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Preliminary Study on the Detection of Cardiac Arrhythmias based on Multiple Simultaneous Electrograms

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Abstract— **Although implantable cardioverter-defibrillators have improved significantly in the past decades, the algorithms used in the identification of life-threatening arrhythmias are still not accurate enough. Conventional methods commonly misclassify tachycardias, sometimes initiating an unnecessary and uncomfortable treatment. In this paper, we proposed a new method for the identification of ventricular tachycardias and fibrillations based on the comparison of simultaneous electrograms. Our method could successfully separate supraventricular tachycardias and normal sinus rhythm, which do not require any treatment, from ventricular tachycardias and fibrillation, which are life-threatening arrhythmias and must be terminated, with a sensitivity of 93.0% and a specificity of 92.7% from the comparison of ventricular electrograms. In future studies, the classification using electrograms from the right heart must be improved.**

I. INTRODUCTION

Each year in the United States, about 450,000 people die of unexpected sudden cardiac death [1]. Further, it is known that the risk of a recurrence is high in survivors of sudden cardiac death. Therefore, in patients at risk for recurrent sustained ventricular tachycardia (VT) or fibrillation (VF), implantable cardioverter defibrillators (ICDs) are used to automatically deliver electrical shocks in order to restore the normal rhythm.

The ICDs have been used for more than 2 decades; in this period they have improved substantially becoming highly effective in terminating malignant arrhythmias. However the detection of life-threatening arrhythmias still lacks accuracy. Delivery of inappropriate shocks, commonly related to the misclassification of a supraventricular tachycardia (SVT) as a VT, can lead to pain, anxiety, depression, impaired quality of life, proarrhythmia, and poor tolerance of life-saving ICD therapy [2], [3], [4], [5], [6].

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On the other hand, the long ICD lifetime operating with typical batteries demands very low power consumption by the ICD microprocessor, which limits the use of complex detection algorithms [3].

Conventionally, ventricular arrhythmias are detected either based on the heart rate or based on the electrograms (EGMs) morphology. One example of criterion based on the heart rate is to use programmable thresholds to discriminate the arrhythmias since during a VF the heart rate is higher than during a VT, and during a VT the heart rate is higher than during a normal sinus rhythm (SR). The morphologic criterion is based on comparing the EGM morphology with a sample of pre-stored EGMs of each arrhythmia. However, both heart rate and EGM morphology are not stable, which makes it difficult to define a threshold or a particular morphology for each arrhythmia.

In this paper we propose a method for detection of ventricular arrhythmias based on the comparison of simultaneous EGMs from the left ventricle (EGM_{LV}), the right ventricle (EGM_{RV}) and the right atrium (EGM_{RA}). Preliminary results indicate that this algorithm permits earlier classification of the cardiac rhythm and with a lower computational cost than the conventional methods; however, further comparative studies are necessary. During the SR or during a SVT, the excitation is transmitted from the atrium to both ventricles through the His-Purkinje bundle; therefore, the EGM of both ventricles are synchronized with each other and with the EGM_{RA}. On the other hand, VTs and VFs are caused by an ectopic electrical excitation in the ventricle which is not transmitted through the His-Purkinje bundle causing the ventricular electrograms to be independent of each other and also of the EGM_{RA}.

II. METHODS

A. Data Description

In this study *in vivo* data were obtained from a dog in an acute experiment. EGMs were measured from leads in the left and right ventricles and right atrium and sampled at 250Hz. SVT was simulated by right atrial pacing. VT was simulated by right or left ventricular pacing. And VF was induced by electrical stimuli after the R-wave of the surface electrocardiogram. The distribution of the episodes and the length of the data of each rhythm are detailed in Table I.

TABLE I

NUMBER OF EPISODES AND TOTAL DURATION OF THE DATA OF EACH RHYTHM

	Number of Episodes	Total Duration [s]
SR	14	179.2
SVT	5	41.6
VT	7	61.4
VF	4	40.6

B. Preprocessing

The data were analyzed in a moving data window with 1.0s length and 0.2s shift. Before the analysis, the signals were band-pass filtered between 0.8Hz and 35Hz to reduce noise and remove the baseline. Next, the relative distribution of each pair of EGMs was extracted from two dimensional histograms with 5x5 bins. In Fig. 1 are represented examples of histograms of EGM_{LV} versus EGM_{RV} for the SR and for some arrhythmias.

