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Computational method for high resolution spectral analysis of fractionated atrial electrograms

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ABSTRACT

Background: The discrete Fourier transform (DFT) is often used as a spectral estimator for analysis of complex fractionated atrial electrograms (CFAE) acquired during atrial fibrillation (AF). However, time resolution can be unsatisfactory, as the frequency resolution is proportional to *rate/time interval*. In this study we compared the DFT to a new spectral estimator with improved time-frequency resolution.
Method: Recently, a novel spectral estimator (NSE) based upon signal averaging was derived and implemented computationally. The NSE is similar to the DFT in that both estimators model the autocorrelation function to form the power spectrum. However, as derived in this study, NSE frequency resolution is proportional to $rate/period^2$ and thus unlike the DFT, is not directly dependent on the window length. We hypothesized that the NSE would provide improved time resolution while maintaining satisfactory frequency resolution for computation of CFAE spectral parameters. Window lengths of 8 s, 4 s, 2 s, 1 s, and 0.5 s were used for analysis. Two criteria gauged estimator performance. Firstly, a periodic electrogram pattern with phase jitter was embedded in interference. The error in detecting the frequency of the periodic pattern was determined. Secondly, significant differences in spectral parameters for paroxysmal versus persistent AF data, which have known dissimilarities, were determined using the DFT versus NSE methods. The parameters measured were the dominant amplitude, dominant frequency, and mean spectral profile.
Results: At all time resolutions, the error in detecting the frequency of the repeating electrogram pattern was less for NSE than for DFT ($p < 0.001$). The DFT was accurate to 2 s time resolution/0.5 Hz frequency resolution, while the NSE was accurate to 0.5 s time resolution/0.05 Hz frequency resolution. At all time resolutions, significant differences in the dominant amplitude spectral parameter for paroxysmal versus persistent CFAE were greater using NSE than DFT ($p < 0.0001$). For three of five time resolutions, the NSE had greater significant differences than DFT for discriminating the dominant frequency and mean spectral profile parameters between AF types.
Conclusions: The results suggest that the NSE has improved performance versus DFT for measurement of CFAE spectral properties.

1. Introduction

Complex fractionated atrial electrograms (CFAE) are generally recorded with a bipolar contact electrode, and contain either multiple deflections without interruption, a baseline perturbation with continuous deflection, or a cycle length ≤ 120 ms that include isoelectric intervals between deflections [1]. Recently it has been suggested that CFAE can be useful to detect and localize arrhythmogenic regions in atrial fibrillation (AF) patients, with the potential to guide radiofrequency catheter ablation for prevention of arrhythmia recurrence [1,2]. Alternatively, widespread ablation of CFAE may have a debulking effect, reducing the overall arrhythmia substrate [3]. These conflicting possibilities suggest the need to characterize more completely the morphologic and frequency content of CFAE. In patients with short paroxysmal episodes of AF, CFAE morphology as measured by the amplitude, slope, and width of electrogram deflections, and by linear prediction, tends to be highly variable, as compared with electrograms acquired from patients with longstanding persistent AF [4,5]. Similarly, the frequency spectra of CFAE from paroxysmal AF patients appear more random as compared with CFAE from persistent AF [6]. Although both time and frequency domain methods have therefore been helpful to characterize the AF substrate, they do not necessarily have equal robustness. When electrogram amplitude varies randomly, time-domain methods lose performance, while frequency-domain methods remain stable [7]. Therefore spectral analysis may have special efficacy for characterizing these signals.

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Recent work has suggested that ablation of high dominant frequency (DF) areas may be assistive in preventing AF reinduction in both paroxysmal and persistent AF patients [8]. Although it is desirable to measure high DF components in order to target arrhythmogenic regions, such components are often quasi-periodic and exhibit phase jitter and drift [9]. Furthermore, there can be subtle changes in frequency, on the order of 0.1 Hz, depending upon recording location and type of intervention [10,11]. The frequency resolution of the discrete Fourier transform (DFT), commonly used for analysis of atrial electrograms, is dependent upon *rate/time interval*. For the 1 kHz sampling rate and 8 s interval that is typical for analysis of atrial electrogram sequences [12], the DFT frequency resolution is 0.125 Hz. At this time and frequency resolution, measurement of subtle properties of atrial electrograms can be inaccurate. In this study, a novel spectral estimator (NSE) with frequency resolution dependent upon *rate/period*^{2} is compared to the DFT by measuring electrogram spectral properties. We hypothesized that the NSE would provide improved time resolution while maintaining satisfactory frequency resolution for computation of CFAE spectral parameters.

