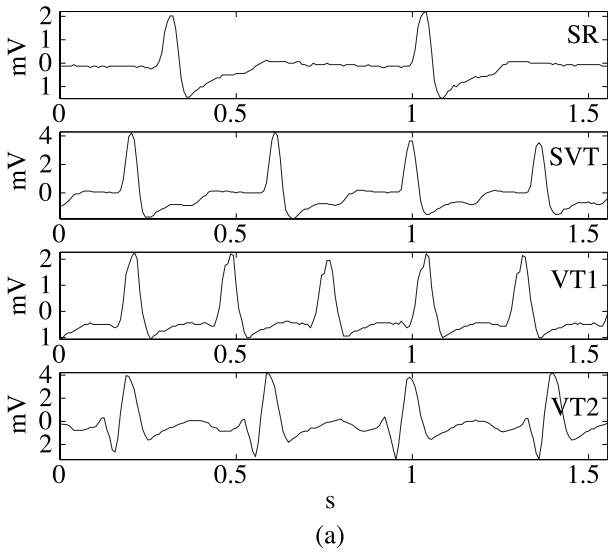
Spontaneous episodes (Group 2)
This was the validation group, in which the accuracy of the algorithm obtained from the control episodes was tested. A set of spontaneous episodes of tachycardia from 22 patients with an implanted, dual chamber ICD (GEM-DR 7271, Medtronic, Minneapolis, MN, U.S.A.) was collected. Each episode was classified as ventricular or supraventricular by a cardiologist highly experienced in arrhythmia interpretation and ICD follow-up with the aid of the atrial and ventricular EGMs stored by the device. The use of dual chamber devices was required in order to reduce the potential diagnostic errors of this arrhythmia classification.

Development of the discrimination algorithm

The ventricular EGM, when recorded with a global, far-field source, contains electrical components with different intensities that are generated at different cardiac sites, so that a reliable automatic detection of the onset of a far-field detected EGM is hard to obtain. Hence we decided to rely on the first EGM-peak detection and to analyse a period of time preceding the peak long enough always to include the EGM onset. As previously stated, group 1 episodes were used to build the discrimination procedure. For each stored episode the R-wave peaks were automatically detected in every EGM, and the first derivative of the preceding 150 ms was extracted, averaged, and then rectified to analyse the absolute voltage changes. Figure 1 shows the rectified first derivative templates for a SR, a SVT and two VT examples. Visual analysis showed that the EGM onset was within the 80 ms preceding the EGM peak in all VT and SVT recorded episodes. Therefore, the analysis of initial voltage changes was performed in this 80 ms time window. The EGMs of VT complexes usually presented a slowly rising deflection from the beginning of the window. In contrast, most SVT complexes had a later onset, showing an isoelectric signal during the first part of the window followed by a steep upwards deflection. Therefore VT complexes exhibited higher voltage increments during the first part of the window when compared with SVT complexes, whereas the opposite occurs at the end of the analysed time. Consequently, a simple comparison of voltage changes in the complete window would not be useful to differentiate supraventricular from ventricular arrhythmias in all cases, and a separate analysis of several time periods within the window was required. In order to find the epochs containing the relevant information to discriminate the two rhythms, a neural network analysis of the voltage changes in the window of interest was performed (Appendix I). The results showed that the best discrimination power was obtained when three consecutive time epochs (E1: -80 to -65 ms, E2: -65 to -20 ms, and E3: -20 to 0 ms, with 0 ms corresponding to the EGM peak) were considered within the window. The difference in voltage changes between tachycardia and sinus rhythm EGMs were calculated for each time epoch (E1 to E3) using the statistics:

$$V(E_1)=\int_{-80\ \mathrm{ms}}^{-65\ \mathrm{ms}} f(t)dt;\ V(E_2)=\int_{-65\ \mathrm{ms}}^{-20\ \mathrm{ms}} f(t)dt;$$
$$V(E_3)=\int_{-20\ \mathrm{ms}}^{0\ \mathrm{ms}} f(t)dt \qquad (1)$$

where $f(t)$ represents the difference between the rectified first derivative of the tachycardia and the rectified first derivative of the SR templates at the instant 't'. A normalization procedure was applied to combine the three statistics into a single parameter (Ro), based on the estimation of the covariance matrix for SVT episodes (Appendix II). The Ro value is the statistic used to classify the episode and represents the deviation of initial voltage changes in the analysed episode with respect to