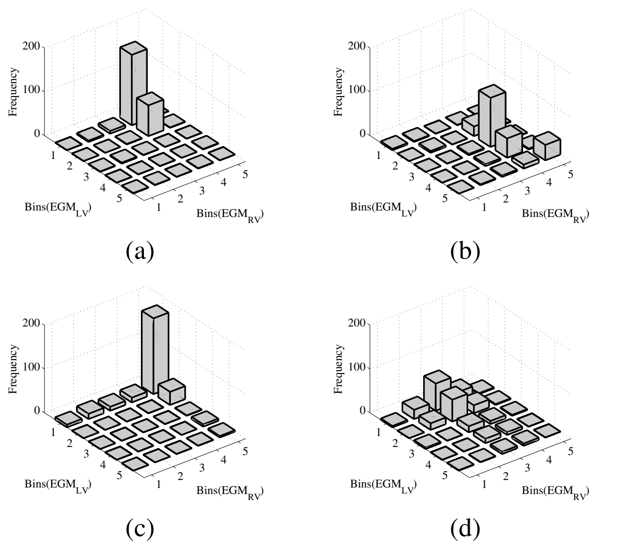

Fig. 1. Histograms representing relative distribution of EGM_{LV} and EGM_{RV} during (a) SR, (b) SVT, (c) VT and (d) VF

C. Classification

The classification was based on a decision tree using the Pearson's χ^2 statistic and the variation of the histograms. The first index was used to separate SRs and SVTs from VTs and VFs, while the second one was used to separate VTs from VFs.

The Pearson's χ^2 statistic was used to test the null hypothesis that the EGM_{LV} and the EGM_{RV}, or the EGM_{RA} and the EGM_{RV}, are independent, which is false in SRs and SVTs. The value of the test statistic χ^2 is

$$\chi^2 = \sum_{i=1}^{n_i}\sum_{j=1}^{n_j}\frac{(O_{ij}-E_{ij})^2}{E_{ij}}, \qquad (1)$$

where O_{ij} is an observed frequency, E_{ij} is the expected frequency if confirmed the null hypothesis and n is the number of possible outcomes of each event.

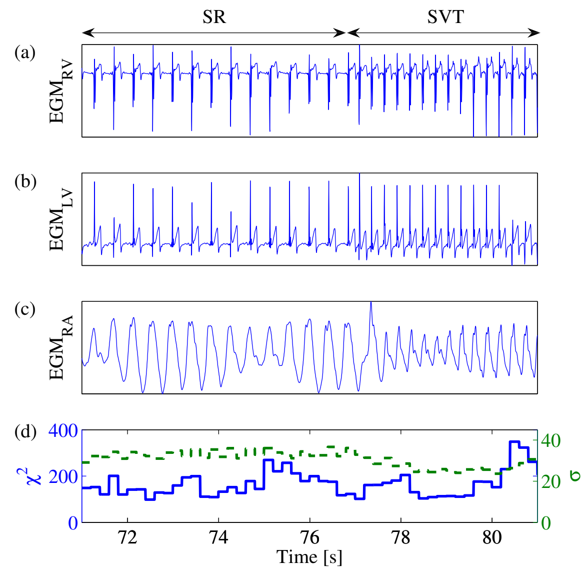

Fig. 2. Example of (a) EGM_{RV}, (b) EGM_{LV}, (c) EGM_{RA} and (d) the calculated χ^2 statistic (continuous line) and dispersion σ (dashed line) during a SVT episode.

We calculated the χ^2 using (2) approximating the joint probability distribution ($p(a_i,b_j)$) to the frequency of each bin of the histogram and the probability distribution corresponding to each EGM ($p(a_i)$ and $p(b_j)$) to the sum of the frequency of each column and each row, respectively.

$$\chi^2 = \sum_{i=1}^{5}\sum_{j=1}^{5}\frac{(p(a_i,b_j)-p(a_i)\cdot p(b_j))^2}{p(a_i)\cdot p(b_j)}. \qquad (2)$$

Next, the dispersion of the histogram of two EGMs was used to identify VFs. The dispersion of the histogram was calculated as the standard deviation (σ) of the counts in each bin of the histogram, as in (3).

$$\sigma = \frac{1}{n_a\cdot n_b}\sum_{i=1}^{n_a}\sum_{j=1}^{n_b}(p(a_i,b_j)-\mu)^2, \qquad (3)$$

where μ is the mean of $p(a_i,b_j)$.

