Analysis of Ventricular Late Potentials Prior to the Onset of Ventricular Tachyarrhythmias: End of QRS Point Detector

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Abstract

Ventricular Tachyarrithmias are one of the most dangerous cardiac pathologies often causing sudden death. Studies for the prediction of these events are based on feature extraction prior to their initiation. Ventricular Late Potentials are considered a marker of abnormality in ventricular function which can cause Ventricular Tachycardia and Ventricular Fibrillation. A Ventricular Late Potential detector is proposed in this paper based on the continuous wavelet transform. Simulated ECGs with added artificial Ventricular Late Potentials was used to develop and test the proposed algorithm. A second study of the ECGs of 8 CCU patients who subsequently developed a Ventricular Tachyarrhythmia was then carried out. However, no Ventricular Late Potentials were found for this small group of patients using the proposed algorithm.

1. Introduction

The detection of ventricular late potentials (VLPs) is interesting for clinical diagnoses. These small voltage signals are believed to be produced in abnormal conduction tissues due to pathologic conditions such as necrotic regions within the ventricular wall. These cells are a substrate for electrical re-entry and form the focus of Ventricular Tachyarrithmias. Late Potentials are thought to be a non-invasive marker of potential re-entrant circuits. [1-4] These low amplitude and high frequency signals are localized at the terminal portion of the QRS or at the beginning of the ST interval. Several studies have indicated that the presence of ventricular late potentials is a useful clinical marker for the onset of further Ventricular Tachyarrhythmias and Sudden Death syndrome [1]. Antiarrhythmic drugs have no clear effect on the manifestation of Ventricular Late Potentials [5]. As late potentials are signals of very small power compared to the main features of the ECG, usually falling within the region of background signal noise, a method of signal enhancement and noise reduction is sought. In this paper we detail a method based on the wavelet transform which provides a high resolution time-frequency partitioning of the signal thus allowing enhanced separation of the VLP from noise.

2. Theory

The wavelet transform of a continuous time signal, *x (t),* is defined as:

$$T(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t)\psi^*(\frac{t-b}{a})dt \quad (1)$$

where $\psi^*(t)$ is the complex conjugate of the wavelet function $\psi(t)$, a is the dilation parameter of the wavelet and b is the location parameter of the wavelet. In order to be classified as a wavelet, the function must satisfy certain mathematical criteria. These are:

1 – A wavelet must have finite energy:

i.e. $$E = \int_{-\infty}^{\infty} |\psi(t)|^2 dt < \infty \quad (2)$$

2 - If $\hat{\psi}(f)$ is the Fourier transform of $\psi(t)$,

i.e. $$\hat{\psi}(\omega) = \int_{-\infty}^{\infty} \psi(t) e^{-i(\omega)t} dt \quad (3)$$

then the following condition must hold:

$$C_g = \int_0^{\infty} \frac{|\hat{\psi}(\omega)|^2}{\omega} d\omega < \infty \quad (4)$$

This implies that the wavelet has no zero frequency component, i.e. $\hat{\psi}(0) = 0$, or to put it another way, it must have a zero mean. Equation 4 is known as the *admissibility condition* and *Cg* is called the *admissibility constant.* The value of *Cg* depends on the chosen wavelet.

3 - For complex (or analytic) wavelets, the Fourier transform must both be real and vanish for negative

frequencies.

The contribution to the signal energy at the specific *a* scale and *b* location is given by the two-dimensional wavelet energy density function known as the scalogram:

$$E(a,b) = |T(a,b)|^2 \tag{5}$$

The total energy in the signal may be found from its wavelet transform as follows:

$$E = \frac{1}{C_g}\int_{-\infty}^{+\infty}\int_{0}^{+\infty}\frac{1}{a^2}|T(a,b)|^2\,dadb \qquad \left[= \int_{-\infty}^{+\infty} x(t)^2 dt \right] \tag{6}$$

In practice a fine discretisation of the continuous wavelet transform is computed where usually the *b* location is discretised at the sampling interval and the *a* scale is discretised logarithmically. The *a* scale discretisation is often taken as integer powers of 2, however, we use a finer resolution in our method where the *a* scale discretisation is in fractional powers of two. The discretised continuous wavelet transform (CWT) is made distinct from the discrete wavelet transform (DWT) in the literature. In its basic form, the DWT employs a dyadic grid (integer power of two scaling in *a* and *b*) and orthonormal wavelet basis functions and exhibits zero redundancy. Our method, i.e. using a high resolution in wavelet space as described above, allows individual maxima to be followed accurately across scales, something that is often very difficult with discrete orthogonal or dyadic stationary wavelet transforms incorporating integer power of two scale discretisation. Further background information concerning continuous wavelets can be found in references [6] and [7].

