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Analysis of the robustness of spectral indices during ventricular fibrillation

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ABSTRACT

The spatiotemporal characteristics of cardiac fibrillation are often investigated by using indices extracted from the spectrum of cardiac signals. However different signal acquisition systems may produce signals of different spectra and affect the estimation of some spectral indices. In this study, we investigate the robustness of four spectral indices previously proposed for describing fibrillation, namely the dominant frequency (DF), the peak frequency (PF), the median frequency (MF) and the organization index (OI). The effects of different lead configurations on the values of the spectral indices are statistically quantified and further analyzed in a database consisting of unipolar and bipolar intracardiac electrograms (EGM), recorded by implantable cardioverter-defibrillators during ventricular fibrillation. Our analysis shows that the lead configuration significantly affects the PF, the MF and the OI, whereas the DF remains unaffected. We further explore the nature of cardiac spectrum and show that unipolar EGM concentrate power at lower frequencies than bipolar EGM. We conclude that indices that depend on the envelope of the spectrum of cardiac signals are in general sensitive to the lead configuration.

1. Introduction

Ventricular fibrillation (VF) has been traditionally described as a highly irregular and disorganized cardiac rhythm [1]. This description is motivated by the observation of VF in the electrocardiogram (ECG), in which VF lacks any discernible pattern and is characterized by irregular deflections whose frequency, amplitude and shape are continually changing. However, some studies based on spectral analysis of cardiac signals have suggested otherwise, that fibrillation is not completely chaotic and could possess a high degree of spatiotemporal organization. Early applications of spectral analysis revealed that ECG spectrum during VF has a distinct dominant frequency (DF) between 3 and 7 Hz [2], and that median frequency (MF) reflects the evolution of an episode of VF [3]. More recently, two methods based on spectral analysis have been developed for quantifying cardiac spatiotemporal organization during fibrillation. In the first method an organization index (OI) extracted from the spectrum of intracardiac electrograms (EGM) has been used to quantify atrial fibrillation (AF) organization [4]. The second method consists of computing the DF in either optical or electrical recordings to estimate the local activation rate of cardiac tissue during fibrillation. The analysis of DF maps has revealed regional differences in the atria during AF [5–7] and in the ventricles during VF [8,9], which have been interpreted as a manifestation of cardiac spatiotemporal organization. In other practical applications, spectral analysis has been used to detect ventricular tachyarrhythmias [10–13], to predict the success of the defibrillation shock [2,14–16], to characterize VF in implantable cardioverter-defibrillator (ICD) EGM [17–20] and to identify artifact events in ICD EGM [21].

The widespread use of spectral indices for describing fibrillation has motivated to further investigate their nature and their relationship to cardiac spatiotemporal characteristics. On the one hand, from a signal processing perspective it has been shown that EGM complexity and fractionation can hinder the estimation of the local activation rate during DF analysis [22]. Also, the DF and a spectral index used for quantifying EGM regularity have been analyzed in [23]. On the other hand, from a signal measurement perspective there exists the possibility that lead configuration may have an effect on the estimation of some spectral indices. For instance, it has been previously shown that during spatially correlated rhythms

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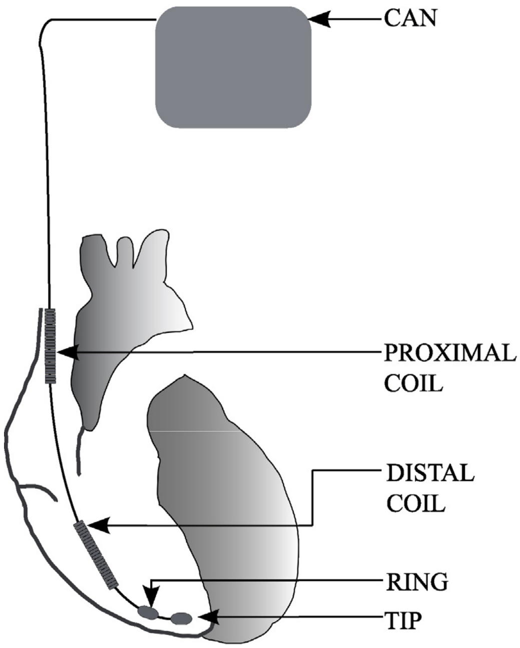

Fig. 1. ICD transvenous lead systems consist of a set of electrodes that are guided through a vein into the heart chambers (tip, ring, or distal coil) in combination with the casing of the implant (active can) and, when available, with the proximal coil.

there exists an inverse relationship between the spatial resolution of the lead system and the spectrum bandwidth [24]. Hence, signals recorded during the same cardiac episode by different lead configurations could have non-identical spectra, possibly resulting in non-robust estimations of some spectral indices.

