Stationarity of Surface ECG Atrial Fibrillatory Wave Characteristics in the Time and Frequency Domains in Clinically Stable Patients

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Abstract

Stationarity of surface ECG fibrillatory (f) wave characteristics over 24 hours in clinically stable patients was studied. Inter- and intra- patient differences of f wave characteristics (after QRS-T cancellation) in the time and frequency domains were evaluated by ANOVA. Short-term peak frequencies of all the patients ranged from 4.6 to 8.0 Hz, while one SD for each patient ranged from 0.2-0.5 Hz. The f wave amplitude of all the patients ranged from 0.02 to 0.12 mV, while one SD of the amplitude for each patient ranged from 0.001 to 0.01 mV. For these and all other parameters tested inter-patient differences were significantly greater compared to intra-patient differences (p<0.0001). This demonstration of stationarity provides a foundation for further study of the relationship of f wave characteristics to pathophysiology and management decisions.

1. Introduction

In the surface ECG, atrial fibrillation is characterized by fibrillatory (f) waves with irregular timing and morphology. If atrial fibrillation were caused by "random" reentry as traditionally described, then there would be no reason to expect any rational pattern to be discovered by studying f waves. However, some evidence shows that atrial fibrillation is not entirely random [1], but constrained by anatomic and electrophysiological factors. Moreover, atrial fibrillation has a quantifiable level of organization [2], and a band limited power spectrum [3].

There are a number of possible mechanisms for atrial fibrillation [4-5], but whether these different mechanisms are reflected in the surface ECG is unknown. However, f wave characteristics do reflect aspects of underlying physiology such as atrial cycle length and refractory period [6] and change of clinical conditions such as response to anti-fibrillatory drugs [7-8].

The untested underlying foundation of studying f waves in order to discover reflections of different mechanisms of atrial fibrillation, the effects of electrophysiological and anatomical remodeling, or drug effects, is that f wave characteristics in an individual patient are reasonably stationary during stable clinical conditions. In addition, there should be measurable differences in f wave characteristics from patient to patient. Therefore, a series of ECGs were recorded in a group of clinically stable patients over 24 hours. The f wave characteristics and their variability in individual patients compared to variability between patients were examined. If f wave characteristics are reasonability stationary for each individual, but are significantly different between patients, one could reasonably expect that, using surface ECG as an inexpensive and non-invasive means, further study of these characteristics can inform us about clinically relevant characteristics of populations or even individual patients who suffer from atrial fibrillation.

2. Methods

2.1. Subjects

Subjects were clinically stable inpatients with atrial fibrillation. Rate control medications and dosages were stable over the 24 hours during which the recordings were made. This project was reviewed and approved by the Institutional Review Board of Evanston Northwestern Healthcare. All patients gave informed consent.

2.2. Recording protocol

For each patient, ten ECGs were recorded during the 24-hour duration of the study. On the first day, the second ECG immediately followed the first, the third was five minutes after the first, the fourth was thirty minutes after the first, and the fifth was one hour after the first. On the second day, this pattern was repeated as close to the same time as the first day as clinically possible. Following the fifth recording of the first day, the locations of the electrodes were marked on the skin so that they could be placed at the identical sites on the second day.

2.3. Data pre-processing

Ten standard 10-second diagnostic ECGs (GE/ Marquette Electronics, Inc., Milwaukee, Wisconsin) were digitally recorded with a sampling rate of 250 Hz and saved on floppy disks. Analysis software was developed using Matlab (MathWorks, Inc., Natick, MA). Lead V1 was chosen for the analysis because it typically has the highest f wave to QRS-T signal amplitude ratio. PVCs and aberrant beats were manually eliminated by replacing that part of ECG with zeros. The signal was then digitally filtered with cutoff frequencies of 1 and 50 Hz.

2.4. Cancellation

F waves were isolated from ventricular components by subtracting QRS complexes and T waves from each surface ECG using a previously reported template cancellation method [9] that recently has been tested and validated [10]. Briefly, following QRS detection based on a Pan and Tompkins' algorithm [11], the point of maximum negative slope was chosen as the fiducial point. All beats were then aligned at the fiducial point to generate a median beat template. Finally, the template was aligned at each fiducial point and subtracted from the original ECG to obtain isolated f waves in the remainder.

2.5. Time and frequency analysis

The use of peak and median frequencies from the power spectrum calculated using the fast Fourier transform (FFT) has been previously described [6, 12]. However, variability of f waves in the remainder ECG might result in multiple peaks with similar amplitudes at different frequencies of the power spectrum. Therefore, to avoid an arbitrary choice of one of the peaks, time-frequency analysis was performed for all 10 ECGs for each patient using a short-time Fourier transform (STFT) method with a moving window (window length of 1 s and window moving step of 0.1 s). The short-term peak frequency (defined as the mean of peak frequencies from each STFT window over the 10-second ECG) was calculated for each ECG. This method was also shown to be robust in presence of QRS-T cancellation residuals [10].

