Orthogonal Component Analysis to Remove Ventricular Far Field in Non Periodic Sustained Atrial Flutter

Gustavo Lenis[1], Tobias Oesterlein[1], Dan-Timon Rudolph[1], Olaf Dössel[1]

[1] Institute of Biomedical Engineering (IBT), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Abstract

Automatic signal processing of intracardiac electrograms plays a decisive role in the diagnosis and treatment of supraventricular arrhythmias. During sustained atrial flutter, a repetitive signal is measured in the atrium. However, the ventricular far field may overlap with the atrial activity and compromises the automatic signal processing tools during the intervention. Recently, a new method based on periodic component analysis was proposed as an artifact removal technique. The method works satisfactorily with highly periodic atrial activities but fails to reconstruct not regularly repeating signals .

In order to account for that case, we developed a new method based on orthogonal component analysis to reconstruct the corrupted atrial electrocardiograms obscured by ventricular far field. We tested the method on synthetic signals and proved it to be successful. The reconstructed signals were of higher quality and the computation time was drastically shorter than the already existing periodic component analysis. We conclude that the new method can be used in realistic scenarios in the future.

1. Introduction

The automatic signal processing of intracardiac electrograms (EGM) is a decisive step when diagnosing and treating atrial electrophysiological diseases. Atrial flutter (AFlu) and atrial fibrillation (AFib) are some of the most common cardiac arrhythmias accounting for an estimated prevalence of up to 1% in developed countries such as USA and Germany [1]. Specially AFlu tends to be very symptomatic because of its stable conduction ratios of 2:1 to even 5:1 and possible combinations of these. In many cases, AFlu appears after a previous catheter ablation therapy for AFib. However, its diagnosis and secondary therapy are not trivial because of already existing ablation lesions on the atrial tissue [1].

An additional difficulty when processing the EGM is posed by the artifacts generated by the ventricular far field (VFF). This kind of artifacts corrupt the morphology of the measured atrial activity (AA). They tend to hinder the intracardiac procedure, leading often to misdetection and characterization of AA in unipolar electrograms. A large variety of methods have been proposed in the past to remove VFF [2]. The majority of them is based on the fact that VFF and AA tend to be uncorrelated or even statistically independent and can be therefore separated using methods such as template matching and subtraction or principal component analysis (PCA). These methods were successfully applied for QRS removal in the surface ECG in patients with atrial fibrillation [3]. However, they cannot be used during stable AFlu because VFF and AA are synchronized and overlap in time and frequency domains. This leads to a significant correlation between the two signals and no template can be created to be matched, nor principal components can be use to separate the signals. Figure 1 shows a typical example of sustained AFlu with conduction ratio of 2:1 and its corresponding ECG. The EGM presented there is a filtered unipolar supraventricular signal with an atrial cycle length (ACL) of 327 ms. The pure AA and the corrupted AA by VFF can be also seen in figure 1.

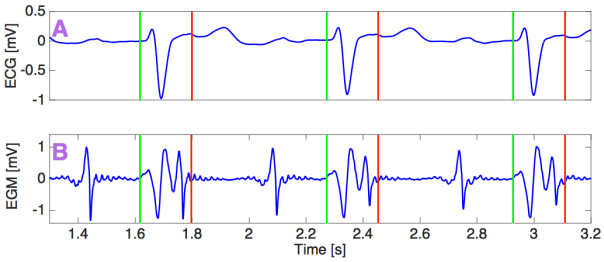

Figure 1. Surface ECG and intracardiac EGM from a patient with AFlu. A stable conduction ratio of 2:1 is present. The corrupting VFF is synchronous to the QRS complex. Its beginning and end are marked by vertical lines.

Recently, an innovative method based on periodic component analysis (PiCA) was proposed as artifact removal technique [1]. This method exploits the periodicity of sustained AFlu to reconstruct the corrupted AA. Even though

PiCA proved to be a very successful method in many scenarios, it cannot be securely applied when the atrial activity is not highly periodic. Small fluctuation in the period of the signal or changes in the the morphology of each AA lead to wrong reconstructions. Therefore, we propose a new method based on orthogonal component analysis (OCA) that can be used to reconstruct the original AA in the case of non periodic sustained AFlu.

