Application of Wavelet Techniques in ECG Signal Processing: An Overview

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Abstract—ECG signals are non-stationary, pseudo periodic in nature and whose behavior changes with time. The proper processing of ECG signal and its accurate detection is very much essential since it determines the condition of the heart. The analysis of ECG signal requires the information both in time and frequency, for clinical diagnosis. Hence the wavelet transforms becomes handy for analyzing these types of the signals. In this paper we have given an overview of some wavelet techniques published in journals and conferences since 2005 onwards for processing the ECG and also we have compared the performance, advantages and limitations of these techniques.

Keywords: ECG, CWT, DWT, SWT, FWT, Fractional WT,Multiwavelet Transforms ,SNR

I. Introduction:

An Electrocardiogram (ECG) is a test used to determine the regular rhythmic activity of the heart condition. This activity is recorded on graph sheets or some kinds of monitors by placing the electrodes on specific locations of the body of a person. The record shows a series of electrical waves that occurs during each beat of the heart. The recorded waves have peaks and valleys and normally represented by the letters P, Q, R, S, T and U waves. But the U weave is not consistent and is invisible among 70% of the people. Clinically the U wave is not that much of important as those of other waves. These human ECG signals are very weak and in the mV range and the frequency range is 0.05-100Hz and most of the useful information contained in the range of 0.5-45Hz [3][8][15]. Electrocardiography is the starting point to detect many heart related problems and is normally used to detect any damage to the heart and congenital heart defects and coronary artery diseases etc.

The human heart consists of four chambers two atria called upper chambers and two ventricles called lower chambers. Under healthy condition of the heart these chambers beat in an organized manner. Normally the heart begins at the right atrium called Sino atria (SA) node and a special group of cells transmits these electrical signals across the heart. This signal moves from atria to the atrio ventricular (AV) node. The AV node connects to a group of fibers in ventricles that conducts the electrical signal and sends the impulse to all parts of the ventricles. This path of propagation of electrical waves must be traced exactly to ensure that the heart is functioning properly. The standard ECG waveform for one cardiac cycle is shown in figure (1), [25] and the various ECG parameters and their values are given in table 1, [5].

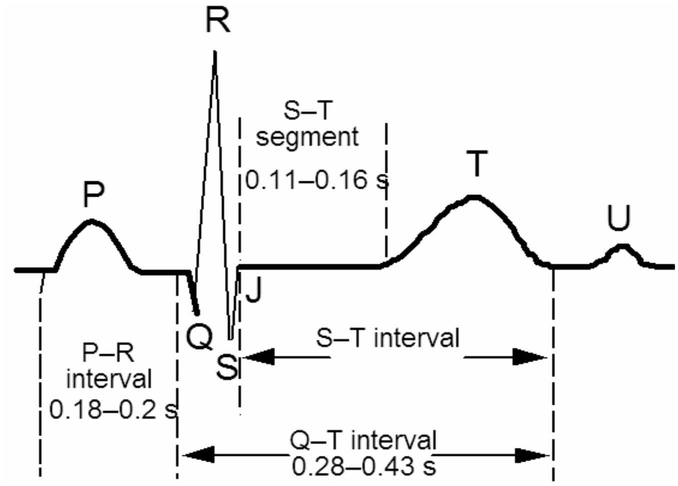

Figure.1 standard ECG waveform for one cardiac cycle

Table1: ECG parameters and their normal values

Parameters	Normal value	Abnormal conditions	Remarks
Heart Rate(HR)	60-100 bpm	Bradicardia: < 60 bpm Tachycardia: > 100 bpm Sick sinus : 100<HR<60bp Atrial flutter :250< HR < 350 bpm	Atrial and ventricular fibrillation causes stroke and heart quivers leading to sudden death of person
P wave	Amplitude: 0.25±0.05 mV Interval: 110 ± 20ms	---	Electrical activity associated with the contraction of atria.
QRS complex	Amplitude: 1.60 ±0.5 mV Interval: 100ms±20 ms	---	Associated with ventricular contraction
R wave	Amplitude: 1.60±0.5mV		---
Q wave	Amplitude: 0.25 times R wave		---
T wave	Amplitude: 0.1to 0.5mV Interval:		Repolarisation of ventricles

