Automatic Electrocardiogram Delineator Based on the Phasor Transform of Single Lead Recordings

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Abstract

The present work introduces a new ECG delineator, based on the Phasor Transform, which is able to operate in single lead recordings. The method converts each instantaneous ECG sample into a phasor, thus being able to deal very precisely with P and T waves, which are of notably lower amplitude than the QRS complex. Initially, the method relies on the detection of R peaks and, next, onset and offset of the QRS complex are identified. Finally, taking the QRS as a reference, P and T waves are detected and delineated. This delineator was validated with the QT database, available at Physionet, providing average values of sensitivity higher than 98.60% for the detection of all the significant ECG waves and fiducial points. Concretely, P wave sensitivity was 98.65% for the onset, peak and offset. The QRS onset and offset achieved a sensitivity of 99.85% and, finally, the T wave provided a sensitivity of 99.20% both for its peak and offset. Additionally, the average maximum time delineation error was lower than 6 ms and its standard deviation was in agreement with the accepted tolerances for expert physicians in the onset and offset identification for QRS, P and T waves. As a consequence, this new algorithm is able to achieve a performance similar to the top rated ECG delineators, but with notably lower computational cost.

1. Introduction

The surface electrocardiogram (ECG) provides a widely used and comfortable way to study the heart function, being a conventional tool for the diagnosis of cardiac diseases, which are the main cause of mortality in our society [1].

Given that most of the clinically useful information in the ECG is found within the intervals and amplitudes determined by its fiducial points, the development of accurate and robust methods for automatic ECG delineation is a very interesting challenge for clinicians and biomedical engineers [2]. To this respect, the proper ECG fiducial point detection could help in the achievement of more accurate results in a number of applications, such as pattern recognition or arrhythmia classification [3] and to develop improved solutions for the diagnosis of some certain phenomena such as T-wave alternants [4], atrial fibrillation [3] or QT-prolongation [5].

To date, many authors have addressed the automatic delineation of ECG waves. Thus, a wide diversity of algorithms have been proposed in the literature [2]. Most of them work on a single ECG lead and use to perform, as a first step, an R-peak detection in order to take this point as a reference. The most significant proposed approaches to locate the R-peak are summarized in [6]. The next usual step is to delineate the QRS complex together with the P and T waves. To this respect, most of the algorithms usually start from the R-peak and define forward and backward search windows.

However, the onsets and offsets precise detection of the ECG waves taken directly from the ECG is a hard task because, in general, the signal amplitude is notably low close to the wave boundaries and the noise level can be even higher than the signal itself [2]. Thereby, once the search window is defined, some technique has to be applied to the ECG in order to enhance the proper waves and fiducial points. To this respect, different mathematical tools, including filters, second-order derivatives, low-pass differentiation, non-linear time-scale decomposition, dynamic time warping, artificial neural networks, hidden Markov models, etc., have been used [2]. However, the wavelet transform (WT) has proved to be the delineation technique with the highest accuracy [2, 4]. Nevertheless, WT-based delineation algorithms require intensive mathematical operations and, therefore, notable computational time and cost [7].

Overall, in the present contribution, a fast algorithm based on the Phasor Transform is proposed for the detection and delineation of QRS, P and T waves from the ECG.

2. Methods

2.1. Phasorial signal for delineation

The Phasor Transform (PT) is a tool able to represent a sinusoidal function in the complex domain. The result is a complex number, called the phasor, which preserves the signal information regarding root mean square and phase values [8]. Thus, for a generic discrete sinusoid such as

$$x[n] = A\cos(\omega n + \varphi) = \Re\{Ae^{j(\omega n+\varphi)}\}, \qquad (1)$$

being A the amplitude and φ the phase of the sinusoid, its PT would provide a rotating phasor in the complex plane with magnitude A, rotation speed ω and initial phase φ, i.e.

$$\mathrm{PT\{x[n]\}} = \mathrm{Ae^{j\varphi}} = \mathrm{A}\cos(\varphi) + \mathrm{jA}\sin(\varphi). \qquad (2)$$

To enhance the ECG waves, PT was used to convert each instantaneous ECG sample into a phasor. A constant value R_v was considered as the real part, whereas the original value of the ECG was used as the imaginary component of the phasor. Thus, if we denote an ECG recording of N samples in length by $x[n]$, being n the discrete time, the phasor $y[n]$ could be defined for each sample as

$$y[n] = R_v + jx[n], \qquad \text{for } n = 1, \ldots, N. \qquad (3)$$

The magnitude $M[n]$ and phase $\varphi[n]$ of this phasor could be computed as

$$M[n] = \sqrt{R_v^2 + x[n]^2} \quad \text{and} \qquad (4)$$

$$\varphi[n] = \tan^{-1}\left(\frac{x[n]}{R_v}\right). \qquad (5)$$

In this way, by considering the instantaneous phase variation in consecutive samples of the phasor transformed ECG, the slight variations provoked by P and T waves in the original recording are maximized, regardless of their eventually low amplitude. The value of R_v determines the degree with which ECG waves are enhanced into the phasorial signal and it was calculated experimentally for each wave by using the QT database as learning set [9].

