ECG WAVE DETECTOR AND DELINEATION WITH WAVELETS

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ABSTRACT

Efficient R wave detection is a crucial preprocessing step of most of the ECG signal analysis. Likewise, ECG delineation comprising P wave and QRS complex, is required for ECG processing, namely in High-Resolution Electrocardiography (HR-ECG). We have performed R wave detection using the Mexican Hat wavelet and achieved a sensibility Se=97.77 % and a positive prediction P_+=99.46%. Our data is HR-ECG and the delineation process occurs in two steps: wavelet detection and application of the Task Force (Breithardt et al.)[1] detection rules.

Keywords : ECG delineation, R wave detection, Wavelets and HR-ECG.

R WAVE DETECTION

For any ECG delineator, the most critical step of the entire process is the R wave detection. In spite of being the most energetic wave on the ECG signal, it is not always easy to identify it, due to QRS complex morphology, noise and baseline drift. Despite the fact that this detector was developed for HR-ECG data, the applied procedure is identical to the one applied to the regular ECG signal (Hamilton and Tompkins)[2] (Afonso et al.)[3].

Wavelet Detection

To perform the R wave detection we have used the Mexican Hat wavelet (Witten et al.)[4], given by:

$$\psi(x) = \left(\frac{2}{\sqrt{3}}\pi^{-\frac{1}{4}}\right)\left(1 - x^2\right)e^{-\frac{x^2}{2}} \qquad (1)$$

This function (figure 1) is proportional to the second derivate of the Gaussian function, and it does not have a scale function, Φ, therefore leading to the use of the continuous wavelet transform (CWT).

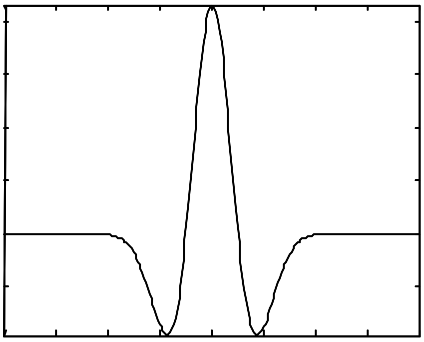

Fig. 1 – Mexican Hat Wavelet

The application of this wavelet performs well in edge detection and signal singularities[4] (Daubechies)[5]. Therefore, assuming that the peak due to an R wave is an "edge", this wavelet should be efficient for R peak detection. Its shape is similar to the QRS complex and by performing the analysis of an ECG signal it should give a considerably higher coefficient value for the R peak against very close to zero coefficients to non-QRS/R peak complex.

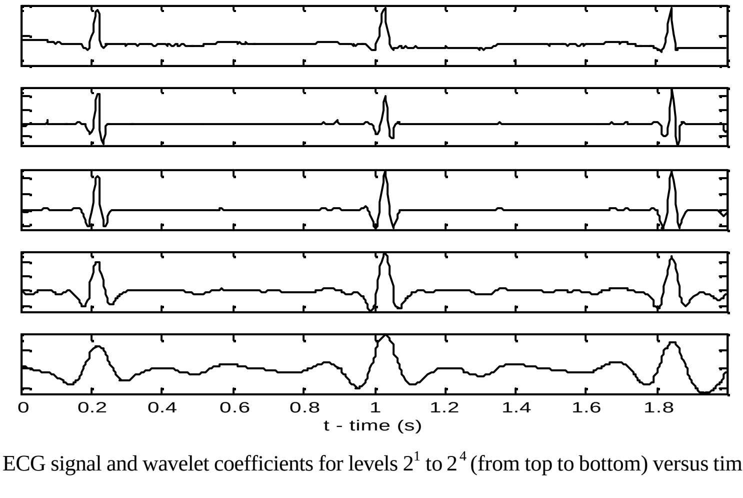

Fig. 2 – ECG signal and wavelet coefficients for levels 2^1 to 2^4 (from top to bottom) versus time.

