Wavelet Analysis of Atrial Electrical Activity

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Abstract: - In this paper we present the use of the Continuous Wavelet Transform and the subsequent energy distribution derived from the transform of Electrocardiogram (ECG) signals to analyse atrial electrical activity. The atrium produces a low amplitude wave in the ECG, which can often be overwhelmed by noise making it difficult to analyse by eye and therefore limiting the P wave as an indicator in cardiological diagnosis.

Key-Words: - Wavelet, ECG, Analysis, Atrial Activity, Atrial Abnormalities

1. Introduction

The Electrocardiogram (ECG) is an important tool in cardiology; it is a recording made of the surface potential of the electrical activity in the heart. Clinical ECG are recorded in a 12 lead format; 6 limb leads placed in the same axis on the limbs of the subject and 6 precordial limbs placed from the front of the chest to the back around the torso [1][2].

The characteristic points of the ECG include the P wave, QRS complex and T wave which represent the sino-atrial impulse and atrial electrical activity, ventricular depolarisation and ventricular repolarisation respectively.

The majority of work into processing and automated analysis of the ECG has focused on the QRS or T waves, [3][4][5][6] here we are concerned with the P wave, which specifically represents the initial impulse created by the sino-atrial node and the conduction of this pulse through the left and right atria. The P wave has been largely overlooked by previous work into automated ECG analysis or characterisation.

Several factors make the analysis of the P wave difficult in recorded ECGs. Firstly the P wave is a relatively low amplitude component of the ECG and therefore can be susceptible to noise in recordings. [2] In addition the ageing of patients results in lower amplitudes through a combination of reduced muscle mass and electro-physical changes in tissue constitution [7] that can significantly reduce amplitudes in recorded ECGs.

This paper uses wavelet techniques to analyse atrial electrical activity. The wavelet is applied to a healthy p wave and then applied to an abnormal signal to determine the effectiveness of the analysis.

2. Wavelet Analysis

Wavelet analysis has become popular in recent years as an effective means of analysing localised power and frequency components of time series data. The performance of Wavelet analysis as compared to Fourier analysis is also well documented [8][9]. Wavelet Analysis has been applied to several forms of time series data including weather oscillation patterns [10], EEG and ECG [5].

The continuous wavelet transform (CWT) provides a time-frequency transform of a temporal signal, $x(t)$, and a basis function, $\psi_{a,b}(t)$, to produce an output which is their temporal correlation for set dilations of the basis function. The CWT is defined as:

$$C(a,b) = \frac{1}{\sqrt{a}} \int x(t) \psi_{a,b}(t).dt \qquad (1)$$

Where represents the CWT coefficients at scale a and temporal location b. The constant term $1/\sqrt{a}$ is called the scaling term. The basis function is also referred to as the wavelet function.

2.1. Wavelet Energy Distribution

Wavelet transformations provide several perspectives for analysis. In this paper, we will concentrate on the use of the wavelet energy distribution as an indicator in the analysis of P waves.

The Energy Distribution function E is defined as:

$$E = \frac{1}{k} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |C(a,b)|^2 . \frac{dbda}{a^2} \qquad (2)$$

Equation 2 is the total energy contained in the signal where the constant k is a normalisation constant derived from the Fourier transform of the basis function.

It is also possible to obtain the energy contained in each scale of wavelet using:

$$E(a) = \frac{1}{k}\int_{-\infty}^{\infty} |C(a,b)|^2 \cdot \frac{db}{a^2} \qquad (3)$$

3. P Wave Analysis

It was found that the majority of the P wave energy is contained within a band from 3 – 12 Hz, which corresponded to wavelet scales of 8 – 50 for the chosen mother wavelet. The chosen mother wavelet is a first order Gaussian derivative that is defined by (4).

$$\psi(t) = -t\exp\left(-\frac{t^2}{2}\right) \qquad (4)$$

Although the Gaussian derivative is non-zero phase and therefore does not provide the best frequency localisation [11] it was chosen as a basis function due to its high correlation to the P wave. That is, it closely “fits” the P wave. The presence of frequencies below 3Hz was most likely to be due to “bleeding” of baseline frequencies.