The classification was validated using a 10-fold cross validation. The training and validation sets were separated maintaining a constant rate of 9:1 samples of each rhythm. The thresholds were interactively defined as the value that maximizes the sensitivity and the specificity of the classification of the training set.

III. RESULTS

Figs. 2, 3 and 4 show examples of EGMs and the calculated indices during the transition to a SVT, a VT and a VF episode, respectively. In the top three graphs ((a), (b) and (c)) of each figure are represented segments of EGMs acquired simultaneously from the right ventricle, left ventricle and right atrium. In the bottom graph (d) of each figure are shown the values of the indices used for the classification: χ^2-statistic and σ, extracted from the ventricular EGMs represented in the top graphs.

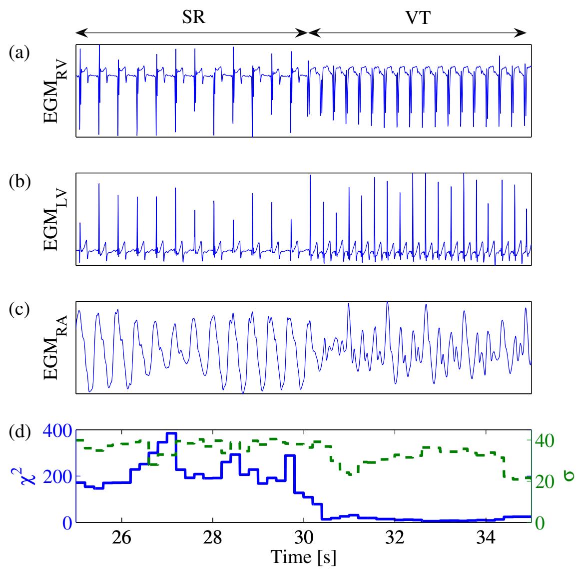

Fig. 3. Example of (a) EGM_{RV}, (b) EGM_{LV}, (c) EGM_{RA} and (d) the calculated χ^2 statistic (continuous line) and dispersion σ (dashed line) during a VT episode.

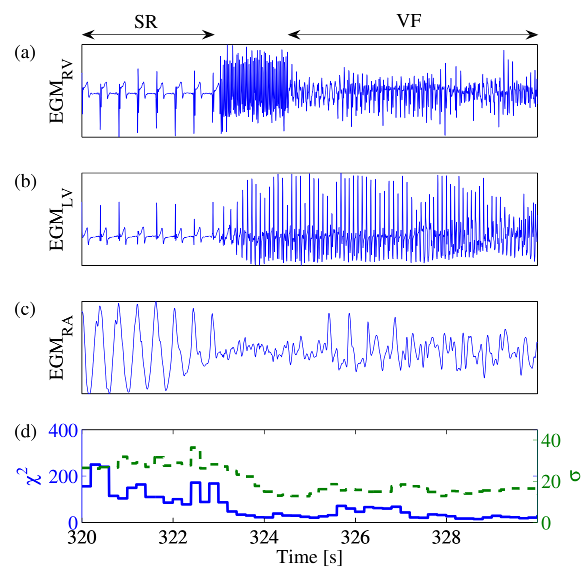

Fig. 4. Example of (a) EGM_{RV}, (b) EGM_{LV}, (c) EGM_{RA} and (d) the calculated χ^2 statistic (continuous line) and dispersion σ (dashed line) during a VF episode.

TABLE II

PERFORMANCE OF THE CLASSIFIER USING EGM_{LV} AND EGM_{RV} (VENTRICULAR ARRHYTHMIAS VS. OTHER RHYTHMS)

	VT or VF	SR or SVT
Shock	TP = 549	FP = 86
Ignore	FN = 41	TN = 1104
	Sensitivity = 93.0%	Specificity = 92.7%

TABLE III

PERFORMANCE OF THE CLASSIFIER USING EGM_{LV} AND EGM_{RV} (VT VS. VF)

	VF	VT
Shock	TP = 229	FP = 7
Pacing	FN = 10	TN = 303
	Sensitivity = 95.8%	Specificity = 97.7%

The results from the validation of the classifier are shown in Tables II - V. In the classification using both ventricular EGMs, EGM_{LV} and EGM_{RV}, the mean ($\pm$ standard deviation) threshold for the χ^2 was 76.4 ($\pm$ 1.9) and the mean threshold for the σ was 16.8 ($\pm$ 0.3). In the classification using ECGs from the right heart, EGM_{RA} and EGM_{RV}, the mean ($\pm$ standard deviation) threshold for the χ^2 was 61.1 ($\pm$ 0.9) and the mean threshold for the σ was 13.2 ($\pm$ 0.2).

