Heart Rate Variability Analysis and Pathological Detection

Payal Patial
Student, ECE Department
LPU, Punjab,
India.

Kawaldeep Singh
Asst. Prof. ECE Department
LPU, Punjab,
India.

ABSTRACT
In order to measure the mortality in the patients suffering from the heart disease we use the term HRV that i.e. Heart Rate Variability. Estimation methods as Parametric and Non-Parametric are used in the analysis of Heart Rate Variability but Heart Rate Variability requires the specific capabilities which are not provided by either of these. The term EMD i.e. Empirical Mode Decomposition adaptively estimates the IMF i.e. Intrinsic Mode Function of the nonlinear and nonstationary signal. The IMF obtained from the EMD is used for the analyses of the HRV latencies of Healthy subjects and of Congestive Heart Failure subjects. In this paper we have considered the 15 Congestive Heart Failure patients, 20 healthy young control patients and 20 healthy old control patients. After finding the IMF from EMD we have calculated the average periods, absolute power, normalised power and cumulative power and concerned plots are drawn for the comparison of the considered subjects. The results obtained shows that the HRV of healthy subjects rises rapidly to its maximum response as compared to the HRV of the pathological subjects. This fact can be used as a promising approach in clinical practise for the screening of specific risk group.

General Terms
HRV Analysis using EMD, Pathological Detection.

Key-words
Empirical Mode Decomposition, Heart Rate Variability, Average Period, Absolute Power, Normalised and Cumulative Power.

1. INTRODUCTION
The phenomenon that focuses on the oscillation in the interval between consecutive heartbeats as well as the oscillations between consecutive instantaneous heart rates is known as the Heart rate variability. Heart Rate Variability has become the conventionally accepted term to describe variations of both instantaneous heart rate and RR intervals. The results obtained from HRV data are capable of portraying physiological condition of the patient moreover they are an important indicator of cardiac pathologies. Variations in heart rate are clinically linked to various lethal arrhythmias, congestive heart failure, hypertension, organ transplant, coronary artery disease, tachycardia, bradycardia, diabetes and neuropathy etc. Heart is influenced and para-sympathetic activities of the autonomic nervous system. Sympathetic activities i.e. fight and flight it accelerates the heart rate where as parasympathetic activity i.e. rest and digest it decelerates the heart rate. Sympathovagal balance gives the influence of both the branches of autonomic nervous system and this balance is reflected in HRV and HRV is non invasive measure of autonomic nervous system. EMD is given by Huang et al and showed that it is a method of decomposing the nonlinear non stationary multi component signal. The components which results from EMD are known as IMF. Algorithm used for defining EMD has no analytical formulation implementation. Decomposition of the signal is understood easily by the experimental investigation of it rather than the analytical results. As EMD is fully data dependent and adaptive in nature, hence it is highly efficient method for decomposition of any nonlinear and non stationary signals [6].

2. EMPIRICAL MODE DECOMPOSITION
There are few assumptions we made for EMD which are as follows.

- The signal has at least two extrema's: one maxima and one minima.
- Characteristic time scale must be equal to the time lapse between the extrema.
- Differentiation once or more than once is done in order to reveal the extrema, it the data is totally devoid of extrema and have some inflection points [6].

Net final result i.e. the signal is obtained from the integration of IMF components. Decomposition of data is done accordingly after identifying the intrinsic oscillatory modes.

3. INTRINSIC MODE FUNCTION
The results obtained after the decomposition the process consists of components known as IMF. IMF has two conditions which have to be satisfied.

- The no. of extrema and zero crossing must be either equal to or differ by at most 1.
- Mean value of an envelope defined by local minima and an envelope defined by local maxima is zero [9].

In each cycle of IMF, zero crossing involves only one mode of oscillation with no complex riding waves.

4. MATERIAL AND METHODOLOGY

Dataset for HRV analysis is obtained from Physionet Fantasia Database; we have considered the ECG signal for concerned subject and obtained the R peaks for HRV analysis. We have considered three different groups as.

