EVALUATION OF HRV BY PP AND RR INTERVAL ANALYSIS USING A NEW TIME DELAY ESTIMATE

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Abstract

The heart rate variability (HRV) is basically controlled by the effect of vagal and sympathetic influence on the sino-atrial (SA) node. Then the time intervals used in the analysis of HRV should be the time distance from the onset of consecutive P-waves. In most cases this analysis is performed through RR interval instead of PP interval. This aproximation is permisible in many cases given that fluctuations in the PR interval are comparable with the accuracy of most QRS detectors. In cases with higher PR variations the PP interval is a more precise measure of heart rate.

In this work we proposed a method to analyse HRV through PP interval. The PP interval is determined using a QRS detector and a new time delay estimate that improves the accuracy of the QRS detection. Results obtained by this method are presented. The extension of the method to measure RR and TT intervals and the effect of sampling rate are considered. Also a discussion about the PP and RR intervals is presented by means of the PR variability analysis.

Introduction

The heart rate variability (HRV) is a useful index in diagnosis of cardiac disfunctions. This index reflects the spontaneous fluctuations in the heart rate due to the effect of vagal and sympathetic influence on the sino-atrial (SA) node. According to that, the HRV should be measured through the time distance from onsets of consecutive P waves[1]. This implies a reliable and accurate P-wave detector, but P waves usually have a low signal-to-noise ratio (SNR) that difficults the P-wave detection.

In most cases this problem is solved measuring HRV through the variability of the RR interval given by a QRS detector that, in general, is more reliable and accurate than a P-wave detector. This can be done if fluctuations in PR interval are assumed to be small in comparison with the accuracy of the QRS detector, but this assumption is not always fulfilled. For example, the PR interval progressively lengthens in the Wenckebach phenomenon[2]. Even in normal subjects during physical rest or minor physical load the standard deviation of PR interval[3] ranges from 0.5 to 5 ms. In other cases it can be higher. The error introduced by these variations is not important when we are interested in heart rate, but it should be analysed when we are interested in HRV. Otherwise, intrinsic variations of PR interval would be considered as heart rate variations. Inaccuracy of detected QRS positions are other source of errors in HRV.

By other hand, if we want to measure PP interval, the definition of the P-wave position is generally performed by a occurrence detector. These detectors analyse the presence of P wave, but do not give an accurate location of it due to the low SNR (5 to -5 dB). Then PP intervals are not precisely defined.

In this work we propose the use of a QRS detector and a new time delay estimate to measure the PP interval and to analyse the HRV through it. The QRS detector, that gives reliability to the method, opens windows that contain the P waves. The time delay estimate defines in these windows the positions of P waves taking the whole wave information and not only local information. This method allows a more accurate definition of P-wave position.

An application to the ECG recordings of different patients and a discussion of the results obtained in two patients are presented. The extension of the procedure to get measures of PR, TT, RR and QRS-T intervals and a discussion about limitations of the method and the effect of sampling rate are considered.

The Method

The objective of this method is to get a precise definition of the PP interval. Firstly we apply a conventional QRS detector that defines the position of each i-QRS complex (QRS(i)). From this point we define a window at a fixed distance from QRS(i) that contains the P wave. The width of this window is called Wp (figure 1). Analogously, it can be done with QRS complexes and T waves. The windows opened to contain QRS and T waves have a width of Wqrs and Wt, respectively.

Windows opened to contain P waves are considered as records $p_i(t)$ of the P-wave signal ($p(t)$). The P-wave position inside the windown will be delayed in one record with respect to the other, if the PR interval is not constant for every beat or the QRS position mark has some variability. The time delay estimation method[4,5] calculates the delay (D_{P_i}) between two consecutive records of the P wave, $p_{i-1}(t)$ and $p_i(t) = p_{i-1}(t - D_{P_i})$.

The basis of the method is the following. The delay D is calculated according to the estimate

$$D = \frac{\int_a^b \int_a^T (s^2(t) - s^2(t - D))\, dt\, dT}{\int_a^b s^2(t)\, dt} \qquad (1)$$

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where $s(t)$ and $s(t-D)$ are the same signal ($s(t)$, $t \in$ [a,b]) delayed a time D (figure 2).

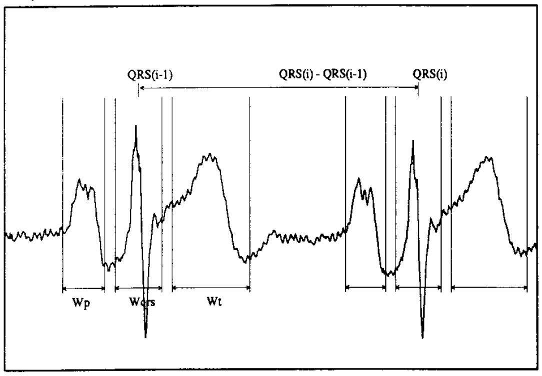

Figure 1:
ECG signal with the marks of the QRS detector (QRS(i)) and the windows opened to contain the different waves of each beat. Wp, Wqrs and Wt are the width of windows that contain P, QRS, and T waves, respectively.