The sensitivity and specificity of the classifier were calculated from the sum of the respective true positive (TP), false positive (FP), false negative (FN) and true negative (TN) of each interaction of the cross validation. The detailed results of the detection of life-threatening arrhythmias, by separating VTs and VFs from SVTs and SRs, are shown in Tables II and IV. The results of the decision of whether the ICD should apply a shock to recover from a VF, or start pacing to recover from a VT, are detailed in Tables III and V.

The results presented in Tables II and III correspond to the classification based on the EGM_{LV} and the EGM_{RV}, which are available only in biventricular ICDs. The results presented in Tables IV and V correspond to the classification based on the EGM_{RA} and the EGM_{RV}, which are available also in dual chamber ICDs.

IV. DISCUSSION

Conventional methods for the discrimination of the cardiac rhythms have a special limitation for the separation between SVTs and VTs. Studies using morphology-based algorithms have reported higher specificity and sensitivity in this detection, however it was still necessary to have a more accurate method that could fit the low computational cost requirements of an ICD [5].

In this paper, we proposed a new algorithm for the detection of arrhythmias for ICDs. On the basis of the comparison of EGMs, VF and VT were separated from SVT or SR by the comparison of the independence of the two simultaneous EGMs. It was observed that during the normal SR, and also during SVT, there was a high similarity especially between the EGM_{LV} and the EGM_{RV}, which decreased during ventricular arrhythmias. Dependencies are commonly measured using mutual information or χ^2 statistics; in this study, we

TABLE IV

PERFORMANCE OF THE CLASSIFIER USING EGM_{RA} AND EGM_{RV} (VENTRICULAR ARRHYTHMIAS VS. OTHER RHYTHMS)

	VT or VF	SR or SVT
Shock	TP = 439	FP = 318
Ignore	FN = 151	TN = 872
	Sensitivity = 74.4%	Specificity = 73.3%

TABLE V

PERFORMANCE OF THE CLASSIFIER USING EGM_{RA} AND EGM_{RV} (VT VS. VF)

	VF	VT
Shock	TP = 223	FP = 1
Pacing	FN = 26	TN = 189
	Sensitivity = 89.6%	Specificity = 99.5%

choose the χ^2 statistics due to its lower computational cost.

Once a life-threatening arrhythmia is detected, the ICD must apply a shock, if rhythm is a VF, or start pacing, if rhythm is a VT. During a VF, the EGMs have higher frequencies and are desynchronized; therefore, the dispersion of one ventricular EGM against the another is high. Using a two-dimensional histogram of two ventricular EGMs, or of two EGMs from the right heart, the dispersion was extracted from the deviation of the frequency in each of the bins.

A 10-fold cross-validation showed that the method has a high sensibility and specificity even in the separation of SVTs from VTs when using ventricular EGMs. However, EGMs of both ventricles are not usually acquired in dual-chamber ICDs. The results of the classification using EGMs from the right heart showed a poor separation of SVTs and VTs. These results are expected to be improved when accounting information from past windows. For instance, during a SVT if some isolated samples was classified as VT, the classification as a VT is probably wrong. The low standard deviation of the threshold during the cross validation reflects the stability of the chosen indices.

These results were obtained from a limited data set. The algorithm must be evaluated in more data from different conditions. The use of indices obtained from histograms has the advantage to be independent of the signal amplitude. Therefore, it is expected to be more robust, for example, to differences among patients and to patients activities.

V. CONCLUSIONS AND FUTURE WORKS

In a limited dataset, this preliminary study showed the possibility to detect life-threatening arrhythmias from the comparison of simultaneous electrograms by the extraction of the independence of electrograms using the χ^2 statistic and of the relative dispersion of electrograms using the standard deviation of their joint probability.

In future studies, other features should be extracted from the EGM_{RV} and EGM_{RA}, such as phase synchronization and delay or relative period, in order to improve the classification using EGMs from the right heart only, which would permit the application of this algorithm not only in biventricular ICDs but also in dual-chamber ICDs.

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