Morphological Descriptors Based on Eigen Value Decomposition for P-Wave Analysis

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Abstract

In this study, several morphological parameters to assess the P-wave from the surface electrocardiogram are proposed and analysed. In order to evaluate spatial features, two parameters are defined: P-wave complexity and P-wave residuum. Additionally, in order to evaluate beat to beat features, the P-wave regularity is defined. All three parameters are computed from the eigenvalue decomposition of the original data, and were applied on patients who suffered from either dilated or ischemic cardiomyopathy. The results showed that both the P-wave complexity and P-wave regularity are able to find and emphasize interpatient differences, whereas the results of P-wave residuum where rather similar for all patients.

1. Introduction

The analysis of P-waves from the surface electrocardiogram is of great interest for the study of patients with atrial abnormalities and patients who suffered atrial surgery interventions in order to evaluate atrial depolarization during sinus rhythm as well as to assess the potential risk to develop atrial arrhythmias such as atrial fibrillation. P-waves have been usually assessed with temporal parameters, e.g. P-wave duration and dispersion, among others [1]. These parameters are extracted after a previous detection of the fiducial points, i.e. P-onset and P-offset. However, temporal information is only one aspect of P-waves, and therefore these parameters provide valuable but limited information regarding the atrial depolarization process. In fact, it may occur that P-waves with clearly different morphologies (e.g. normal P-wave, notched, biphasic) present similar duration measurements.

Another limitation of temporal parameters is that they are subject to a robust detection of the fiducial points. Indeed, P-waves are the signals with the lowest amplitude within the P-T segment, and therefore, the signal with the lowest signal-to-noise ratio (SNR). SNR of the P-wave can be increased by averaging successive P-waves, which gives as a result the so called P-signal averaged ECG (PSAECG) [2]. Nevertheless, the detection of the P-onset and P-offset may fail in case of (1) P-waves with very low amplitude and (2) irregular P-wave morphology, with a variable beat to beat pattern, since the PSAECG would not be able to extract a representative waveform. In addition, PSAECG can not be employed if beat to beat changes are to be analysed. Finally, it should be considered that the patients under analysis do not present a P-wave as regular as in case of healthy subjects, and hence the robustness of fiducial points detection decreases considerably.

Consequently, the information given by temporal parameters should be complemented and enriched with other measurements that attempt to extract morphological features of the waves [3]. These parameters should not rely on the detection of fiducial points and should be simple to interpret for clinicians. In this study, novel indicators for the assessment of P-wave morphology based on eigenvalue decomposition (EVD) have been proposed and explored. Several parameters are defined, which attempt to extract beat to beat morphology variations as well as to extract spatial measurements of the P-wave.

2. Materials

The analyzed patients underwent a cardiac catheterization at Otto-von-Guericke University's department of cardiology. All patients suffered from either dilated or ischemic cardiomyopathy (left ventricular ejection fraction (LVEF) $\leq$ 45% with a median LVEF of 31,32±11,20%). Of the overall number of 145 patients, 109 were male and 36 were female, with an average age of 62,9 years (± 11,01 years). The average Body Mass Index (BMI) amounted to 27,84 (± 4,09). Only patients with sinus rhythm were included, patients with a pacemaker were excluded.

3. Methods

3.1. Preprocessing

ECG signals were bandpass filtered between 0.7Hz and 60Hz in order to preserve the waveform of the signal and remove or reduce baseline and high frequency noise. After QRS detection, P-wave segments were extracted using a fixed window temporally referenced to the QRS complex. All segments were supervised to ensure that the P-wave was completely within the selected segment, whereas any part of the previous T-wave and successive QRS complex was excluded. Segments containing the P-wave were once more low-pass filtered below 20Hz.

3.2. Eigenvalue decomposition

The parameters to be described in the following subsections are based on the eigenvalue decomposition of a vector of components. If these components present some redundancy and are correlated, a transformation of them can be found so that the original data are decomposed in uncorrelated eigenvectors. Additionally to this decomposition, an eigenvalue is associated to each eigenvector, which explains how much of the variance in the original data is contained in its corresponding eigenvector. Accordingly, an eigenvalue sequence in decreasing order can be obtained, where the first eigenvalue corresponds to the eigenvector with more presence in the original data and the last eigenvalue is associated with the less relevant eigenvector. This study will be focused on the relation of the different eigenvalues and will extract some valuable morphologic information from them, whereas the eigenvectors will remain disregarded.

3.3. Spatial analysis

The spatial analysis refers to extract morphological relations among different leads. Indeed, EVD may be useful to extract these relations. The procedure employed is as follows: firstly, the PSAECG is computed for each lead, with the aim to increase the SNR of the P-wave. The PSAECG for each lead is considered as the original data, and after EVD the eigenvalue sequence is obtained. A total number of 8 eigenvalues are computed, since only 8 out of the 12 leads are independent.