	160ms		
PQ or PR interval	Interval: 120-200ms	PR>200ms:first degree of heart block PR<120ms:early activation of ventricles Variable PR interval gives information about heart block	Time taken by the electrical signal to travel from atria to ventricle
QT interval	Interval: 350-440ms	Prolonged or shortened QT interval leads to ventricular arrhythmias.	QT depends on heart rate and for clinical relevance the corrected parameter QT_c is used.
ST interval	Period: 80- 120ms	---	Represents state of ventricular depolarization. Generally isoelectric
U wave	very low amplitude or even absent	---	Invisible among 70% of the people

II. CONCEPTS OF WAVELETS:

Wavelets are being useful in various fields of science and engineering such as signal and medical imaging processing etc.Wavelet research is proceeding at a rapid space and every year a new development appears, expanding the new domain of wavelet analysis. The wavelet transform gives a large number of small coefficients and a small number of large coefficients. Large coefficients mainly represent the signal values and the coefficients with smaller values represent the noise components. Some characteristics which make them useful are:

· Wavelets are localized in both time and frequency

· for analyzing non-stationary signals such as ECG and which have jumps and non smooth features.

· Wavelet separates a signal into multiresolution components.

A. Continuous Wavelet Transform(CWT):

The wavelet means a “small wave”, which maps a function f(t) into the time-scale plane and is denoted by W_s (a,b) and given by[8][10]

$$Ws(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\, h^{*}\left(\frac{t-b}{a}\right) dt \qquad (1)$$

Where $h(t)$ is called mother wavelet, a is the scaling parameter in y-axis and b is the shift parameter in x-axis. The signal $f(t)$ can be recovered from the wavelet coefficients $Ws(a,b)$ by the inverse wavelet transform and is given by

$$f(t) = \frac{1}{c}\iint_{-\infty}^{\infty} Ws(a,b)h(\frac{t-b}{a})\frac{da}{a^2}db \qquad (2)$$

With admissibility condition given as

$$c = \int_{-\infty}^{\infty} \frac{|(w)^2}{w} dw < \qquad (3)$$

B. **Discrete wavelet Transform (DWT):**

In practice, when implemented on computers, CWT must be discrete. The redundancy that is present in CWT can be reduced by discretizing the transform parameters a and b but not the time t parameter as follows.

$a = ao^m, b = nbo\ ao^m m, n \epsilon Z\ ao \neq 1, bo \neq 0$ (4)

For fine resolution ao has to be chosen sufficiently close to 1 and bo close to 0.

C . Stationary Wavelet Transform (SWT):

The DWT is non-invariant and non-redundant in its nature. The time invariant property is useful for feature extraction. On other hand the SWT is time invariant and gives better denoising effect compared to DWT. The SWT suppresses the noise effectively and retains better information regarding amplitude and location of the signal features. Comparing with DWT the approximation and detailed coefficients of the filters are not down sampled when the SWT is applied to the signal. Instead an up sampling is performed by padding the zeros between the coefficients at each stage. Thus SWT introduces some redundancy in the signal but no information is lost and precise reconstruction of the signal is possible. And reconstructed signal does not produce translation along time axis. Therefore SWT gives better signal denoising effect, feature extraction and accurate localization of signal.

III. PERFORMANCE EVALUATORS:

To evaluate the performances of various techniques the following equations are used in the literature. The important equations are given as below [7][44] [45].

1. Standard deviation (σ) which gives the variation of the noise through the signal and is given by

$$\sigma = \sqrt{\sum_{i=1}^{N} \frac{(Secg - S'ecg)^2}{N}} \qquad (5)$$

Where Secg is the original ECG signal, S'ecg is the mean of all the samples in the signal and N is length of the filtered signal.

2. Percentage RMS difference (PRD), which gives the information about percent of distortion of the filtered signal and is given by

$$PRD = \sqrt{\sum_{i=1}^{N} \frac{(original\ signal - filtered\ signal)^2}{\sum_{i=1}^{N}(original\ signal)^2}})X\ 100 \qquad (6)$$

$$PRD = \left(\sqrt{\frac{\sum_{i-1}^{N}(So - Sf)^2}{\sum_{i=1}^{N} So^2}}\right) X100 \qquad (7)$$

3. The root mean square error (RMSE) of original signal and denoised signal is given by the following equation

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Soriginal - Sdenoised)^2} \qquad (8)$$

