Optimal Cancellation Template Analysis for Ectopic Beats Removal in Atrial Fibrillation Recordings

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Abstract

Ectopic beats are early heart beats notably different to the normal beat morphology. These beats are very common in atrial fibrillation (AF) being the source of important residua when ventricular activity is intended to be removed. Recently, their detection and clustering to build an efficient cancellation template, via principal component analysis (PCA), allowed us to obtain ECG signals with notably reduced ectopic residua. However, only the first principal component (PC) of the clustered ectopics was considered to build up the cancellation template. Hence, the effect of other PCs on cancellation performance has been evaluated in the present work. For this purpose, an index able to quantify the ectopic residue (ER) after cancellation was used. Results showed that cancellation in those cases where the first PC explained a variability of the clustered ectopics higher than 90% *worsened when additional PC's were included into the template. In contrast, for the abnormal beats in which the first PC explained a lower variability, a notable improvement in their cancellation was appreciated when the two first PCs were considered. In this respect, ER decreased from* 0.537 ± 0.041 *to* 0.396 ± 0.041 *when the second PC was considered together with the first one. Finally, considering the three first PCs also provided worse cancellation with respect to the previously analyzed cases. As a consequence, it could be considered that the second PC inclusion can improve cancellation of ectopics with rare morphologies.*

1. Introduction

The appearance of ventricular ectopic beats in the ECG is a sign for disturbance in the depolarization process, disorganizing the blood pumping function of the ventricles and preceding in many cases malignant cardiac arrhythmias [1]. Although this sign of decreased heart function is helpful for predicting life-threatening arrhythmias, such as ventricular fibrillation or tachycardia [2], its presence makes difficult the study of other cardiac diseases from the ECG. In this respect, the presence of ectopics makes difficult the long-time study of a considerable number of atrial fibrillation (AF) recordings.

Although this arrhythmia is commonly found in clinical practice [3], the physiological mechanisms provoking its onset and termination still are not fully explained [4]. Hence, atrial activity (AA) signal extraction under the best conditions is crucial to study the electrophysiological processes that underlie AF, such as refractory periods, autonomic response, drug effects, etc. [5]. However, AA extraction requires nonlinear signal processing techniques since the atrial and ventricular activity overlap spectrally and, therefore, cannot be separated by linear filtering [5].

In this respect, average beat subtraction (ABS) is the most widespread technique for AA extraction. This method relies on the assumption that the average beat can represent approximately each individual beat [6]. However, the presence of ventricular ectopics, which exhibit a very different morphology with respect to normal beats, provokes important residua in the AA signal. To overcome this problem, a method able to detect and cancel out ventricular ectopics in long-time AF recordings has been recently proposed as a previous step to the AA extraction with ABS or any of its variants [7]. In this algorithm, ectopic beats are located and clustered to build an efficient cancellation template, via principal component analysis (PCA), allowing us to obtain ECG signals with notably reduced ectopic residua. The use of the highest variance principal component (PC) as subtraction template has provided a better cancellation of both normal and ectopic beats than ABS [8, 9]. However, the effect of other PCs on cancellation performance has not been evaluated yet. Thereby, in the present work, the two and three first PCs are used to reevaluate how cancellation could be improved.

2. Materials

Twenty 10 h-length ECG segments with AF and a considerably high density of ectopic beats, extracted from 24-h Holter recordings corresponding to 15 and 5 patients

with paroxysmal and persistent AF, respectively, were analyzed in the study. Although three leads (II, aVF and V1) were recorded, only V1 was considered for the study. The recording was upsampled to 1 kHz in order to improve the accuracy of the time alignment performed between each ectopic and its cancellation template [10]. Additionally, this lead was filtered to remove baseline wander, high frequency noise and powerline interference.