Two parameters are defined to evaluate this information: P-wave complexity and P-wave residuum. P-wave complexity attempts to account how much complex is the data under study. Data with low complexity will concentrate most of the information on the first eigenvector, and therefore, the first eigenvalue will be much larger than the other. In contrast, in data with high complexity, the percentage of the first eigenvalue will not be so high, since the rest of eigenvectors also contain an important part of the original data. Mathematically, P-wave complexity is defined as the proportion of all but the first eigenvalues:

$$Complexity = \frac{\sum_{i=2}^{8} \lambda_i}{\sum_{i=1}^{8} \lambda_i}, \quad (1)$$

where λ_i is the i-th eigenvalue. The lower bound for this parameter is 0, achieving this value only in the limit case when all signals are identically the same. Moreover, this parameter is overbounded by 0.875, achieving this value when all signals are mutually uncorrelated. This parameter was firstly defined for T-wave analysis [4], although in this study it has been employed to analyze the signal averaged P-wave.

The concept behind the P-wave residuum is linked to the fact that cardiac signals have been usually represented in a three dimensional space, such as the vectocardiogram (VCG). Accordingly, some studies claim that the ECG can be well explained using only three components, so that just with the first three eigenvectors and eigenvalues the essential information of the ECG is contained. This property motivated the definition of the T-wave residuum [5], which accounts for the proportion of the data that lies out of the aforementioned three dimensional space, and can be expressed as:

$$Residuum = \frac{\sum_{i=4}^{8} \lambda_i}{\sum_{i=1}^{8} \lambda_i} \quad (2)$$

Obviously, in this paper we employed this parameter for P-wave analysis. The theoretical range for this parameter is from 0 to 0.625, where higher ratios are expected to be associated to more heterogeneous activations. Although high residuum values are expected to be associated to more heterogeneous activations, the possibility to obtain values close to the upper limit would be rather unrealistic, since most of the values provided by P-wave residuum are considerably low. Indeed, the capability of this parameter to capture relevant morphological features is still a controversial issue [6].

3.4. Beat to beat analysis

In order to evaluate changes in the P-wave morphology, a beat to beat analysis is performed. In this case, the original data are the successive P-waves from a lead. EVD is applied to these data, and a regularity coefficient is computed as the first eigenvalue divided by the sum of all eigenvalues:

$$Regularity = \frac{\lambda_1}{\sum_{i=1}^{8} \lambda_i} \quad (3)$$

From this expression, it can be inferred that more homogeneous patterns will be associated with higher regularity values. This process is repeated for each lead, and a regularity parameter is finally computed by averaging the similarity coefficients of all leads. A key aspect of this parameter is that the number of P-waves to be considered for each patient must be strictly the same, otherwise the results would be biased and could not be compared. In this paper, we employed 5 P-waves for each lead and consequently, 5 eigenvalues could be computed. The theoretical range for this parameter considering 5 eigenvalues is from 0.2 to 1, where the lower bound is achieved when all P-waves are mutually uncorrelated and the upper bound applies when all P-waves are identically the same.

In order to compare the results with other parameters, the regularity was also computed from the correlation of the different P-waves from a lead. Finally, a regularity parameter was obtained by averaging all these correlation values. The range for this parameter is from 0 to 1. The theoretical ranges of all values are given in Table 1.

Table 1. Upper and lower bounds of P-wave parameters

	Lower bound	Upper bound
P-wave complexity	0	0.875
P-wave residuum	0	0.625
P-wave regularity (EVD)	0.2	1
P-wave regularity (Corr.)	0	1

4. Results

The methods described in section 3 were applied to all patients. All this procedure was automatically carried out and no corrections were needed. The results for both spatial and beat to beat analysis are given in Table 2.

After computing the spatial parameters, the P-wave complexity exhibited a mean value of 0.423±0.088, ranging from 0.217 to 0.627. Additionally, the P-wave residuum showed a mean value of 0.073±0.027, ranging from 0.030 to 0.161.

Regarding beat to beat parameters, the regularity using EVD was 0.601±0.083, ranging from 0.389 to 0.783. Finally, the regularity computed from the correlation values was 0.935±0.053, ranging from 0.642 to 0.987.

Fig. 1 and 2 illustrates an example comparing two patients with different morphological P-wave properties. Fig. 1 shows lead II for both patients. As can be observed, the patient on top (patient A) has a regular P-wave with time, whereas this can not be observed in the patient at the bottom (patient B). Indeed, the regularity computed with SVD was 0.709 and 0.486 for patients A and B, respectively. Furthermore, the regularity values computed from correlation value were 0.978 for patient A and 0.880 for patient B. The PRSA for each lead from those patients is shown in fig. 2. As can be observed, the spatial heterogeneity is higher in patient B. This is reflected in the complexity value, which was 0.285 and 0.585 for patients A and B, respectively. Finally, the residuum values were 0.044 for patient A and 0.084 for patient B.

