Analysis of the Surface Electrocardiogram to Predict Termination of Atrial Fibrillation: The 2004 Computers in Cardiology/PhysioNet Challenge

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Abstract

Paroxysmal atrial fibrillation (AF) is self-terminating by definition, but the mechanisms by which this occurs are not well understood. Holter recordings were used to develop and test algorithms for distinguishing between AF segments that are Non-terminating (N), Terminating within a second (T), and Soon terminating (within a minute, S). From the training set, the peak frequency ranges (mean ± SD) were 4.8-6.0 (5.3±0.4) Hz for T, 4.7-6.4 (5.2±0.6) Hz for S, 4.8-7.3 (6.5±0.8) Hz for N. In 8 of 10 T recordings there was a decrease in peak frequency from the penultimate to the ultimate second and in 8 of 10 T recordings there was a decrease in peak power. The last second had a lower peak frequency for T when compared to S of the same patient in 9 of 10 patients. Between N and T we correctly classified 20 of 20 from the training set and 29 of 30 from the test set. Between S and T we correctly classified 20 of 20 from the training set and 20 of 20 from the test set.

1. Introduction

The mechanisms by which atrial fibrillation (AF) persists or terminates are uncertain. Paroxysmal or self-terminating atrial fibrillation (PAF) has been thought to be the precursor to sustained AF, although this concept has been challenged recently [1]. It is not completely known why AF is self-terminating in certain individuals and not in others, though both electrophysiologic and structural remodeling have an important role. Further, it is not known why PAF terminates at a particular moment in time, and whether the process by which termination occurs takes place gradually or suddenly. Understanding the mechanisms of spontaneous termination of PAF could be useful in developing new ways to treat this arrhythmia by promoting the necessary conditions.

Many studies have been done to determine the effects of anti-arrhythmic drugs on the termination of atrial fibrillation [2,3], but very few have looked at the specific mechanisms by which termination occurs. Our laboratory has previously used intraatrial recordings to observe both the spontaneous and procainamide-induced termination of electrically-induced fibrillation [4]. Whether increased AF organization is part of the mechanisms of termination and whether these mechanisms are reflected in the surface ECG is unknown.

It has been reported that fibrillatory activity slows prior to termination, but that might not be true in all cases [4]. It is not certain that slowing from anti-fibrillatory drugs is part of the mechanisms of termination or if it is merely an epiphenomenon. For some reentrant rhythms, slowing from drugs can prevent termination [5]. It has been shown that the frequency of the fibrillatory waves on the surface ECG is a good indicator of the average rate of AF [6]. Our lab recently demonstrated that patients with paroxysmal AF have lower-frequency fibrillatory waves than those with persistent or permanent AF [7], most likely as a reflection of electrophysiologic and structural remodeling. For the 2004 Computers in Cardiology/PhysioNet Challenge, we hypothesized that lower-frequency fibrillation might therefore be expected to terminate while higher-frequency fibrillation is expected to persist.

2. Methods

2.1. Recordings

Holter recordings from the 2004 Computers in Cardiology/PhysioNet Challenge database [8] were used to develop and test algorithms for distinguishing between non-terminating and terminating AF. These recordings were classified into three groups: AF segments that are Non-terminating (N), Terminating within a second (T), and terminating Soon (within a minute, S). The database consisted of a training set containing 30 recordings (10 N, 10 T, 10 S), and two test sets, one for distinguishing recordings that terminate within a second from non-terminating recordings (30 T or N – Challenge I), and one for distinguishing immediately-terminating recordings from recordings that will soon terminate (20 T or S –

Challenge II).

2.2. Data processing

The signals were first digitally filtered with cutoff frequencies of 1 and 50 Hz. To obtain a more robust QRS detection, we chose the channel with a lower ratio of atrial to ventricular activity. PVC and aberrant beat detection was performed by comparing the morphology of the median beat with all detected QRS complexes. The abnormal beats were zeroed out in both channels.

For QRS detection, the point of maximum negative slope was chosen as the fiducial point. An adaptive median beat was computed and a template of median beats was generated and subtracted from the original signal, resulting in a remainder ECG.

Following QRST cancellation, the power spectrum of each remainder ECG was calculated using the fast Fourier transform (FFT). We recorded the overall peak frequency in the 4 to 9 Hz band and also computed short term peak frequencies and powers for non-overlapping 30-second, 15-second, 10-second, 5-second, 2-second and 1-second segments. We looked at different time intervals to explore the time scale of AF termination and determined that along with the overall peak frequency, the 1-second intervals provided the most important information as described in the following sections.

