Removing Ventricular Far Field Artifacts in Intracardiac Electrograms during Stable Atrial Flutter using the Periodic Component Analysis – Proof of Concept Study

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Abstract. *Post-ablation atrial flutter (AF) is a frequently occurring arrhythmia after treatment for persistent atrial fibrillation. However, mapping the flutter circuit using intracardiac electrograms is often challenging due to low signal voltage and scar areas caused by prior substrate modification. In addition, signals are frequently compromised by ventricular far field (VFF) artifacts, which obscure atrial activity (AA). This work introduces a new approach for VFF removal, which is based on the Periodic Component Analysis (πCA). It utilizes the stable temporal relationship between AA and VFF, which poses a problem for other techniques like Principal Component Analysis (PCA) when both components superpose. A benchmark using simulated electrograms demonstrated significantly better correlation for this case when comparing pure AA to the reconstructed data using πCA instead of PCA (0.98 vs. 0.90, p<0.001). Its benefit for diagnosis is demonstrated on clinical data.*

Keywords: Intracardiac Electrograms; Ventricular Far Field; Periodic Component Analysis; Atrial Flutter; Signal Processing

1. Introduction

Atrial flutter (AF) following catheter ablation of atrial fibrillation (AFib) poses a major problem since it occurs in about 36-40 % of cases and is highly symptomatic due to dominant 2:1 conduction [1]. For diagnosis, atrial activity (AA) is the most important component of intracardiac electrograms (EGM), since it indicates the flutter circuit. However, scars from previous ablation and low amplitude signals make diagnosis difficult. Also significant ventricular far field (VFF) can obscure AA if EGMs are measured close to the mitral valve.

Various techniques have been suggested to remove VFF artifacts during AFib, like Template Matching and Subtraction [2] or Principal Component Analysis (PCA) [3].

This is the first work known to the authors introducing the Periodic Component Analysis (πCA) as a new method for VFF removal in AF, in which it utilizes the stable dynamic pattern of cardiac excitation for optimized signal filtering.

2. Available data and methods

Simulated electrograms

In total 1200 signals s_{comp} of length 5s were simulated, containing both AA and VFF (compare Fig. 1 (a-c)). Flutter cycle length (FCL) was chosen to be 280 ms and 200 ms for 2:1 and 3:1 conduction rate, respectively [1]. RR intervals were varied within the signals to mimic variability in atrioventricular conduction time. A time shift between VFF and AA was introduced to simulate recordings at 6 different phases of the flutter circuit, including both simultaneously (S, as in Fig. 1 (c)) and non-simultaneously (NS) occurring VFF and AA.

Clinical signals

A clinical signal recorded during stable atrial flutter (FCL 330 ms, rate 2:1) was selected for demonstration. Data was acquired during activation time mapping using a 10 pole circular mapping catheter (Optima, St. Jude Medical, St. Paul, MN, USA), in connection with the EnSite Velocity electroanatomical mapping system (St. Jude Medical). It was filtered by the mapping system (30-250 Hz) and exported for a continuous segment of 7.9 s (sampling rate 2034.5 Hz) with stable catheter position close to the inferior mitral valve annulus.

Principal Component Analysis

PCA was used in previous works to remove VFF in both AFib and AF [3]. It was applied on a matrix of segmented VFF to identify eigenvectors accounting for at least 90 % of the total variance. These were expected to primarily contain VFF and subsequently neglected when reconstructing the signal s_{PCA}, resulting in pure AA without VFF. Since this approach relies on the statistical independence of atrial and ventricular depolarization, its applicability during stable AF is questioned as atrial and ventricular activities are temporarily coupled in this case.