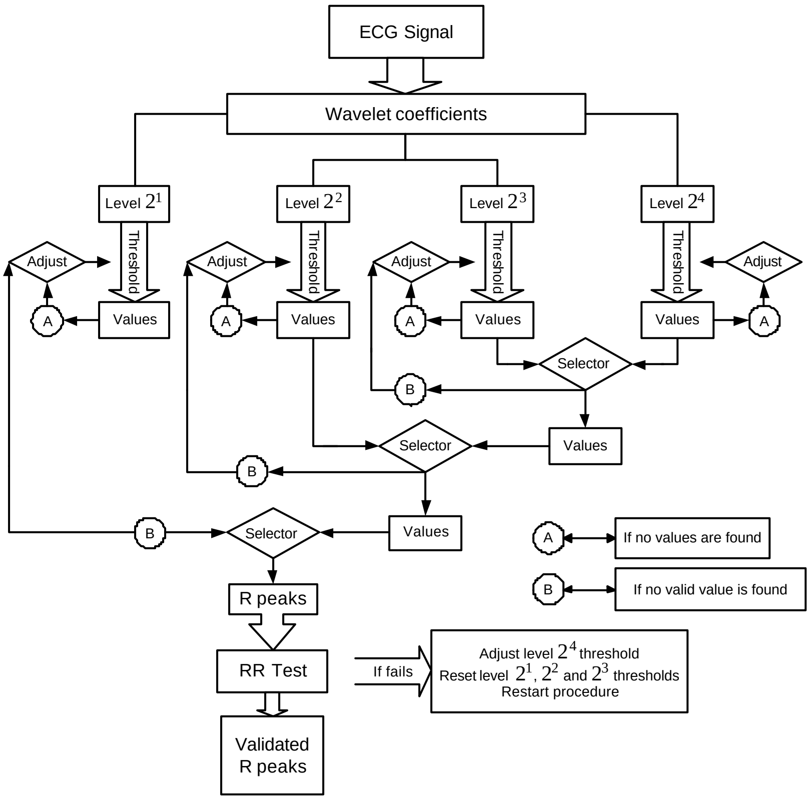

Fig. 3 – R peak detector algorithm block diagram.

Most of the energy of the QRS complex is at scales 2^3 and 2^4 (figure 2). P and T waves energy exists at scales 2^4 and 2^5. So, to avoid redundant calculations and save processing resources, we choose scales 2^j (j=1,…,5) as relevant coefficient scales (Thakor et al.)[6].

R Wave Detection

The algorithm starts by calculating the average deviation relatively to the averaged value of all wavelet coefficients in each level (scale). It's assumed that, in each level, no coefficient due to an R peak has an absolute value inferior to its level average deviation value. To avoid the risk of having coefficients not due to an R wave and to simplify the data processing, the initial threshold value is set to the average deviation multiplied by a factor a. This factor has a value of a=5 for levels 2^1, 2^2 and 2^3, and a=4 for level 2^4. Level 2^5 is not used for detection.

Then, in each level, the algorithm sweeps the coefficients, selecting the ones with absolute value greater than the level threshold value. If no coefficient is found, then the threshold is adjusted to 90% of its value.

To finish the initial procedures, the algorithm keeps only the coefficients that are local maximum/minimum. To avoid the processing of redundant or repeated coefficients, the algorithm selects the maximum absolute coefficient value in a 200ms time interval. This time window is set because we consider that only one QRS complex exists in each 200ms.

After the identification of relevant coefficients at level 2^4, a search is performed in level 2^3. This search is done by the combination of these two levels. Considering the given coefficient value that occurs at time instant t_4, it is performed a time search of pre-determined relevant values of level 2^3. This search begins with a time window of [t_4-200ms; t_4+200ms]. If no relevant coefficient is found, then the search time window is set to [t_4-300ms; t_4+300ms] and then to [t_4-400ms; t_4+400ms]. If still no relevant value is found, the algorithm adjusts the threshold (the adjustment is always made to 90%) and repeats the search until a relevant coefficient is found, or the threshold reaches the value of the average deviation.