3. Methods

Equipment was installed within the Coronary Care Unit of the Royal Infirmary of Edinburgh to collect ECG signals continuously from all six beds within the unit over an 18-month period [8]. The signals were sampled at 500 Hz using 16 bits per sample. The ECG signals from all patients who had an episode of VTA during their stay were scrutinised. Those that were not suitable for VLP analysis were discarded [Figure 1]. Those signals that were not suitable included patients who were not in sinus rhythm, patients who experienced multiple ectopic beats, and signals that had high levels of noise interference. The 60-minute ECG signals directly before the VTA event in the remaining 8 patients that were suitable for inclusion were then analysed.

We know that VLPs are small features that occur at the end of the QRS complex and usually extend into the S-T segment enhancing the QRS energy beyond its normal length. For this reason, it has been proposed that the detection of the end of the QRS complex could be a good indicator of the presence of VLPs [9].

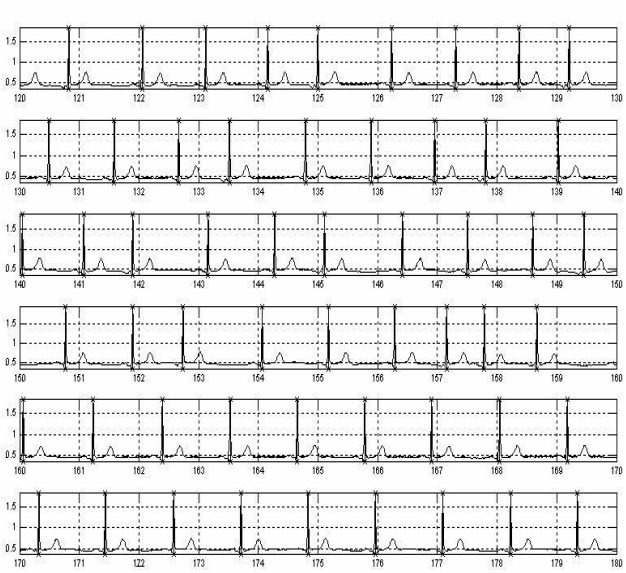

Figure 1. A section of an ECG signal obtained from a Coronary Care Unit, showing an irregular rhythm. The locations of the R-waves as detected by our R-wave detection algorithm prior to editing.

The CWT was computed using the Mexican hat as the mother wavelet and the scales considered corresponded to the frequencies in the range 1 – 200Hz. The R wave was located as a reference point using our own in house method [10]. Two time-frequency intervals were selected where cardio electrical activity was not normally expected and the energy calculated using the equation (6). These intervals were of 10 msec length in regions before the P wave (*tf-1*: 260 – 250 msec before the R wave) and after the T wave (*tf-2*: 400 – 410 msec after the R wave). The frequency interval considered was (70 - 200 Hz). The minimum value of both energies was used as a reference level for establishing a threshold.

Starting from the R wave point the energy in intervals of 10 msecs length (and the same frequency interval) is calculated ($E_{tf\text{-}VLP}$). A threshold is defined as the reference energy (minimum of the energy in *tf-1* and *tf-2*) plus 1% of the difference of $E_{tf\text{-}VLP}$ and the reference energy. The expression that defines the threshold is:

$$th = \min(E_{tf-1}, E_{tf-2}) + 1\%(E_{tf-VLP} - \min(E_{tf-1}, E_{tf-2})) \tag{7}$$

The point where the energy after the QRS complex computed in intervals of 10 msecs falls below this threshold is considered the *End of the QRS complex*.

4. Results

The algorithm proposed to find the *End Point of the QRS complex* was tested with synthetic signals generated from real ECGs obtained from healthy and young individuals. Artificial VLPs and different levels of noise were added to these healthy ECGs. The artificial VLPs were generated from the combination of sinusoidal signals of different amplitudes and frequencies of 75, 10 and 125 Hz. The VLPs generated exhibited a range of different amplitudes and morphologies due the combination of sinusoidal signals of different amplitudes and frequencies. [Figures 2 and 3].