- 20 Healthy young subjects.
- 20 Healthy old subjects.
- 15 Congestive Heart Failure.

4.1 QRS Detection

In order to get the RR-Interval we need to obtain the R peaks in the concerned signal. For R peaks we undergo through QRS detection and there various methods associated with it. In this paper Pan and Tompkin method for QRS Detection is applied. R_i - R_{i-1} intervals are obtained from the R peaks of the concerned ECG signal and also known as NN interval. Variation in these RR intervals is knows as Heart Rate Variability [10] [12] [13].

4.2 EMD Methodology

- EMD is used to estimate the local time scales of HRV signal decomposition and consists of various steps.
- Signal to be analysed = s(t); auxiliary variable = x; variable = k; it is the no. of estimated IMF which is set to zero.
- Apply spline to the upper and lower extrema. It will give us the upper and lower envelope.
- Find the arithmetic mean between the upper and lower envelope. It is called the average envelope (m).
- IMF is estimated by the difference between mean of upper and lower envelop and the signal.
  IMF = x – m or h = x – m
- There are various conditions associated with IMF in case if h does not satisfy those conditions then repeat the steps for x, m, h.
- If h satisfies the conditions required for h then save IMF as C_k and k is k^{th} component.
- Mean square error between two consecutive IMF. c_{k-i} and c_k and the value obtained is compared with stopping condition.
- Partial residue (r_k) is estimated as difference between a previous partial residue (r_{k-1} and c_k) and assigned to dummy variable (x) and repeat the steps.
- After stopping condition, the final residue (r_{final}) can be estimated as the difference between s(k) and sum of all IMFs.

After sifting process the original signal s(t) can be represented as

$$s(t) = \sum_{k=1}^{n} c_k + r_{final} \quad \text{..... (1)}$$

Where n = no. of IMF, c_k= k^{th} IMF, r_{final}=final residue [15] [16].

4.3 Time Domain HRV Measures

4.3.1 Using EMD

The power of the n^{th} IMF is computed as given in:

$$V_n = \frac{1}{N}\sum_{j=1}^{N} | Cn(j) |^2 \quad \text{..... (2)}$$

where, C_n = nth IMF and j=1….N samples.

The average period (mean period) of the IMF, C_n is given as:

$$T_n = \frac{dist}{Z_c - 1} \quad \text{..... (3)}$$

where, dist = distance between the first and last zero crossings and Z_c = number of zero crossings.

4.3.2 Using RR-Intervals

Time domain parameters are obtained using the RR-Intervals [3] [4] [11]. The associated formulae with the frequency and time domain parameters are given in Table 1 as follows.

Table 1. Time domain parameters of HRV

Parameter	Description & Mathematical Expression
NN 50 Count	No. of adjacent RR intervals differing by more than 50 ms in entire ECG recording.
pNN 50	NN 50 count divided by total number of all RR Intervals. $$pNN\ 50\% = [(\frac{NN\ 50}{N-1}) * 100]$$
Max-Min	Difference between shortest and longest RR interval.
SDNN	Standard deviation of all RR (NN) Intervals. $$sdnn = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2$$
SDNN Index	Mean of the standard deviations of all RR Intervals for all 5 min segments in the entire recordings.
SDANN	Standard deviation of averages of RR Intervals for all 5 min segments in the entire recordings.

RMSSD	Root mean square of the difference of successive RR Intervals. $rmssd = \sqrt{[\frac{1}{N-1}\sum_{i=1}^{N-1}(x_{i+1} - x_i)^2]}$
SDSD	Standard deviation of differences between adjacent RR (NN) Intervals. $sdsd = \sqrt{[\frac{1}{N}\sum_{i=1}^{N}(dx_i - d\bar{x})^2]}$
HRV Index	Total number of all RR Intervals divided by amplitude of all RR Intervals.