At this point, the number of relevant coefficients selected at level 2^3 is at most equal to the number of relevant coefficients at level 2^4.

The algorithm continues the R peak detection, in a similar procedure, at levels 2^2 and 2^1. The only difference between these two levels and the search in level 2^3 is the search time window. While for level 2^3 the search window has the values above, for level 2^2 the search windows are set to [t_3-25ms; t_3+25ms], then to [t_3-50ms; t_3+50ms] and finally to [t_3-75ms; t_3+75ms]. For level 2^1, these windows are set to [t_2-10ms; t_2+10ms], [t_3-15ms; t_3+15ms] and [t_3-20ms; t_3+20ms].

To verify if any R peak on the ECG signal has been undetected, the algorithm performs a confirmation by comparing the R-R interval with the immediate two before and after intervals. In case of the number of the R-R intervals being lower than required, it only uses the existing ones, without exceeding two before and two after. Basically, this procedure is required to verify if the detector algorithm has given a false negative and correct the threshold level so it may identify the undetected R peak. In case of this occurrence, the algorithm adjusts the threshold in level 2^4, resets the other levels thresholds and restarts the entire process. If the threshold value in level 2^4 is less than *2.4* times the average deviation, it is assumed that no R peak is undetected. In spite of being an unusual occurrence, this may happen mainly after a ventricular premature beat.

ECG DELINEATION WITH WAVELETS

To any kind of delineation of an ECG signal, it's necessary to identify reference points. Usually R peaks are used as these points because they are the easiest and trustworthy references points for beat identification. As soon as we have the R peaks detected, it's possible to proceed to the delineation of the ECG, namely the QRS onset and offset, and P wave detection (peak, onset and offset).

Wavelet Used for ECG Delineation

The wavelet used for ECG wave delineation is a quadratic spline wavelet, with compact support and one vanishing moment (Mallat)[7] [8]. The quadratic spline Fourier transform (figure 4) is given by:

$$y\,(w) = jw\left(\frac{\sin\left(w/4\right)}{w/4}\right)^4 \qquad (2)$$

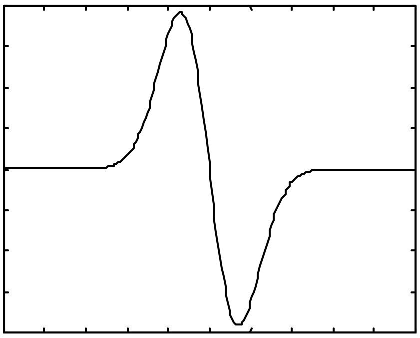

Fig. 4 – Quadratic Spline Wavelet.

The wavelet transform equivalent low-pass and high-pass filters transfer function are given by:

$$H(w) = e^{\frac{jw}{2}}\left(\cos\frac{w}{2}\right)^3 \qquad (3)$$

$$G(w) = 4e^{\frac{jw}{2}}\left(\sin\frac{w}{2}\right) \qquad (4)$$

These are FIR filters with impulse responses given by:

$$h[n] = \frac{1}{8}\{d[n+2] + 3d[n+1] + 3d[n] + d[n-1]\} \quad (5)$$

$$g[n] = 2\{d[n+1] - d[n]\} \qquad (6)$$

QRS Delineation

Once R peaks are determined, remains the task of locating the QRS complexes onsets and offsets. The onsets and offsets of the QRS complexes can be located at level 2^1, due to Q and S waves being high frequency and low amplitude waves (Li et al.)[9]. To accomplish this, we establish that all coefficients closer than 150ms to R peak time instant are selected, keeping only those that are local extremes (figure 5).

QRS offset detection. The offset detection starts by selecting the local extremes after R peak. As the first value is due to the R peak, then it's performed a search for the first value after a zero crossing. This point will be set as the QRS complex offset.

QRS onset detection. The QRS onset detection is performed by a similar way as the offset detection, but not quite as simple.

