Proceedings of the 2005 IEEE
Engineering in Medicine and Biology 27th Annual Conference
Shanghai, China, September 1-4, 2005

Cardiac Health Diagnosis using Wavelet Transformation and Phase Space Plots

Rajendra Acharya U[1], P.Subbanna Bhat[2] , Kannathal N[1], Lim Choo Min[1], Swamy Laxminarayan[4]

[1] Dept. of ECE, Ngee Ann Polytechnic, 535 Clementi Road, Singapore 599 489
[2] Dept. of ECE, National Institute of Technology Karnataka, Surathkal, India.
[3] CEDT, Indian Institute of Science, Bangalore, India.
[4] Dept. of Rural health, Idaho State Univeristy, Pocatello, USA

Abstract: **Analysis of heart rate variation (HRV) has become a popular noninvasive tool for assessing the activities of the autonomic nervous system (ANS). HRV analysis is based on the concept that fast fluctuations may specifically reflect changes of sympathetic and vagal activity. It shows that the structure generating the signal is not simply linear, but also involves nonlinear contributions. These signals are essentially non-stationary; may contain indicators of current disease, or even warnings about impending diseases. The indicators may be present at all times or may occur at random in the time scale. However, to study and pinpoint abnormalities in voluminous data collected over several hours is strenuous and time consuming. This paper presents the continuous time wavelet analysis of heart rate variability signal for disease identification. Phase space plots of heart rate signal for a chosen embedding dimension are compared with the wavelet analysis patterns.**

Keywords: ***Heart rate, phase space plot, continuous wavelet transform, correlation dimension.***

I. INTRODUCTION

Bio-signals are essentially non-stationary signals; they display a fractal like self-similarity. They may contain indicators of current disease, or even warnings about impending diseases. The indicators may be present at all times or may occur at random –in the time scale. However, to (study and) pinpoint anomalies in voluminous data collected over several hours is strenuous and time consuming. Therefore, computer based analytical tools for in-depth study and classification of data over day long intervals can be very useful in diagnostics.

The ECG belongs to the above category of bio-signals. It displays an apparent periodicity (of about 60 — 80 bpm in a healthy adult), but is not exactly periodic. Disease and affliction do influence the heart rate, and therefore, the pattern and the range of heart rate variability would contain important information about the robustness of health, type of disease etc. Therefore, classification based on the spread and pattern of this parameter can provide useful insight about the type and intensity of the affliction.

HRV is a useful signal for understanding the status of the autonomic nervous system (ANS). HRV refers to the variations in the beat intervals or correspondingly in the instantaneous heart rate (HR). The normal variability in HR is due to autonomic neural regulation of the heart and the circulatory system[1]. The balancing action of the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) branches of the autonomic nervous system (ANS) controls the HR. The degree of variability in the HR provides information about the functioning of the nervous control on the HR and the heart's ability to respond.

A complex system like cardiovascular system can not be linear in nature and by considering it as a nonlinear system can lead to better understanding of the system dynamics. Recent studies have also stressed the importance of nonlinear techniques to study HRV in both health and disease. There have been several methods of estimating invariants from nonlinear dynamical systems reported in the literature. Recently, Fell et al and Radhakrishna et al have tried the nonlinear analysis of ECG and HRV signals respectively [2,3]. Also, Paul at al showed that coordinated mechanical activity in the heart during ventricular fibrillation may be made visible in the surface ECG using wavelet transform [4]. Khadra et al [5] have proposed a classification of life-threatening cardiac arrhythmias using wavelet transforms. Later, Al-Fahoum et al[6], have Combined wavelet transformation and radial basis neural networks for classifying life-threatening cardiac arrhythmias. Also, recently Eran et al, have studied autonomic control during thrombolysis using wavelet analysis of HRV signal [7]. In work, heart rate variability is used as the base signal for classification of cardiac abnormalities. Rajendra et al [8] have classified the HRV signals using ANN and Fuzzy equivalence relation. This paper uses the heart rate variability as the base signal for continuous time wavelet analysis. The emerging patterns are compared with known types of disease. Phase space plots of the HRV signal for a chosen embedding dimension are

0-7803-8740-6/05/$20.00 ©2005 IEEE.

compared with the wavelet transform patterns. Correlation Dimension factor is evaluated from the phase space plot and its range is identified for each type of disease.

