A New Spectral Based Characterization of Electrocardiogram Signals in Sudden Cardiac Death

Hedi Khammari

College of Computers and Info. Tech., Taif University, Saudi Arabia

Abstract
A new method of characterization of patient Electrocardiograms (ECG) suffering from Sudden Cardiac Death (SCD) permits to confirm the role of lower order higher harmonics when approaching the moment of SCD instant. Besides, several peak amplitudes are detected during the normal heart beat oscillations preceding such cardiac arrest. Abrupt qualitative changes often encountered in the behavior of nonlinear dynamical systems may be regarded as analogous to the main features of the changing dynamics of the heartbeat. Indeed, under certain circumstances, the heart rhythm oscillations may undergo an abrupt change in frequencies and amplitudes of spectral lines. A sliding window FFT performed on ECGs of two patients suffering from Sudden Cardiac Death, leads to put into evidence the reorganization of the higher harmonics involving changes in their ranks and their amplitudes.

Keywords: *Electrocardiogram (ECG), Spectral Analysis, Sudden Cardiac Death (SCD), sliding window (FFT), Higher Harmonics.*

1. Introduction

The human circadian rhythms, in normal or abnormal situations or in healthy and diseased cases, present complex oscillations that undergo several changes under either external or internal excitation: sleep/awake, happiness/sadness, light/darkness. The heart oscillatory behavior can be examined in frequency domain, in order to reveal what are the harmonics that have major effect in such or such state. Several research studies based on spectral analysis of ECGs have revealed important results [1], [5], [7], [8], [11]. In former studies, it was shown that the harmonic predominance can characterize certain bifurcation structures in a nonlinear electric circuit [2]. Similarly, ECG is a nonlinear oscillation that may be characterized by the spectral line ranks changes.

The obtained results in nonlinear system theory, offer new descriptive and perspective insights into physiological systems that may more reflect complex behaviors such as bifurcation and chaos. Nonlinear dynamic behavior seems to occur in the heartbeat time-series data. Thus, the analysis of some recordings of ECGs by means of nonlinear theory approaches, may lead to highlight the existence of nonlinear phenomena. Methods from nonlinear dynamics have revealed new insights into heart rate variability (HRV) changes under various physiological and pathological conditions leading to provide further prognostic [3], [4], [12]. Sudden Cardiac Death refers to natural cardiac death due to loss of the body consciousness caused by heart's electrical system malfunctions. The most common cause of SCD is a heart rhythm disorder or arrhythmia called ventricular fibrillation (VF). The cardiac arrest occurs for a very short time which is preceded and followed by normal ECG [10]. Patients at high risk of sudden cardiac death show evidence of nonlinear heart rate dynamics, including abrupt spectral changes and sustained low frequency (.01-.04 Hz) oscillations in heart rate. Characteristically, frequency domain methods are used for quantifying the autonomous nervous system control as well as to guess sudden cardiac death [6]. According to [16], despite the remarkable progress in the field of prediction and prevention of SCD, there is always a need to develop new appropriate methods for reliable testing of the clinical utility of known risk variables for the prediction of arrhythmic death.

The main features of a normal ECG rhythm of patient suffering from Sudden Cardiac Death are mainly the lower spectral energy and the low frequency range of first lobe [10]. Power spectral methods analysis of HRV is a useful noninvasive tool that permits to categorize cardiac patients according to risk of SCD [9].

Some Holter variables can predict the occurrence of SCD among the patients with slightly reduced or preserved left ventricular (LV) function [15]. Other tools of prediction and prevention of SCD have been reported in [14], [17], such as T-wave alternans (TWA) and Modified Moving Average (MMA).Such tools were used to identify individuals at heightened risk for SCD. Spectral and MMA-TWA would both predict arrhythmia-free survival [8]. It was stated that risk of SCD rises when a cutoff point of 46 μV TWA is exceeded [14]. The application of FFT on QRS complex used to provide information from normal ECG signals was sufficiently performed on small portions (4-5 minutes) of any patient ECG to detect possibility of SCD [10]. The remainder of this paper is split into four sections; section 2 contains the basic reminders and the methodology. An experimental setup is given in section 3. Section 4 presents the main obtained results. Finally, section 5 is devoted to interpret such results.

2. Methodology

In recent literature, approaches to understanding and intervening in the cardiovascular system are being developed using the new methods from nonlinear system theory. Spectral analysis of ECG signals is a preliminary study aiming to classify certain particular physiological signal through their spectral composition and the associated ranks of higher harmonics so that, such analysis may become an important tool to reveal particular healthy or diseased situations. It is well known that a typical heart beat has the extremes P, Q, R, S and T, the beat-beat interval is the time between two consecutive R-peaks. This can be considered as the period of heart oscillation.