4.4 Frequency Domain HRV Measures

4.4.1 Using RR-Intervals

Frequency domain parameters are obtained using the RR-Intervals [3] [4] [11]. The associated formulae with the frequency and time domain parameters are given in Table 2 as follows.

Table 2. Frequency domain parameters of HRV

Parameter	Description	Frequency
	Absolute Measures	
Total Power	Variance of all RR intervals.	TP[ms^2]<=0.4Hz
ULF	Power in Ultra Low Frequency Range.	ULF[ms^2]<=0.003 Hz.
VLF	Power in Very Low Frequency Range.	VLF[ms^2]=0.003Hz –0.04Hz.
LF	Power in Low Frequency Range.	LF[ms^2]=0.04Hz-0.15 Hz.
HF	Power in High Frequency Range.	HF[ms^2]=0.15Hz–0.4 Hz.
	Relative Measures	
VLF Normalized	Normalized Very Low Frequency Power.	VLF_n[%]=(VLF/TP)*100.
LF Normalized	Normalized Low Frequency Power.	LF_n[%]=(LF/TP)*100.
HF Normalized	Normalized High Frequency Power.	HF_n[%]=(HF/TP)*100.
Ratio of LF/HF	Ratio of Low and High Frequency.	.....

5. RESULTS

5.1 Using EMD

The EMD method is applied to half hour duration i.e. for 450000 samples as recording of 1 hour consists of 900000 samples. HRV measurements of 20 healthy young subjects, 20 healthy old subjects and 15 congestive heart failure subjects have been considered and method is applied to them. The EMD method decomposes the signals into IMF effectively. Here, we have considered three signals as CHF02, f1o04 and f1y07, and results shows that CHF02 consists of 11 IMF, f1o04 consists of 9 IMF and f1y07 consists of 8 IMF. The additional component in CHF patient's HRV was due to the latencies present in the signal. Further we have calculated the average period (t_n) and absolute power (V_n) of the IMF of the concerned signals using eqn. 2 and 3 respectively and calculated values of average period (t_n) and absolute power (V_n) given in table 3 and 4. Plotting the average periods (t_n) of IMFs against its IMF number gives an exponential graph as shown in Fig. 1. According to the plot average period (t_n) of IMFs of CHF 02 subject is significantly lower in value and the rate of increase w.r.to IMFs also smaller compared to healthy controls. The computed absolute power (V_n) of IMFs for the 3 subjects was presented in Fig. 2. For healthy young control subject f1y07 the absolute power (V_n) was high in all IMFs. For healthy old control subject f1o04 the power is less compared to healthy young in all IMFs except in IMF4 and dominates all the other IMFs. But for CHF 02 the absolute powers (V_n) of all IMFs were completely suppressed and found in lower range. Here are the Table 3 and Fig 1 representing the Average period of the IMF's of the signals and Table 4 and Fig 2 showing the Absolute Power of the IMF's of signals.

Table 3. Average period of IMF's

IMF	CHF 02	f1o04	f1y07
1	1.538181818	1.54829134	1.949811794
2	2.484466835	3.424778761	3.969309463
3	4.672985782	7.03196347	7.701492537
4	8.618075802	16.63043478	16.97802198
5	17.63855422	26.89285714	34.65116279
6	32.75555556	51.5862069	60.3627564
7	57.43137255	98.86666667	101.5714286
8	125.8571429	206.3333333	292.75234
9	216.3333333	329.6666667	
10	470		
11	1460		

Table 4. Absolute Power of IMF's

IMF	CHF 02	f1o04	f1y07
1	0.001451031	0.000958115	0.005615173
2	0.000257937	0.000478912	0.003366224
3	0.0000503	0.001098492	0.00326
4	0.0000915	0.002692335	0.00374
5	0.0000818	0.001631771	0.00495
6	0.000106161	0.000494106	0.001570335
7	0.0000913	0.0000618	0.000469
8	0.000154688	0.0000921	0.000374977
9	0.000610	0.0000386	
10	0.00000769		
11	0.000148885		