II. Materials and Method

For the purpose of the present work, more than 300 subjects – patients suffering from various cardiac diseases as well as those in normal health – have been studied. The data for this work is collected from Kasturba Medical Hospital, Manipal, India. The details of the age, sex and number of subjects in various groups is indicated in Table 1. The ECG data is stored in a holter monitor for the duration of 10-15 minutes. Then this data is sampled at a rate of 200 sps with a resolution of 12bits/sample and stored in a random access file. Later, from this file, QRS complex is obtained [9]. The interval between two successive QRS complexes is defined as the R-R interval ($t_{r\text{-}r}$ seconds), from which the heart rate (beats per minute) is derived. Since the volume of the data is enormous, the study is tedious and time consuming. Naturally, the possibility of the analyst missing (or misreading) vital information is high. Therefore, computer based analysis and classification of diseases can be very helpful in diagnostics**.** The heart rate is calculated using the r-r interval thus:

$$HR=60/t_{r\text{-}r} \tag{1}$$

TABLE I
NUMBER OF SUBJECTS IN VARIOUS GROUPS

Type of disease	Male (21-34 yrs)	Male (45-70 yrs)	Female (21-34 yrs)	Female (45-70 yrs)	Total
Normal	30	30	30	30	120
Ectopics	11	35	12	31	89
Sick Sinus Syndrome (SSS)	4	13	1	11	29
Atrial Fibrillation (AF)	0	15	7	14	36
Isc./Dilated Cardiomyo pathy	4	18	8	12	42
Complete Heart Block (CHB)	3	8	7	9	27

For the purpose of this study, the cardiac disorders are classified into six categories and the number of subjects in each class are shown in Table I.

A. Wavelet Analysis

A *'wavelet'* implies a small wave of finite duration and finite energy, which is correlated with the signal to obtain the wavelet coefficients [10]. The reference wavelet is known as the *mother wavelet*, and the coefficients are evaluated for the entire range of the signal interval by *translating* (shifting) the wavelet continually along the time scale. In the next phase, the wavelet is *dilated* (scaled) to a different width, and the process is repeated. Dilation is accompanied by modification of amplitude to normalize the energy of the wavelet. The wavelet coefficients are real numbers usually shown by the intensity of a chosen color, against a two dimensional plane with y-axis representing the dilation (scaling factor) of the wavelet, and the x-axis, its translation. In the CWT , the wavelet coefficients are evaluated for infinitesimally small shifts of translation as well as scale factors. That is, the intensity of each pixel in the *scalogram* represents a wavelet coefficient, evaluated separately for a specific pair translation and dilation factors. Thus the resulting color pattern provides a visual indicator of both the size and location of the 'transient event' occurring along the time scale. For a given wavelet $\psi_{a,b}(t)$, the coefficients are evaluated using Eq. (2):

$$W(a,b) \equiv \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{|a|}} \psi^{*}\left(\frac{t-b}{a}\right) dt \tag{2}$$

where $\psi^{*}\left(\frac{t-b}{a}\right) = \psi^{*}_{a,b}(t)$, a is scale factor, b is translation factor.

The *scalogram* patterns thus obtained also depend on the wavelet chosen for analysis. Bio-signals usually exhibit self similarity patterns in their distribution, and a wavelet which is akin to its fractal shape would yield the best results in terms of clarity and distinction of patterns. In the present work, the analysis is based on the Morlet wavelet shown in Fig. 1. This wavelet gives good result compared to all the other wavelets. The Morlet wavelet function is given by :

$$h(t) = \exp\left(\frac{-t^2}{2} + j\,w_0 t\right) \tag{3}$$

where $w_0 = 5.33$

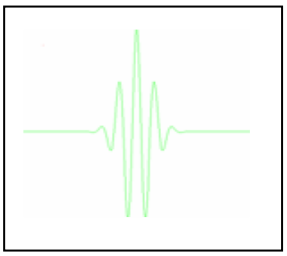

Fig. 1. Morlet wavelet function

B. Phase Space Plot

In this approach, a phase space plot is obtained with the X-axis representing the heart *rate* x (k), and the Y-axis representing the *heart rate after a delay* x (k+T). The choice of an appropriate delay interval T is calculated using the minimal mutual information technique [11]. It has been observed that the patterns emerging on the screen can be correlated to the various types of diseases.