This study aims to characterize Electrocardiogram (ECG) signals, for patient suffering from SCD, through the reorganization of the higher harmonics. Approaching the SCD moment, the spectra of ECGs include higher harmonics which undergo changes of their ranks and their amplitudes in a certain classification defined as follows: Let r be the place occupied by an order-p harmonic spectral line from an ordering based on the amplitudes of spectral lines in descending order. So if r=2, the order-p harmonic is said to be simple predominant and if r=1, it is a full predominant one.

The spectral composition of an ECG signal depends on its clinically relevant parameters such as time interval between waves, duration of each wave or composite waveforms, peak amplitudes. ECG exhibits clinical information from generation and propagation of electric signal in the hearts. Among our objectives, we attempt to localize abnormality in frequency domain as well as in time domain. Aiming to analyze Electrocardiogram (ECG) signals given as discrete time signals, one can investigate how the frequency content varies with time. Defining a sliding window FFT algorithm, we proceed with two different ways: separated windows or overlapped windows. We choose a short window size (of 2024 points) and slide this window across the 15000 data samples while taking the 2024 point FFT and shifting the window by more than 2024 samples for separated windows or by less than 2024 samples for overlapped windows. After doing so, continue this operation until the end of the 15000th sample. The 2024 points FFT provides one spectrum, represented as a 1D vector that describes the whole data segment.

The result from applying the sliding window FFT is in fact a 2D image of dimension frequency versus time that sketches the spectrum for different time intervals. This image is known as a spectrogram.

3. Experimental Setup

The current study included only two subjects and relied on spectral analysis of ECG signals. From Sudden Cardiac Death Holter Database (Physionet)[13], the selected waveform records 30 (male 43 years old) and 47 (male 34 years) are of two patients suffering from a cardiac arrhythmia. Such patients experienced sudden cardiac death during the recordings. The spectral analysis of their Electrocardiograms leads to study in depth the main frequency features of the heart rhythm signals.

Aiming to characterize the heart beat oscillations before and during the sudden change, we sketch the continuous change of the spectral composition corresponding to a sliding window taken on the temporal data of the ECG. Every spectrum is associated to a certain classification based on decreasing amplitudes of the spectral lines, including the constant Fourier coefficient, the fundamental and the higher harmonics. In a first attempt, we perform a spectral analysis of an one minute length recording for patient 30, within which the sudden cardiac death happens. Such interval is split into separated or slightly overlapped windows. Such analysis devotes to highlight the spectral reorganization prior the SCD, is then applied to strongly overlapping intervals for both patients 30 and 47.

In a second attempt the spectral analysis is applied to a 7-minute interval preceding the SCD moment in order to observe the earlier changes in the ECGs spectra for the considered patients.

4. Results

Spectral Reorganization

Using the sliding window FFT, the ECG changes in temporal domain are accompanied by spectral changes. Some properties are basically deduced from spectral rather than from temporal signal representation. Following the ECG dynamics through spectral analysis leads to underline the spectral reorganization going with the transition from healthy to diseased cardiac rhythm state or vice versa. In the following we summarize some obtained results corresponding to the patient 30, this study focuses on one minute interval including SCD after nearly 40 seconds. We realize that approaching the SCD instant the spectra undergoes several changes illustrated by the higher harmonics descending order classification defined above. Each temporal window is characterized by the so called HH ordering as follows:

