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Application of the relative wavelet energy to heart rate independent detection of atrial fibrillation

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ABSTRACT

Background and Objectives: Atrial fibrillation (AF) is the most common sustained cardiac arrhythmia and a growing healthcare burden worldwide. It is often asymptomatic and may appear as episodes of very short duration; hence, the development of methods for its automatic detection is a challenging requirement to achieve early diagnosis and treatment strategies. The present work introduces a novel method exploiting the relative wavelet energy (RWE) to automatically detect AF episodes of a wide variety in length.
Methods: The proposed method analyzes the atrial activity of the surface electrocardiogram (ECG), i.e., the TQ interval, thus being independent on the ventricular activity. To improve its performance under noisy recordings, signal averaging techniques were applied. The method's performance has been tested with synthesized recordings under different AF variable conditions, such as the heart rate, its variability, the atrial activity amplitude or the presence of noise. Next, the method was tested with real ECG recordings.
Results: Results proved that the RWE provided a robust automatic detection of AF under wide ranges of heart rates, atrial activity amplitudes as well as noisy recordings. Moreover, the method's detection delay proved to be shorter than most of previous works. A trade-off between detection delay and noise robustness was reached by averaging 15 TQ intervals. Under these conditions, AF was detected in less than 7 beats, with an accuracy higher than 90%, which is comparable to previous works.
Conclusions: Unlike most of previous works, which were mainly based on quantifying the irregular ventricular response during AF, the proposed metric presents two major advantages. First, it can perform successfully even under heart rates with no variability. Second, it consists of a single metric, thus turning its clinical interpretation and real-time implementation easier than previous methods requiring combined indices under complex classifiers.

1. Introduction

Atrial fibrillation (AF) is nowadays a major cardiovascular challenge in the developed world [1], being the most common supraventricular arrhythmia in clinical practice and affecting approximately 1.5–2% of the general population [2]. Its prevalence increases with age, such that 3.7–4.2% of people aged between 60 and 70 years and 10–17% of those aged 80 years or older suffer from this arrhythmia [2]. By the middle of this

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century, it is estimated that AF may affect about 6.12 million people in the USA and 17.9 million in Europe [3]. Furthermore, the lack of a full understanding about its pathophysiological mechanisms makes the diagnosis and treatment of AF difficult and, often, poorly effective [4]. As a consequence, this arrhythmia constitutes a significant public health problem, thus accounting for a remarkable percentage spent on any health service in developed countries [5].

Depending on their duration AF episodes can be classified into three main groups [6]. Paroxysmal AF (PAF) is usually the first stage of the arrhythmia, where the episodes terminate spontaneously within seven days of its onset. Although many patients present very short initial episodes, they increase in frequency and duration as the arrhythmia progresses to become persistent [7]. In this stage, AF is sustained, at least, longer than 7 days and external intervention is required for its termination. Pharmacological and electrical cardioversion, as well as catheter ablation, are typical interventions to restore sinus rhythm (SR) in this kind of patients. Finally, in permanent AF, both the patient and the clinician make a joint decision to stop further attempts to restore SR, and only interventions to control the heart rate are pursued. Observational studies have shown that permanent AF is the most diagnosed arrhythmia, followed by PAF and persistent AF [2].

Regardless of its duration, when AF occurs, the electrical impulses provided by the sinus node are replaced by multiple and irregular wavefronts, which uncoordinatedly depolarize the atrial cells [8]. As a result, the typical P-waves observed on the surface electrocardiogram (ECG) are replaced by a sawtooth-like pattern, which is variable in time, shape and timing, named fibrillatory (*f*) waves [9]. Moreover, given that very high activation rates can be reached in the atria (400 per minute and above), whereas the atrioventricular (AV) node is only able to conduct some of them to the ventricles, a fast and irregular ventricular rhythm is often observed during AF [10].

These electrophysiological alterations can sometimes provoke symptoms such as palpitations, weakness, fatigue, dizziness or chest pain. However, some studies have concluded that up to 40% of AF patients [11] and up to 90% of PAF episodes [12] may be asymptomatic. Hence, AF is often found during routine physical examinations, thus leading to a delayed diagnosis. Although this arrhythmia is not a deadly disease by itself, it has been associated with a relevant reduction in the quality of life [13] and a substantial increased risk of stroke [14] and mortality [15]. Indeed, AF patients have a five-fold risk of stroke and a two-fold risk of death compared with healthy people of the same age [8]. Consequently, an early diagnosis of PAF is a priority to prevent more serious complications [16].

Although the use of long-term ECG recordings can be useful, the early identification of PAF is not an easy task. These episodes often consist of only a few beats in length, and therefore their detection by visual inspection is very time-consuming [17]. Within this context, automatic PAF detection would involve a significant advance, because it would allow real-time continuous ECG monitoring of AF. In fact, a wide variety of automatic AF detectors have been proposed during the last years. Most of them are based on detecting the aforementioned irregular ventricular rhythm by means of time, frequency and complexity metrics [17–23]. These algorithms have provided a high ability to identify long AF episodes, but they require long enough intervals (around 30 seconds), and hence they cannot deal with very short AF events. Moreover, the presence of ectopic beats often causes variations in the heart rate, thus provoking high false AF detection rates from these algorithms [17,20,22]. To reduce these problems, some recent works have complemented this ventricular rhythm analysis with information from the P-wave absence [24–26]. However, these techniques still fail to work successfully under regular ventricular rhythms. This situation is very frequent in AF during the presence of AV block as well as in ventricular or AV junctional tachycardia [24,27]. Furthermore, the use of pacemakers as well as drugs to stabilize the heart rate during AF also eliminate the ventricular irregularity inherently associated with the arrhythmia [24,27]. *Similarly, these algorithms may also be unable to properly identify SR within an irregular ventricular response, which can occur in the presence of a high number of ectopic beats* [28] *or in sinus arrhythmia* [24].

Contrarily, those methods that are only based on detecting the P-wave absence do not suffer from these problems [27]. Indeed, they only analyze the beat interval containing the atrial activity, i.e., the TQ interval, their performance being independent on the heart rate variability. However, not many algorithms working under this philosophy can be found in the literature [27,29], because their performance may be notably degraded by the presence of noise [30]. In the present manuscript a new heart rate independent algorithm to automatically detect PAF episodes is proposed. It is based on the stationary wavelet decomposition of the TQ interval for every single beat and the further analysis of the relative energy contained by each wavelet scale. Its robustness to different conditions, such as the presence of different heart rates, P-wave and *f*-wave amplitudes, regular and irregular ventricular rhythms, and noise levels, is first analyzed, making use of synthesized signals. Next, the proposed method's performance is validated by using real ECG recordings from patients of PAF as well as from other arrhythmias.

The remainder of the manuscript is organized as follows. Section 2 describes how the synthesized ECG signals were generated, as well as the databases of real recordings that will serve to test the proposed algorithm. Section 3 introduces the processing applied to the recordings as well as the algorithm for the relative wavelet energy (RWE) computation from each scale. Section 4 summarizes the obtained results, which are then discussed in section 5. Finally, section 6 presents the concluding remarks.

2. Materials

In order to provide a thorough study of the RWE ability to detect AF and SR within a wide variety of realistic contexts, several sets of synthesized signals have been generated. Different aspects that could influence the identification of SR as well as AF, such as the heart rate and its variability, P- and *f*-wave amplitude, and the presence of noise, can be managed within the synthesized recordings. The McSharry et al.'s model [31] was used to synthesize SR episodes with a sampling rate of 250 Hz. The main parameters of this algorithm were varied as a function of the developed experiments, such as will be described