The aim of this paper is to investigate experimentally the robustness of a family of spectral indices previously proposed for describing cardiac fibrillation. We use retrospectively a database of intracardiac EGM recorded by ICD during VF. The ICD is the primary treatment for patients at high risk of undergoing sudden cardiac death due to tachyarrhythmias and it can provide with intracardiac EGM recorded by a diversity of lead configurations during VF. In this study we use EGM recorded by ICD to analyze the effects of the lead system on the values of the spectral indices under investigation. Statistical methods allow us to quantify the robustness of each spectral index, and the effects of the lead configuration on the spectrum of cardiac signals are further analyzed.

2. Materials and methods

2.1. ICD lead system

Most current ICD monitor heart rhythm by analyzing intracardiac EGM sensed by transvenous leads, which consist of a set electrodes some of which are inserted into the heart chambers [25]. The basic set of electrodes in transvenous lead systems includes the following (Fig. 1): the tip, placed near the apex of the right ventricle; the ring, located in the proximity of the tip electrode; the distal coil, located close to the tip electrode; the proximal coil, placed in the superior cava vein; and the active can, which constitutes the casing of the ICD and is usually implanted in a left subpectoral position. The combination of two or more electrodes defines the following lead configurations:

– *Unipolar configurations*, consisting of a distal electrode (such as the tip or the distal coil) and the active can, which is connected to the proximal coil.
– *True bipolar configurations*, consisting of the tip and the ring electrodes.
– *Integrated bipolar configurations*, consisting of the tip and the distal coil electrodes.

The signal provided by the sensing leads pass subsequently through anti-aliasing filters, low-noise preamplifiers and finally it is converted to digital form by an A/D converter [26]. Additionally, since bipolar EGM are used for arrhythmia detection, EGM signals can be further processed by band-pass filtering, which attenuates the noise generated by physiological and environmental sources.

The ICD constitutes a suitable experimental framework to study the robustness of spectral indices during fibrillation. Firstly, ICD technology is widely used as the only effective therapy against VF. Therefore, ICD can provide with cardiac signals recorded in humans during VF episodes of varied etiology and termination. And secondly, ICD can provide with intracardiac EGM recorded simultaneously by unipolar and bipolar lead configurations during the same episode of VF. Hence, the effects of lead configuration on the estimation of spectral indices can be statistically quantified.

2.2. EGM database

In this study we analyzed retrospectively a database of EGM signals collected from 342 patients from Hospital Universitario Virgen de la Arrixaca (Murcia, Spain) and Hospital General Universitario Gregorio Marañón (Madrid, Spain), of which 215 were implanted Boston Scientific devices (belonging to the Contak Renewal® and Ventak Mini® families) and 127 were implanted Medtronic devices (belonging to the GEM® family).

A total of 1079 spontaneous episodes of VF were identified in the database. Each VF episode was recorded by unipolar leads, bipolar leads, or both. EGM signals were classified into four disjoint EGM groups based on the lead configuration (unipolar or bipolar) and the device manufacturer (Boston Scientific or Medtronic). Unipolar and bipolar EGM were labeled for Boston Scientific devices as U_B and B_B, respectively, and for Medtronic devices they were labeled as U_M and B_M, respectively. Bipolar B_B leads were integrated, while B_M leads were true bipolar. Additionally, it was noted that EGM from Boston Scientific devices were sampled at 200 Hz, while EGM from Medtronic devices were sampled at 128 Hz.

The episodes that were included in this study were chosen based on two criteria. Firstly, in order to prevent selection bias, only one episode from each patient was selected. And secondly, in order to minimize the variability in the statistical analysis, only episodes that were recorded simultaneously by unipolar and bipolar configurations were considered. A total of 71 devices out of the 215 Boston Scientific ICD and 78 devices out of the 127 Medtronic ICD were found to record unipolar and bipolar EGM simultaneously. As a result 149 episodes of VF were included in the analysis (71 episodes from Boston Scientific devices and 78 episodes from Medtronic devices).

2.3. Spectral indices during VF

This section describes the family of spectral indices that were analyzed, namely the DF, the peak frequency (PF), the MF and the OI. These spectral indices have been previously proposed for describing fibrillation and they are based on the assumption that fibrillation is a quasi-periodic process. In quasi-periodic signals, power distributes over a series of equidistant narrow frequency bands, i.e. harmonic frequencies (HF). This feature is illustrated for VF signals in Fig. 2(b). The separation between consecutive HF is known as the fundamental frequency (FF) and it coincides with both the first HF and with the inverse of the mean fundamental