After selecting all local extremes before the R peak, the algorithm searches for the two closest zero crossings to the R peak. This means that at most 4 values will be identified as relevant points. If only one zero-crossing is found, this means that 2 points are relevant, and so, the onset of the QRS is located at the time instant of the point more apart from the R peak. Usually this is not the case and more than one zero-crossing are found. This means that it's necessary to identify which one is relevant to set the QRS onset. In this case, the zero-crossing with greater value variation is selected, setting the QRS onset to the time instant of the point more apart from the R peak time instant.

P Wave Delineation

As soon as the QRS complexes are characterized, the following step is the P wave detection. This means, finding its peak, onset and offset (figure 6). This was performed also using the quadratic spline wavelet due to its characteristics (Martinez et al.)[10].

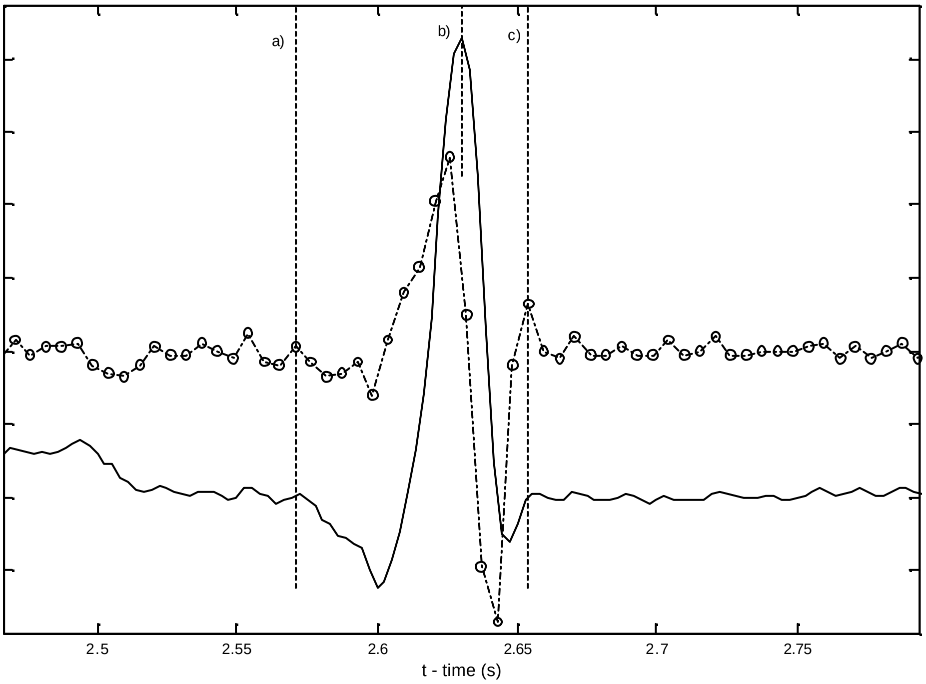

Fig. 5 – ECG signal (solid) with level 2^1 coefficients (dashed).
a) QRS onset; b) R peak; c) QRS offset.

P wave peak detection. As a start up procedure, the P wave delineation is performed beat-by-beat, since only one P wave and one T wave exist between two QRS complexes. Therefore, the algorithm selects all the coefficient values, in level 2^4, between one QRS offset and the onset of the next one. To limit the number of points for the detection of the P wave, only the last 40% of the interval between the first QRS offset to the next QRS onset is hold, and the average value of the modulus of these coefficient values (Av_P) is determined. The next step is to keep only the level 2^4 local extremes.

The following steps are the most important for the P wave detection. The algorithm selects, in the remaining local extremes, the ones that vary more than $2Av_P$, and then keeps only those that have a zero crossing. If less than 3 points are found, it repeats the last step selecting the local extremes with variations of at least Av_P. The identification of at least 3 points is crucial to detect P wave peak, and later on, onset and offset.

To determine which zero crossing is due to the P wave peak, the 2 points that contribute to the major variation are selected. These 2 points will be references to locate the position of the P wave peak, since it's more likely the peak be located between those 2 points. Basically, level 2^4 is used to identify if a P wave is present or not.