In this paper results are shown for the analysis of three limb leads; Lead I, Lead II and Lead aVF. These leads were chosen as they cover the main directions of atrial electrical propagation. The analysis highlights changes in conduction direction (deviation from mean) and duration (frequency distribution).

3.1. Detection

Before analysis each P wave was automatically detected and marked in each lead of the ECG. This was performed using a custom detection method based upon correlation of CWT coefficients and a peak-picking algorithm. A discrete wavelet transform baseline removal algorithm was also employed in the detection process to improve the performance of the peak-picking algorithm.

3.2. Formulation

For the analysis we concentrated on the energy distribution spectrum of the P waves across the chosen leads. The general pattern of each leads’ distribution and its consistency throughout the recording provided an indicator of conduction direction, propagation consistency and energy.

We used the scale wise energy distribution time averaged over the duration of each P wave to derive the individual P wave energy distributions in a single recording and for each lead of the recording.

$$E_p^i(a) = \frac{1}{k}\int_{-\infty}^{\infty} \left|C(a,b_p^i)\right|^2 \cdot \frac{db}{a^2} \qquad (5)$$
$$p_1^i \geq b_p \geq p_2^i$$

Where p_1^i and p_2^i represent the temporal onset and offset points of the i^{th} P wave in one lead of the ECG recording and $E_p^i(a)$ is the energy of the i^{th} P wave at scale a.

The mean and standard deviation of the P wave distribution was found by averaging the energy distribution of all P waves in each lead.

$$\hat{E}_p(a) = \sum_{i=1}^{R} E_p^i(a) \qquad (6)$$

Where $\hat{E}_p$ is the mean P wave energy distribution and R is the number of P waves contained in a recording.

The variance, V , of the energy distributions across each lead is used as an indicator of conduction consistency.

$$V = \frac{1}{R}\sum_{i=1}^{R}\left(E_p^i - \hat{E}_p\right)^2 \qquad (7)$$

4. Results

The ECG signal in Figure 1 is a lead II recording which exhibits normal sinus rhythm; P waves are followed by a QRS complex and T wave in a quasi-periodic manner.

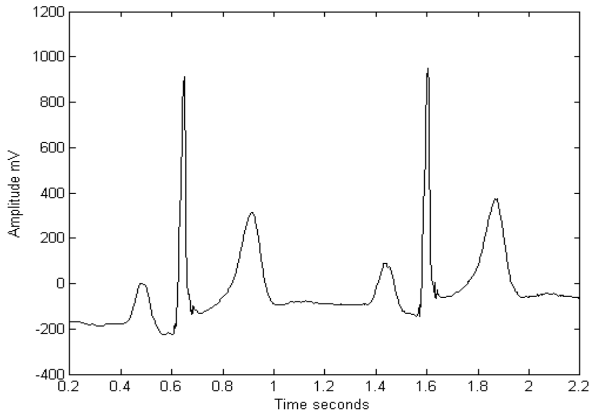

Figure 1 ECG exhibiting normal sinus rhythm

In Figure 2 the plot shows the wavelet energy distribution of every individual P wave versus the wavelet scale a in the recording of Figure 1.

When performed on Leads I, II and aVF the main direction of the atrial conduction in the limb lead plane is shown to fall between Leads II and aVF due to the higher energy contribution in these leads. The conduction pattern is also consistent in each lead.

This is shown in Figure 3 where the solid line represents the mean energy distribution of all P waves in the Lead, as given by (6), and the dashed lines show the one standard deviation away from this mean. The low deviation from the mean in all three leads indicates that the atrial conduction in this recording is regular in the limb lead plane.