C. Correlation Dimension Analysis

A Correlation Dimension factor is defined to obtain a quantitative measure of the nature of trajectory, and the ranges of CD factor for various heart diseases are identified. Grassberger and Procaccia [12] have proposed a method of evaluating a CD factor from the phase space plot. This technique is used here to determine the Correlation Dimension (CD) of the HRV data:

$$CD = \lim_{r \to 0} \frac{\log C(r)}{\log(r)} \tag{4}$$

where the correlation integral C (r) is given by

$$C(r) = \frac{1}{N^2} \sum_{x=1}^{N} \sum_{y=1, x \neq y}^{N} \Theta(r - |X_x - X_y|) \tag{5}$$

where X_x, X_y are points of the trajectory in the phase space, N is number of data points in phase space, r is radial distance around each reference point X_i and Θ is Heaviside function.

TABLE II
RESULTS OF CD FOR VARIOUS SUBJECTS

TYPE	Correlation Dimension	'p' value
Normal	5.301+-1.703	0.0001
Ectopics	5.925+-0.317	0.15
Sick Sinus Syndrome (SSS)	1.62+-0.010	0.0048
Atrial Fibrillation (AF)	5.890+-0.0053	0.089
Isc./Dilated Cardiomyopathy	1.396+-1.290	0.0001
Complete Heart Block (CHB)	0.654+-0.525	0.0001

III. RESULTS

The results of the CD for various types of subjects is listed in Table II. The resulting wavelet scalograms, and the corresponding phase space plots for various types of disease are shown in Fig. 2 – 7. In the CWT plots shown, white color indicates high value of (wavelet) coefficient and black corresponds to low value. As can be seen in the figures, the patterns show continuity in the patterns indicating a continuous variation of heart rate. For Normal cases, the CWT pattern appears to be flowery and regular (Fig. 2). In the *Ectopic beats*, there would be a sudden impulsive jump in the heart rate. This may be due to a Pre-Ventricular beat in the ECG signal. This is indicated as a sudden surge of radial white lines in the CWT plot, and a spike in the phase space plot (Fig. 3). The black patches indicate the *Bradycardia* and the rest is normal. In the Atrial *Fibrillation* (AF), heart rate signal records highly erratic variability; this is depicted as sudden changes in color (Fig. 4). In *Complete Heart Block* (CHB) cases as the A_V node fails to send electrical signals rhythmically to the ventricles, the heart rate remains low. The pattern is predominantly red (low coefficient value) with very little change in color intensity (Fig. 5). The phase space plot reduces almost to a point, indicating very little change with time. In *SSS - III* (*Sick Sinus Syndrome - III, Bradycardia-Tachycardia*) there is a continuous variation of heart rate between *Bradycardia* and *Tachycardia*, which shows up by way of alternating patches of black (*Brady*) and colored (*Tachy*) patterns (Fig. 6(a)). The phase space plot spreads over a larger area (Fig. 6(b)). In the case of *Ischemic/Dilated cardiomyopathy*, the ventricles are unable to pump out blood to the normal degree. Here the heart rate variation is very small. Correspondingly, the color variation too is gradual and periodic (Fig. 7).

In the case of CHB, the CD value is 0.654+-0.525 a small range, indicating low variation in the heart rate data. For *SSS - III,* the CD is low (CD= 1.62+-0.010) indicating the inherent periodicity, for *AF* has too much variation (CD=5.89+-0.0053. In *Ischemic/Dilated cardiomyopathy,* the variation between the consecutive heart rates is low (CD = 1.396+-1.290). During *Ectopic beat* variation is high (CD= 5.92+-0.317), finally, the *Normal* subjects have variation in their heart rates (CD=5.30+-1.70). For the normal subjects and ectopics and AF, the CD is high and as the abnormality becomes more severe (CHB, SSS, Isch./Dilated Cardiomyopathy) the CD will fall (TableII).

