Methods for Intracardiac Electrogram Compression Suitable with Implantable Devices

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Abstract

Rationale: this paper studies methods for intracardiac electrograms compression suitable with implementation on implantable devices. Algorithms are based on piecewise linear approximation (PLA methods) and beat detection (Peak method).

Data set: intracardiac electrograms are obtained, from right atrium and ventricle, during electrophysiological studies. Total atrial set consists of 5060 seconds of bipolar recordings and 680 secs. of unipolar electrograms; ventricular data set contains 1210 secs. of bipolar and 480 secs of unipolar signals.

Results: Peak method clearly perrms better than the others to compress bipolar signals, while PLA methods are needed to have reliably compressed unipolar data. Performances over the whole bipolar data base (including atrial and ventricular sets) reach average compression rate CR=7.6, while first order piecewise linear approximation reaches, on unipolar electrograms, a compression ratio CR=6.6. These preliminary results show that time consuming can be reduced to suitability with real time compression on implantable devices.

Conclusion: The ability to compress and store intracardiac electrograms in implantable devices allows detailed verification of appropriate intervention of the device and it might open new perspectives in the study of the mechanisms involved in the onset of malignant tachyarrhythmias

1. Introduction

New generation of cardiac implantable devices are able to record intracardiac electrograms during peculiar heart conditions. This allows, on the one hand, to verify whether the device did the proper therapy, and on the other hand, to open a wide perspective in the analysis of intracardiac electrograms obtained in critical heart condition. Such increasing capabilities will spin off new insight in the underlying changes of the heart electrical activity nearby dramatic events such as the onset of malignant tachyarrhythmias, or will allow the monitoring of the cardiac dynamics in a more precise way since electrograms will be obtained from within the heart.

In this context, the study of methods for intracardiac electrogram compression can be used to: (i) maximize storage capabilities of the devices; (ii) choose the best compression method for the type of recording (unipolar or bipolar).

From the technological point of view, compression methods suitable with implementation on implantable devices need very small computational cost. It is known that the limitations of these devices are due to slow central process unit (CPU) clock, and small memory storage capability. Roughly, CPU clock can reach 30-50 KHz, while memory size can reach 100 – 250 Kbytes depending on the producers and the type of device [1].

2. Data set

Electrograms are obtained from patients undergoing electrophysiological (EP) study. Recordings are obtained using an EMS Mennen Digital Polygraph (by Mennen Ltd, Rehovot, Tel Aviv, Israel), and Daig – St.Jude Medical company (7F bipolar pacing catheters 1 cm electrode spacing) which allow bipolar and unipolar recordings of the intracardiac activity. Unipolar electrograms are measured between the distal electrode and a reference virtual electrode derived from the 12 surface ECG leads. Intracardiac sites are the lateral wall of the high right atrium (HRA), and the apex of the right ventricle (RV). Bipolar recordings monitor very precisely the electrical heart activity at the site, while unipolar electrograms reflect the whole cardiac activity from within the heart, thus reducing side effects such as movements or changes in the geometry [2].

Intracardiac electrograms are recorded with a sampling frequency of 1 KHz, and a resolution of 12 bits. Bipolar recordings are digitally filtered in the 40-500 or 80-500 Hz frequency band, while unipolar electrograms are filtered in the frequency band 0.2-500 Hz. Gain is adjusted to appropriate peak amplitude. For the purpose of this work, to better approximate the recording condition used by an implantable device, electrograms

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are low-pass filtered and down-sampled at 250 Hz, while resolution is reduced to 8 bits. In this study 27 patients (21 males and 6 females) are analyzed. In some patients, one or two electrocatheters are introduced and thus both atrial and ventricular activity are recorded. In Table 1 are reported the information about the considered data base which includes patients with sinus rhythm, atrial flutter and fibrillation. The Table shows the number of patients and seconds of HRA and RV electrograms, and the type of electrogram recordings which can be unipolar or bipolar.

Table 1: The data set.

Polarity	HRA		RV	
	Patients	Secs.	Patients	Secs.
Bipolar	20	5060	8	1210
Unipolar	7	680	4	480

In Figure 1 examples of intracardiac atrial and ventricular activity during sinus rhythm are shown. In both cases also surface ECG lead II is reported to allow comparison.

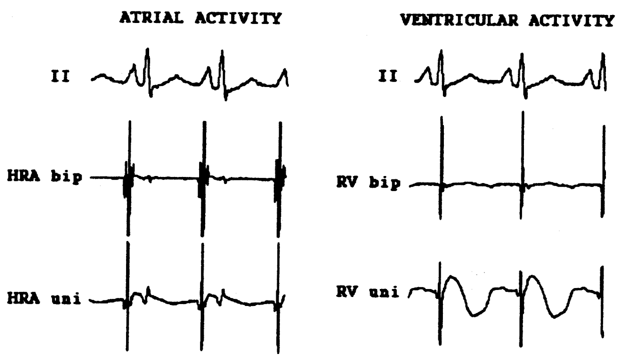

Figure 1: Left panel shows ECG lead II and the corresponding intracardiac electrogram monitored from the high right atrium as bipolar (HRA bip) and unipolar (HRA uni); Right panel shows similar recordings obtained from surface and right ventricle (RV). Both panels in sinus rhythm.