2.3. Challenge I

To distinguish between T and N, the overall peak frequency and 1-second peak frequencies and powers were used. Based on overall peak frequency we determined regions of non-terminating, terminating and undetermined cases. From the training set, recordings with overall peak frequency greater than 6.4 Hz were classified as non-terminating. Recordings with the overall peak frequency less than 5.5 Hz were classified as non-terminating if both peak frequency and power of the ultimate second were greater than the peak frequency and power of the penultimate second. All other recordings with the overall peak frequency less than 5.5 Hz were classified as terminating. Recordings in the 5.5 to 6.4 Hz range needed some additional testing. If both the peak frequency and peak power increased from the penultimate to the ultimate second the recordings were classified as non-terminating. If there was a large peak power increase, or if the peak frequency of the last second was greater than the overall peak frequency, the recording was classified as non-terminating. All other recordings in this range were classified as terminating.

2.4. Challenge II

For the second part of the challenge we used QRST morphology matching to determine which two recordings belonged to the same patient. To distinguish between T and S the peak frequency and power of the penultimate and ultimate second were compared. If both power and frequency decreased in one recording and not in the other from the same patient, the recording with the decrease was classified as T, while the other one was classified as S. A tie was considered if both recordings from the same patient showed a decrease in only one attribute, either peak frequency or peak power in the last second, or a decrease in both attributes in the last second. If there was a tie, the peak frequency of the last second was compared between the two recordings from the same patient, and the recording with a lower value was classified as T.

3. Results

3.1. Training set – Challenge I

Peak frequency for the entire 1-minute recordings ranged from 4.8 to 6.0 (mean ± SD, 5.3 ± 0.4) Hz for the 10 T recordings compared with 4.8 to 7.3 (6.5 ± 0.8) Hz for the 10 N recordings (Figure 1). Immediately-terminating recordings had a lower overall peak frequency than non-terminating recordings (p = 0.0002).

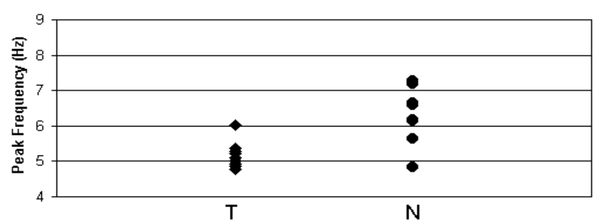

Figure 1. Overall 60-second peak frequency for 10 T and 10 N recordings.

Peak frequency for the ultimate second of the 10 T recordings ranged from 4.0 to 6.1 (4.7 ± 0.7) Hz compared with 4.1 to 6.9 (5.1 ± 0.8) Hz for the penultimate second (NS). There was a decrease in peak frequency from the penultimate to the ultimate second in 8 of the 10 T recordings. These 8 recordings showed a mean decrease of 0.7 ± 0.6 Hz, while the other 2 recordings showed an increase of 0.3 Hz and 1.1 Hz.

In 8 of 10 T recordings the peak frequency of the ultimate second was lower than the overall peak frequency with a mean difference of 0.7 ± 0.5 Hz. For 2 recordings peak frequency of the ultimate second was higher than the overall peak frequency (0.1 Hz, 0.5 Hz, respectively).

Peak power for the ultimate second of the 10 T recordings ranged from 0.16 to 7.64 (2.16 ± 2.33) mV^2 compared with 0.31 to 9.72 (3.10 ± 3.02) mV^2 for the penultimate second. There was a decrease in peak power in 8 of 10 T recordings, where the mean decrease was 1.96 ± 2.26 mV^2, and an increase in 2 recordings (2.32 mV^2 and 3.96 mV^2, respectively).

Of the 10 terminating recordings, from the penultimate to the ultimate second, 6 showed a decrease in peak frequency and power, while 4 showed a decrease in peak frequency or a decrease in power. No patient showed an increase in both parameters. In contrast, of the 10 non-terminating recordings, 5 showed a decrease in peak frequency and power, 3 showed a decrease in peak frequency or a decrease in power, while 2 showed an increase in both peak frequency and power.

3.2. Training set – Challenge II

Peak frequency for the entire 1-minute recordings ranged from 4.8 to 6.0 (mean ± SD, 5.3 ± 0.4) Hz for the 10 T recordings compared with 4.7 to 6.4 (5.2 ± 0.6) Hz for the 10 S recordings (Figure 2). The overall peak frequency was not significantly different between recordings from the same patient.

