A New Method for Atrial Electrical Activity Analysis from Surface ECG Signals Using an Energy Ratio Measure

N Weissman[1], A Katz[2], Y Zigel[1]

[1]Department of Biomedical engineering, Ben Gurion University of the Negev, Israel
[2]Barzilai Medical Center, Ashkelon Israel, Faculty of Health Sciences Ben Gurion University Israel

Abstract

A new method called separation using maximum energy ratio (SUMER) is introduced. Using 12 lead ECG signals, SUMER tries to separate the atrial activity from the ventricular activity. Relying on the assumption that the atrial activity can be reconstructed from a linear combination of 12 lead ECG signals, SUMER looks for the combination that will give us the best representation of the atrial activity. A cost function that is the energy ratio between different segments in the ECG signal is created. Forcing the linear combination to find the maximum possible cost function gives us the desired combination. The method presents better separation performances than the ICA method, and provides tools for the next phase of P wave detection.

1. Introduction

In many arrhythmias, extraction of atrial activity (AA) or cancellation of ventricular activity (VA) can be a great help for the physician who tries to identify the type of arrhythmia from ECG signals. In many cases, the P wave is hidden in a QRS complex or in a T wave, and cannot be observed. There are several techniques of VA cancellation and P wave detection [1-4]. The different approaches have different shortcomings; the average beat subtraction [4] relies on the assumption of fixed shape QRS complexes, the independent component analysis (ICA) method [2] relies on the independency of the sources and the sparse source separation [3] relies on a-priori knowledge of the shape of the different components of the ECG. Because of those assumptions, those algorithms have good performances in the atrial fibrillation case but have worse performances in other cases. One of the recent techniques [2] presents separation of AA from VA using the ICA method. The ICA method relies on the assumption that the AA can be constructed by a linear combination of the 12 ECG leads. Our proposed method, called separation using maximum energy ratio (SUMER), relies on the same assumption but takes a different approach. Using a-priori information, the physician/user marks at least one P wave segment, and then the algorithm forces the linear combination of the 12 leads to converge to the signal that has the maximum ratio between the energy in the marked segments and the energy in the non-marked segments. The result is a signal with emphasized P waves and reduced QRS and T waves. The advantages and disadvantages over the ICA method are discussed later.

2. Experiment setup

We used signals from the GE Cardiolab IT which produces standard 12 lead ECG and invasive measurements from the high right atrium (HRA) which help the researcher to identify AA and mark it (for the first step of the algorithm), and for performance evaluation of the algorithm. We used 5 sinus rhythms, 3 AV node re-entry tachycardia (AVNRT) signals, an AV re-entry tachycardia (AVRT) signal, 2 atrial flutter and 2 atrial fibrillation signals. The atrial fibrillation signals are from the St Petersburg INCART 12-lead Arrhythmia Database.

In the pre-processing phase, the ECG signals were filtered using a band-pass with band between 0.5-60 Hz. Elimination of the 50Hz power supply noise had been carried out by the Cardiolab machine itself using notch filter. All the algorithms were developed using the Mathworks Matlab software.

3. Methods

3.1. The concept of the proposed method

Assume a simplified heart activity which contains only two sources: S1 which is the VA (with QRS complexes only) and S2 which is the AA (P-wave) (See Fig. 1 for simulated source signals).

The surface ECG measures the heart activity using different leads; leads I and lead II measure the heart activity from different sites. For an example, lead I is equal to S1+S2 and lead II is equal to S1+0.5*S2. In other words, lead I is a linear combination of the sources with weight coefficients (1,1) and lead II is a linear combination of the sources with weight coefficients (1,0.5). (Fig. 2 shows the linear combinations of the simulated source signals.)