2. Methods

2.1. Synthetic data

In order to test the new algorithm proposed in this paper and compare it to the existing PiCA method, we developed a data set of synthetic but realistic signals. The synthetic "measured" unipolar atrial EGM was composed by both AA and VFF. In order to bring non periodic behavior into the signal, three parameters were randomly varied in every AA: the time distance between two successive AA (local ACL), its amplitude and its duration. The VFF was also generated varying the same parameters. Random noise was also added to the signal. Two type of realizations were created for this study. The first used perfectly regular signals without any variations in ACL, amplitude or width of AA or VFF but in the presence of noise. The second experiment varied significantly the mentioned parameters. Each experiment was repeated 500 times in order to create a statistical comparison of the performance of the two algorithms. An example of the kind of signals created for this study can be seen in figure 2.

Every AA was modeled as the derivative of a Gaussian bell. The time distance between every AA was set to have an expectation value of 290 ms, which is also a realistic ACL [1]. However, the signal should not be perfectly periodic and therefore we chose this time distance to vary randomly. Every ACL was extracted from a uniform distribution ranging from 250 to 330 ms. The amplitude of the wave was also randomly generated in the interval between 0.5 and 1.5 mV. The width (standard deviation) of the original Gaussian bell was randomly but realistically chosen from a uniform distribution ranging from 2.5 to 7.5 ms.

Every VFF was modeled as the second derivative of a Gaussian bell. An alternating conduction ratio of 2:1 and 3:1 was chosen to reduce periodicity. The time distance between an AA and its corresponding VFF was set to be fixed at 30 ms to recreate atrioventricular conduction and ensure a fixed overlap between AA and VFF signals. The amplitude of the wave was randomly set in the interval between 1 and 3 mV. The width (standard deviation) of the original Gaussian bell is randomly but realistically chosen from a uniform distribution ranging from 8 to 11 ms.

White Gaussian noise (σ=0.04 mV) was added to the signals to recreate measurement errors. However, we did not add any kind of power line interference or baseline wander. This would have been important when testing prefiltering techniques but not for the kind of artifact removal of this work. The synthetic signals were sampled at 2034.5 Hz and a total length of 5 s was chosen. Thus, the synthetic data created for this work were very similar to the one used in [1].

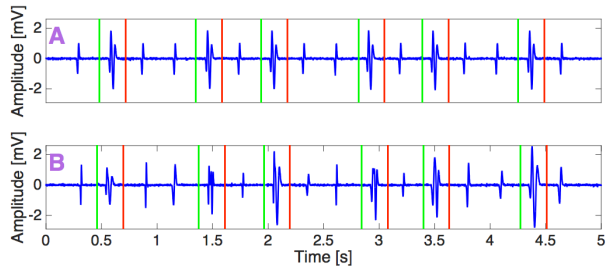

Figure 2. Synthetic atrial EGM with corrupting VFF created to test the algorithms for artifact removal. A: Perfectly periodic AA. B: Non periodic signal with varying ACL, amplitude and duration of AA and VFF.

2.2. Periodic Component Analysis

PiCA is an optimization method that finds a set of coefficients for a linear combination of given signals and creates a new resulting signal that has the highest periodicity. Sustained AFlu is often characterized by highly periodic signals. Therefore, it is possible to combine a single EGM with a set of orthonormal basis functions to maximize the periodicity of the signal by canceling VFF and thus reconstructing AA. The method is demonstrated in [1]. In that work, the set of orthonormal functions consisted of non overlapping adjacent Dirac pulses.

2.3. Orthogonal Component Analysis

The idea behind OCA is to learn how the clean, not corrupted AA are distributed in the first components of a PCA and to extrapolate that knowledge to reconstruct the original AA from the corrupted EGM. The method starts by extracting all the not corrupted EGM and placing them in a matrix that is analyzed using PCA. The mean atrial not corrupted EGM together with the first principal components and its scores are computed. The number of principal components used, is chosen such that they account for 90% of the total variance of the set of clean EGM. The second step is to project the set of corrupted EGM into the space spanned by the previously calculated principal components. The scores of the corrupted EGM in this previously chosen space are different from the ones that were calculated from the clean EGM. Therefore, a correction is needed. For this purpose, the "corrupted" scores are shifted and rescaled to have the same expectation value and

standard deviation of the scores of the clean EGM. After the correction, the resulting EGM should be free of VFF. A sketch describing the functionality of the algorithm can be seen in figure 3.