2. Method

2.1. Clinical data acquisition

Atrial electrograms were recorded in 19 patients referred to the Columbia University Medical Center cardiac electrophysiology laboratory for catheter ablation of AF. Acquisition of electrogram recordings was approved by the Institutional Review Board and they were analyzed retrospectively for this study. Nine patients had clinical paroxysmal AF with normal sinus rhythm as their baseline cardiac rhythm. AF was induced by burst pacing from the coronary sinus or from the right atrial lateral wall, and continued for at least 10 min prior to data collection. Ten other patients had longstanding persistent AF without interruption for several months to many years prior to catheter mapping and ablation. Bipolar atrial mapping was performed using a NaviStar ThermoCool catheter, 7.5F, 3.5 mm tip, with 2 mm spacing between bipoles (Biosense-Webster Inc., Diamond Bar, CA, USA). Electrograms were acquired using the General Electric CardioLab system (GE Healthcare, Waukesha, WI), and filtered at acquisition from 30–500 Hz with a single-pole bandpass filter to remove baseline drift and high frequency noise. The filtered signals were sampled at 977 Hz and stored. Although the bandpass high end was slightly above the Nyquist frequency, negligible signal energy resides in this range [13]. Only signals identified as CFAE by two cardiac electrophysiologists were included for retrospective analysis. CFAE recordings were obtained from two sites outside the ostia of each of the four pulmonary veins. Recordings were also obtained at two left atrial free wall sites, one in the mid-posterior wall, and another on the anterior ridge at the base of the left atrial appendage.

2.2. CFAE data structure

A total of 204 recording sequences of length greater than 16 s, acquired from both paroxysmal and longstanding persistent AF patients, and all meeting the criteria for CFAE, were selected for analysis. DFT and NSE power spectra were computed in the standard electrophysiologic frequency range from 3–12 Hz. The time windows over which spectra were calculated were 8192, 4096, 2048, 1024, and 512 sample points (approximately 8s, 4s, 2s, 1s, and 0.5 s). Binary step changes in window length were used so as to be maximally compatible with the DFT method. The upper limit of 8192 points is considered the optimal time window [12]. The lower limit of 512 sample points is the theoretical minimum to analyze 3 Hz content, which has a period of 977 samples per second/3 per second = 325 sample points for this data. The next binary step at 256 sample points would not extend the entire period of 3 Hz frequency content. Rectangular windowing was used to extract segments for analysis, as unlike other window functions, it does not diminish frequency resolution [14]. For the DFT calculation, the 4096, 2048, 1024, and 512 sample point analysis windows were padded with zeros to 8192 points. For conformity, all DFT and NSE analyses were done using the same 8192 sample point intervals of data. Thus, at the 4096 time resolution level, spectra were generated for two successive 4096 point windows and then averaged, and similarly four 2048 point windows, eight 1024 point windows, and sixteen 512 point windows were averaged for the 2048, 1024, and 512 time resolution levels, respectively.

2.3. Digital power spectra

The DFT power spectrum was constructed using a radix-2 implementation [15]. The NSE power spectrum was constructed as follows [13]. In all equations, underscore denotes a vector, a capital letter signifies a matrix, and the first subscript gives the dimensionality of the vector or matrix. A vector $\underline{e}_w$ of dimension $w \times 1$ was calculated by averaging n successive segments of an $N \times 1$ dimensional signal $\underline{x}_N$, where $\underline{x}_N$ is a CFAE signal normalized to mean zero and unity variance prior to analysis. Each segment $\underline{x}_{w,\ i}$ of this signal, of dimension $w \times 1$, is used for averaging:

$$\underline{e}_w = \frac{1}{n}\sum_i \underline{x}_{w,i}, \quad i = 1 \text{ to } n \tag{1}$$

where:

$$\underline{x}_N = \begin{bmatrix} \underline{x}_{w,\,1} \\ \underline{x}_{w,\,2} \\ \vdots \\ \underline{x}_{w,\,n} \end{bmatrix} \tag{2}$$

The process described by Eqs. (1) and (2) is illustrated in Fig. 1. A selected CFAE, signal $\underline{x}$, is graphed from discrete sample point 1 to 1000. Let $w = 250$ sample points. Segments $i = 1$–4 are noted below $\underline{x}$, and they are the signal segments $\underline{x}_{w,i}$ for $w = 250$. When the four segments shown are averaged together, the result is depicted at the bottom of the figure. Any periodicity at $w = 250$ will be reinforced in the sum, while random components will diminish. Even in the presence of phase jitter, quasi-periodic components will be reinforced [16]. For a signal $\underline{x}_N$ of length N, the total number of signal segments, and therefore the total number of summations used for

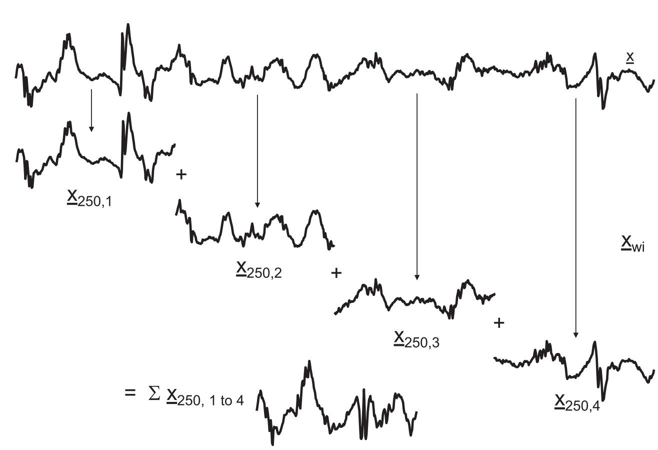

Fig. 1. Process of segment extraction and addition using a complex fractionated atrial electrogram. When the separate segments of length *w* are added, the result of summation is shown by the trace at the bottom of the figure.