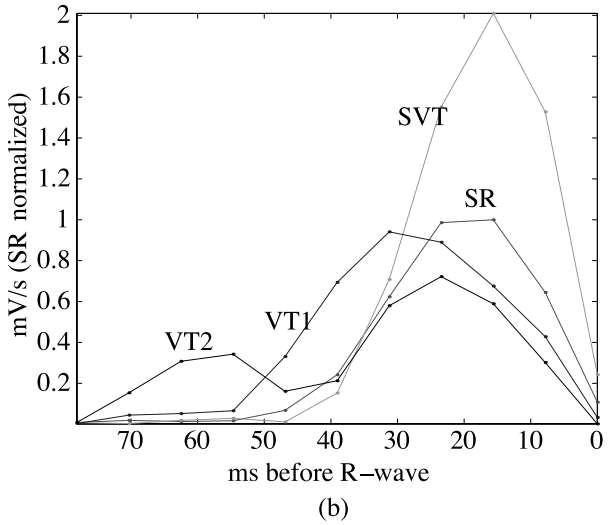


Figure 1 **Changes in the QRS onset. (a) Recordings from sinus rhythm, SVT and 2 VT episodes: VT1 with a morphology similar to the baseline rhythm and VT2 with a very different waveform. (b) Averaged, rectified, 80 ms templates of the EGM first derivatives. The R-wave peak will correspond to 0 ms, and preceding times are denoted as negative times. Note the early activation in both VT templates when compared with the sudden activation of the SV rhythms.**

the baseline beat template, thus being low in SVT and high in VT electrograms.

Validation procedure

The algorithm was tested in the spontaneous episodes in group 2, using the covariance matrix previously estimated from the control group. Thus for each arrhythmia episode in the validation group the algorithm first calculates V(E1) to V(E3), then estimates the normalized parameter *Ro* using the fixed previously obtained covariance matrix and finally determines whether the episode is ventricular or supraventricular according to the *Ro* value.

Statistical analysis

The area under the ROC curve was calculated and used to estimate the performance of the method separately in groups 1 and 2. In order to avoid potential bias due to the different number of episodes per patient the tolerance intervals (TI) were calculated for the areas in both groups[14]. A high sensitivity in VT detection is required to use a discriminating algorithm in a clinical setting since underdetection of VT may result in absent or delayed delivery of ICD therapy. Therefore, the specificity at 95% sensitivity was also obtained as a measure of the algorithm performance.

Results

Sixteen patients (16 men, age: 64 ± 7 years, ischaemic heart disease in 11, LVEF: 31 ± 11%) were included in group 1. Thirty-eight SVT episodes (CL: 493 ± 54 ms) and 68 VT episodes (CL: 314 ± 49 ms) were analysed in this group. The number of episodes per patient were 2·3 ± 4·0 (range 0–17) for SVT and 4·3 ± 3·3 (range 0–13) for VT. One patient had SVT episodes alone, only VT episodes were recorded in 4 (25%) and 11 patients (69%) presented both types of arrhythmias. The validation group (group 2) consisted of 22 patients (17 men, age: 63·5 ± 13·0 years, ischaemic heart disease in 18, LVEF: 37·5 ± 15·8%). Ninety-seven episodes were labelled as SVT (CL: 514 ± 64 ms) and 442 as VT (CL: 398 ± 83 ms) with an average of 4·4 ± 14·1 SVT episodes per patient (range 0–57) and 20·5 ± 29·8 VTs per patient (range 0–88). All except one patient in this group presented VT episodes. In 4 cases (18%) supra and ventricular tachycardias were recorded. The visually estimated EGM width during sinus rhythm was 90 ± 24 ms in group 1 and 107 ± 32 ms in group 2 (ns). An EGM duration higher than 120 ms was present in 2 and 8 patients respectively. The area under the ROC curve for the analysed algorithm was 0·95, TI (0·85, 0·99) for group 1 and 0·98, TI (0·87, 0·99) for group 2. Figure 2 shows the sensitivity and specificity obtained in both groups as a function of the *Ro* value. Note that curves in control and validation data sets are very similar, suggesting that the algorithm obtained in group 1 is still useful when tested in an independent set of arrhythmias. The specificities were 0·95 and 0·91 at 95% sensitivity in groups 1 and 2 respectively. A separate analysis was performed in patients having both SVT and VT episodes. The algorithm was able to separate the episodes with 100% accuracy in 8 of 11 patients in group 1 and in one of 3 in the validation group. The areas under the ROC curve ranged between 0·65 and 1, with a