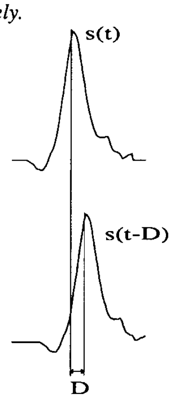

Figure 2:
Two records (windows) of a wave $s(t)$ delayed a time D.

This estimate was presented in detail by Rix and Jesus[4] and Laguna *et al.*[5]. The behaviour of the estimated delay in presence of noise and a range of its standard deviation as a function of the SNR were also presented[5].

With the value of D_{P_i} we can calculate the PP interval between the $i-1$ and the i beats (PP_i) as

$$PP_i = (QRS(i) - QRS(i-1)) + D_{P_i} \qquad (2)$$

The proposed time delay estimation method takes the information of the whole signal p(t). This method to determine the P-wave position is more accurate than others methods that use local criteria.

Same procedure can be followed with the windows that contain QRS complex signals. In this case we will have a more precise estimation of the RR interval that reduces the QRS detector inaccuracy. The RR interval at the i beat (RR_i) will be

$$RR_i = (QRS(i) - QRS(i-1)) + D_{QRS_i} \qquad (3)$$

where D_{QRS_i} is the estimated delay between two consecutive QRS complexes. With the two previously calculated delays (D_{P_i}, D_{QRS_i}) we can obtain a precise variability analysis of PR interval (PR_i), according to the whole information contained in the QRS complex and P wave. The recursive expression for the PR_i interval as a function of D_{P_i} and D_{QRS_i} is

$$PR_i = PR_{i-1} + D_{QRS_i} - D_{P_i} \qquad (4)$$

This expression needs an initialization that can be done at the initial beat or at any with poor noise contribution. The initial PR interval is calculated defining the P position (P_0) and R position (R_0) as

$$P_0 = \frac{\int_{a_p}^{b_p} t\, p^2(t)\, dt}{\int_{a_p}^{b_p} p^2(t)\, dt} \quad \text{and} \quad R_0 = \frac{\int_{a_{qrs}}^{b_{qrs}} t\, qrs^2(t)\, dt}{\int_{a_{qrs}}^{b_{qrs}} qrs^2(t)\, dt}. \qquad (5)$$

where $p(t)$ and $qrs(t)$ are the P wave and QRS complex signals, respectively. The temporal limits of $p(t)$ and $qrs(t)$ are $a_{p,qrs}$ and $b_{p,qrs}$, respectively. This definition is like the gravity center of the squared waves. If the intervals of interest were TT and QRS-T, the procedure would be the same taking the windows that contain T wave signals, and considering D_{T_i} the delay between two consecutive T waves.

$$TT_i = (QRS(i) - QRS(i-1)) + D_{T_i} \qquad (6)$$

$$(QRS-T)_i = (QRS-T)_{i-1} + D_{T_i} - D_{QRS_i} \qquad (7)$$

Limitations in the accuracy of the proposed method to define the PP interval or any other are analysed below. Firstly, the time discretization results in a uniformly distributed estimation error with a standard deviation[3] proportional to the intersampling time T_s ($\sigma = T_s/2\sqrt{3}$). For sampling rates of 1 kHz it gives $\sigma = 0.3$ ms that is negligible in front of PR variations. Secondly, the time delay method estimates exactly if the signal is free of noise and constant in morphology. This never happens in real situations, and simulation results[5] have shown that the estimated delay has a standard deviation of around $\sigma \simeq 5$ ms for SNR of 0 dB and $\sigma \simeq 1$ ms for 10 dB.

P waves usually have SNR around these considered values. Then, when PR variability is in these ranges the method does not give a real improvement in the performance of HRV measured through PP instead of RR. In cases where PR variability is higher than those standard deviations, PP interval is a more accurate mesure of heart rate and then is more appropiated to analyse HRV.

Results

To test the proposed method we have taken the ECG signal from different patients and we have calculated the different time intervals considered before. The recorded ECGs belong to bipolar leads and are sampled at 1 kHz with 12 bits resolution in a PC based digital acquisition system. The signal processing is made on a VAX 11/785. A digital high-pass filter is applied with a cutoff frequency (-3 dB) of 0.5 Hz. After that the QRS detector and the time delay estimate calculate the intervals of interest.