3. Methods

3.1. Cancellation of ectopic beats

Given that ectopics cancellation requires their previous identification, they were firstly detected by using an algorithm characterizing morphologically each beat in the ECG. This algorithm has been previously published and has proved sensibility and positive predictivity values higher than 97% [7]. Next, the Q-wave onset and the T-wave offset for each ectopic were located making use of a PT-based delineator [11]. To delimit all the ectopic beats with the same duration, the median values of the QR ($\overline{QR}$) and RT ($\overline{RT}$) intervals were obtained and the Q-wave onset and the T-wave offset for the ith ectopic were defined as $q_{i-} = r_i - \overline{QR}$ and $t_{i+} = r_i + \overline{RT}$, respectively, r_i being the R peak wave event. Hence, this beat was represented by the column vector

$$\begin{aligned}\mathbf{x_i} &= \left[\begin{array}{ccccc} y(q_{i-}) & y(q_{i-}+1) & \dots & y(t_{i+}-1) & y(t_{i+}) \end{array}\right]^{\mathsf{T}} \\ &= \left[\begin{array}{ccccc} \mathbf{x_i(1)} & \mathbf{x_i(2)} & \dots & \mathbf{x_i(L-1)} & \mathbf{x_i(L)} \end{array}\right]^{\mathsf{T}},\end{aligned} \tag{1}$$

where L is the number of samples and $y(n)$ is the preprocessed ECG under study.

In order to generate the cancellation template of an ectopic beat, only the N most similar complexes to it were chosen. Similarity among ectopics was obtained in terms of the cross-correlation index (κ), which can be defined for the ith and jth beats as

$$\kappa = \frac{E[\mathbf{x_i}\widetilde{\mathbf{x}}_\mathbf{j}]}{\sigma_i \sigma_j}, \tag{2}$$

where $E[\cdot]$ is the expectation operator and σ_i and σ_j are the standard deviations of both beats. It is noteworthy that the jth ectopic was adapted in amplitude to the ith beat for a better comparison of morphologies, such that

$$\widetilde{\mathbf{x}}_j = \frac{y(r_i) - y(r'_i)}{y(r_j) - y(r'_j)}\mathbf{x_j}. \tag{3}$$

Temporal redundancy of the set of N complexes was exploited through PCA. For the ith beat, these N complexes were assembled in a matrix $\mathbf{X_i} \in \Re^{\mathbf{L}\times\mathbf{N}}$, such that

$$\mathbf{X_i} = [\mathbf{x_{i1}}, \mathbf{x_{i2}}, \dots, \mathbf{x_{iN}}]. \tag{4}$$

Note that all the beats were temporally aligned using their R-peak timings. The principal components of this matrix associated with PCA were obtained by singular value decomposition (SVD) [12], such that

$$\mathbf{X_i} = \mathbf{U_i}\mathbf{S_i}\mathbf{V_i^{\mathsf{T}}}, \tag{5}$$

where $\mathbf{U_i} \in \Re^{\mathbf{L}\times\mathbf{N}}$ is a unitary matrix so that $\mathbf{U_i}\mathbf{U_i^{\mathsf{T}}} = \mathbf{I}$, being $\mathbf{I}$ the identity matrix, $\mathbf{S_i} \in \Re^{\mathbf{N}\times\mathbf{N}}$ is a diagonal matrix, and $\mathbf{V_i} \in \Re^{\mathbf{N}\times\mathbf{N}}$ fulfills $\mathbf{V_i}\mathbf{V_i^{\mathsf{T}}} = \mathbf{I}$. The matrix $\mathbf{U_i} = [\mathbf{u_{i1}}, \dots, \mathbf{u_{iN}}]$ contains the N normalized principal components of $\mathbf{X_i}$, their cross-correlation coefficients being null. The eigenvalues, i.e. the amplitude coefficients corresponding to the PCs, corresponds with the diagonal elements of $\mathbf{S_i}$. Given that the first PC $\mathbf{u_{i1}}$, i.e., the highest variance eigenvector, could be considered as the mother representation of the ith beat [8, 13], this vector has been taken as ventricular template for its cancellation in previous works [7, 8]. Thus, the subtraction of this ectopic was obtained as

$$\widehat{\mathbf{y}}_\mathbf{i} = \mathbf{x_i} - \widetilde{\mathbf{u}}_\mathbf{i1}, \tag{6}$$

$\widetilde{\mathbf{u}}_\mathbf{i1}$ being the vector $\mathbf{u_{i1}}$ adapted in amplitude to the ith beat in the way expressed in eq. (3).