- Interval A [0, 2.5*s*]: 1, 2, 6, 5, 9: the fundamental harmonic is in the first rank the other higher harmonics have smaller amplitudes, see figure 1.
- Interval B [2, 4.5*s*]: 1, 2, 5, 8, 6, 0: the 6^{th} higher harmonic is moved from the 3^{rd} to the 5^{th} rank and the 8^{th} HH gains the 4^{th} rank of the classification, see figure 2.
- Interval C [11, 14*s*]: 0, 1, 2, 3, 5: the dc Fourier coefficient becomes larger in amplitude than all the rest of harmonics, and occupies the 1^{st} rank: permutation of HHs 3 and 5.
- Interval D [14, 16.5*s*]: 0, 1, 2, 3, 6, 8: no changes in the 4 first ranks.
- Interval E [16, 18.5*s*]: 1, 8, 5, 6, 13: several changes: the higher harmonics of orders 2 and 3 are shifted from the 2^{nd} and the 3^{rd} rank respectively.
- Interval F [18, 21*s*]: 5, 3, 8, 2, 13 : The fundamental harmonic is no more among the first ranks, and the 5*th* higher harmonic is predominant.
- Interval G [21.5, 24.5*s*]: 0, 8, 5, 3, 13, ..: permutation between HH 8 and 5, 3.
- Interval H [30, 32.5*s*]: 0, 7, 3, 5, 8, 1, ..: the fundamental harmonic is in the 5^{th} rank.
- Interval I [40, 42.5*s*]: 1, 8, 13, 5, 0, 3, ..: the fundamental harmonic is in the 1^{st} rank.
- Interval J [42, 44.5*s*]: 1, 0, 2, 7, 8, 3, ..: closer to the beginning of the sudden heart death, the lower order HH gain the first ranks.
- Interval K [44, 46.5*s*]: 0, 1, 5, 3, 2, ...: more odd harmonics among the first ranks.
- Interval L [46, 48.5*s*]: 0, 1, 2, ..: very important amplitude of the dc Fourier coefficient, then the fundamental harmonic, then the 2^{nd} HH with significant amplitude and the remainders HH with vanishing amplitudes.
- Interval M [48, 50.5*s*]: 1, 2, 0, 6, 3, ...: permutation of 0 and HH 1,2.
- Interval N [50, 52.5*s*]: 0, 4, 2, 1, 6, 8, ..: besides the dc Fourier coefficient, even order harmonics becoming important in amplitudes.
- Interval O [52, 54.5*s*]: 2, 4, 0, 6, 8, 5, 1, .. : Higher harmonics of even orders become in the first ranks and the odd order ones are shifted far in the classification.
- Interval P [57, 60*s*]: 4, 2, 6, 8, 19, 12, .. :More even higher harmonics in the first ranks.

The transition between two overlapping intervals involves minor changes compared to those that appear between two disjoint intervals. Such changes may be even less if the intervals are strongly overlapped.

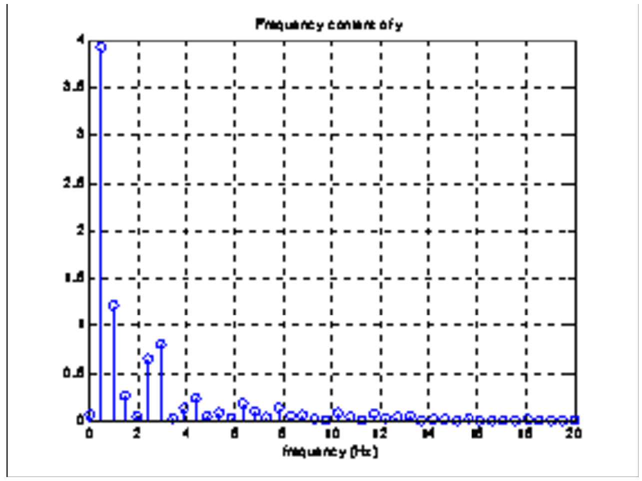

Fig. 1 Spectrum for Range A.

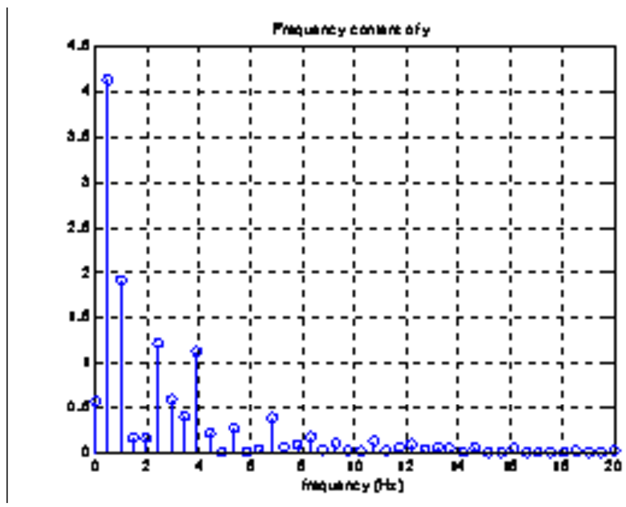

Fig. 2 Spectrum for Range B.

Overlapped Sliding Windows

Aiming to carry out an efficient spectral prediction tool of SCD, we defined common width windows of 2024 samples (nearly 8 s) and a sliding time step of 256 samples (almost 2 s). Over a 1-minute interval waveform 56 windows are generated. We attempt to analyze the few minutes preceding the SCD instant. We compute the corresponding spectrum of each window of a time series. Emphasizing on the most relevant harmonics over each 1-minute ECG spectrum, we define for each spectrum four sets Si, i=1,4 including either dc Fourier coefficient, fundamental harmonic and higher harmonics occupying the *ith* rank in the amplitudes classification in descending order.