Periodic Component Analysis

The general concept behind πCA is to find an optimal mixing vector **w** for the linear combination $s(t)=\mathbf{w}^T\mathbf{x}(t)$ of input signals **x**(t), which maximizes the periodicity of the output signal s(t) for a given period of τ. This can be formulated as minimizing the measure

$$\epsilon(\mathbf{w},\tau)=\frac{\sum_t |s(t+\tau)-s(t)|^2}{\sum_t |s(t)|^2}=2\left(1-\frac{\mathbf{w}^T C_{xx}(\tau)\mathbf{w}}{\mathbf{w}^T C_{xx}(0)\mathbf{w}}\right) \quad \text{with} \quad C_{xx}(\tau)=E_t\left\{\mathbf{x}(t+\tau)\mathbf{x}(t)^T\right\}$$

and solved using the Rayleigh-Ritz theorem [4]. The mixing vector **w** corresponds to the eigenvector of the largest generalized eigenvalue of the matrix pair $\{C_{xx}(\tau),C_{xx}(0)\}$.

In the context of VFF removal, the desired output signal $s\pi_{CA}=s(t)$ is given by pure AA, repeated periodically with FCL. Since VFF is caused by ventricular depolarization, all samples recorded during the QS time t_{QS} might be compromised by VFF. Therefore the compromised EGM channel s_{comp} is combined with a set of N additional channels to form the input signal matrix **x**(t), where N corresponds to the number of samples recorded during t_{QS}. Single Dirac pulses are placed synchronously to the ventricular depolarization in each new channel, see Fig. 1 (e). No Dirac pulses are placed outside t_{QS}, so that pure AA cannot be altered by the linear combination. Consequently, πCA is supposed to determine the optimal vector **w,** which enables us to uncover the periodic component of AA by weighting the additional channels to form an inverse VFF template.

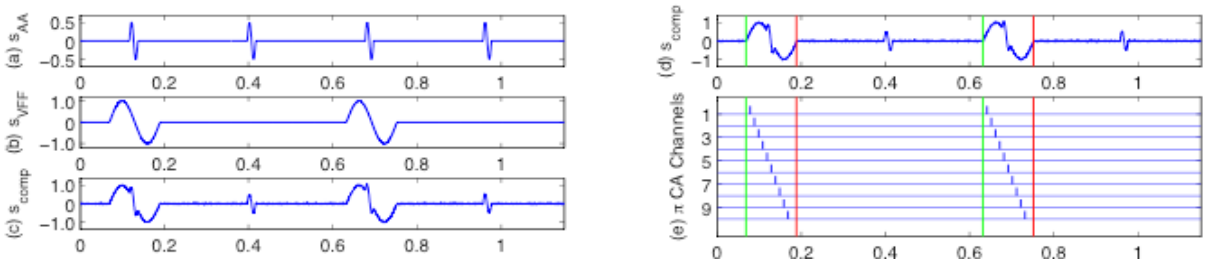

Fig. 1. Composition of simulated signals and additional channels for application of πCA. Simulated signals s_{comp} (c) are composed of pure AA s_{AA}(a), ventricular far field s_{VFF} (b) and noise. AA and VFF can superpose (S) or occur non-simultaneously (NS). For πCA application, additional channels (e) are added to form the πCA input matrix **x**. Each channel contains Dirac pulses placed synchronously to the ventricular depolarization only during t_{QS} (indicated by vertical lines). Amplitudes in mV, time in s.

Performance evaluation

Correlation coefficients between s_{AA} and signals s_{comp}, s_{PCA} and $s\pi_{CA}$ were computed. Statistics were generated considering both types S and NS. White Gaussian noise (σ_n=0.02 mV) was added to each signal. Statistical values were computed as μ±SD. Statistical significance was evaluated using the one-sided paired t-test at a significance level of 0.01, after Gaussian-like distribution of the data was confirmed.

3. Results

The result of filtering compromised signals of type S using both PCA and πCA is depicted in Fig. 2 (a-c). While AA was recovered using πCA, its morphology was deformed when PCA was applied. The same result can be observed in the clinical signal in parts (d-f), where the VFF preceding the atrial component was successfully removed by πCA.