The percent power in the 4-9 Hz frequency band of each ECG was also calculated. This parameter had previously been used for detection of fibrillation and is defined as the ratio of power in the 4-9 Hz band to the total power of the signal [13].

In the time domain, for quantifying amplitude, the regions near QRS complexes were excluded to avoid cancellation residuals, then the average value of the peak-to-peak f wave amplitude for the entire 10-second remainder ECG was taken.

Inter- vs. intra- patient differences were evaluated for all the parameters described above by performing the analysis of variance (ANOVA) with a significance level $\alpha=0.05$.

3. Results

Twenty patients in total with atrial fibrillation were included in this study resulting in 200 ECGs. The patients were 8 males and 12 females, ages 54 to 92 (77 ± 9) yrs. All patients were in atrial fibrillation at the time of each ECG during the 24-hour study.

3.1. Fibrillatory wave frequency

Similar to previous studies [3], the power spectra of all 200 ECGs had primarily band-limited characteristics with most of the energy concentrated in the 4 to 9 Hz band. Shown in figure 1 are examples of the short-term peak frequency of 10 ECG recordings of the first six patients. The 24-hour stationarity of 10 recordings can be clearly seen. Notice that, for example, all 10 ECGs from patient 4 have frequencies between 5 and 6 Hz, while patient 5 has frequencies between 6 and 6.5 Hz. It did not appear that the two recordings with the shortest time interval (i.e. ECGs 1 and 2 from day 1, ECGs 6 and 7 from day 2) were closer in frequency values than others with longer time intervals up to 24 hours.

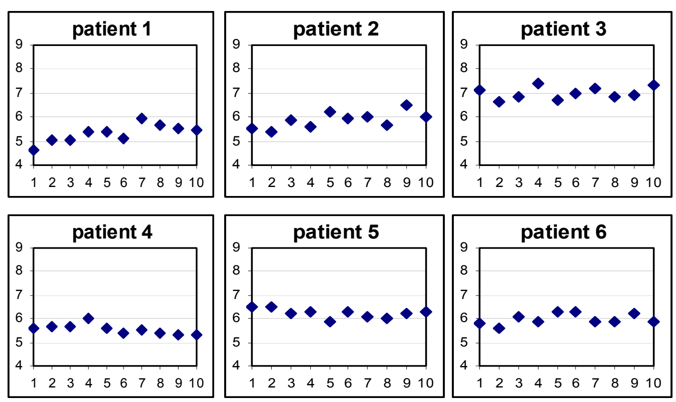

Figure 1. Examples of short-term peak frequency of 10 ECG recordings. In each panel, the horizontal axis represents the 10 ECGs with 1-5 from the 1st day and 6-10 from the 2nd day. The vertical axis represents the short-term peak frequency in Hz.

In addition, values from ECG 1-5 from each day (1 hour) and those from day 1 to day 2 (24 hours) showed no evident trend to suggest that the stationarity of these parameters changed within 24 hours in these clinically stable patients.

Shown in figure 2 is the variability of f wave frequency for each of the 20 patients. Frequency (Hz) is represented on the y-axis, and each patient is represented on the x-axis as a dot at the mean value of frequency for the 10 ECGs with a vertical line showing ± one SD. Peak frequencies ranged from 4.6-8.0 (6.1 ± 0.7) Hz. One SD of the peak frequency over 10 ECGs for each patient ranged from 0.2-0.5 Hz. Inter-patient differences were significantly higher than intra-patient differences (p<0.0001).

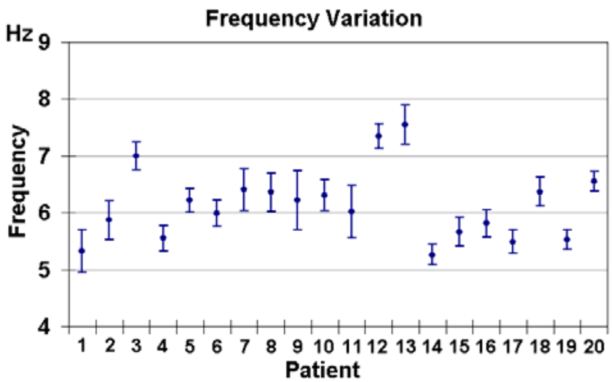

Figure 2. Short-term peak frequency variation for all 20 patients. The dots represent the mean and each vertical line represents ± one SD for each patient.