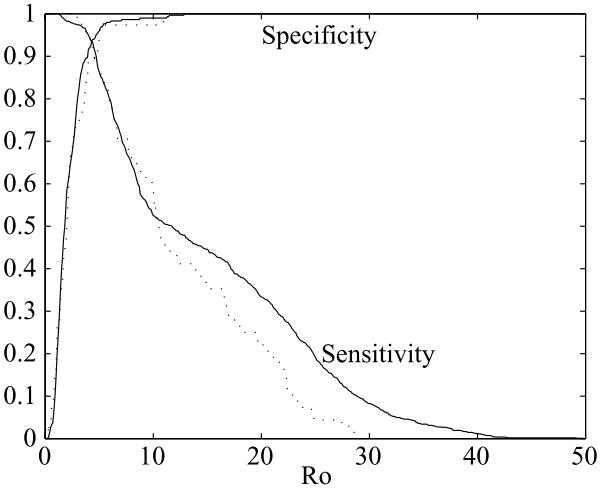


Figure 2 **Sensitivity and specificity for VT detection as a function of the threshold *Ro* obtained from the algorithm: group 1 (dotted line) and group 2 (continuous line).**

mean of 0·91 and 0·82 for groups 1 and 2 respectively in this per-patient analysis.

Discussion

Our study shows that the analysis of initial voltage changes in the far-field stored EGM is useful to differentiate ventricular from supraventricular tachycardias in patients with ICDs, according to the hypothesis that the ventricular activation onset is faster in supraventricular than in ventricular rhythms. The designed algorithm obviates the need for an exact estimation of the EGM onset, a critical issue usually requiring a human operator validation to be reliable. The performance of this method when tested in a group of spontaneous episodes is comparable or superior to those obtained with other morphology-based previously reported criteria.

Delivery of inappropriate therapy due to inaccurate arrhythmia classification remains an important clinical concern in patients with ICDs. Several criteria based on the stability of the cycle length, sudden onset of tachycardia or the analysis of atrioventricular activation timing have been developed to improve VT detection specificity by rejecting inappropriately detected supraventricular rhythms[4–12]. In single chamber devices, the assessment of the EGM morphology upon visual inspection during tachycardia and sinus rhythm is crucial to classify stored spontaneous episodes[15]. The implementation of similar morphologic analysis capabilities as an automatic and reliable algorithm in current devices should improve the diagnostic accuracy and reduce the number of inappropriate therapies. This hypothesis has led to the development of several morphology based discrimination algorithms. The EGM width criterion implemented in some recent ICDs intends to improve the diagnostic accuracy by measuring the width of intracardiac EGM signals. The algorithm may be activated after analysing the optimal EGM source, slew and width thresholds during sinus rhythm. Overall sensitivity of this criterion for VT detection in a clinical study was 64%, not superior to that obtained by the use of rate dependent criteria[9]. The low clinical performance may be related to real QRS width changes due to exercise, ischaemia or the use of antiarrhythmic drugs, inappropriate detection of the EGM onset and offset points due to baseline irregularities or presence of bundle branch block[16,17]. Our algorithm may present some advantages when compared with other EGM width based criteria. First, a careful assessment of the individual EGM characteristics during sinus rhythm does not seem to be essential. In our study a good diagnostic accuracy was obtained in an independent test set of episodes using generic parameters obtained from a control group. Second, the determination of the onset and offset points of the EGM, an estimation critically dependent on the baseline noise and other subtle interferences, is not needed. Finally, the presence of fixed or intermittent bundle branch block should not essentially affect the performance of the algorithm, since only the initial activation energy changes are used to discriminate supraventricular from ventricular complexes. No significant differences were found in our series between patients with and without bundle branch block but this should be interpreted with caution since only 10 patients had wide baseline QRS complexes in our study.