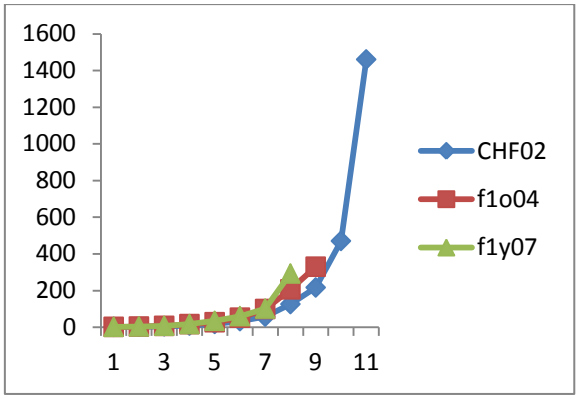

Fig 1: Average period of IMF's

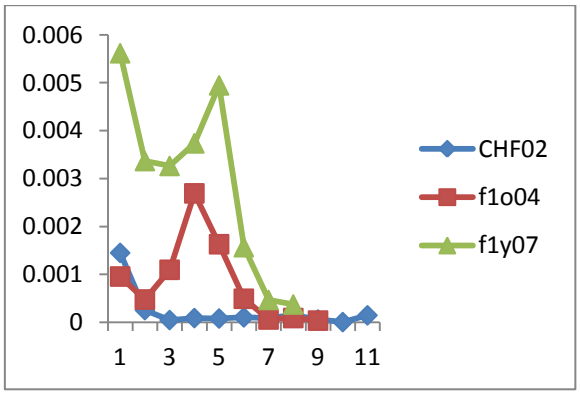

Fig 2: Absolute Power of IMF's

5.2 Using RR-Intervals

5.2.1 Time Domain Parameters

The estimation of HRV can be done by the time domain measures. The HRV was measured manually from the mean R-R interval in time domain and its standard deviation is measured on short-term 5 minute ECG segment. On the basis of these methods either the heart rate or each QRS complex or the RR intervals between successive normal complexes are determined and then analyzed. But the recordings for a longer period of 24 hours sometimes lead to complex statistical time-domain analysis.

These statistical parameters may be derived from direct measurements of the RR intervals or from the differences between RR intervals. The simplest variable to calculate is square root of variance i.e. the standard deviation of the NN interval (SDNN). Time domain HRV variables are detailed in Table 1 and calculated values of time domain parameters is given in Table 6.

5.2.2 Frequency Domain Parameters

Frequency Domain Analysis includes the frequency measures on the ECG data and frequency measures involve the spectral analysis of HRV. If the spectrum estimate is calculated from this irregularly time sampled signal, additional harmonic components appear in the spectrum, and then interpolation is required. The RR interval signal is then interpolated before the spectral analysis so that they can recover an evenly sampled signal from the irregularly sampled event series. The HRV spectrum contains the high frequency (0.18 to 0.4 Hz) component, which is due to respiration and the low frequency (0.04 to 0.15 Hz) component that appears due to both the vagus and cardiac sympathetic nerves. Ratio of the low-to-high frequency spectra is used as an index of parasympathetic sympathetic balance. Frequency domain HRV variables are detailed in Table 2, calculated values of frequency domain parameters is given in Table 5 and plot is given in Fig 3.

The non parametric frequency domain parameters for the RR-Intervals have been calculated. The use of computationally efficient algorithms such as Fast-Fourier Transform, the HRV signal is decomposed into its individual spectral components and their intensities, using Power Spectral Density (PSD) analysis [14]. These spectral components are then grouped into three distinct bands: very-low frequency (VLF), low frequency (LF) and high frequency (HF).