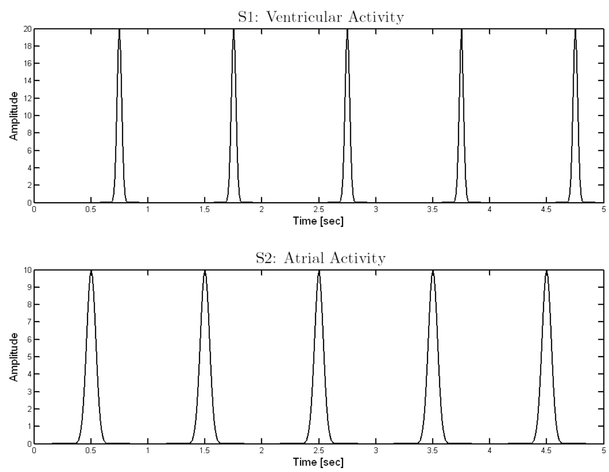

Fig 1. Simulated ventricular and atrial activity source signals

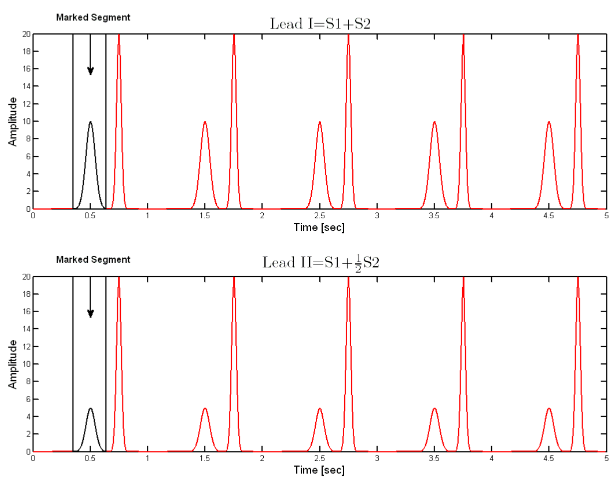

Fig 2. The leads are linear combinations of the sources. The marked segment is between the two vertical lines.

Now, we mark one segment in the ECG leads (Fig 2). The marked segment contains one P-wave; we are looking for a linear combination of the two leads that will produce the highest ratio between the marked segment's energy and the non-marked segment's energy. Since we can't reduce the other P-waves' amplitude without reducing the marked P-wave's amplitude, the energy ratio will get its maximum when the QRS complexes will reduce to zero but the amplitude of the P-waves doesn't have an influence on the energy ratio. The desired signal can be obtained by a linear combination of the two leads with the coefficients (1,-1). The obtained signal contains the atrial activity source signal only. (Fig 3)

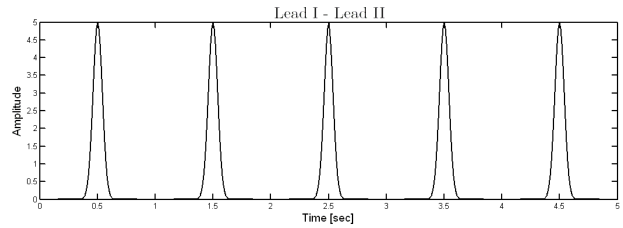

Fig 3. Linear combination of the leads produces the atrial activity source signal.

3.2. Separation of atrial activity

The first step in the proposed algorithm (SUMER) is manually marking of at least one P wave in the ECG signal. The researcher segments the signal into AA segments (P-waves) and NAA (non-AA) segments (Fig 4a). Instead of manual marking of the P wave, there is an option of finding the P waves automatically using SUMER with unsupervised clustering, this option is under research and is out of the scope of this paper.

Now we're looking for 12 weight coefficients, one weight coefficient for each ECG lead signal. The linear combination using these weights should produce an output signal with emphasized AA.

$$out(l) = \sum_{i=1}^{12} a_i lead_i(l) \qquad (1)$$

Where *out* is the output signal, a_i is the weight coefficient of lead *i*, $lead_i$ is the *i*-th lead signal and l is the sample index.

The algorithm subtracts the mean of every segment. For instance, if we have one AA segment and two NAA segments (as in Fig 4a); the algorithm subtracts the mean from the 12 signals in the AA segment and from the 24 signals in the NAA segments.

Next, the algorithm chooses 12 coefficients randomly (initial values). Now the algorithm computes the cost function which is the energy ratio between the marked and the non-marked segments in the output signal.

$$f(a_1, a_2 ... a_{12}) = \frac{\sum_{n=1}^{N} (\sum_{i=1}^{12} a_i G_i(n))^2}{\sum_{m=1}^{M} (\sum_{i=1}^{12} a_i R_i(m))^2} \qquad (2)$$

Where G_i is all the marked segments of lead *i* after concatenating them into one signal with *N* samples. R_i is all the non-marked segments of lead i after concatenating them into one signal with M samples.

Next, the algorithm finds the coefficients that produce the maximum cost function. Gradient ascent method [5] is performed to find the optimal coefficients by adding iteratively the gradient of the function to the coefficients from the last iteration until we get to convergence:

$$(a_1, a_2, ..., a_{12})_{p+1} = (a_1, a_2, ..., a_{12})_p + \mu \nabla f \quad (3)$$

Where ∇f is the gradient of the cost function, μ is the step size and p is the iteration index. The gradient is defined by:

$$\nabla f = (\frac{\partial}{\partial a_1}, \frac{\partial}{\partial a_2}, ..., \frac{\partial}{\partial a_{12}}) \quad (4)$$