4. Signal to Noise Ratio (SNR), which gives the information about quality of the signal. Higher the SNR better is the performance of the system and the signal to noise ratio is given by the following equation

$$SNR = 10\, log_{10}\left[\frac{\sum_{i=1}^{N}(filtered\ signal)^2}{\sum_{i=1}^{N}(original\ signal - filtered\ signal)^2}\right] \qquad (9)$$

IV. WAVELET TECHNIQUES OVERVIEW:

1. Based on Discrete Wavelet Transform (DWT):

In **2005**, Gordan Cornelia et al [3] used wavelet transforms as tool for processing non stationary signals like ECG signals.R.F.Von Borries et al [22] developed two channel filter banks to remove effectively the base line drift and S.Z.Mahmoodabadi et al [20] demonstrated the filtering of ECG signal by using Db4 and Db6 at higher scales to preserve various components of ECG signal. The distortion of R morphology occurs in classical wavelet approach and this drawback is removed by A Choukari et al [10] by applying their algorithm on detail coefficients of both noise free ECG signal and ECG signal corrupted with WGN. The authors claimed that the performance of their algorithm is superior compared to classical wavelet transform in restoring P and T waves without distorting R morphology. But the limitation is that it heavily depends upon the presence of the R waves in the first level of approximation of the noisy ECG signal. Again in **2006**,S.A.Choukari et al [6] used second level decomposition for detecting QRS complex and fourth and fifth level of decomposition for detecting P and T waves.. They compared the performance of their algorithm with db5, db10, coif5, sym6, sym8, biorth5.5 by calculating MSE and SNR. This algorithm works effectively at low SNR to remove various noises but the main limitation is the presence of huge base line wonder .A robust QRS detection algorithm can be used for removing baseline wonder. In **2007**, M.Kania et al [17], studied the importance of the proper selection of mother wavelet with appropriate number of decomposition levels for reducing the noise from the ECG signal. The authors claim that they obtained good quality signal for the wavelet db1 at first and fourth level of decomposition and sym3 for fourth level of decomposition. In **2008,** C.Saritha et al [5] have identified different types of abnormalities using daubechies wavelets in MATLAB environment. D.T Ingole et al [26] used Dyadic wavelet Transform for extraction of ECG features, which is robust, highly efficient ,accurate and reliable. Fayyaz A.Afsar et al [35] proposed a method which is robust to noise based on DWT and PCA for classifying six different types of beats from the ECG. The merits of this algorithm are less complexity, good accuracy and time saving. In **2009** Tan Yun-fu et al [8] used Daubechies and symlet wavelets for the removal of various kinds of noises present in the ECG signal and reconstructed ECG signal with minimum distortion at faster rate. Abed Al Raof Bsoul et al [41] used two mother wavelets namely Haar for the detection of QRS morphology and db2 for the detection of P and T waves at fourth decomposition level to obtain high accuracy. In **2010,** Abdel-Reman at el [7] used the high pass filtering for noisy signal before reconstruction by inverse discrete wavelet transform (IDWT).This algorithm is very robust for noise removal and it does not smoothens QRS complex. Ruchitha Goutham et al [23] have demonstrated the application of DyWT for QRS complex detection. Naregalkar Akshay et al [24] demonstrated the application of UWT for base line wonder removal and QRS morphology detection in LABVIEW environment. Antonio et al [42] used wavelet transform to detect the R-wave and wavelet segmentation approach for the extraction of ECG features.

2. Based on Multiresolution DWT:

In **2008,** Wei Zhang et al [2] used the multiresolution concept along with adaptive filters (LMS) to detect effectively the weak ECG signal in strong noisy environment. The method is simple, fast and effective and in **2009**,Arman Sargolzaei et al [27] proposed a new automatic base line wander removal algorithm. This algorithm preserves clinical information and morphology of ECG with high signal-to-noise ratio.

3. Based on Fast Wavelet Transform (FWT):

In **2008,** Rizzi et al [25] proposed and implemented an algorithm called R-point detector based adaptation of fast parallelized wavelet transforms for the detection of R-wave in the presence of different types of noises. The algorithm gives high degree of noise immunity and predictivity

4. Based on Lifting Wavelets:

In 2006, Mohamed O.Ahmed Omar et al [32] applied morphological based approach for feature extraction of ECG signal and curve fitting algorithm for base line wander removal and R.Shantha Selva kumari et al [34] designed two wavelets W1 and W2 which satisfies perfect reconstruction condition for the removal of base line wander from the cardiac signal and compared with existing wavelets namely db4,bior4.4 and bior6.8.The authors claim is that wavelet W2 is better for cardiac signal analysis. In **2009,** Huaigang Zang,et al [39] proposed a new thresholding function slightly different from the thresholding methods proposed by D.L.Dohono and I.M Johnston. They used two parameters k and m in their threshold function. The authors claim that the performance of their algorithm is better than the hard and soft threshold methods.