The cumulative spectral power in the LF and HF bands and the ratio of these spectral powers (LF/HF) has demonstrable physiological relevance in healthy and disease states. Changes in the LF band spectral power (0.04– 0.15Hz) reflect a combination of sympathetic and parasympathetic ANS outflow variations, while changes in the HF band spectral power (0.15–0.40Hz) reflect vagal modulation of cardiac activity. The LF/HF power ratio is used as an index for assessing sympatho-vagal balance. The calculated LF/HF values are given in Table 6 & plot for it is shown in Fig 3.

Table 5 Frequency domain parameters (Parametric) using RR-Intervals

Signal	VLF	LF	HF	TP	LF (N.U)	HF (N.U)	LF/HF (Ratio)
CHF01rri	119	38	120	277	23.9	76.1	0.315
CHF02rri	63	30	31	124	49.4	50.6	0.978
CHF03rri	181	592	2301	3074	20.5	79.5	0.257
CHF04rri	44	10	43	97	19.1	80.9	0.236
CHF05rri	38	27	14	79	66.2	33.8	1.959
CHF06rri	27	68	406	501	14.3	85.7	0.167
CHF07rri	32	57	463	552	11	89	0.123
CHF08rri	226	185	300	711	38.1	61.9	0.616
CHF09rri	11	22	86	119	20.4	79.6	0.256
CHF10rri	5	3	4	12	47.3	52.7	0.896
CHF11rri	15	7	22	44	23	77	0.3
CHF12rri	24	20	5	49	78.6	21.4	3.663
CHF13rri	3	2	9	14	17.1	82.9	0.207
CHF14rri	25	14	28	67	33.2	66.8	0.496
CHF15rri	229	757	1130	2116	40.1	59.9	0.67
f1o01rri	668	24	30	722	39.3	48.9	0.804
f1o02rri	79	0	178	257	0	38.2	0
f1o03rri	0	226	35	261	77.2	11.9	6.462
f1o04rri	3011	0	175	3186	0	52.8	0
f1o05rri	231	1	5	237	0	31.5	0
f1o06rri	60	0	16.3	76.3	0	57.9	0
f1o07rri	234	109	116	459	35.9	38.2	0.9
f1o08rri	258	0	63	321	0	35.7	0
f1o09rri	0	2331	2886	5217	26.2	32.4	808
f1o10rri	625	59	24	708	48.2	20	2.408
f2o01rrii	0	378	862	1240	10.5	24	0.439
f2o02rrii	0	522	430	952	36.2	29.8	1.214
f2o03rrii	0	151	152	303	33.1	33.4	0.991
f2o04rrii	0	246	226	472	49.4	45.2	1.092
f2o05rrii	180	0	43	223	0	28.8	0
f2o06rrii	1400	505	340	2245	55.7	37.6	1.483
f2o07rrii	505	0	120	625	0	57.9	0
f2o08rrii	226	0	2552	2778	0	40.2	0
f2o09rrii	0	783	153	936	62	12.1	5.114
f2o10rrii	148	0	55	203	0	29.2	0
f1y01rri	250	713	546	1509	37.7	28.9	1.306
f1y02rri	22	1118	66.5	1206.5	51.4	24.9	2.064
f1y03rri	279	617	73	969	86.8	10.2	8.481
f1y04rri	2117	671	645	3433	36.1	34.7	1.041
f1y05rri	431	1072	191	1694	75.4	13.4	5.607
f1y06rri	1848	1581	490	3919	74.2	23	3.227
f1y07rri	5331	0	2406	7737	0	82.1	0

f1y08rri	881	562	150	1593	70.3	18.8	3.737
f1y09rri	0	1416	99	1515	78.6	5.5	14.247
f1y10rri	725	767	290	1782	64.9	24.5	2.648
f2y01rrii	240	435	510	1185	37.5	44	0.853
f2y02rrii	2056	733	796	3585	46.3	50.3	0.921
f2y03rrii	821	0	278	1099	0	71.9	0
f2y04rrii	286	161	103	550	53	3.8	1.5
f2y05rrii	454	1057	788	2299	47	35	1.342
f2y06rrii	391	1509	146	2046	96.4	9.3	10.362
f2y07rrii	810	878	1031	2719	49	57.5	0.852
f2y08rrii	306	952	934	2192	36.5	35.8	1.019
f2y09rrii	0	988	1621	2609	19.6	32.1	0.609
f2y10rrii	4031984	15482	829	4048295	91.1	4.9	18.683