If a P wave is considered present, then the algorithm moves on to level 2^3, selecting all coefficient values located between the 2 points (in time) identified in the step before. Due to level 2^3 having more coefficients than level 2^4, at least 2 coefficient values in the level 2^3 will be found between the 2 reference points.
In case of more than 2 coefficients are found, only those that crosses zero are kept. If none of them crosses zero (all have the same value sign), the algorithm searches the closest zero crossing. This is done by checking the sign of the coefficient before the first relevant value in level 2^3 and the one after the last relevant value. If no zero crossing is found, the procedure is repeated for the second point before the first relevant one and second point after the last relevant one. In case both of them provide a zero crossing, the one with major variation is selected. Therefore, using the 2 points of the major variation, the closest one to zero is selected and set as the P wave peak.

P wave onset. The onset is located between the first relevant point of the P wave peak and the immediate previous zero crossing, in level 2^4. So, all coefficients of level 2^4 are swept, from the first relevant point, until finding the first value after zero cross. As soon as these 2 points are identified, all level 2^3 corresponding coefficient values between them are selected, keeping only those that crosses zero. Usually only one zero crossing is found, but it may happen none being detected, due to the zero crossing being located outside the search window. In this case, the algorithm searches the closest zero crossing by checking the value of the coefficient before the first relevant value in level 2^3 and the one after the last relevant value. When no zero crossing is found, it repeats the procedure for the second point before the first relevant one and second point after the last relevant one. If more than one zero crossings are identified, the one with major value variation is selected and sets the P wave onset at the

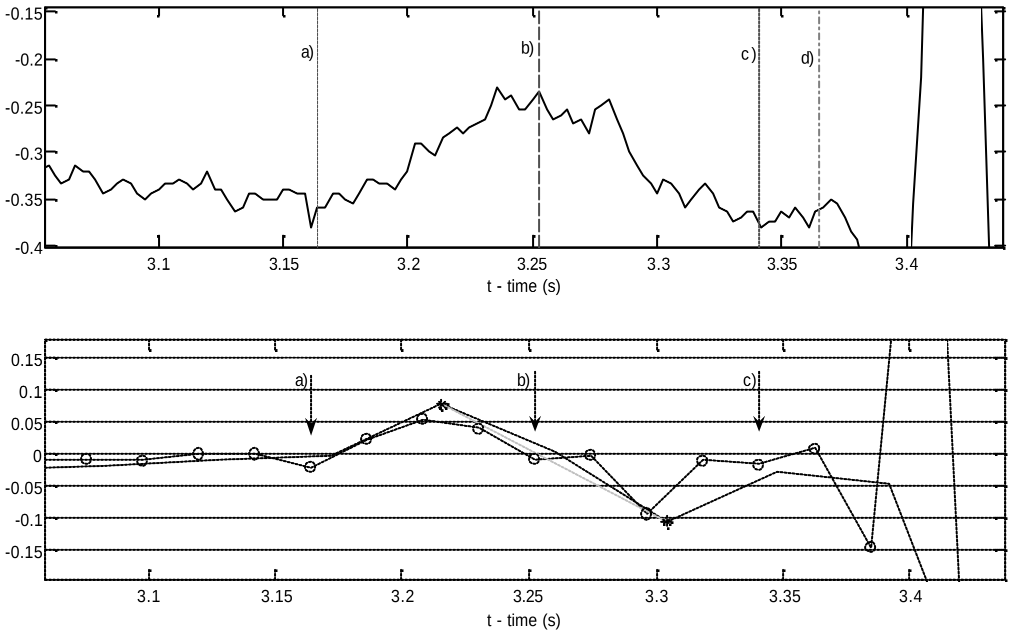

Fig. 6 – Above: P wave signal; Below: Levels 2^3 (solid) and 2^4 (dashed) coefficients values.
a) P wave onset; b) P wave peak; c) P wave offset; d) QRS onset.

time instant of the coefficient value closest to zero.