5. Based on Multiwavelet Transforms:

In 2009, Jeong Yup Han et al [11] proposed a new translation invariant method called multiwavelet transform to filter the noise from ECG without significant distortion of ECG morphology and characteristic features.

6. Based on Stationary Wavelet Transform (SWT):

The classical wavelet transform which does not preserves the shift invariant property introduces some kind of distortion in the reconstructed signal.**In 2010,** Pramodkumar et al [1], compared the performance of DWT and SWT for denoising the ECG using three different thresholding methods namely universal(sqtwolog),minimax and heursure thresholding methods. SNR obtained by SWT is more compared to DWT .This indicates that SWT, which is time invariant in nature, provides good denoising effect over DWT and Beatric Arvinti et al [12] selected SWT along with MAP filter which is also called bishrink filter to control the morphology distortion of ECG signal.

7. Based on Wavelet Packet Decomposition (WPD):

As the frequency spectrum of low frequency base line wander is below the desired ECG signal, in **2005**, Behzad Mozaffary et al [30] used the energy concept algorithm based on wavelet packet transform to eliminate base line wander from the desired ECG signal. In **2009,** Suiyi Li et al [4] used and compared the performance of wavelet transform, wavelet packet, lifting wavelet transform and stationary wavelet transform in the application of denoising ECG signal in terms of SNR and they showed that SWT gives better results.

8. Based on Fractional Wavelet Transform (Fractional WT):

In 2006, F.Abdelliche et al [31] examined the fractional wavelet transform by choosing the cole-cole function as mother wavelet to detect the QRS complex buried in various kinds of noises and the results are comparable to the other types of the techniques .Yet there is a scope to devolope the detection algorithm for the complete use of the data base.

9. Based on Shrinkage and Threshold Methods:

In 2005. Donghui Zhang [28] demonstrated the application of DWT and level dependent thersholding methods for removal of low frequency base line wander and high frequency noise interferences respectively. S.Poornachandra et al [29] proposed a new modified hyper-shrinkage function for analysis of complex bio signals and in **2008,** [18], proposed an efficient wavelet based shrinkage method to filter out the power line frequency. According to the authors the proposed algorithm is simple to implement in real time application, involves less computational complexity and gives better visual display. **I** Motoki Sakai et al [37] treated EEG signal as noise component and applied wavelet shrinkage algorithm to remove the EEG from ECG signal. **In 2009,** Yang Ying et al [21], proposed a new shrinkage function for denoising ECG signal and compared the results with various shrinkage functions. Their proposed method gives better results they claimed. In **2010** L.N.Sharma et al [19] have proposed ECG processing method based on higher order statistics at different wavelet sub bands to analyze the statistical nature of the signal in time- frequency domain. The kurtosis and energy contribution of the sub bands combined to assess the noise quantity in the signal and Zaffery Z.A et al [9] have evaluated the performances of four different threshold estimators rules in the application of denoising the ECG signal in the MATLAB7 environment .The simulated results show that the universal method performs better at all SNR.

10. Based on wavelets along with other concepts:

In **2006**,Marius Oltean et al [13],demonstrated the effective denoising algorithm based on WAP using circular convolution in wavelet domain. The two transforms namely Diversity Enhancement DWT (DE DWT) and translation Invariant DWT (TI DWT) are used for the purpose of accurate detection of ECG signal. Zhi-Dong Zhao et al [16] proposed Emphirical mode Decomposition(EMD) with notch filter to remove power line frequency noise effectively without significant distortion of the ECG signal and B,Natwong, et al [14] used the concept of wavelet entropy to categorize the persons with and without ventricular late potentials (VLP).The entropy is related to the degree of irregularity of the signal. Higher the entropy more is the irregularity of the signal under consideration. In **2007**, an algorithm based on the computation of an auxiliary signal from the envelope of the ECG along with statistical hypothesis test was proposed and demonstrated by Alfredo Illanes Manriquez et al [33] for the detection of onset and offset of QRS complex. The performance of the algorithm is better compared to many existing technique. In **2008**, Xiao-li Yang et al [36] proposed Hilbert-Huang Transform which consists of computation of Hilbert transform and empirical mode decomposition of series of narrow band signals obtained from decomposition of original signal based on instantaneous frequency concept to detect R-wave in presence of various noise and artifacts.In **2009**, A.K.M.Fazlul Haque et al [38], demonstrated and compared the procedure using FFT and WT for detection of parameter variations of ECG signal due to sudden pain in the body by simulation method. They showed that WT gives better result for non stationary signal like ECG and in **2010,** G Ranganathan et al [43] presented HRV analysis for evaluation of mental stress assessment using Dyadic wavelet transform.