IV. CONCLUSION

Heart rate variability (HRV) signal can be used as a reliable indicator of heart diseases. A continuous time wavelet transform of the HRV signal can provide a visual pattern, which can be of considerable help in diagnostics. Bio-signals display fractal like self-similarity, and therefore, a wavelet akin to the signal is most suitable for the purpose, as it yields sharp and well-defined patterns. A different kind of pattern can be obtained by phase space plot of heart rate signal ; the spread and width of the plot can be used as the basis of classification of diseases. This plot can be used to derive a Correlation Dimension factor, which can serve as a quantitative measure of its spread. As can be seen, the CD factor decreases from normal for the abnormal subjects. And the results of these were subjected to 't' test with more than 95% confidence interval giving excellent 'p' values in all cases except one where the 'p" value is 0.15 (for Atrial Fibrillation TableII).

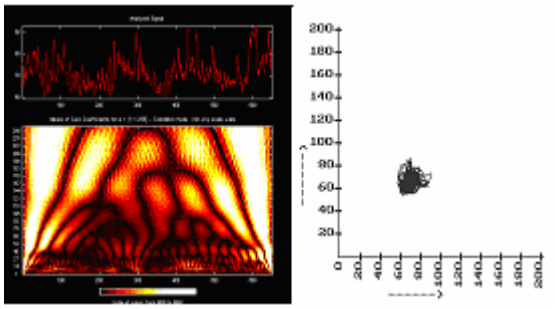

Fig. 2. a. CWT plot of Normal heart rate b. Phase space plot of Normal heart rate (CD = 5.30+-1.70)

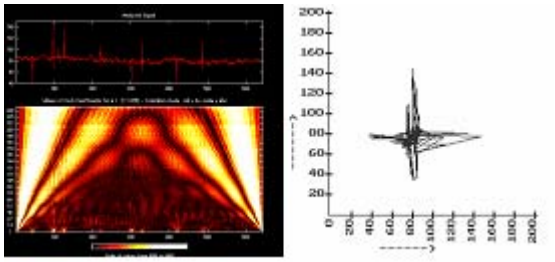

Fig. 3. a. CWT plot of heart rate with Ectopic beat b. Phase space plot of heart rate with Ectopic beat (CD = 5.92+-0.317)

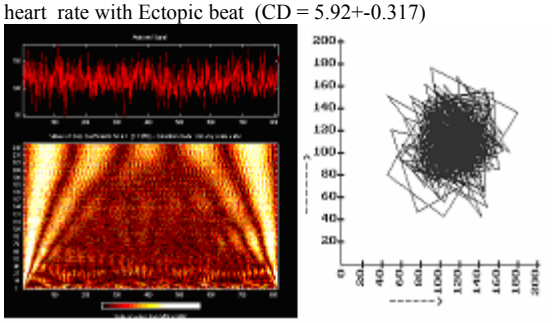

Fig. 4.a. CWT plot of heart rate with AF b. Phase space plot of heart rate with AF (CD = 5.89+-0.0053)

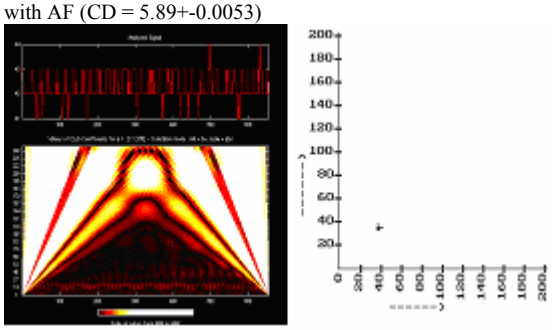

Fig. 5.a. CWT plot of heart rate with CHB b. Phase space plot of heart rate with CHB (CD = 0.654+-0.525)