The use of the first PC as subtraction template for normal complexes has provided better results than ABS [8]. However, the effect of other PCs of $\mathbf{X_i}$ on cancellation performance has not been evaluated yet. As a consequence, in the present work the two and three first PCs were used to reevaluate how cancellation could be improved. To this respect, for the ith ectopic, its template t_i was obtained as

$$\mathbf{t_{i2}} = \mathbf{M_i(1,1)u_{i1}} + \mathbf{M_i(1,2)u_{i2}}, \tag{7}$$

and

$$\mathbf{t_{i3}} = \mathbf{M_i(1,1)u_{i1}} + \mathbf{M_i(1,2)u_{i2}} + \mathbf{M_i(1,3)u_{i3}}, \tag{8}$$

for the two and three first PCs, respectively. The mixing matrix $\mathbf{M_i}$ was obtained as

$$\mathbf{M_i} = \frac{\mathbf{V_i}\mathbf{S_i}}{\sqrt{\mathbf{L}}}. \tag{9}$$

Finally, the ectopic subtraction was reached as

$$\widehat{\mathbf{y}}_\mathbf{i} = \mathbf{x_i} - \widetilde{\mathbf{t}}_\mathbf{i}, \tag{10}$$

$\widetilde{\mathbf{t}}_\mathbf{i}$ being the template adapted in amplitude to the ith abnormal beat in the way expressed in eq. (3).

As next section will show, ectopics cancellation was not improved in general terms through the use of more than one PC. However, it was observed that cancellation could be improved by using several PCs in those cases where the variability of $\mathbf{X_i}$ carried by the first eigenvalue was lower than 90%. Variability of $\mathbf{X_i}$ was defined as $v_{i1} = \frac{s_{i1}^2}{\sum_{m=1}^{N} s_{im}^2}$, being s_{im} the mth diagonal value of $\mathbf{S_i}$.

Table 1. Ectopic cancellation results ($N = 10$). Template created by the first, the 2 first and the 3 first PCs of $\mathbf{X_i}$.

Template	ER
$\mathbf{u_{i1}}$	0.312 ± 0.038
$\mathbf{t_{i2}}$	0.324 ± 0.037
$\mathbf{t_{i3}}$	0.370 ± 0.038

Table 2. Cancellation results discerning between ectopics whose first PC explained more and explained less than 90% of $\mathbf{X_i}$ variability. $N = 10$ and a template generated from the first, the 2 first and the 3 first PCs of $\mathbf{X_i}$ were used for the analysis.

	ER	
Template	$v_{i1} > 90\%$	$v_{i1} \leq 90\%$
$\mathbf{u_{i1}}$	0.305±0.038	0.537±0.041
$\mathbf{t_{i2}}$	0.321±0.037	0.396±0.041
$\mathbf{t_{i3}}$	0.364±0.038	0.549±0.041
% of ectopics	96.7	3.3

3.2. Cancellation assessment

When real ECG recordings are analyzed, the only evidence for a successful cancellation of any ectopic is the absence of its residue [8]. Unfortunately, there is no parameter in the literature able to quantify robustly the existence of QRST residua in the resulting signal after cancellation. Hence, a new parameter to estimate ectopic residue (ER) after cancellation is next proposed. Thus, for the ith ectopic, ER was defined as the normalized difference between two groups of quantiles. On the one hand, the 90-quantile of the resulting signal after cancellation within the interval corresponding to the beat, $Q_{90}(\widehat{\mathbf{y}}_i)$ and, on the other hand, the 90-quantile corresponding to the TQ segment prior to the preceding normal beat, $Q_{90}(\mathbf{tq_i})$, i.e.

$$ER_i = \frac{|Q_{90}(\widehat{\mathbf{y}}_i) - Q_{90}(\mathbf{tq_i})|}{\max\{Q_{90}(\widehat{\mathbf{y}}_i), Q_{90}(\mathbf{tq_i})\}}, \qquad (11)$$

where $\mathbf{tq_i} = \left[\ y(t_{(k-2)+}) \quad \dots \quad y(q_{(k-1)-})\ \right]^{\mathsf{T}}$, being k the position corresponding to the ith ectopic. This index ranges from 0 to 1, being higher as the ventricular residue increases.