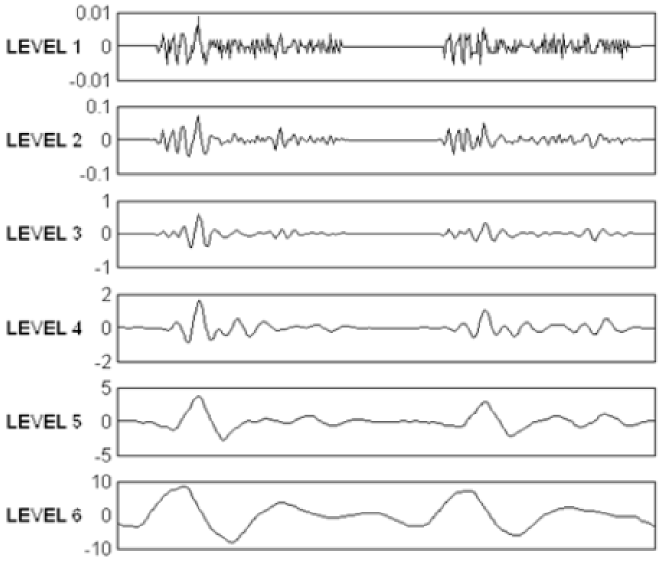

Figure.2 Decomposition of ECG signal over six Dyadic scales using a'trous algorithm

Results obtained in [25]

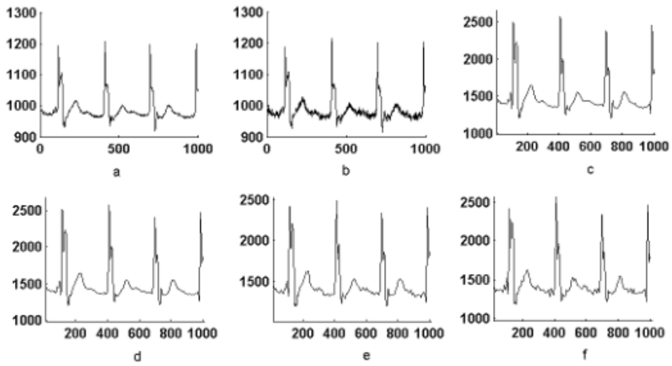

Figure (3)

Figure.3 a) Original ECG signal b)Noisy ECG (30% noise level) c)recovered ECG from 10% noise level d) recovered CG from 30% noise level e)recovered ECG from 50% noise level f) recovered ECG from 70% noise level. Result from[29]

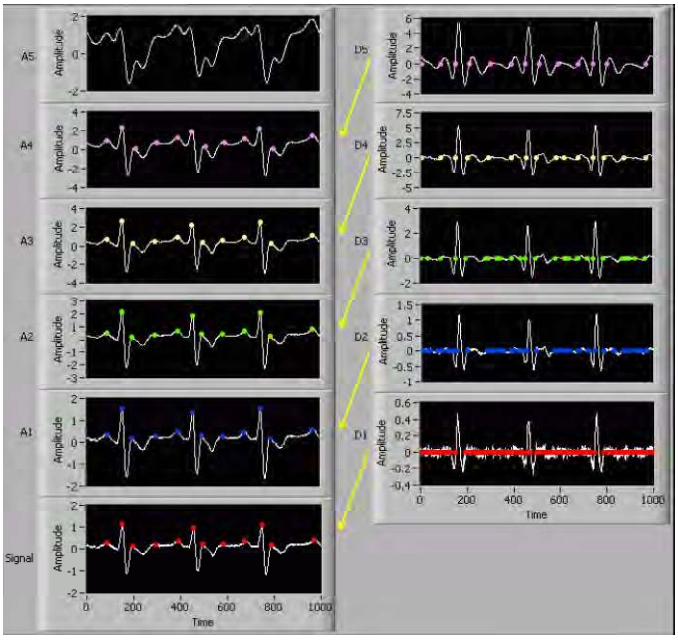

Figure 4.Multiresolution process of wavelet-based peak detection. Result obtained in [26]