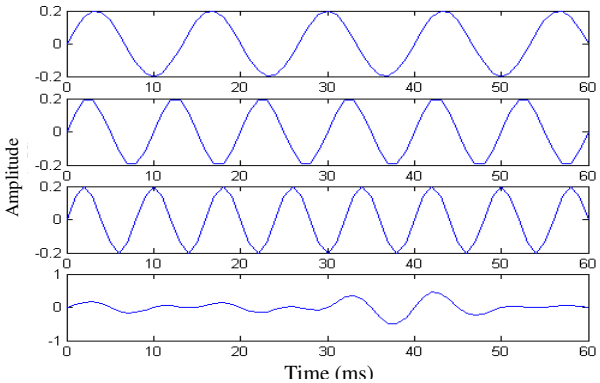

Figure 2. Generation of an artificial VLP. In this case, 3 sinusoidal signals of amplitude 0.4mV, length of 60 msec and frequencies of 75, 100 and 125 Hz are added and the sum is multiplied by a Kaiser Window.

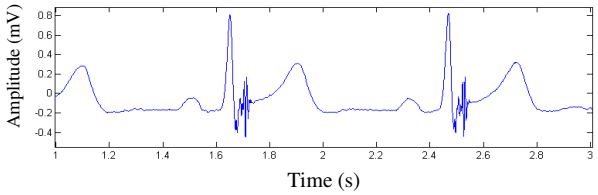

Figure 3. Fragment of 2 seconds length of one ECG with and artificial VLP added at the end of the QRS. The VLP is the example shown in figure 2. No added noise.

The algorithm produced satisfactory results and found the *End of the QRS* after 40 or 50 msecs after the R wave in all the signals that did not have added artificial VLPs nor added noise. When added artificial VLPs of 60 msecs of length after 20 msecs from the R wave, the *End Point* was detected in the range of 70 to 90 msecs from the R wave. The algorithm was tested over a range of VLP amplitudes with similar results obtained for VLPs with amplitudes corresponding to 10%, 5% and 2% of the QRS peak height. However VLPs with an amplitude of 1% of the QRS complex did not exhibit the same level of performance. For these small amplitude VLPs only 25% of them were detected. When artificial noise was added the algorithm exhibited a good performance at 50dB and 40dB of SNR. However, at higher levels of noise the performance degraded markedly, as can be seen in table 1.

Table 1. Percentage of VLP detected from the Tests signals generated with the artificial VLPs and noise to healthy ECGs.

VLP Amplitude/Noise	10%	5%	2%	1%
No Noise	100%	100%	100%	25%
50dB	100%	100%	100%	29%
40dB	100%	100%	89%	25%
30dB	54%	43%	36%	23%
20dB	43%	14%	6%	4%

After testing, the algorithm was used to analyze patient signals obtained from the Coronary Care Unit of the Royal Infirmary of Edinburgh as described in the previous section in order to study the behaviour of the electrical ventricular activity immediately prior to the onset of ventricular tachyarrhythmias.

Two beats from each of the eight patients selected within the ECG one hour prior to a Tachyarrhythmic episode were analysed using the algorithm which detected the *End of the QRS complex*. In total 16 beats were analysed. In seven patients (14 beats) the *End of the QRS complex* was detected at 30 – 60 msecs after the R wave. The 8th patient had a long QRS complex due to an abnormal morphology [Figure 4] From the results of this limited pilot study it can be concluded that the length of the QRS complex was normal prior to the onset of a Ventricular Tachyarrhythmia and, therefore, this measure was not useful as a predictor for these patients.

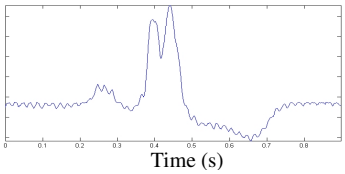

Figure 4. Beat from patient 2 which shows abnormal QRS shape and ST segment which can explain the long QRS complex detected by the algorithm.

5. Discussion and conclusions

VLPs are believed to be possible predictors for Ventricular Tachyarrhythmias. Work by other groups has investigated the presence of VLPs in post myocardial infarction patients as a marker in conjunction with other information to determine which patients are at the highest risk for sudden death. These studies usually include a

follow up of the patient's evolution for some months to study the feature as a mark of ventricular electrical malfunction and find some correlation with the development of Ventricular Tachyarrhythmias. This work aimed to study the presence of VLPs just prior the onset of a Ventricular Tachyarrhythmia, more specifically within one hour before the event.

The Continuous Wavelet is described by many authors as a promising technique which provides high resolution analyse of high frequency signal components due to the variable window width of the wavelet function. [11-15]. For this reason the authors considered it a good basis for a method of the analysis of VLPs within ECGs.

A VLP detector was developed based on the Continuous Wavelet Transform whereby the *End Point of the QRS complex* is located in wavelet space. The algorithm is simple and achieves a good performance under reasonable levels of noise. The main problem in detecting VLPs are their small amplitude which the noise easily masks. For that reason a clean portion of signal must be found for an accurate analysis.