P wave offset. The offset is located between the second relevant point in level 2^4, of P wave peak, and the following QRS onset. Therefore, all level 2^3 coefficients between them are processed and the algorithm selects those that crosses zero. The offset will be located at the point far apart from zero, but if no zero crossing is found, the P wave offset will be set at the time of the second relevant point for the wave peak, in level 2^4.

QRS DELINEATION REFINEMENT

Since our data will be of HR-ECG, the algorithm must also perform the application of the Task Force standards for QRS delineation, which includes the use of a pass-band 4th order Butterworth filter with cut-off frequencies of 40 Hz and 250 Hz. [1].

After the delineation is made under wavelet analysis, we isolated every beat and measured the noise level of 40 ms of signal, in segment TP. The QRS onsets and offsets are searched with a sliding time window of 5 ms. When the mean voltage exceeds the level noise plus 3 times the noise standard deviation, the points are set accordingly. To find the QRS onset, the search is made from t_R-(50+40) ms to the R peak, while for QRS offset the search is made from t_R+ (50+80) ms to the R peak (figure 7).

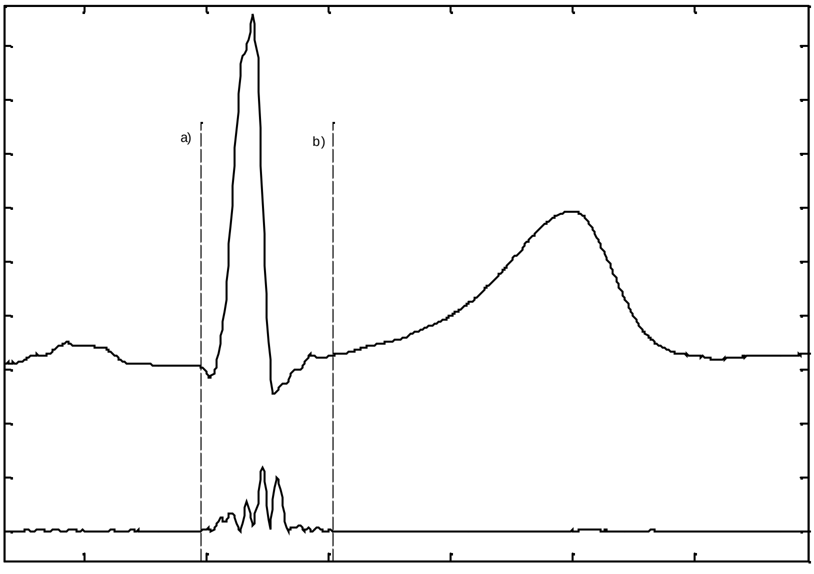

Fig. 7 – ECG signal (above) end filtered signal (below), using Task Force standards;
a) QRS onset, b) QRS offset.

RESULTS

To perform the R detector validation it was necessary to use a trustworthy arrhythmia database, such as the MIT/BIH database, which has 2 channels sampled at a frequency of 360 Hz and does have several beat and non-beat annotations that are used to verify the results[10] (Sahambi et al.)[11].

R Peak Detection

Using only the first channel, the signal was analyzed under the Matlab environment, processing one minute each time. Due to Mexican Hat wavelet being highly sensitive to border distortion, if a second before and after the 60 seconds of the selected signal were available, they were also included in the processed signal, to avoid the distortion effect. These two seconds of add-on signal are not accounted in terms of results (Table 1). We have achieved a sensibility Se=97.77 % and a positive prediction P_+=99.46%.

Several threshold values are set, in accordance with the entire processed signal. They are insensitive to the signal instantaneous variations, therefore for long signals this may lead to false detections.

Having in mind that this detector will be used to process short duration HR-ECG signals, we selected a two minutes segment in record 104. For this, we got 38 false negatives and none false positives. We then processed the signal with a similar method, but in 10 seconds fractions. We obtained 12 false negatives and none false positives, for the same two minutes.

Record	Beats	FN	FP
100	2272	0	0
101	1866	3	6
102	2185	8	0
103	2083	6	0
104	2229	153	0
105	2572	133	33
106	2028	87	15
107	2137	46	0
108	1763	27	61
109	2531	21	0
Totals	21666	484	115

Table 1 – R peak detector algorithm results.

