Segregating Non-isthmus Dependent Atrial Flutter from Organized Atrial Fibrillation Using Spectral and Spatial Phase Analysis of the Electrocardiogram

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Abstract

Distinguishing atrial flutter (AFL) from 'organized' atrial fibrillation (AF) from the ECG is important for optimal therapy, yet remains difficult. We hypothesized that analyzing the temporal and spatial regularity (phase) of ECG F-waves would separate AFL, even with F-wave variability, from AF. We studied ECGs in patients with isthmus (IDAFL; n=19) and non-isthmus (NIDAFL; n=11) dependent AFL, and AF (n=7). ECG atrial activity in AFL, represented as correlations of a template to successive ECG timepoints, showed a dominant spectral peak at a frequency corresponding to the measured atrial cycle length; no distinct spectral peak was seen in AF. F-wave spatial vector, measured as the relationship of atrial correlations between axes, was more consistent in IDAFL than NIDAFL, and inconsistent in AF. Temporal and spatial phase therefore separate NIDAFL with variable F-waves from AF, and from IDAFL. This technique may help to guide the approach to ablation.

1. Introduction

Despite distinct and evolving approaches for the ablation of AF [1] and AFL [2, 3], the ECG suboptimally separates these arrhythmias prior to electrophysiologic study [4, 5]. Although studies have quantified stereotypical F-wave shapes in AFL, F-waves vary with co-existing left atrial enlargement or heart failure despite an identical arrhythmia circuit [6].

Since NIDAFL and AF lie along a spectrum of intracardiac organization [3], we *hypothesized* that careful ECG analysis will reveal regularity in timing (temporal phase) and maintenance of F-wave shape between axes (spatial phase) in NIDAFL but not AF. We tested this hypothesis in 37 cases of AFL and AF referred for ablation.

2. Methods

We studied 37 patients referred to the Arrhythmia service of the University of California (UCSD), and Veterans Administration (VA) Medical Centers, San Diego, for ablation. All studies were approved by the joint UCSD/VA Institutional Review Board for the study of Human Subjects. We studied 19 patients with IDAFL, 11 with NIDAFL and 7 with AF.

ECGs were digitized at 1 kHz and 16 bit resolution from the physiologic recorder (Bard, MA, USA) in each patient. ECG analysis of temporal and spatial phase was performed using custom software written by the authors in the *Labview* language (National Instruments, TX, USA) running under Windows 2000 on a PC.

2.1. Determining Temporal Phase

First, an atrial waveform (e.g. F-wave) was sampled using a 120 to 200ms template. F-wave periodicity in the ECG was extracted from a series of its correlation values to the ECG over time. Each correlation value was computed using the Pearson's coefficient on M pairs of data $\{A_{k+i}, B_{j+i}\}$ from a given ECG lead, where A_{k+i} is the template (duration, M data points, and ECG start position L) and B_{j+i} is the ECG sample of duration M selected for successive time ECG intervals, as follows:

$$r_j = \frac{M(\sum_{i=1}^{M} A_{k+i}B_{j+i}) - \sum_{i=1}^{M} A_{k+i}\sum_{i=1}^{M} B_{j+i}}{\sqrt{[M\sum_{i=1}^{M} A_{k+i}^2 - (\sum_{i=1}^{M} A_{k+i})^2][M\sum_{i=1}^{M} B_{j+i}^2 - (\sum_{i=1}^{M} B_{j+i})^2]}}$$

where r_j, is the correlation coefficient value at the j^{th} ECG time point, $1 \le j \le$ Q-M-1, Q is the last ECG point; also $L \le k \le$ L+M-1, L is the first template point, $1 \le L \le$ Q-M. Fig. 1 shows the correlation time series in a case of IDAFL.

Precise regularity in intracardiac timing should maintain temporal phase on the ECG, resulting in a dominant spectral peak. We computed Fast Fourier Transforms on 8.192 seconds (2^{13} data points) of each ECG, as well as on the time series of correlation values of the F-wave template to its ECG.

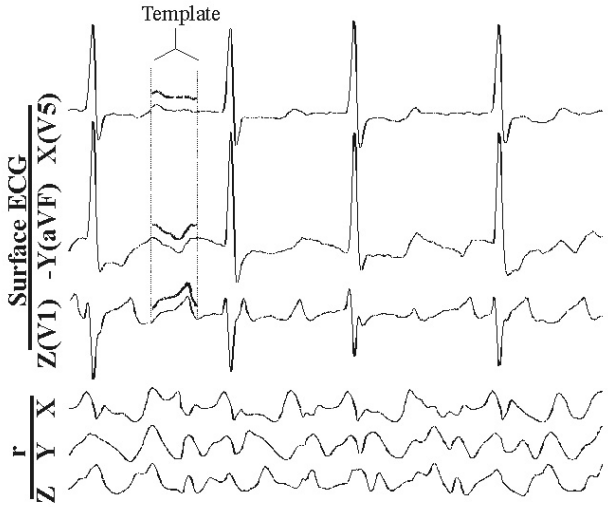

Figure 1. In NIDAFL, F-wave templates for each ECG lead are correlated to its ECG at successive timepoints. The resulting correlation time series for each lead reflect atrial activity, with F-waves recurrence depicted by $r \approx 1$, even when F-waves are superimposed on QRS complexes.