And every partial derivative is defined by:

$$\frac{\partial f}{\partial a_i} = \frac{\partial}{\partial a_i} \frac{\sum_{n=1}^{N} (\sum_{j=1}^{12} a_j G_j(n))^2}{\sum_{m=1}^{M} (\sum_{j=1}^{12} a_j R_j(m))^2} =$$

$$= \frac{(\sum_{n=1}^{N} \sum_{j=1}^{12} 2a_j G_i(n) G_j(n))(\sum_{m=1}^{M} (\sum_{j=1}^{12} a_j R_j(m))^2)}{(\sum_{m=1}^{M} (\sum_{j=1}^{12} a_j R_j(m))^2)^2} -$$

$$- \frac{(\sum_{m=1}^{M} \sum_{j=1}^{12} 2a_j R_i(m) R_j(m))(\sum_{n=1}^{N} (\sum_{j=1}^{12} a_j G_j(n))^2)}{(\sum_{m=1}^{M} (\sum_{j=1}^{12} a_j R_j(m))^2)^2} \quad (5)$$

After the optimization, we get coefficients that should produce a signal that has emphasized AA. (Fig 4b)

Summary of the algorithm:

1. Filtering the 12 channels. (preprocessing, see experiment setup)
2. Segmenting the channels into marked and non-marked segments (AA and NAA)
3. Subtracting of the mean of each segment.
4. Creating a cost function of the energy ratio between the AA segment and the NAA segment with initial coefficients for the linear combination.
5. Optimization of the cost function to its maximum by changing the coefficients using gradient ascent method until converging to a fixed value.

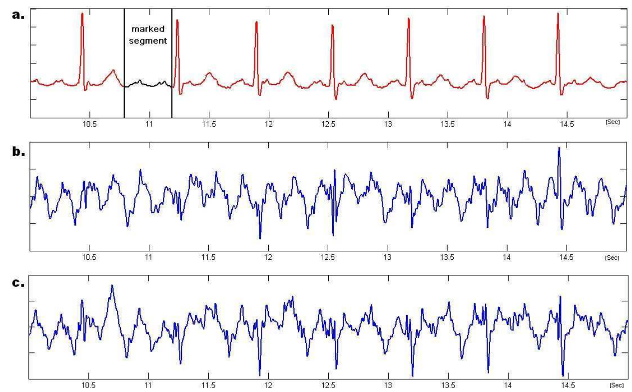

Fig 4. **a**. Atrial fibrillation (lead II) the segment between the vertical lines is the AA segment. The segments outside of the vertical lines are the NAA segments. **b**. results of the SUMER algorithm. **c**. results of ICA algorithm.

3.3. Expanding to P-wave detection

SUMER can be used for P wave detection using the following steps:

1. Marking (manually) one P-wave in the ECG signal and performing SUMER. We get a result signal with emphasized P-waves. $P(t)$ denotes the result signal when t denotes time.
2. Marking the beginning of the ECG signal with a window with the same size as the marking window in the previous step.
3. Performing SUMER. We get a candidate result signal denoted by $C(t,i)$ when i is the candidate result signal index.
4. Moving the marking window a little step in time, updating i to i+1 and repeating step 3 until the end of the ECG signal.
5. Calculating the correlation coefficients for all the candidates signals $C(t,i)$ with $P(t)$. We get a correlation coefficients signal.

If a certain marking window contains a P-wave, $C(t,i)$ for that window should contains emphasized P-waves and has high correlation with $P(t)$. If not, $C(t,i)$ has low correlation with $P(t)$. Choosing a certain threshold for the correlation coefficients signal should detect the P-waves. (See Fig. 5 for an example)

4. Results and discussion

In the atrial fibrillation case (which is the main interest in the ICA method) the results of SUMER are visually similar to the ICA method results (Fig 4c). In other cases such as AVNRT, AVRT, atrial flutter and simple sinus, the AA is emphasized and the QRS complexes are reduced although not disappear (Fig 6). In the ICA method we get similar results in some cases such as atrial flutter but much worse results in other cases such as sinus rhythm. Even when there are good results in the ICA method, another advantage of SUMER is that we get only one result signal while in ICA we get up to 12 sources and we have to find which of them is the atrial activity signal, which is not a trivial task since in different arrhythmias the characteristics of the AA are different.

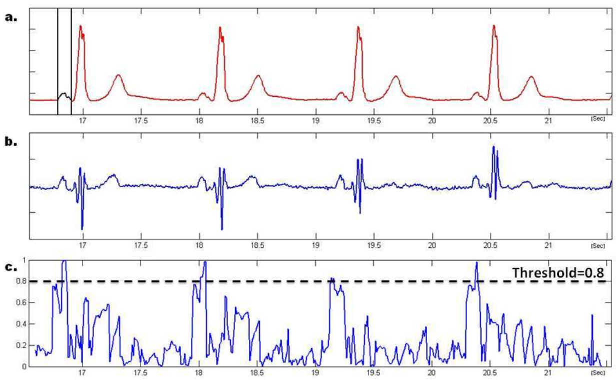

Fig 5. **a**. Sinus rhythm (lead II) with AA and NAA segments. **b**. $P(t)$- the result of SUMER, contains emphasized P-waves. **c**. Correlation coefficients signal – the correlation coefficients between $P(t)$ and $C(t,i)$ – the results of SUMER for the moving window. Threshold of 0.8 (dashed line) will detect the P-waves.