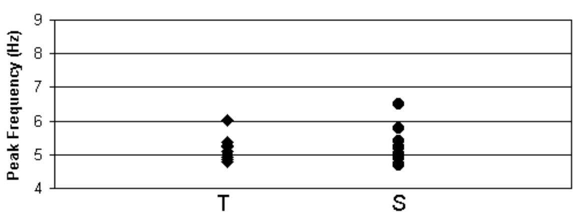

Figure 2. Overall 60-second peak frequency for 10 T and 10 S recordings.

The ultimate second for the T recording had a lower peak frequency when compared to the ultimate second of the S recording of the same patient (p = 0.001), with a difference in the range of –0.1 to 2.1 (0.9 ± 0.6) Hz (Figure 3). In 9 out of 10 patients the ultimate second peak frequency was lower in T when compared to S, with a mean difference of 0.9 ± 0.6 Hz, and greater in 1 patient (0.1 Hz).

3.3. Test sets

When criteria developed from the above findings (see Methods section) were applied to the Challenge I training set, our algorithm correctly classified 20 out of 20 recordings, as expected. From the Challenge I test set, our algorithm correctly classified 29 out of 30 recordings.

From the Challenge II data, our algorithm correctly classified 20 out of 20 recordings from the training set, and also 20 out of 20 recordings from the test set.

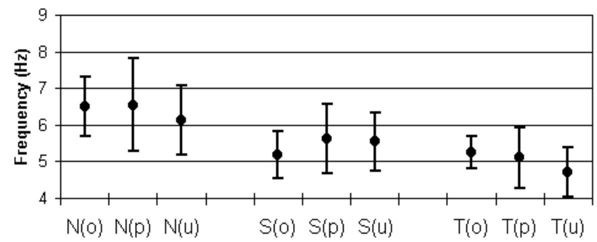

Figure 3. Overall 60-second, penultimate second and ultimate second mean peak frequencies for 10 N, 10 S, and 10 T recordings.

4. Discussion

The main theories of the mechanisms of AF initiation and maintenance include rapid firing of foci, mostly from the pulmonary veins [9], and multiple reentrant wavelets circulating within the atria [10]. It is not known if these mechanisms are mutually exclusive or if the mechanism of initiation, the mechanism of maintenance, and the mechanism of termination are the same. Based on the focal theory, slowing or complete cessation of the firing of foci and/or exit block could lead to termination. The mechanisms of these events are unknown. In the multiple circulating wavelet model, the size of the wavelets is dependent on atrial wavelength, defined as the product of conduction velocity and refractory period [11]. Shorter wavelengths result in a larger number of wavelets circulating within a given mass of atrium and therefore are associated with persistent AF. Based on the multiple circulating wavelet theory, termination could occur by either fusion or block of all wavelets [10]. One could also hypothesize theories that combine rapid foci with circulating wavelets, with combinations of the above modes of termination.

To what degree the mechanisms of termination are reflected in the surface ECG remains unclear, but the results of the Challenge, both ours and those of other groups, suggest that the ECG registers some of these events. The mechanisms of AF maintenance, including both structural and electrophysiologic remodeling, are reflected in the surface ECG [7] and these findings correctly predicted our findings from Challenge I.

As to the Challenge II findings, slowing of the rapid firing of pulmonary vein foci should result in slowing of fibrillation throughout the atria, with less fibrillatory conduction, and might result in the slowing that was seen in the surface ECG. Why the foci change their behavior is not known. It is hard to imagine why sudden exit block should result in any measurable change prior to termination. With multiple circulating wavelets, the progressive fusion could result in measurable slowing by a number of mechanisms. Increased path length due to increased refractoriness would result in slowing. In addition, since the surface ECG reflects a composite of atrial events happening in diverse anatomic locations, the composite "rate" should be slower if there are fewer wavelets.

Though slower fibrillation was prone to terminate, there seems to be some additional event confined to a short time period (on the order of one second) prior to termination. The nature of this event is unknown. Larger numbers of patients and additional clinical and/or mapping data might be required to get a better understanding of these findings.

5. Conclusion

Terminating AF can be distinguished from non-terminating AF by using surface ECG fibrillatory wave characteristics, including overall peak frequency, short term peak frequency and amplitude. Further investigation of these findings may improve our understanding of the mechanisms of termination of atrial fibrillation.

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