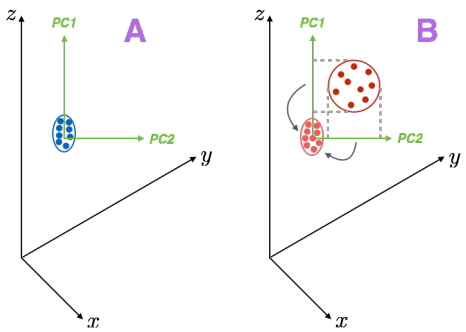

Figure 3. Sketch describing the functionality of OCA. A: First principal components and scores are obtained for the distribution of pure AA. B: Same principal components are used to represent and correct the corrupted AA. Scores in the corrected distribution have the same mean and standard deviation as the scores of the original distribution of AA.

2.4. Comparing original and reconstructed signals

In order to compare the original signals containing only AA to the reconstructed ones, a special procedure is applied. Since changes in amplitude are also relevant here, the correlation coefficient is not the best operator to quantify similarity and consequently the performance of the algorithms. Therefore, we used the "$l\_operator$" introduced in [4] and defined as:

$$l\_operator\{x(t), y(t)\} = \frac{2 \cdot E\{x(t) \cdot y(t)\}}{E\{x^2(t)\} + E\{y^2(t)\}} \quad (1)$$

The expectation value operator is denoted by $E\{\cdot\}$. Like the correlation coefficient, the output value of the $l\_operator$ is restricted to the the interval $[-1, +1]$. Only perfectly equal signals $x(t)$ and $y(t)$ can achieve an $l\_operator$ value of 1. In contrast to the correlation coefficient, the $l\_operator$ is sensitive to scaling or offsetting any of the two signals.

3. Results

A statistical analysis was carried out to quantify the performance and computation time of each of the reconstruction methods. Three signals were compared to evaluate the quality of the artifact removal: no reconstruction at all, reconstruction using PiCA and reconstruction using OCA. The three signal were compared to the reference AA that had no noise and no VFF. In this comparison, the values of the $l\_operator$ were used to measure performance. The higher the value, the better the reconstruction. An example of a VFF removal for each of the two cases considered here can be seen in figure 4 and figure 5.

The statistical analysis of the computation expense compares the duration in seconds of each algorithm. A 2.8 GHz Intel Core i7 processor running MATLAB® 2015a was used for this purpose. Even though computation time is strongly dependent on the technical specifications of the computer, its purpose here is to reflect how the efficiency of the two algorithms relate to each other. A short summary of the results can be seen in table 1.

3.1. Perfectly periodic signals

In the case of perfectly periodic signals, the results show that PiCA and OCA both deliver a very strong performance with similar median (med) $l\_operator$ values of 0.98 and 0.99. Interquantile range (iqr) was equally low for the two methods. This shows that they are not only accurate but also very robust in the presence of noise. For comparison, the unprocessed signal, that was substantially corrupted by VFF and noise, had a median $l\_operator$ of 0.58.

A major difference between the two algorithms was the computation time. The OCA method was significantly faster than PiCA taking 0.03 s in median. This was over 100 times faster than the PICA algorithm. In addition, the random noise was reduced in the reconstructed AA by the OCA method. This can be visually observed in figure 4.

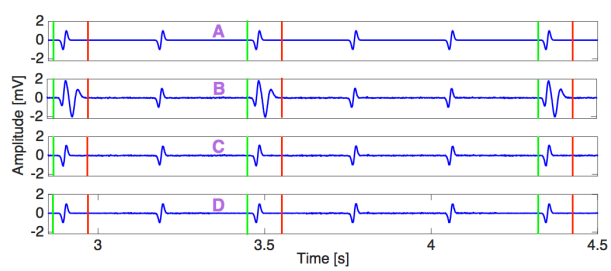

Figure 4. A: Perfectly periodic AA. B: Corrupted atrial EGM with noise and VFF. C: Reconstruction using PiCA. D: Reconstruction using OCA.

3.2. Non periodic signals

When the non periodicity is brought into the problem, the performance of PiCA is significantly affected. The median performance of this method dropped to 0.55 which is almost the same value as the unprocessed signal. Its iqr went high to 0.08 demonstrating that the algorithm is less robust when periodicity can no longer be assumed. In contrast to this, OCA delivered satisfactory results with a median performance of 0.97 and an iqr of 0.01. Differences

Table 1. Summary of results: quality of reconstruction and computation time for the two methods.