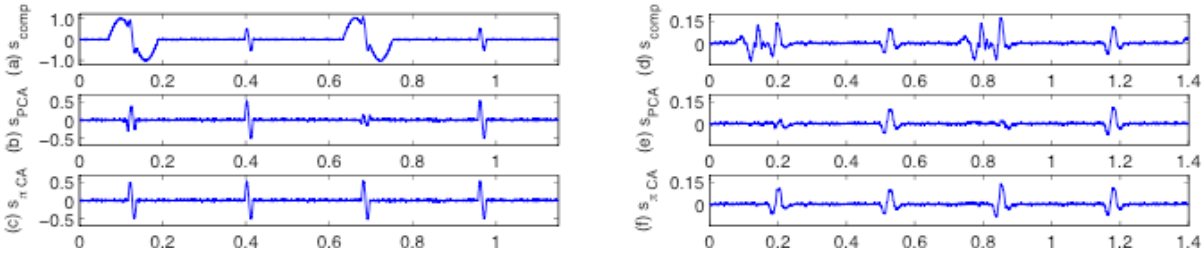

Fig. 2. Removing VFF artifacts using PCA and πCA. Each signal contains four atrial activations with the first and third compromised by VFF. Filtering the simulated signal (a) using PCA resulted in changes to AA morphology (b), while it was retained when applying πCA (c). Measured clinical signal with biphasic VFF preceding AA (d). Using PCA, every second AA complex was removed since it was synchronous to the VFF (e). Application of πCA yielded reasonable results (f). Amplitudes in mV, time in s.

Since the ground truth was known for simulated data, correlation coefficients were computed as measure of performance and are provided in Table 1. Similar results were obtained for both rates 2:1 and 3:1. Averaging over both, difference between PCA and πCA was significant for type S (0.98 vs. 0.90, $p<0.001$), but not for NS (0.98 vs. 0.98, ns).

Table 1. Statistics of correlation coefficients between s_{AA} and s_{comp}, s_{PCA} and $s_{\pi CA}$ filtered data.

Signal	Compromised Signal		Filtering using PCA		Filtering using πCA	
Type	S	NS	S	NS	S	NS
Rate 2:1	0.26±0.07	0.27±0.00	0.88±0.04	0.98±0.00	0.98±0.00	0.98±0.00
Rate 3:1	0.33±0.05	0.30±0.03	0.91±0.03	0.96±0.04	0.98±0.00	0.98±0.00

4. Discussion

Qualitative and quantitative benchmarking

Initial average correlation coefficient between s_{AA} and s_{comp} was strongly improved by both filtering methods. However, πCA performed better than PCA on global average over all types (0.98 vs. 0.93) and significantly for superimposed AA and VFF. This is in agreement with the assumption for PCA, that simultaneous AA would be considered part of VFF and thus be removed, while AA would not be affected when occurring non-simultaneous to VFF.

Impact on clinical signal processing
VFF artifacts can obscure diagnostically relevant atrial activity in uni- and bipolar EGMs. πCA seems to provide a new mean of removing VFF, requiring only the time of ventricular depolarization (which can be determined from QRS position) and the atrial activation rate (derived from coronary sinus activity). Thus no manual settings are required.

Limitations and future goals
Further work should include more realistic templates for AA and VFF, or realistic simulations using cardiac excitation models. However, impact of this aspect on benchmarking results seems limited. It is important to note that πCA relies on stability of AA and VFF morphology.

Conduction rates were set to 2:1 or 3:1, but might also be varying in clinical practice. Considered RR interval dynamics ranged 560±6.7 ms and 600±6.6 ms, respectively.

Additional channels for πCA were formed using periodic Dirac pulses. Other functions like the Gaussian bell or the Mexican hat wavelet might be applicable as well. They could potentially reduce the number of basis functions needed for VFF cancellation.

5. Conclusions

Periodic Component Analysis (πCA) was shown to be a suitable new method to remove VFF artifacts by utilizing the stable dynamics of atrial flutter. Comparison with Principal Component Analysis (PCA) on simulated data yielded statistically significant superior performance (correlation of 0.98 vs. 0.90, $p<0.001$) for superimposed activities. This was in agreement with the initial assumption that PCA might fail since it relies on the statistical independence of atrial and ventricular activity. Recovering obscured atrial activity using πCA was also demonstrated on clinical data. All parameters necessary for πCA application could be determined automatically from surface ECG and intracardiac recordings, making it a perfect filtering tool for next generation electroanatomical mapping systems.

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