Fig. 2A shows a typical broadband ECG spectrum of NIDAFL (same patient as fig. 1); the atrial filtering that results from correlation series emphases atrial components in correlation spectra (fig. 2, lower panel).

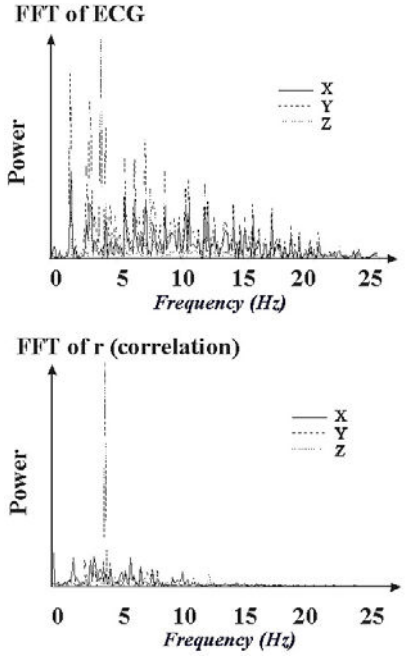

Figure 2. In a case of NIDAFL Top. ECG Spectrum shows broadband spectra that is significantly narrowed in Bottom. Correlation Spectrum, where the 'atrial filtering' results predominantly in an atrial component at a frequency that corresponds to the atrial cycle length of NIDAFL.

We defined maintained temporal phase (*coherence*) as atrial peak magnitude $\geq$ 6 dB compared to 2 harmonics on either side, in ECG or correlation spectra. Fig. 2 Bottom, but not 2 Top, exhibits temporal coherence.

2.2. Determining Spatial Phase

F-wave vector consistency from cycle-to-cycle was determined by assessing whether F-wave correlation-time series maintained a fixed relationship relative to each spatial axis (i.e. *spatial phase*). For the XY plane, this required plotting X- versus Y- correlation values at each time point; similarly for YZ and XZ planes. Fig. 3 shows that loops for NIDAFL (same patient as figs 1,2) maintained spatial phase (*coherence*) in the XY plane, since loops are reproducible, lie parallel to the line of identity and approach the point (0.8, 0.8) signifying that F-waves recurred in each axis simultaneously.

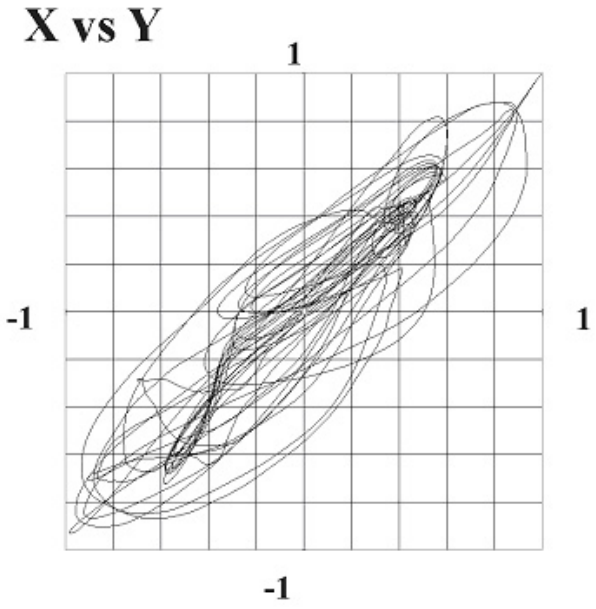

Figure 3. Spatial Correlation Loops (XY plane) in NIDAFL showing reproducible loops approaching the (1,1) point. This implies that F-waves recurred simultaneously in the X and Y axes on each cycle.

3. Results

At EPS, all diagnoses were confirmed by mapping, activation sequence and concealed entrainment. All cases of AFL and NIDAFL were successfully ablated. ECG temporal and spatial phase analyses successfully separated NIDAFL from AF (and from IDAFL) and are summarized below.

Rhythm	Spectral Peak $\geq$ 6 dB	Peak Frequency / Hz	Spatial Coherent Loops
IDAFL (*n*=19)	19/19	3.96$\pm$0.56	19/19 All planes
NIDAFL (*n*=11)	11/11	3.99$\pm$0.86	11/11 Up to 1 plane
AF (*n*=7)	0/7	Broadband	No planes

3.1. Temporal Phase

A predominant spectral peak of magnitude $\geq$ 6 dB was seen in spectra in all cases of NIDAFL and IDAFL (table), reflecting atrial waveform regularity (*temporal coherence*). In IDAFL temporal coherence was present in ECG and correlation spectra. In NIDAFL, it was typically present only in correlation spectra, with significant additional components in ECG spectra. Conversely, AF spectra (ECG and correlation) were broadband (both >10 Hz; fig. 4).