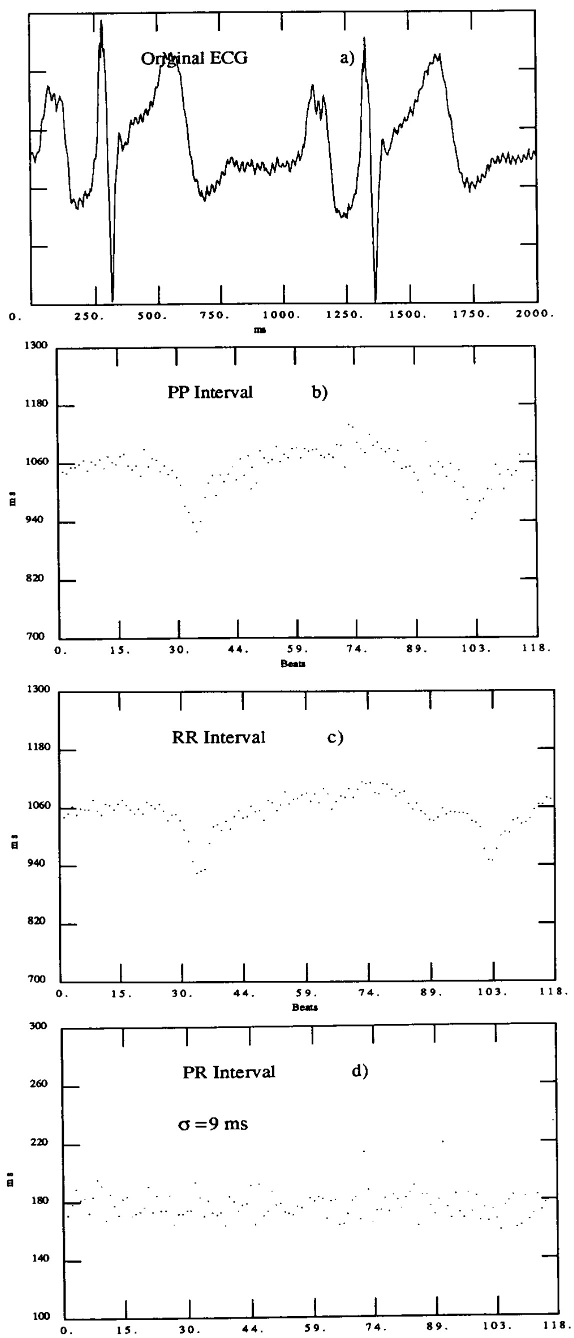

Figure 3:

(a) Two seconds of ECG signal from the first patient considered. (b) PP interval measured in the ECG by the proposed method in 118 beats. (c) RR interval according to equation 3. (d) PR interval according to the recursive equation 4.

Figure 3a shows the original ECG from the first patient considered. The width of the windows that contains the different waves are: Wp=200 ms, Wqrs=180 ms and Wt=280 ms. The positions of window centers from the QRS position mark are: for P wave, 180 ms previous to the QRS mark; for T wave, 230 ms after the mark, and for QRS complex, 20 ms before the mark. Figures 3b and 3c shows the PP and RR interval in 118 beats. Figure 3d display the PR interval in the same beats.

Regarding to the absolute value of RR or PP intervals, both are practically the same. The PR interval presents a standard deviation of 9 ms, and the deviation of the time delay estimate[5] for a signal with the SNR presented in figure 3a is about 5 ms. That means in this case we get a more precise definition of the heart rate through the PP interval measured in this way than through the RR interval.

In figures 4 a,b,c,d we present the results of other patient where the variability of PR interval is 4 ms, that is in the range of the method precision. In this case, same precision is got with PP and RR intervals. Windows width were Wp=100 ms, Wqrs=120 ms and Wt=160 ms; and center positions from QRS mark were 150 ms before for P wave, 20 ms before for QRS complex and 200 ms after for T wave. In figure 5a we present the TT interval measured through windows opened to contain T waves. In this case TT variability is higher than PP or RR given that intrinsic variability of QRS-T distance is higher than those of PR interval (fig. 5b)

Analogous measures were made for sampling rates of 500 and 250 Hz. No significative differences were found in any case. The standard deviation for sampling error is $\sigma = 1.2$ ms in case of sampling at 250 Hz, and this is small compared with the intrinsic desviation in intervals of both patients considered.

Conclusions

Physiological origen of heart rate is linked to the P wave. Then the PP interval is the more appropiate magnitude for computation of heart rate. In cases where fluctuations of PR interval are small, in comparison with accuracy of most QRS detectors, RR interval can be considered as a good measure of heart rate.