A second morphology discrimination algorithm has been implemented in commercially available ICDs, based on the comparison of each EGM sensed during tachycardia with a stored patient-specific QRS template obtained during sinus rhythm. Subsequently a similarity score of both patterns is calculated and used to classify the beat as ventricular or supraventricular[10]. A recent clinical study showed a limited sensitivity and specificity for this criterion (77 and 71% respectively) and suggested its combination with the sudden onset feature in order to improve the sensitivity up to 99%[18]. Our results suggest that the analysis of the onset activation voltage changes may yield a sensitivity and specificity close to 95% as an isolated criterion. These figures are slightly inferior to those reported by Gold *et al.*[8] in a preliminary study using a two-step algorithm, which estimates the width of the EGM and defines the arrhythmia complex as wide if the duration is at least 30% greater than the template obtained during baseline rhythm. Narrow complexes are morphologically analysed in a second step and classified according to the degree of similarity with the baseline template. The reported sensitivity of 100% must be cautiously interpreted since it was tested in only 27 VT episodes. Moreover, its computational burden is higher than that required in our study, about 55 sums and 9 products per analysed cardiac cycle.

Study limitations

Our results are based on a small number of patients and thus must be considered preliminary. Moreover, the majority of SVT and VT episodes concentrated in a small part of the patients. Tolerance intervals instead of

standard deviations were used in the statistical methods to minimize this effect, but a bias in the study due to a different number of episodes per patient cannot be ruled out. The discrimination algorithm was fed with parameters obtained from the control group, reflecting the hypothesis that initial ventricular activation voltage changes mainly depend on the supraventricular or ventricular origin of the complex rather than on other patient-related factors. The advantage of such an approach is that the need for an individualization of ICD programming is minimized. Nevertheless, individual patient-based adjustments of the algorithm or its combination with other discrimination criteria such as stability or sudden onset might have yielded better discrimination results. The effects of organic or functional bundle branch blocks on the performance of the proposed algorithm are not clear, since only a limited number of patients with wide sinus complexes was studied. Finally, several conditions such as ischaemia, changes in the autonomic balance, antiarrhythmic drugs or electrolytic abnormalities are known to modify the voltage changes of the initial ventricular activation process, thus potentially affecting the discrimination capabilities of morphology-based criteria. The effects of such modulating factors on the sensitivity and specificity of the proposed or other similar algorithms are unknown.

Conclusions

The analysis of voltage changes during the initial ventricular activation process is feasible using the detected EGMs and the computational capabilities of an ICD system and may be useful to discriminate between supraventricular and ventricular rhythms. The proposed algorithm yields relatively high sensitivity and specificity for arrhythmia discrimination in spontaneous episodes. The diagnostic capabilities of this algorithm in combination with other discrimination criteria as well as in patients with bundle branch block deserve further study.