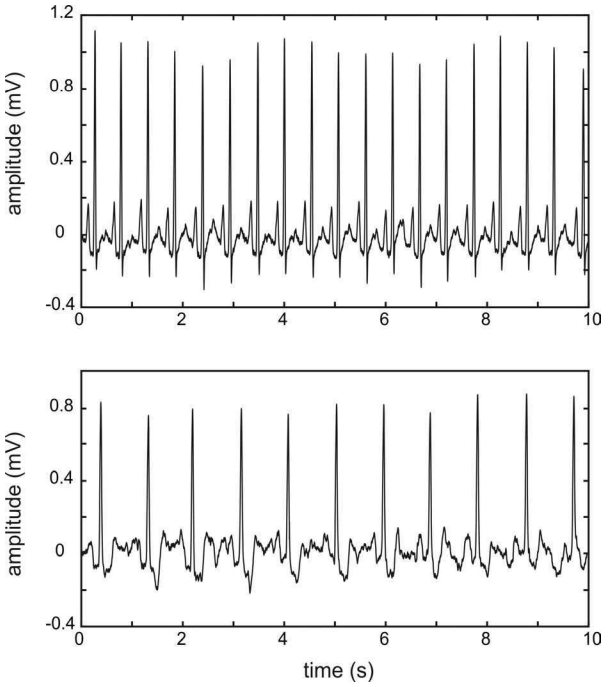

Figure 1. Top: lead II from a patient with regular P-waves (patient A). Bottom: lead II from a patient with irregular P-waves (patient B).

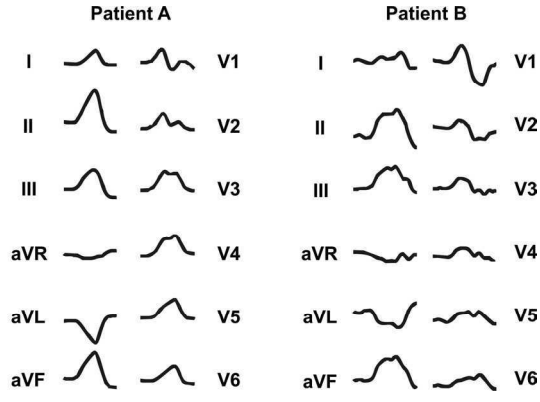

Figure 2: PRSA of patients A and B.

Table 2. Results for morphogical P-wave parameters for the database under study

	Minimum	Maximum	Range	Mean	Std
P-wave complexity	0.217	0.627	0.410	0.423	0.088
P-wave residuum	0.030	0.161	0.131	0.073	0.027
P-wave regularity (EVD)	0.389	0.783	0.395	0.601	0.083
P-wave regularity (Corr)	0.642	0.987	0.345	0.935	0.053

5. Discussion

One important aspect to take into account when evaluating new parameters is their potential to find interpatient differences. In this sense, it would be desirable that the results cover the theoretical range of the parameters as much as possible, as well as to obtain high standard deviation values. Finally, it would be convenient the mean value to be centred within the theoretical range, i.e. not to be close to any of the upper or lower bounds. Otherwise it may indicate that the parameter measured gets easily saturated, and therefore it would not be appropriate to emphasize differences among patients.

From the results detailed in table 2, and considering the theoretical ranges in table 1, it can be observed that both the P-wave complexity and the P-wave regularity using EVD accomplish these requirements. In both cases the mean value is centred within the range, since the central points are 0.438 for P-wave complexity and 0.600 for P-wave regularity.

As can be observed, the regularity using EVD is more suitable to enhance interpatient differences than the regularity using correlation coefficients, since in this case the values are close to the upper bound. This discrimination capability can be observed when comparing patient A and B, since the regularity from EVD displayed much different values than with the regularity from correlation, which exhibited large values in both cases.

Analogously, the values of the P-wave residuum are close to the lower bound, and hence it is less appropriate than the P-wave complexity to evaluate the spatial features of the P-wave. This effect can be observed when comparing the results for patients A and B given in the previous section.

6. Conclusions

In this work novel parameters based on EVD for the analysis of P-wave morphology have been proposed. Among them, P-wave complexity for spatial analysis and P-wave regularity for beat to beat analysis arise as promising indicators to unmask differences among patients. Both parameters can be computed in an automated and robust manner which does not depend on P-onset or P-offset detections, hence avoiding subsequent corrections by experts as it usually occurs when evaluating temporal parameters such as P-wave duration or P-wave dispersion.

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