4. Results

Table 1 shows ER values obtained for ectopics cancellation with a template generated from the first, the two first and the three first PCs of $\mathbf{X_k}$. The number of ectopic beats clustered to build the cancellation template was $N = 10$, because it showed the best performance taking into account efficiency and computational burden [7]. As

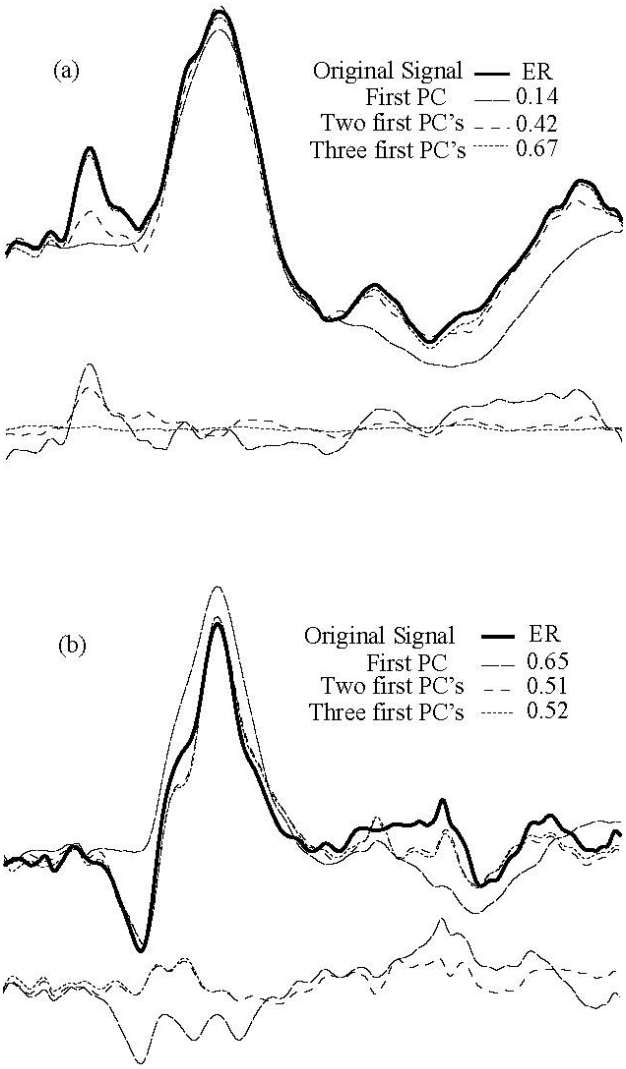

Figure 1. Cancellation examples for two ectopics. Original QRS complex is depicted at the top panel and resulting signals after cancellation with several PCs are displayed at the bottom panel. (a) Ventricular residue in the resulting signal increases for more than one PC. (b) Residue decreases when additional PCs are considered.

can be appreciated, the inclusion of additional PCs did not improve the cancellation with respect to the only use of the first PC. To this respect, Table 2 shows how the cancellation of ectopics whose first PC explained more than 90% of $\mathbf{X_i}$ variability worsened when additional PCs were added to the template. In contrast, for those abnormal beats in which the first PC explained a more limited variability (<90%), which were a limited number in comparison with the others, a notable improvement in their cancellation can be appreciated when the second PC was considered together with the first one. Considering the 3 first

PCs also turned worse cancellation with respect to the previously analyzed cases. Hence, making use of the 2 first PCs, for those ectopics whose first PC explained a limited variability of $\mathbf{X_i}$, and only the first one for the remaining, the cancellation improved with respect to the sole use of $\mathbf{u_{i1}}$, given that the ER proved to be 0.308 ± 0.038.