Fig 3: Plot of LF/HF Ratio

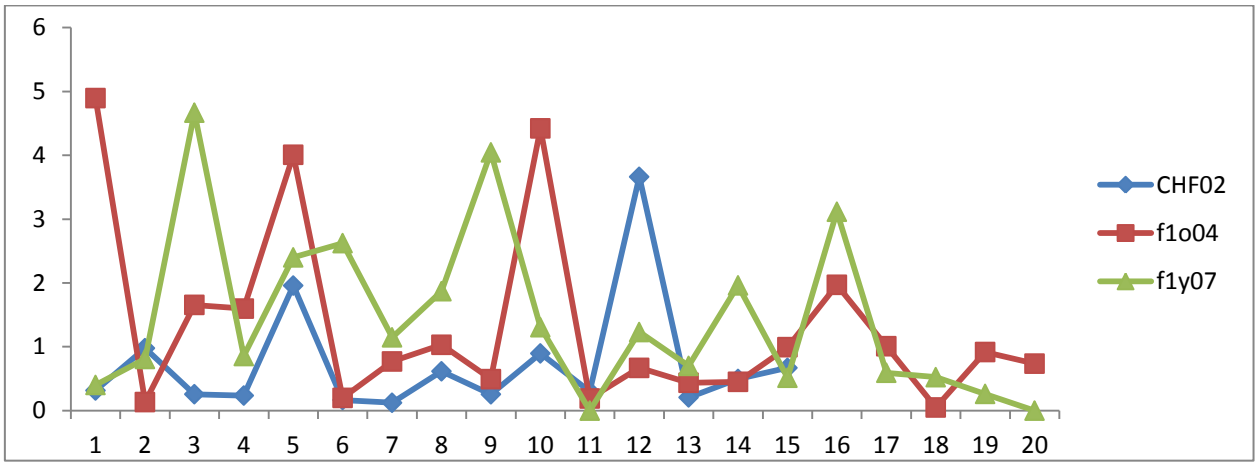

Table 6 Time domain parameters using RR-Intervals

Signal	MEAN RR	STD	MEAN HR	STD	RMSSD	NN50	PNN50
CHF01	0.962	0.032	62.81	10.85	38.6	39	2.1
CHF02	0.608	0.034	99.42	12.14	55.7	146	4.9
CHF03	0.893	0.079	68.05	10.04	121.8	142	7
CHF04	0.633	0.021	95.06	4.29	30	133	4.7
CHF05	0.541	0.016	111.14	3.87	17.7	43	1.3
CHF06	0.55	0.067	111.52	18.55	107.2	1952	59.7
CHF07	0.72	0.056	84.12	9.08	91.2	182	7.4
CHF08	0.825	0.054	73.52	10.85	64	103	4.7
CHF09	0.589	0.03	102.29	7.02	47.2	191	6.2
CHF10	0.486	0.007	123.49	1.95	7.3	5	0.1
CHF11	0.564	0.013	106.82	2.69	16.7	22	0.7
CHF12	0.549	0.015	109.83	18.77	16	15	0.5