2.2. Detection of fiducial points

2.2.1. QRS detection

QRS complexes were detected by applying directly the PT to the absolute value of the preprocessed ECG (without baseline wandering), $|x[n]|$, with a value of $R_v = 0.001$. As can be appreciated in the lower part of Fig. 1 (a), P and T waves were notably enlarged by the PT operation. However, the maximum instantaneous phase variation can be yet found for the QRS complex, see Fig. 1 (b). Thus,

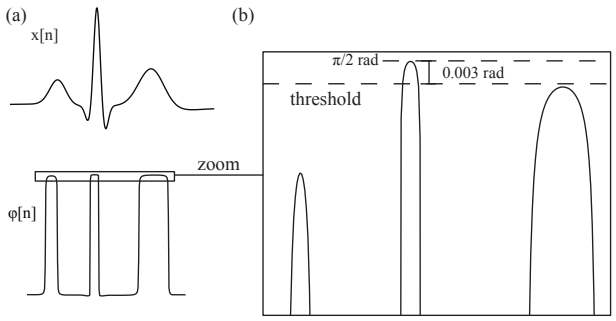

Figure 1. (a) Representation of a normal beat from a typical ECG (top) together with its phase variation obtained from the phasor transform (bottom). (b) Detailed representation of the phasor transformed signal $\varphi[n]$ to illustrate the process for R-peak identification.

by establishing a threshold of 0.003 rad below the maximum phase variation of $\pi/2$ rad, the QRS complexes can be located as the segments that exceed the threshold. In those cases where a time longer than 150% of the last computed R–R distance elapsed without detecting any QRS, a new backward search with lowered thresholds was repeated until successful detection. Finally, for each detected QRS complex within the segment exceeding the threshold, the R-peak was selected as the maximum modulus point, $M[n]$.

2.2.2. QRS delineation

Once the R-peak was detected, it served as a reference for the identification of Q and S waves. Two boundary points, γ_{QRS-} and γ_{QRS+}, around the R-peak were primarily established. They were defined as the closer points to the R-peak in which $\varphi[n]$ was lower than 25% of the maximum phase variation of $\pi/2$ rad. Before γ_{QRS-}, a window of 35 ms was considered to seek for the Q wave. Only for this window, the PT was newly applied to the absolute value of the ECG, $|x[n]|$, subtracting previously the median of the segment. In this case the value of R_v was 0.005 in order to minimize the effect of interfering noise. Finally, the local minimum of $\varphi[n]$ was searched within the defined window. If any point presented a phase higher than 75% of the maximum variation of $\pi/2$ rad, the marked local minimum was annotated as the Q wave, given that the absence of a significant negative deflection with respect to the isoelectric line between Q and R was deduced, see Fig. 2 (a). In other case, among the phasors exceeding the threshold, the one with the highest modulus $M[n]$ was marked as Q wave, because this point will be the local minimum preceding the described deflection, see Fig. 2 (b). The same strategy and window length were used for S wave delineation, with the only peculiarity that

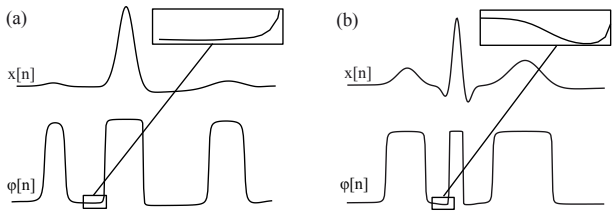

Figure 2. Example of a beat without (a) and with (b) negative deflection, with respect to the isoelectric line, between the fiducial points Q and R.

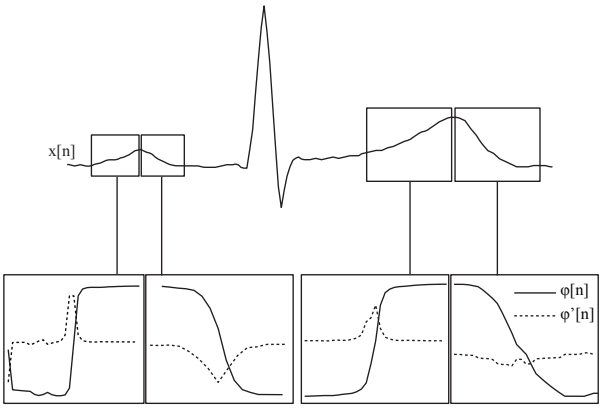

Figure 3. Representation of the phasorial signals, $\varphi[n]$, and their corresponding derivative, $\varphi'[n]$, used to delineate the onset and offset associated to P and T waves for a normal ECG beat.

the search window was defined after the point γ_{QRS+}.