ECG Delineation

The MIT/BIH database has been used for the wavelet algorithm development and testing. Since there is not a database for HR-ECG, we could not assess the delineator efficiency at this time. We had successfully delineated our test HR-ECG.

Using 10 seconds of a HR-ECG signal, we performed its delineation by wavelet transform (figure 8) and by the application of the standards of the Task Force committee for QRS delineation refinement[1] (figure 7).

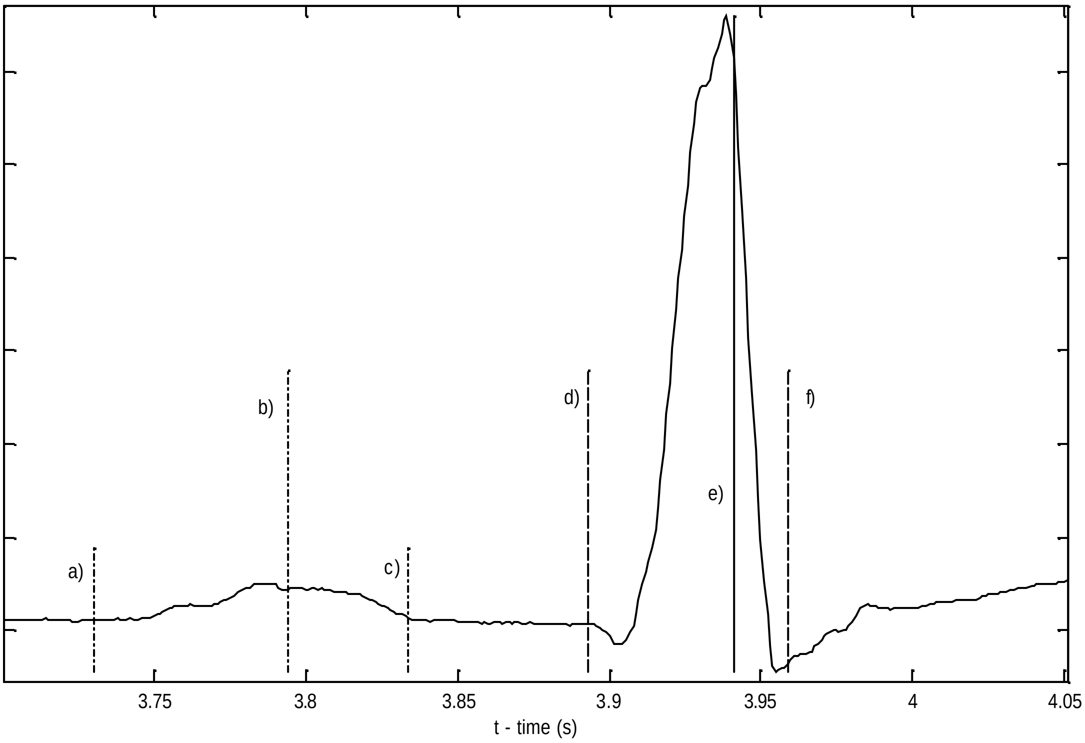

Fig. 8 – QRS and P wave delineation using wavelet transform.
a) P wave onset, b) P wave peak, c) P wave offset, d) QRS onset, e) R peak, f) QRS offset.

FINAL COMMENTS

The sensibility and positive prediction depends on the used wavelet. We have used the Mexican Hat wavelet for its edge and singularities detection properties. Other wavelets could have produced better results and we look forward exploring this venue. Regarding the ECG delineation, we manage to efficiently delineate the QRS and the P wave, which is the basis for our work in atrial and ventricular arrhythmia studies. The lack of a HR-ECG database is a limitation since these signals have different resolution parameters. Yet again, R wave detection and ECG delineation may not be accomplish with the same wavelet and should be separately investigated, as we have done in this work. Nevertheless, the application of wavelet analysis to the delineation and detection is established as an efficient methodology.

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