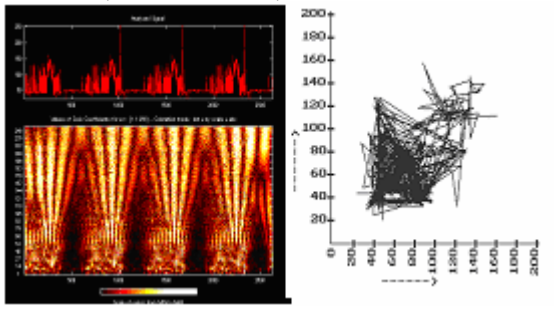

Fig. 6. a. CWT of heart rate with SSS – III b. Phase space plot of heart rate with SSS - III (CD = 1.62+-0.010)

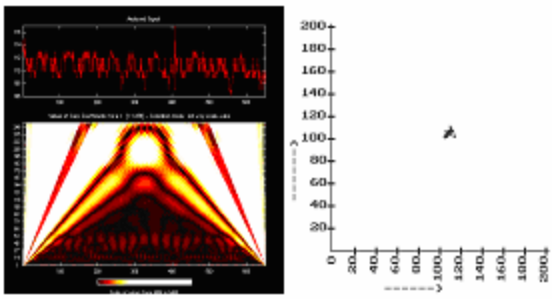

Fig. 7.a. CWT plot of heart rate with Isc./Dil. Cardiomyopathy b. Phase space plot of heart rate with Isc. /Dil. Cardiomyopathy(CD = 1.396+-1.290)

REFERENCES

[1] JP. Saul, " Beat to beat variation of heart rate reflect modulations of cardiac autonomic outflow," *News Physiological Science*, vol. 5, pp.32-37, 1990.

[2] J. Fell, K. Mann, J. Roschke and MS. Gopinathan, "Nonlinear analysis of continuous ECG during sleep I. Reconstruction," *Biological Cybernatics*, vol. 82, pp.477-483, 2000.

[3] KA. Radhakrishna Rao, Vikram Kumar Yergani, Narayana Dutt and TS. Vedavathy, " Characterizing Chaos in heart rate variability time series of panic disorder patients," *Proceedings of Proceedings of ICBME*, *Biovision 2001*, Bangalore , India, pp.163-167, December 2001.

[4] P. Addison, J. Watson, GR. Clegg, PA. Steen and CE. Robertson, " Finding Coordinated Atrial Activity During Ventricular Fibrillation Using Wavelet Decomposition," *IEEE Engineering In Medicine and Biology Magazine*, vol.21(1), pp. 58-61, January 2002.

[5] L. Khadra, AS. Al-Fahoum and H. Al-Nashash, "Detection of life-threatening cardiac arrhythmias using wavelet transformation," *Medical & Biological Enginering & Computing*, vol. 35, pp. 626-632, November 1997.

[6] AS. Al-Fahoum and I. Howitt, " Combined wavelet transformation and radial basis neural networks for classifying life-threatening cardiac arrhythmias," *Medical & Biological Engineering & Computing*, vol.37, pp.566-573, September 1999.

[7] E. Toledo, O. Gurevitz, H. Hod, M. Eldar, and S. Akselrod, " Wavelet analysis of instantaneous heart rate: a study of autonomic control during thrombolysis," *American Journal of Physiology- Regulatory, Integrative and Comparative Physiology*, vol. 284, pp.R1079-R1091, November 2002.

[8] AU. Rajendra, PS. Bhat, SS. Iyengar, A. Rao and S. Dua, " Classification of heart rate using artificial neural network and fuzzy equivalence relation," *Pattern Recognition*, vol.36, pp.61-68, 2003.

[9] J. Pan and WJ. Tompkins, "Real Time QRS Detector algorithm," *IEEE Transactions on Biomedical Engineering*, Vol.32(3), pp. 230-23, March 1985.

[10] M. Vetterli, "Wavelet and filter banks: Theory and design," *IEEE Trans. Signal Proc.*, vol. 40(9), pp. 2207-2232, September 1992.

[11] AM. Fraser, "Information and entropy in strange attractors," *IEEE transactions on Information Theory*, vol.35, pp. 245-262, 1989.

[12] P. Grassberger and I. Procassia, "Measuring the strangeness of strange attractors," *Physica D*, vol.9, pp. 189-208, 1983.