The proposed method to determine the PP interval improves the precision in the definition of heart rate when PR variation are higher than error of QRS detectors and time delay estimate, and allows to reach the heart rate with same precision than reached through RR interval in cases of low PR variations. The HRV can be more precisely evaluated using this technique, mostly when HRV is evaluated through its spectra in the high frecuency components.

This method takes the information present in the whole wave. Thus it gets higher accuracy than methods based in local measures when defining fiducial points. In cases where SNR in the P wave is very low (lower than -5 dB), the time delay estimate gives a dispersion in the definition of D_{P_i} that does not justify to consider PP interval instead of RR interval.

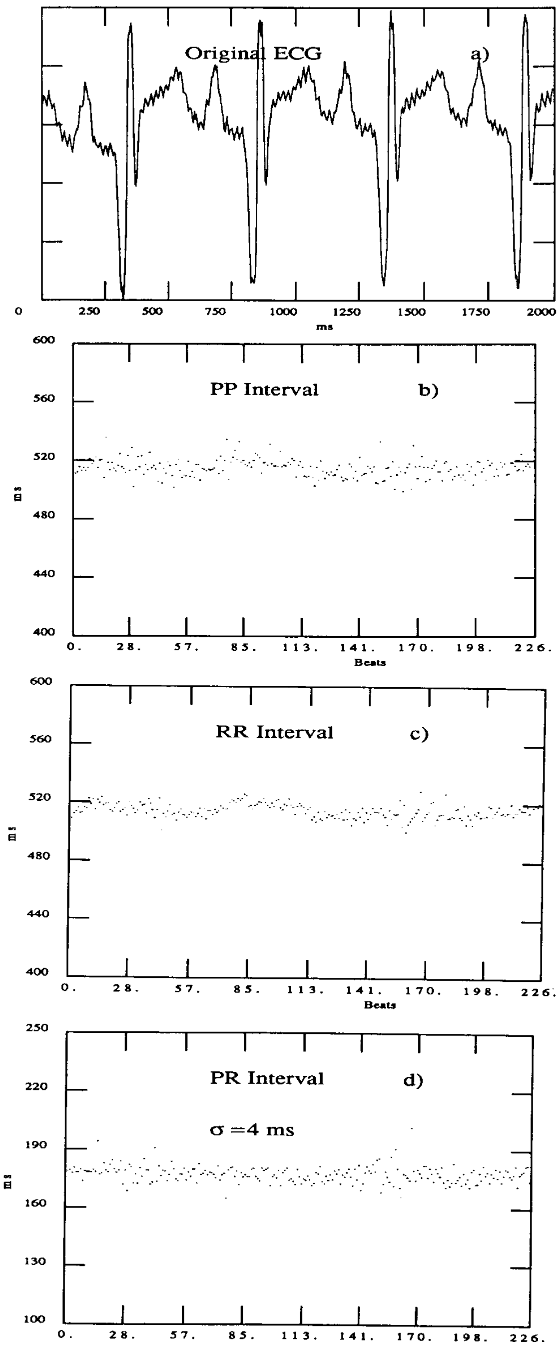

Figure 4:

(a) Two seconds of ECG signal from the second patient considered. (b) PP interval measured in the ECG by the proposed method in 226 beats. (c) RR interval according to equation 3. (d) PR interval according to the recursive equation 4.

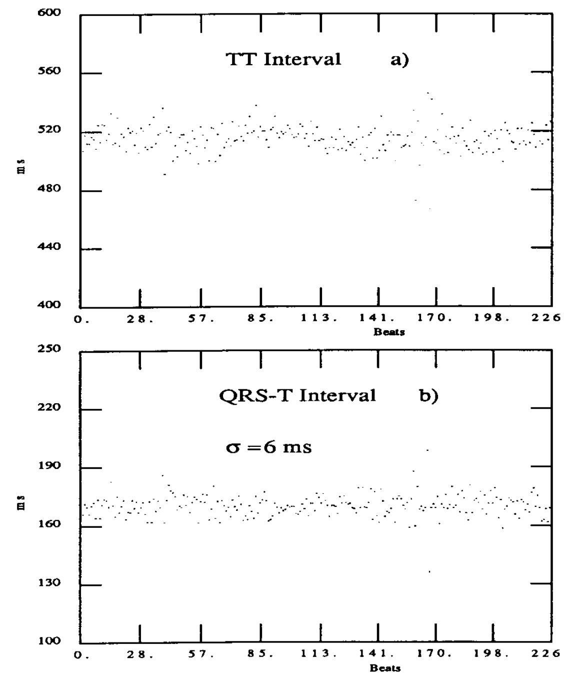

Figure 5:

(a) Evolution of TT interval in 226 beats of the second patient considered. (b) QRS-T interval in the same beats.

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