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Appendix 1. Preliminary analysis with a neural network design

A neural network was designed to analyse the time epochs within the 80 ms window preceding the EGM

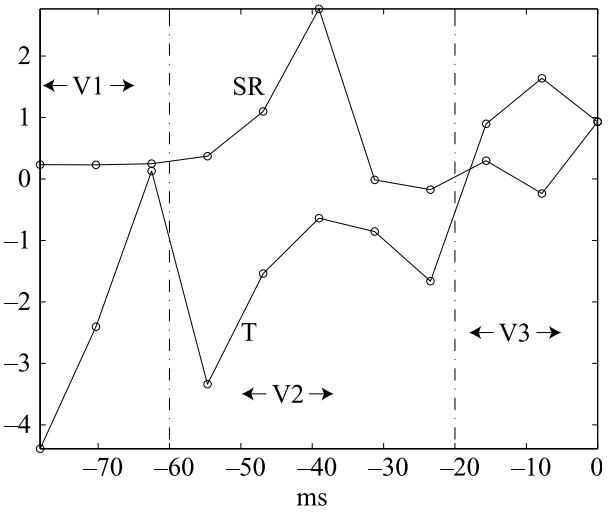

Figure 3 **Preliminary analysis based on SVM neural networks. Plot of the SVM weights as a function of time. Baseline rhythm and tachycardia weights are jointly represented. According to these weights, three different intervals can be defined: E1: (− 80, − 60) ms, E2: (− 60, − 20) ms and E3: (− 20, 0) ms.**

peak that best discriminate supraventricular from ventricular rhythms. The rectified and normalized first derivative of the ICD stored signal was obtained and 22 two samples (11 from the tachycardia and 11 from the baseline rhythm templates) were combined in a 22 dimension vector. A support vector method (SVM) neural network[19,20] with linear activation units was trained to discriminate between the 38 SVT and the 68 VT vectors. This kind of neural network was chosen as it gives the maximum margin solution, which is appropriate in problems with a low number of available data. A bootstrap resampling technique[21] was used to avoid the overfitting in the SVM training. The weights representation of the resulting SVM (see Fig. 3) shows the existence of three time epochs to be compared independently: (a) E1, from − 80 to − 65 ms, (b) E2, from − 65 to − 20 ms, corresponding to a transition interval; and (c) E3, the 20 ms preceding the EGM peak.

Appendix 2. Normalization with the covariance matrix obtained from SVT episodes

When the SVT episodes are represented using the proposed three statistics, the resulting boundary is an ellipsoid, since their order of magnitude is different. A single threshold was obtained using the following normalization procedure. Let us denote as

$$\mathbf{v}=[V_1\ V_2\ V_3] \tag{2.A}$$

the generic vector containing the measures, and $\mathbf{v}_i^{SVT}$ the particular vector for the *i*-th episode of SVT. The average vector for the SVT episodes is:

$$\bar{\mathbf{v}}_{SVT}=\frac{1}{N_{SVT}}\sum_{i\in N_{SVT}}\mathbf{v}_i \tag{2.B}$$

and the covariance matrix[22] is defined as:

$$\mathbf{S}_{SVT}=\frac{1}{N_{SVT}}\sum_{i\in N_{SVT}}(\mathbf{v}_i^{SVT}-\bar{\mathbf{v}}_{SVT})^T(\mathbf{v}_i^{SVT}-\bar{\mathbf{v}}_{SVT}) \tag{2.C}$$

where N_{SVT} is the number of episodes of SVT available and $(^T)$ represents the transposed vector. This matrix represents the different variances in the 3-dimensional space defined by the statistics. By multiplying the measured vector times the inverse of the SVT covariance matrix, each episode is represented by a new set of three features,

$$\mathbf{w}_i=\mathbf{S}_{SVT}^{-1}(\mathbf{v}_i-\bar{\mathbf{v}}_{SVT})=[V_1'\ V_2'\ V_3'], \tag{2.D}$$

so that SVT episodes are centered and equally distributed around the origin, available VT episodes are randomly distributed far from the origin, and non-observed VT episodes being far different in any of the segments also will be far from the origin. A simple classifier is obtained through a single parameter, *Ro*, the radius of the sphere enclosing the SVT episodes.