CHF13	0.614	0.012	97.85	3.73	16.2	28	1
CHF14	0.776	0.019	77.51	6.23	22	40	1.7
CHF15	0.581	0.038	103.98	7.19	55.8	199	6.4
f1o01	0.991	0.028	60.64	1.94	15.7	5	0.3
f1o02	1.03	0.036	58.44	4.35	55.7	14	0.8
f1o03	0.974	0.025	61.69	1.77	21.3	23	1.2
f1o04	1.16	0.072	52.03	4.39	49.6	166	10.7
f1o05	1.058	0.022	56.76	1.4	11.6	1	0.1
f1o06	1.179	0.028	50.96	1.8	43.5	18	1.2
f1o07	0.981	0.039	61.29	2.75	40.8	95	5.2
f1o08	0.818	0.031	73.53	3.46	30.1	39	1.8
f1o09	1.412	0.142	43.25	7.16	190.8	470	36.9
f1o10	0.855	0.038	70.47	3.47	24.5	27	1.3
f2o01	0.901	0.094	67.8	10.68	152.2	236	11.8
f2o02	1.091	0.054	55.16	3.64	74	83	5
f2o03	1.053	0.032	57.1	2.61	44	59	3.5
f2o04	1.024	0.03	58.68	2.11	32.2	82	4.7
f2o05	0.789	0.027	76.22	5.28	29.4	32	1.4
f2o06	1.331	0.063	45.29	3.37	58.4	278	20.6
f2o07	1.198	0.035	50.14	1.93	34.4	60	4
f2o08	0.972	0.119	63.39	13.33	196.1	265	14.3
f2o09	1.123	0.06	53.98	8	52.9	27	1.7
f2o10	0.772	0.027	78.02	3.76	35.2	20	0.9
f1y01	0.784	0.065	77.15	7.33	73.3	853	37.2
f1y02	0.992	0.067	60.85	4.54	68.4	770	42.5
f1y03	0.914	0.044	65.92	3.36	29	153	7.8
f1y04	1.306	0.09	46.35	6.21	106.2	900	65.3
f1y05	0.98	0.059	61.6	4.77	48.6	352	19.2
f1y06	1.027	0.086	59.28	12.5	66.9	536	30.6
f1y07	1.157	0.13	52.94	7.54	113.2	937	60.3
f1y08	0.967	0.06	62.42	4.55	44.9	430	23.1
f1y09	0.852	0.061	71	5.75	35.8	280	13.3
f1y10	0.794	0.06	76.15	6.19	53.6	493	21.8
f2y01	0.0871	0.054	69.23	4.77	68.3	703	34
f2y02	1.071	0.087	56.6	5.18	78.6	616	48.8
f2y03	1.047	0.034	57.47	3.83	36.5	134	7.8
f2y04	0.797	0.035	75.57	3.91	29.5	59	2.6
f2y05	0.767	0.047	78.57	6.66	62.1	24	1
f2y06	982	0.041	61.3	5.43	32.8	104	5.7
f2y07	1.086	0.071	55.67	4.05	78.3	85.4	51.5
f2y08	0.983	0.079	61.65	7.79	99.1	1089	59.5
f2y09	0.797	0.109	77.37	15.06	163.9	746	33
f2y10	0.973	1.297	63.79	11.8	710.8	326	17.8

6. DISCUSSION

A practical method for analyzing the HRV latencies is presented in this study using the database of CHF patients and healthy subjects. It is observed that the latencies of HRV signal effectively discriminates the healthy subjects and congestive heart failure subjects significantly. The opted method of EMD was applied to half an hour HRV measurement of healthy controls and congestive heart failure patients and a good discrimination of the two groups were obtained by it. The EMD method estimates the local time scales adaptively which reflects the intrinsic properties of the signal. This feature makes the healthy systems to reach its maximum response much earlier and makes the system more adaptive than congestive heart failure patients. Moreover, the LF/HF ratio by using frequency domain parametric approach has been calculated. Results are showing that the CHF patients has low LF/HF ratio as compared to the healthy subjects. It represents that the CHF patients have less sympatho-vagal balance of sympathetic and parasympathetic autonomic nervous system.