	Computation time [s] (med±iqr)	$l\_operator$ (med±iqr)
unprocessed periodic	-	0.58±0.00
unprocessed non periodic	-	0.56±0.10
PiCA periodic	3.45±0.33	0.98±0.00
PiCA non periodic	8.19±1.04	0.55±0.08
OCA periodic	0.03±0.00	0.99±0.00
OCA non periodic	0.01±0.00	0.97±0.01

in the computation time were larger in this case with OCA being almost 700 times faster than PiCA.

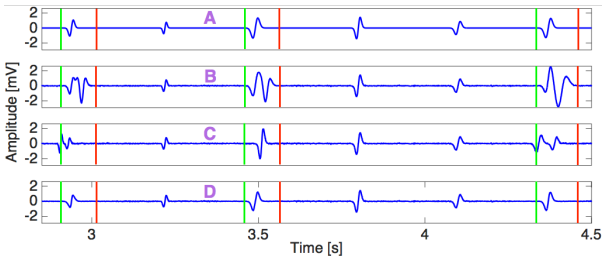

Figure 5. A: Non perfectly periodic AA. B: Corrupted atrial EGM with noise and VFF. C: Reconstruction delivered using PiCA. D: Reconstruction delivered using OCA.

4. Discussion and conclusion

As expected, the PiCA method delivers a very good performance when dealing with perfectly periodic signals which is often the case for sustained periodic AFlu. In these kind of scenarios the periodicity of AA is maximized by removing VFF and the reconstructed EGMs have a high quality. This is not surprising and is in accordance with the previous work presented in [1]. However, the OCA method also proved that it can be applied to this kind of signals. It delivered a slightly better performance but a significantly shorter computation time. The slightly better performance is probably due to the noise reduction achieved by OCA. Since in this method only the first components are considered, noise is suppressed because it tends to be represented by the latter principal components. Even though both methods are based on an eigenvalue decomposition, the dimensionality of the problem in the PiCA method implemented for this work is almost 150 times larger than in OCA. Furthermore, the signals processed by PiCA are also 15 times longer than in OCA. These are probably the reasons why PiCA takes so much longer to compute.

It was also not surprising to see that PiCA did not perform well when the non periodicity was introduced in the signals. As a matter of fact, PiCA tries to reconstruct periodic signals at the expenses of introducing new information that was not previously there. This can be seen in figure 5. The $l\_operator$ values were so low, that it is not recommendable to use PiCA when the signal being processed is not highly periodic. In contrast, OCA showed satisfactory results proving to be a very promising method for artifact correction. However, a priori information, such as the exact location of all AA and VFF in the signal, is needed for the OCA method. If this information cannot be gained accurately, the OCA method might not perform as good.

In conclusion, we were able to show that the newly introduced method can be applied for the reconstruction of corrupted AA in the case of periodic and non periodic sustained AFlu. Specially, the latter was proved to be an impossible task for other methods such as PCA or PiCA [1]. In order to further investigate the performance of OCA, a large data set of real EGM of AFlu with non periodic behavior is needed. It should be tested if in real life conditions, the OCA method can still perform as good as with synthetic signals.

References

[1] Oesterlein TG, Lenis G, Rudolph DT, Luik A, Verma B, Schmitt C, Dössel O. Removing ventricular far-field signals in intracardiac electrograms during stable atrial tachycardia using the periodic component analysis. Journal of electrocardiology 2014; 48:171–180.

[2] Rieta JJ, Hornero F. Comparative study of methods for ventricular activity cancellation in atrial electrograms of atrial fibrillation. Physiological measurement 2007;28: 925–36.

[3] Lemay M , Vesin J, Van Oosterom A, Jacquemet V, Kappenberger L. Cancellation of ventricular activity in the ECG: evaluation of novel and existing methods. IEEE Transactions on Biomedical Engineering 2007;54:542–546

[4] Lenis G, Lutz Y, Seeman G, Garcia-Alberola A, Rojo-Alvarez JL, Barquero-Perez O, Gil E, Dössel O. Post extrasystolic T wave change in subjects with structural healthy ventricles-Measurement and simulation. Computing in Cardiology Conference (CinC) 2014;41:1069–1072

Address for correspondence:

Gustavo Lenis

Fritz-Haber-Weg 1, 76131 Karlsruhe, Germany

gustavo.lenis@kit.edu, publications@ibt.kit.edu