From Figure 1 it can be observed the difference between unipolar and bipolar electrograms: bipolar signals very precisely monitor the depolarization phase of cells close to the tip of the electrocatheter, while unipolar signals are more complex, and in general contain a greater amount of information about intracardiac activity. It can also be noted that unipolar electrograms obtained from high right atrium may differ significantly from those obtained from right ventricle. In the atrium the signal reflects the cardiac activity close to the electrode and a smooth far field from the ventricle which may include both ventricular depolarization and repolarization (often only depolarization is reflected). In the ventricle signal presents stronger activity and it is possible to record (as shown in Figure 1) a pattern similar to an action potential.

3. Methods and performance definition

Three methods are considered.

The first is based on peak detection (Peak) and it simply windows the ECG around each recognized peak. The window is defined by two parameters which indicate the number of points before and after the peak. Only the abscissa of each peak is stored using a long integer. Compressed electrograms are constructed by all points close to each recognized peak [3].

The second method uses a zero order piecewise linear approximation (ZOP) to compress the data. It simply suppresses each sample that differs less than a given error threshold (ε) from the last transmitted sample.

The third method is based on Scan Along Polygonal Approximation (SAPA) method, which essentially is a first order piecewise linear approximation method. The explanation of this method is not reported here, but it can be obtained from [4,5].

Reconstructed electrograms ($\hat{egm}$) are obtained by first order linear interpolation of the compressed sample points. Residual errors are defined as:

$$e(i) = egm(i) - \hat{egm}(i)$$

where *egm* is the original bipolar electrogram. Of course $\hat{egm}$ depends on the choice of the used compression method. The error introduced by the compression algorithms is quantified by the Percent Root-mean-square difference (PRD) defined as:

$$PRD = 100 * \left[\frac{\sum_{i=1}^{N} (egm(i) - \hat{egm}(i))^2}{\sum_{i=1}^{N} egm^2(i)} \right]^{1/2}$$

where egm and $\hat{egm}$ are defined above, and N is the number of electrogram points. This is a simple, mathematically convenient and widely used estimates of the error although other choices are more suitable for electrogram quality description [6]. Qualitative analysis of the compressed signals by visual inspection of the cardiologist was performed to confirm PRD reliability.

In this paper compression performances are given in terms of the compression ratio (CR):

$$CR = \frac{N}{Nc}$$

where N is the electrogram length (in number of samples) and Nc is the number of compressed samples (including abscissa and ordinate when needed). In the literature a different parameter, the compressed data rate (CDR) in bits/sec defined as:

$$CDR = \frac{F * m}{N}$$

is considered. Here m is the amount of compressed data in bits (including abscissa), F is the sampling frequency (F=250 in our case) and N is the electrogram length (in number of samples); note how N/F is the egm length in seconds, and CDR is the average number of bits to store 1 second of $\hat{egm}$. CDR is defined here to allow comparison with results obtained from the literature.

Finally, the computational cost is quantified empirically by counting the average number of operations per second (Nops) required by each compression method on the whole data base.

4. Results

In the Table 2 performances of the methods are presented.

Table 2: Performances of algorithms with the bipolar and unipolar electrograms recorded from HRA and RV sites.

Method	Variable	HRA		RV	
		Bip.	Unip.	Bip.	Unip.
	Nops	*102*	126	45	52
Peak	*PRD %*	*2.1 %*	8.5 %	1.6 %	15.8 %
	CR	6.8	5.2	10.8	9.6
	Nops	551	618	528	536
ZOP	*PRD %*	3.6 %	3.7 %	4.1 %	4 %
	CR	5.5	3.8	6.8	4.1
	Nops	2160	2318	2086	2081
SAPA	*PRD %*	3 %	3.4 %	2.9 %	3.9 %
	CR	6.2	5.1	8.3	7.7

Quantitative results indicate that Peak method is the best to compress bipolar electrograms. Qualitative analysis, by means of visual inspection of compressed signals by the cardiologist, confirms that Peak method performs very well for bipolar electrogram compression. A typical example of compressed bipolar electrogram, using Peak, ZOP and SAPA methods, is shown in Figure 2.

In the case of unipolar electrograms, although similar or better compression rates are obtained using Peak instead of SAPA, the high value of PRD % of the Peak leads to prefer SAPA (or ZOP) for unipolar signal compression. To further investigate this point, a qualitative analysis has been done. Qualitative evaluation of the compression performances using the different methods is reported in Figure 2 for a ventricular bipolar electrogram, and an atrial and a ventricular unipolar electrograms. In the Figure are shown compressed signals with the corresponding residual errors computed using the different methods (Peak, ZOP and SAPA).