7. CONCLUSION

The common hypothesis is that the human cardiovascular system is a highly complex adaptive system and that the complexity of its behaviour allows for the broadest range of adaptive responses. The proposed technique is simple and adaptive method to analyze the complex HRV signal. The fastness in reaching maximum response of the healthy system represents its more adaptiveness for particular level of input and the slowness in reaching maximum response (more latency) of CHF subjects represents the system's inability to respond quickly for various levels of inputs. The estimate of LF/HF ratio also helps in finding the sympatho-vagal balance of sympathetic and parasympathetic autonomic nervous system. This fact makes the method a promising approach to be applied in clinical practice as a screening test for specific risk-groups.

8. ACKNOWLEDGMENTS

I am very thankful to Mr. Kawaldeep Singh Chandok for his kind guidance and support in completion of this paper. And I am also to thankful to my friend Suraj Bhati for his support and motivation.

9. REFERENCES

[1] Rangayyan R.M., Biomedical Signal Analysis: A Case-study Approach, Wiley–Interscience, New York, 2001.

[2] Reddy, D.C., Biomedical Signal Processing: Principles and Techniques, Tata McGraw-Hill, New Delhi, 2005.

[3] Argyro Kampouraki, George Manis, and Christophoros Nikou, (2009). "Heartbeat Time Series Classification with Support Vector Machines', IEEE, July 2009.

[4] Marcel STANCIU, Mihaela ALBU, Anatolie BOEV, (2009). "ECG monitoring: A software tool for deriving time and frequency parameters", IEEE, May 2009.

[5] J. G. Proakis and M. D. G., Digital Signal Processing: Principles, Algorithms, and Applications: Prentice-Hall, 1999.

[6] M.E.S. Chelladurai and N. Kumaravel, 2011. Heart Rate Variability Analysis in Different Age and Pathological Conditions, International Journal of Computer Applications.

[7] Neto, E.P.S., M.A. Custaud, J.C. Cejka, P. Abry and J. Frutoso et al., 2004. Assessment of cardiovascular autonomic control by the empirical mode decomposition. Methods Inf. Med., 43. DOI: 10.1267/METH04010060

[8] Lindsen, J.P. and J. Bhattacharya, 2010. Correction of blink artifacts using independent component analysis and empirical mode decomposition. Psychophysiology, 47.

[9] Feldman, D., T.S. Elton, D.M. Menachemi and R.K. Wexler, 2010. Heart rate control with adrenergic blockade: Clinical outcomes in cardiovascular medicine. Vascular Health Risk Manage, 6. DOI: 10.2147/VHRM.S10358

[10] N. E. Huang, Z. Shen, C. C. Tung, M. C. Wu, H. H. Shih, Q. Zheng, S. R. Long N.- C. Yen, , and H. H. Liu, "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis," Proc. R. Soc. Lond.,1998.

[11] Pan J. and Tompkins W. J. A real-time QRS detection algorithm. IEEE Trans. Biomed. Eng. BME-32.

[12] 1985. Task force of the European society of cardiology and the North American society of pacing and electrophysiology. Heart rate variability: standards of measurement, physiological interpretation, and clinical use. Circulation, vol.93, no.5, 1996.

[13] Bansal Dipali, Khan Munna and Salhan A.K. An ECG monitoring system having simple interface with computer capable of real time data transfer. International Conference, Los-Angeles, USA, P1.7, 2007.

[14] Ahlstrom, M. L. and Tompkins W. J. Digital filters for real-time ECG signal processing using microprocessors. IEEE Trans. Biomed. Eng., BME-32, 1985.

[15] Shafqat, K., S.K. Pal, S. Kumari and P.A. Kyriacou, 2009. Empirical Mode Decomposition (EMD). Proceeding of the 31st Annual International Conference of the IEEE EMBS Minneapolis, Sept. 3-6, IEEE Xplore Press, Minneapolis, MN.

[16] Matlab help, MATLAB MATHWORKS. http://www mathworks.com