3.2. Percent power

Twenty-four hour stationarity existed also for percent power in the 4-9 Hz band. For all 200 ECGs, percent power fell in the range of 21-79 (47 ± 13) %. One SD of the percent power ranged from 4 to 10% over 10 ECGs for each patient. Again, inter-patient differences in percent power were significantly higher compared to intra-patient differences (p<0.0001). A plot of the percent power variation for the twenty patients is shown in Figure 3.

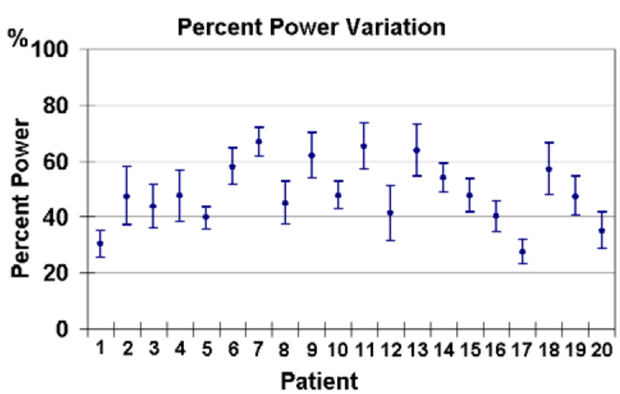

Figure 3. Percent power variation for all 20 patients. The dots represent the mean and each vertical line represents ± one SD for each patient.

3.3. Fibrillatory wave amplitude

For all 200 ECGs, f wave amplitudes varied from 0.02 to 0.12 (0.04 ± 0.02) mV, while one SD for each patient ranged from 0.001 to 0.01 mV. Again, inter-patient differences in amplitude were significantly higher compared to intra-patient differences (p<0.0001). Shown in figure 4 is the amplitude variation data displayed in a similar format to figures 2 and 3.

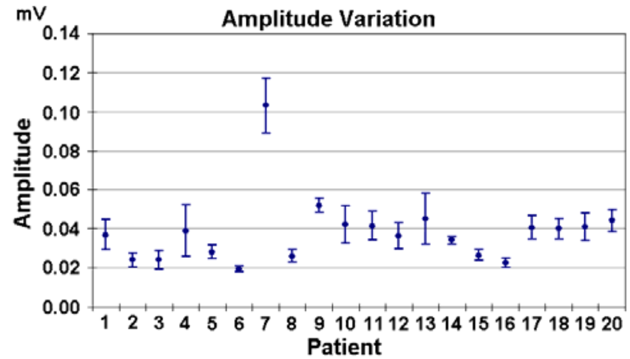

Figure 4. Amplitude variation for all 20 patients. The dots represent the mean, and each vertical line represents ± one SD for each patient.

Notice that f wave amplitude did not change greatly over 24 hours for most patients, but there was an exception. Patient 4 had a relatively large variation in f wave amplitude over the 10 ECGs. There was a change (almost double) in the f wave amplitude from the 1st day to the 2nd day without any comparable change in QRS amplitude. The f wave amplitude within the five ECGs for each day was still quite consistent. The explanation for this change from one day to the next was not apparent. Despite this variability in amplitude, the atrial rate for this patient (represented by the short-term peak frequency) was quite consistent over all 10 ECGs (see above in figure 1).

4. Discussion

In this study, fibrillatory wave characteristics were demonstrated to be stationary over 24 hours in clinically stable patients. Furthermore, significant differences in fibrillatory wave characteristics among patients were shown compared to differences over 10 ECGs of each patient. This increases our confidence that these kinds of studies will provide a better understanding of the meaning of these differences, and their relation to clinical factors, thus potentially leading to improvements in diagnosis and management. In addition, results in this study imply that a standard 10 s ECG may be enough time to characterize atrial fibrillation, at least for some purposes.

However, it was intriguing that there were some exceptions to the general finding that f wave characteristics were stationary. In no case was there an obvious clinical cause for such variability. It is possible that some patients were less "stable" clinically, at least as far as their rhythms were concerned, than was recognized.

It has become increasing evident that mechanisms of atrial fibrillation, although complex, are more organized than previously thought. This study further implies that, atrial fibrillation has explicit, distinct and measurable characteristics that belie its typically described notion of "random".

5. Conclusion

In this study, by recording and analyzing a series of 10-second ECGs of clinically stable patients in 24 hours, the stationarity of f wave characteristics in the time and frequency domains was shown. These characteristics tended to be stable in each patient, but substantially different between patients. This provides a solid underpinning for the further exploration of the relationship of such characteristics to mechanisms, pathophysiology, drug effects, or other aspects of atrial fibrillation.

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