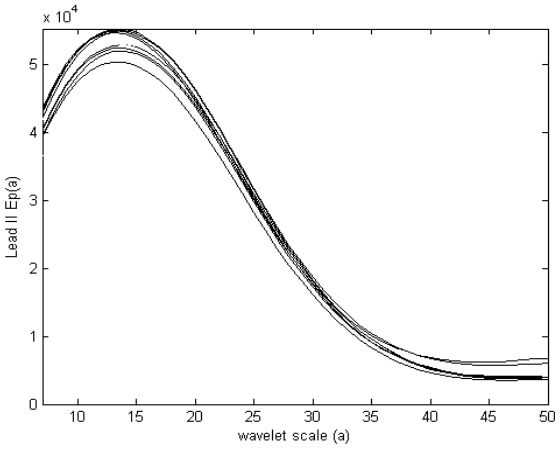

Figure 2 P wave analysis of Figure 1ECG

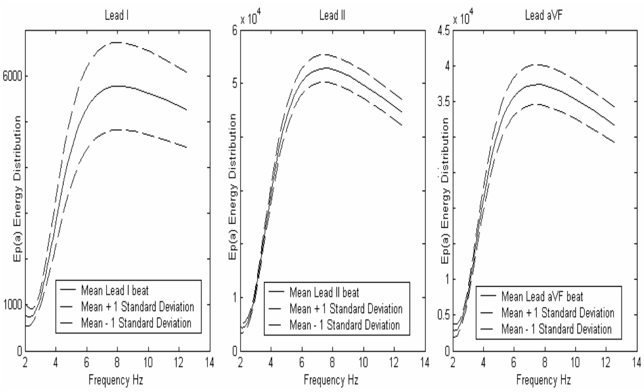

Figure 3 Analysis of Lead I, Lead II and Lead aVF

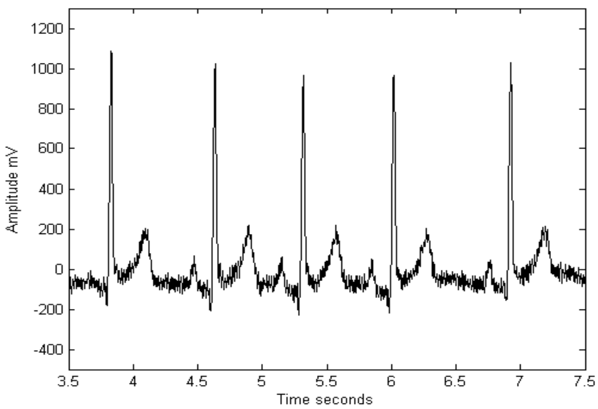

Figure 4 ECG exhibiting changes in atrial conduction

In Figure 4 the ECG contains some variation in atrial activity, however the P waves as recorded are difficult to discern in the recorded ECG and therefore the variations are difficult to observe.

These variations are highlighted in Figure 5 by the large variations in energy distribution across all three leads. This indicates that the atrial conduction direction in the limb lead plane changes significantly over time.

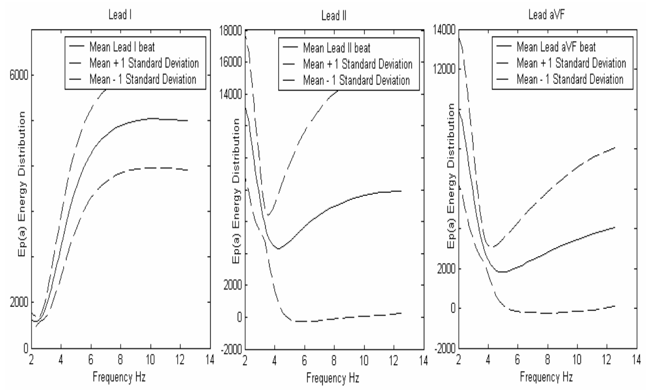

Figure 5 P wave analysis of ECG shown in Figure 4

Variations in atrial conduction direction can often be the case in non-sinus atrial rhythm or retrograde atrial activation [12].

Figure 3 and figure 5 show the spread around the mean values for normal and abnormal heart signals. Comparison of the mean and standard deviation clearly indicates the abnormality.

5. Conclusion

It has been shown that wavelet analysis can be used to enhance and identify regular and irregular atrial conduction in clinical ECGs. The mean P wave energy distribution and the variance of this distribution throughout an ECG recording are indicators of the regularity and normality of the atrial activity.

Further work will be focused on extracting more metrics from the P wave analysis procedure which specifically indicate an arrhythmia, extending the analysis to the precordial leads and improving the frequency localisation properties of the wavelet basis through the use of zero-phase wavelet bases.

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