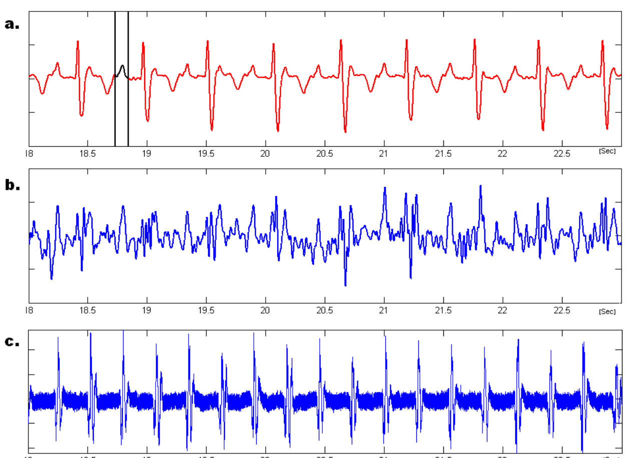

Fig 6. **a**. Atrial flutter (V1) with marked segment. **b**. Results of SUMER. **c**. Invasive information from HRA, comparing b and c shows that the algorithm emphasized the P-waves.

The interesting point is that although we have marked as non-AA (for instance in Fig 5) a segment with some P-waves, the algorithm reduced the energy of the NAA segment but manage to reduce the QRS and T waves' energy but not the P waves' energy. SUMER takes advantage of the fact that the P-waves in the ECG signal are tied to each other, since they're belong to one source signal and when you reduce energy of one P-wave it affects the other P-waves. Even if we mark only one P-wave as AA, the other P-waves will be emphasized.

Another option is to mark a T-wave as AA and the rest of the signal as NAA, resulting emphasized T waves, such as in Fig 7.

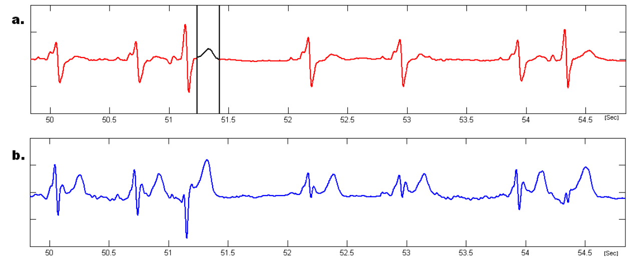

Fig 7. **a**. Lead II with a t-wave marked as AA **b**. after SUMER the T-waves are emphasized.

5. Conclusions

In this paper a new method for extraction of atrial activity from ECG signal was introduced. SUMER isn't specified to a certain arrhythmia while many other published works are specified to atrial fibrillation. In addition, SUMER can be a tool for P-wave detection using comparisons of different SUMER results for different segments.

SUMER's shortcoming - the need for initial manual marking of some atrial activity, can be overcome by combining SUMER with other P-wave detection algorithms. This kind of combination can help making the procedure fully automatic without the need for initial manual marking.

References

[1] Portet F. P wave detector with PP rhythm tracking: evaluation in different arrhythmia contexts. Physiological Measurement 2008;29:141-155

[2] Rieta JJ, Castells F, Sánchez C, Zarzoso V, Millet J. Atrial Activity Extraction for Atrial Fibrillation Analysis Using Blind Source Separation. IEEE Transactions on Biomedical Engineering 2004;51(7):1176-1186.

[3] Escoda OD, Granai L, Lemay M, Hernandez JM, Vandergheynst P, Vesin JM. Ventricular and atrial activity estimation through sparse ECG signal decompositions. International Conference on Acoustics, Speech, and Signal Processing (ICASSP) 2006;2:II-1060-1063.

[4] Stridh M, Sörnmo L. Spatiotemporal QRST Cancellation Techniques for Analysis of Atrial Fibrillation. IEEE Transactions on Biomedical Engineering 2001;48(1):105-111

[5] Snyman JA. Practical mathematical optimization: an introduction to basic optimization theory and classical and new gradient-based algorithms. Springer-Verlag, 2005.

Address for correspondence:
Noam Weissman
Neriah 6, Petach Tikva, Israel
noam1977@gmail.com