5. Discussion and conclusions

In general terms, the use of the first PC of $\mathbf{X_i}$ provided successful cancellation results. In contrast, the use of additional PCs did not improve performance. In fact, for those ectopics whose first PC explained a high variability of $\mathbf{X_i}$, further PCs worsened results. For this case, the template was so similar to the waveform under cancellation that AA was also removed, like Fig. 1(a) shows. In contrast, the two first PCs increased cancellation performance in those ectopics whose first PC explained a limited variability of $\mathbf{X_i}$. The second PC inclusion takes into account latency differences in the QRS complex and T-wave occurrence, such as Fig. 1(b) shows, which could justify the indicated outcome. Furthermore, the third PC did not improve cancellation, since the variability of $\mathbf{X_i}$ explained by the 2 first PCs was considerably high in most of the analyzed ectopics ($v_{i2} > 90\%$). As a consequence, given the low computational burden of this approach, we strongly recommend to include the second PC to deal with ectopics of rare morphologies.

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References

[1] Ng GA. Treating patients with ventricular ectopic beats. Heart Nov 2006;92(11):1707–12.

[2] Wellens HJJ, Gorgels AP, de Munter H. Cardiac arrest outside of a hospital: how can we improve results of resuscitation? Circulation Apr 2003;107(15):1948–50.

[3] Fuster V, Rydén LE, Cannom DS, Crijns HJ, Curtis AB, Ellenbogen KA, et. al. ACC/AHA/ESC 2006 guidelines for the management of patients with atrial fibrillation: a report of the American College of Cardiology/American Heart Association task force on practice guidelines and the european society of cardiology committee for practice guidelines (writing committee to revise the 2001 guidelines for the management of patients with atrial fibrillation): developed in collaboration with the european heart rhythm association and the heart rhythm society. Circulation Aug 2006; 114(7):e257–e354.

[4] Sung RJ, Lauer MR. Atrial fibrillation: can we cure it if we can't explain it? J Cardiovasc Electrophysiol May 2005; 16(5):505–7.

[5] Sörnmo L, Stridh M, Husser D, Bollmann A, Olsson SB. Analysis of atrial fibrillation: from electrocardiogram signal processing to clinical management. Philos Transact A Math Phys Eng Sci Jan 2009;367(1887):235–53.

[6] Slocum J, Sahakian A, Swiryn S. Diagnosis of atrial fibrillation from surface electrocardiograms based on computer-detected atrial activity. J Electrocardiol Jan 1992;25(1):1–8.

[7] Martínez A, Alcaraz R, Rieta JJ. Detection and removal of ventricular ectopic beats in atrial fibrillation recordings via principal component analysis. Conf Proc IEEE Eng Med Biol Soc 2011;2011:4693–6.

[8] Alcaraz R, Rieta JJ. Adaptive singular value cancelation of ventricular activity in single-lead atrial fibrillation electrocardiograms. Physiol Meas Dec 2008;29(12):1351–69.

[9] Martinez A, Alcaraz R, Rieta JJ. Ectopic beats canceler for improved atrial activity extraction from holter recordings of atrial fibrillation. Proc Computing in Cardiology 2010; 37:1015–1018.

[10] Bollmann A, Husser D, Mainardi L, Lombardi F, Langley P, Murray A, Rieta JJ, Millet J, Olsson SB, Stridh M, Sörnmo L. Analysis of surface electrocardiograms in atrial fibrillation: techniques, research, and clinical applications. Europace Nov 2006;8(11):911–26.

[11] Martínez A, Alcaraz R, Rieta JJ. Application of the phasor transform for automatic delineation of single-lead ecg fiducial points. Physiol Meas Nov 2010;31(11):1467–85.

[12] Golub GH, van Loan CV. Matrix Computations. 2nd edition. Baltimore, Md, USA: The Johns Hopkins University Press, 1989.

[13] Castells F, Laguna P, Sörnmo L, Bollmann A, Millet J. Principal component analysis in ecg signal processing. EURASIP J Adv Signal Process 2007;2007(1-22).

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