In order to develop the VLP detector, artificial VLPs were generated and added to ECGs obtained from healthy and young individuals. The VLPs generated exhibited a range of amplitudes and morphologies. It was found that the algorithm could detect VLPs with amplitudes as small as 2% of the amplitude of the QRS complex.

A strength of the method proposed here is that, unlike many contemporary methods, signal pre-processing and averaging was not used in this technique hence this method can be used as a *beat-to-beat* ECG VLP detector. This has the advantage of a quick analysis and the possibility of analysing the variation of the QRS complex length in time.

The method was applied to eight ECGs acquired from patients within the CCU at the Royal Infirmary at Edinburgh. Each of these patients developed a tachyarrhythmic event within one hour of the ECG segment analysed in the study. The *End Point of the QRS* occurred 30-60 msecs after the R wave for seven of these patients. The eighth patient had an abnormal QRS morphology resulting in an inherently longer QRS complex. For these CCU patients no VLPs of an amplitude of 2% or higher of the amplitude of the QRS complex were found. Hence, for this small patient group this technique was not found to be a useful indicator of the imminent onset of a Ventricular Tachycardia.

References

[1] Breithardt G, Borggrefe M, Martinez Rubio A. Signal Averaging. Annals New York Academy of Sciences, 1990; 601: 180-196.

[2] Breithardt G, Cain M.E, El-Sherif N, Flowers N, Hombacj V, Janse M, Simson M.B, Steinbeck G. Standards for analysis of ventricular late potentials using high resolution or signal-averaged electrocardiography. European Heart Journal, 1991; 12: 473-480.

[3] Vester E.G, Strauer B.E. Ventricular late potentials: state of the art and future perspectives. European Heart Journal, 1994; 14 (Supplement C): 34-48.

[4] Cain M.E, Anderson J.L, Arnsdorf M.F, Mason J.W, Scheinman M.M, Waldo A.L. Signal-Averaged Electrocardiography. Journal of the American College of Cardiology, 1996 Jan; 27(1):238-249.

[5] Brachmann J, Hilbel T, Schweizer M, Kübler W. Cardiac late potentials for diagnosis in heart disease. European Heart Journal, 1994; 14 (Supplement C): 49-51.

[6] Addison PS. The Illustrated Wavelet Transform Handbook: Applications in Science, Engineering, Medicine and Finance. Institute of Physics Publishing, Bristol, 2002.

[7] Addison PS, Watson JN, Feng T. Low-Oscillation Complex Wavelets. Journal of Sound and Vibration 2002; 254:733-762.

[8] Romero Legarreta I, Reed MJ, Watson JN et al. Long Term Continuous Collection of High Resolution ECG Signals from a Coronary Care Unit. Computers in Cardiology 2003;30:407-9

[9] Vai MI, Zhou L. Beat-to-Beat ECG Ventricular Late Potentials Variance Detection by Filter Bank and Wavelet Transforms as Beat-Sequence Filter. IEEE Trans. Biomedical Engineering, 2004; 51 (8): 1407-1413.

[10] Romero Legarreta I, Addison PS, Reed MJ et al. Continuous Wavelet Modulus Maxima Analysis of the Electrocardiogram: Beat Characterisation and Beat-To-Beat Measurement. International Journal of Wavelets, Multiresolution and Information Processing, Vol. 3, No. 1 (2005) 19-42.

[11] Lewandowski P, Meste O, Maniewski R, Mroczka T, Steinbach K, Rix H. *Risk evaluation of ventricular tachycardia using wavelet transform irregularity of the high-resolution electrocardiogram.* Medical & Biological Engineering & Computing, 2000; 38: 666-673.

[12] Wu S, Qian Y, Gao Z, Lin J. *A Novel Method for Beat-to-Beat Detection of Ventricular Late Potentials.* IEEE Trans. Biomedical Engineering, 2001; 48 (8): 931-935.

[13] Vai M.I, Zhou L. Beat-to-Beat ECG Ventricular Late Potentials Variance Detection by Filter Bank and Wavelet Transforms as Beat-Sequence Filter. IEEE Trans/ Biomedical Engineering, 2004; 51 (8): 1407-1413.

[14] Addison P.S. The Illustrated Wavelet Transform Handbook: Applications in Science, Engineering, Medicine and Finance. Institute of Physics Publishing, Bristol, 2002.

[15] Addison P.S, Watson J.N, Feng T. *Low-Oscillation Complex Wavelets*. Journal of Sound and Vibration, 2002, Vol.254(4), 733-762.

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