2.2.3. P wave detection and delineation

In order to detect the P wave a search window, relative to the Q wave position, was firstly considered. The width of this window was adapted to each beat, being initially a quarter of the distance between the current R peak and the previous one. Afterwards, the median was removed from the ECG segment within the window and PT was applied with R_v taking a value of 0.003. The local maximum of $\varphi[n]$ was located within the window and it was corroborated the coherence of this point with a peak, establishing the P-peak. For identification of the P wave onset and offset, the detected P-peak was used as reference. Both boundaries were individually searched. Thus, a 15 ms window relative to the P wave peak was established before this point. The median was removed to minimize noise and PT, with $R_v = 0.005$, was applied to the ECG segment within the window. Next, the first derivate of $\varphi[n]$ was obtained to locate the phase transition from its minimum to its maximum, see Fig. 3. Afterwards, from this point towards the window start, the nearest zero-crossing in $\varphi'[n]$ was searched and marked as the P wave onset. For detection of P wave end, the same process with two exceptions was used. Obviously, the search window was established after the P wave peak and the closest zero-crossing in $\varphi'[n]$ was seek from its local minimum towards the window end.

2.2.4. T wave detection and delineation

The strategy to identify the T wave peak and boundaries was similar to the described for the P wave. In this case, a wider search window of 25 ms was used to determine the onset and offset of the T wave, because it is generally longer than P wave. Additionally, given that the T wave amplitude is higher than the P wave, a lower enhancement of this wave was required and, therefore, a value of $R_v = 0.1$ was used.

2.3. Validation with ECG databases

As there is no a *gold standard* to determine the peak, onset and offset of the ECG waves, the proposed delineator was validated making use of manually annotated databases, which has been widely used in previous works [2, 4], such as the QT database. This database includes 105 ECG recordings (2-lead) at 250 Hz and it provides cardiologists annotation for at least 30 beats per recording, with marks including P and T waves peaks, onsets and offsets [9]. In order to assess the detection of each analyzed point, sensitivity was computed as $Se = TP/(TP + FN)$, being TP the number of true positives and FN the number of false negative detections. Additionally, for validation of the wave delineation, m and s were calculated as the average and standard deviation, respectively, of the differences between automatic and manual annotation, such as in previous works [2, 4].

3. Results

The results obtained over the QT database are presented in Table 1. For comparison purposes, the outcomes obtained by the most significant previously published works [2, 4] have been included also in this table. It is noteworthy that both works are based on the Wavelet Transform. In the last row, the accepted standard deviation tolerances given by the Common Standards of Electrocardiography (CSE) working party from measurements made by different experts [10] are also included.

4. Discussion and conclusions

As previous works [2,4], the proposed delineator is able to detect QRS, P and T waves with a sensitivity higher than 98.60% in all the cases. Regarding the delineator, the method can identify the onset and offset of the P and

Table 1. Delineation performance comparison with the most significant previously published works making use of the QT database.

$Method$	$Parameters$	Pon	$Ppeak$	$Pend$	$QRSon$	$QRSend$	$Tpeak$	$Tend$
	$annotations$	3194	3194	3194	3623	3623	3542	3542
PT (this work)	Se (%)	98.65	98.65	98.65	99.85	99.85	99.20	99.20
	$m \pm s(ms)$	2.6±14.5	32±25.7	0.7±14.7	-0.2±7.2	2.5±8.9	5.3±12.9	5.8±22.7
Garaffi et al [4]	Se (%)	99.46	99.46	99.46	99.94	99.94	99.87	99.87
	$m \pm s(ms)$	-1.2±6.3	4.1±10.5	0.7±6.8	-0.6±8	0.3±8.8	0.3 ±4.1	0.8±10.7
Martinez et al [2]	Se (%)	98.87	99.87	98.75	99.97	99.97	99.97	99.97
	$m \pm s(ms)$	2.0±14.8	3.6±13.2	1.9±12.8	4.6±7.7	0.8±8.7	0.2±13.9	-1.6±18.1
Tolerances	CSE(ms)	10.2	-	12.7	-	-	-	30.6

QRS waves with mean errors smaller than one sample (4 ms). These results are very similar to those reported by the most significant single-lead delineators [2], because the slight differences that can be appreciated are small in comparison to the sample interval. For the T wave offset delineation, results showed a mean difference between automatic and manual annotations slightly higher than one sample (around 5.8 ms). However, the identification of this point is the most difficult task in ECG delineation, because a specific criterium to mark the T wave offset has not been adopted yet by specialists [2]. Indeed, T wave offset annotations by different cardiologists on the same ECGs generally show larger differences [2]. Some works considered the values given by the CSE Working Party [10] as a reference for error tolerance. To this respect, the proposed delineator obtained an average error standard deviation lower than the recommended tolerance for the T wave offset delineation and a slightly higher for the onset and offset of the P wave, such as in [2]. However, the difference between the obtained and recommended values are notably smaller than the sampling period.

Overall, it could be considered that the proposed method, based on phasor transform, could appropriately delineate the different morphologies of QRS, P and T waves presented in the QT database without requiring specific rules adapted to each one of them. Moreover, the method presents a low computational cost and mathematical simplicity. Finally, additional validation with different databases would be desired to obtain statistically more robust outcomes.

Acknowledgments

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