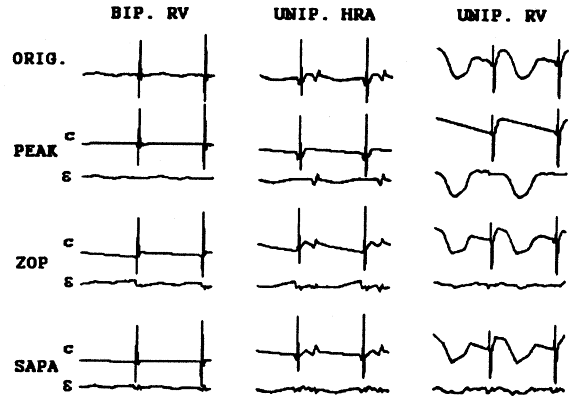

Figure 2: Typical bipolar and unipolar electrogram tracings with corresponding compressed signals (c) and residual errors (ε) obtained using Peak, ZOP and SAPA methods. Ideal compression should have a flat residual error.

In Figure 2 we have considered only the ventricular bipolar electrogram which is very similar to the atrial one. In fact the strong high pass filtering commonly used to record bipolar electrograms practically eliminates all types of slow activity and far field. In the case of bipolar signal it is very important to obtain the maximum reliability around the peak and, for this, Peak method appears to be the most efficient.

Dealing with unipolar signals the residual error ε of Peak method is dramatically high. In fact, in case of HRA electrograms, Peak method completely eliminates the smooth reflections of ventricular activity (far field), while in RV electrograms it eliminates strong part of the repolarization phase. This leads to the conclusion that Peak method is not reliable to compress unipolar electrograms.

5. Discussion

Comparison with the literature

In the literature intracardiac electrogram compression is not very widely exploited, yet. In [7] it has been applied to ventricular tachyarrhythmias (VT). The authors proposed a low-complexity algorithm whose performances appeared to be close to CDR=875 with PRD=5%. It is difficult to make a significant comparison in this case because we did not separate compression performances for the various rhythms. Thus the comparison can only be made with an average CDR obtained from the bipolar ventricular electrogram (almost all of which are sinus rhythm) which penalize results reported in [7] where they considered a tachycardia.

Anyway, this comparison shows that the CDR of the Peak method is 387 (with PRD = 2%), ZOP method is 558 (PRD = 3.7%) and SAPA method is 467 (PRD = 2.9%).

Atrial vs. ventricular electrograms

Atrial electrograms allow a lower CR with a similar PRD. This is obvious if we consider that atrial activity can be faster in patients because of supraventricular tachyarrhythmias (atrial flutter and atrial fibrillation).

Characteristics of bipolar and unipolar egms

Bipolar recordings reflect local cardiac electrical activity and they are less affected by interference than unipolar. Thus, they are commonly used for the sensing of cardiac electrical activity in all devices. Some cardio-defibrillators also define appropriate templates to compare morphologies and distinguish between supraventricular and ventricular arrhythmias obtaining an excellent specificity and sensitivity in term of diagnosis. However, strong high pass filtering and local recording, may be limits and, by sure, they reduce the amount of information that can be obtained from the whole intracardiac activity monitoring.

On the contrary, unipolar electrograms take all the cardiac activity. They are more complex, but they include much more information which is not immediately available nor obvious. At present some devices (e.g. cardioverter defibrillators - ICD) allow anti-arrhythmic therapy in very short time after the onset of a tachyarrhythmia. A research field is the analysis of signals immediately before the change of cardiac dynamics. The hope is to recognize from electrograms stored in pacemakers or ICD peculiar characteristics which may be associated with the coming rhythm transition. To this clinical target, we need to have the whole available information (about substrate and triggers) and thus we believe that unipolar signals could open new perspectives.

Compression of unipolar and bipolar electrograms

Outcome of this paper is to suggest the possibility of treating bipolar or unipolar electrograms using different compression methods. As previously mentioned, bipolar and unipolar electrograms reflect different heart characteristics, thus it is reasonable that their compression require different methods. While bipolar electrograms could be suitably compressed using the Peak method, unipolar would require SAPA algorithm (or SAPA-like algorithms) to reach optimal performances. In case the device would not have a sufficient CPU clock to allow compression in real time using SAPA method, the ZOP method could be used. This can likely be the case of a Pacemaker, while an implantable cardioverter defibrillator would probably be able to support the computational effort required by the SAPA method.

6. Conclusion

This paper is focused on algorithms for intracardiac electrogram compression suitable with implementation on implantable devices.

The data set is constituted by unipolar and bipolar electrograms obtained from the high right atrium and the right ventricle. We consider three compression methods based on peak recognition (Peak method), zero order piecewise linear approximation (ZOP method) and first order piecewise linear approximation (SAPA method). Results show that Peak method gives best performances in the case of bipolar intracardiac recordings, while SAPA (or ZOP) for unipolar signals. Peak and ZOP methods surely are suitable with the implementation on implantable devices, while SAPA still requires some larger computational effort and it might not be suitable with implementation when CPU clock is too small.

Qualitative and quantitative analysis shows that it is possible to reach good compression rate without significant changes in the signal morphology.

New insight about the underlying changes in cardiac dynamics might be obtained from unipolar electrograms stored in implantable devices since they maintain information on whole heart activity.

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