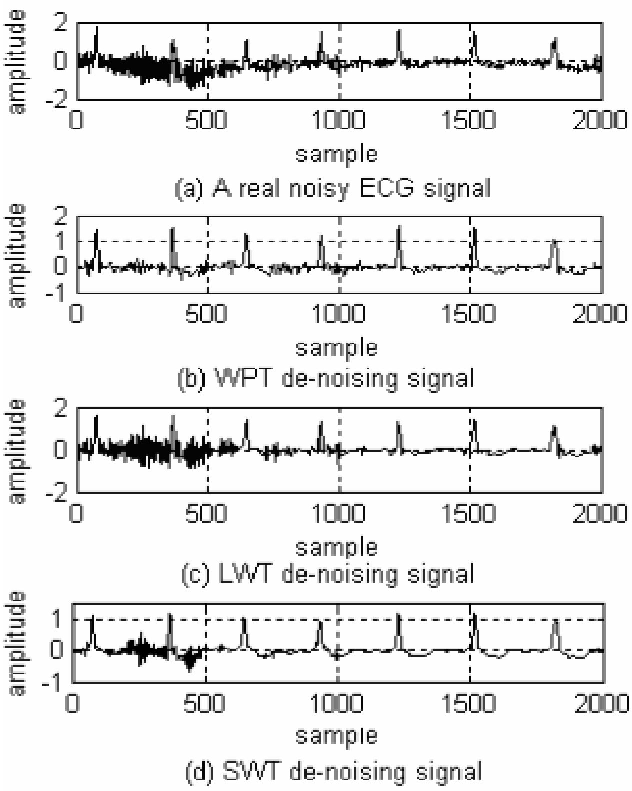

Figure 5.Denoising results using WPT, LWT and SWT on real ECG example. Results from [4]

Sl. No	Methodology	Year/author	Performance	Remark
1	Wavelet packet	2005,[30]	Good results achieved	Energy concept used
2	Fractional wavelet	2006,[31]	Comparable results obtained	For QRS detection, Cole-Cole method is used
3	Orthogonal filter bank	2007,[34]	Effective for base line wander removal	W1,W2 wavelets are desined.construction error is minimum
4	HH/wavelet	2008,[36]	Performance is good	Detection of R wave is 99.8%
5	Wavelet transform	2009,[8]	Good filtering effect	Used coif4 wavelet
6	Robust wavelet transform	2009,[27]	Better than Kalman and digital filtering	Improves S/N ratio
7	FFT and wavelet	2009,[38]	WT is more effective than FFT	Detection of small variation of ECG
8	DWTAE(Automated ECG DWT)	2009,[40]	Better compared to Saxena et al	Sensitivity=95.3% Predictivity=98%
9	UWT	2010,[24]	Better for noise reduction and peak detection	Preserves invariant translation property
10	Wavelet based shrinkage method	2008.[18]	Better or 50 Hz noise elimination	Results are better than other threshold methods
11	multiwavelet	2009,[11]	Better for denoising	R wave will be preserved
13	Multiresolution analysis	2008,[26]	Highly efficient, accurate and reliable	Dyadic WT is used for ECG feature extraction
14	Entropy based wavelet	2006,[14]	---	To catgorise persons with or without VLP

Table 2: Summary of wavelet techniques for ECG signal processing

V. Conclusions:

ECG is the prime human physiological signal which can be used for various clinical applications to detect the healthiness of the human being. Therefore the proper processing and detection of ECG is very much important. Since many decades various methods have been used for processing and accurate detection of human cardiac signal. In the last two decades many researchers and scientists have been using the methods based on Wavelet transforms and found that this Wavelet transform is more suitable for analyzing the non stationary, pseudo periodic ECG signal. Still there is lot of scope of Wavelet transform to be used for analyzing ECG signal. The suitability of Wavelet transform depends upon the proper selection of moth wavelet along with properties. In this paper we made an attempt to give an overview of various wavelet techniques used by the researchers for processing ECG signal. We hope that this material will be helpful particularly for beginners who are interested to work in this field.

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