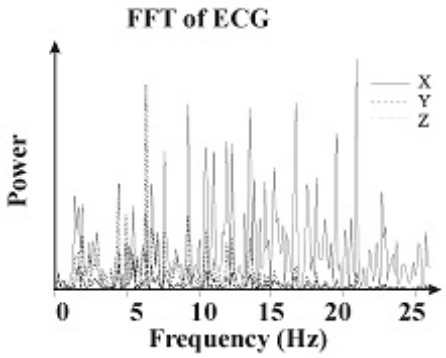

Figure 4. ECG Spectra in AF showing lack of temporal coherence with broadband spectra (>10 dB) and no predominant peak. Similar results were seen for correlation spectra.

3.2. Spatial Phase

Spatial phase was partially maintained in all cases of NIDAFL, such that correlation loops showed reproducible loops that approached (1,1) in up to one plane, often the XY plane. This is shown in fig. 3. Conversely, spatial correlation loops in AF were not coherent in any plane (fig. 5), were space filling and irregular.

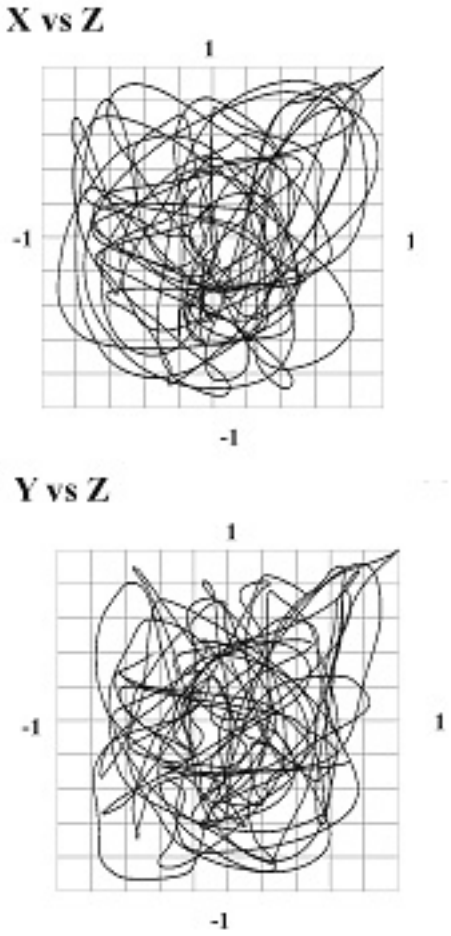

Figure 5. Spatial Correlation Plots of AF, showing irregular and non-reproducible activity between planes (XZ, YZ shown). This indicates that successive cycles trace different spatial vectors.

4. Discussion

This study demonstrates that NIDAFL is reliably separated from AF using the ECG by analyzing whether atrial waveforms maintain regular timing (*temporal coherence*) and regular spatial vectors of activation (*spatial coherence*) between cycles. The algorithm underlying this analysis perform 'feature extraction' such that F-waves are detected and quantified even when superimposed on QRS complexes. This technique can help select candidates for medications versus ablation, and may also help guide the approach to ablation. The result that NIDAFL demonstrates spatial coherence only in one plane, as opposed to three dimensions in IDAFL, supports the concept that IDAFL, NIDAFL and AF lie on

an organizational spectrum, but also sheds potentially important mechanistic insights into NIDAFL, AF and their transitions that must be confirmed on detailed study.

The predominant spectral peak of NIDAFL confirms the intra-atrial regularity seen at EPS prior to ablation. However, the lack of such a peak on ECG spectra and the presence of spatial coherence only in up to one plane (table), compared to IDAFL, suggests wavefront variability. This has not been reported before, and may enable a definitive diagnosis between IDAFL and NIDAFL from the EDCG. Furthermore, this observation may explain transitions between NIDAFL and AF, while the more precise diagnosis may enable the better selection of therapy for these entities.

It is well known that the activation wavefronts of AF are multiple [7] and variable. This is reflected by the broadband spectra and space filling loops in AF. Since AF itself represents an organizational spectrum that relates to the ease of cardioversion [8] and chronicity [9], it remains to be studied whether AF patients with narrower band spectra will better respond to attempts to maintain sinus rhythm [10].

5. Conclusions

Temporospatial phase analysis reliably separates NIDAFL, even with F-wave variability, from AF. The method performs 'feature extraction' to detect atrial activity even when superimposed on QRS and T complexes. This analysis may help improve the ECG diagnosis of complex atrial arrhythmias and may guide the approach to ablation or predict the successfulness of anti-arrhythmic medications in maintaining sinus rhythm.

Acknowledgements

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