Windows including SCD instant

The 1-minute waveforms given in Figures 3 and 8 for patients 30 and 47 respectively, including the instant of SCD, are analyzed with mean of the technique described above. Since we are interested in the four higher harmonics occupying the first ranks, the HH predominance sets S1, S2, S3 and S4 of patient 30 are obtained from Figures 4, 5, 6 and 7 respectively. S1={0, 1, 2, 3,4, 46, 52, 55, 56, 57, 73}, S2={0, 1, 2, 3, 4, 43, 51, 52, 54, 55, 56, 73}, S3={0, 1, 2, 3, 4, 5, 44, 46, 47, 48, 52, 56, 57, 60} and S4={0, 1, 2, 3, 4, 5, 9, 42, 51, 52, 55, 56, 60, 72}. For the patient 47 such sets can be derived from Figures 9,10,11 and 12 : S1={0, 1, 2, 3, 4, 22, 24, 29, 30, 37}, S2={0, 2, 3, 4, 21, 22, 23, 24, 26, 28, 29, 31, 33, 34, 35}, S3={0, 1, 2, 3, 4, 9, 10, 14, 16, 21, 22, 23, 24, 25, 26, 28, 30, 31, 33, 34, 38} and S4={0, 1, 2, 3, 4, 9, 13, 15, 16, 17, 18, 20, 21, 22, 23, 25, 26, 27, 28, 30, 31, 32, 34, 37}. Looking to the evolution of each higher harmonic amplitude separately; one can underline the higher harmonic rank changes in the sliding window FFT going toward the SCD instant and point out the existence of a peak amplitude in each 1- minute interval associated to the fundamental harmonic for record 30 and to the third order higher harmonic for record 47.The amplitudes variations of the spectral lines along a 1-minute interval just before SCD are given in figures 13 and 14 for the patients 30 and 47 respectively. After SCD the 4 first ranked higher harmonics which are mainly the low order or constant Fourier transform components the (0, 1, 2, 3).

One minute before the SCD

The spectral analysis of the 1-minute interval preceding the SCD for both of the patients 30 and 47 leads For the patient 30: S1={0, 10, 20, 21, 30, 31}, S2={0, 10, 20, 21, 30, 31}, S3={0, 10, 11, 20, 21, 30, 31,32}, S4={0, 10,11, 20, 21, 30, 31,32,51,53}. During such minute of record 30, the main HH occupying the first ranks are besides the dc component, the HH 10 (1.22 Hz), 20 (2.44 Hz), 30 (3.66 Hz), this may be a spectral characterization of the patient 30 ECG in a normal situation preceding the SCD. For the patient 47, the 4 sets of predominant harmonics during the 1-minute interval foregoing the SCD are: S1={0, 3,4}, S2={0, 2, 3, 4, 11, 14}, S3={0, 1,2,3, 11, 15}, S4={0, 1, 2, 3, 5, 9, 11, 14, 15}. It is obvious to underline the fact that the lower order HH are already predominant, seemingly the HH which typify the normal state are shifted to higher ranks. Certain distortions of the ECG may affect the symmetry of the signal and leads to an important Fourier constant component. The largest higher harmonic exhibit peak amplitudes in both cases, in tables 1 and 2 are summarizing the main features of the 7-minutes intervals preceding SCD of patient 30 and patient 47 respectively.

Seven minutes interval prior to the SCD

The spectral behavior of a seven minutes interval preceding SCD is analyzed for the two patients 30 and 47. The orders of the higher harmonics occupying the first ranks of the sliding windows spectra are given in figures 15 and 16. Regarding the amplitudes, the most relevant harmonics are those in the low frequency range 0-1.22 Hz (figures 17 and 18), whereas those in the frequency range 1.22-12.2 Hz (figures 19 and 20) are least significant.

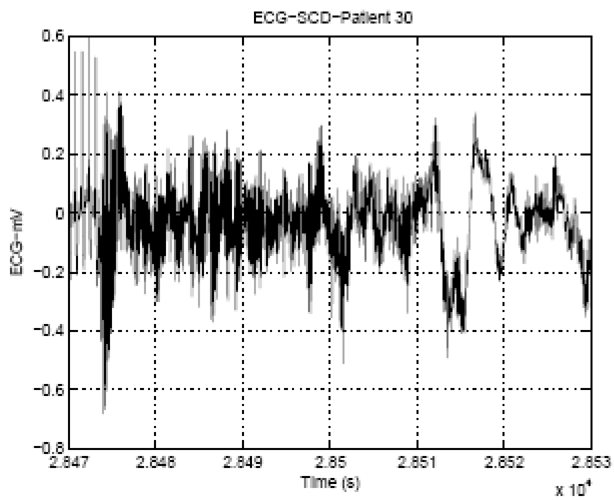

Fig. 3 ECG Waveform for Patient 30.

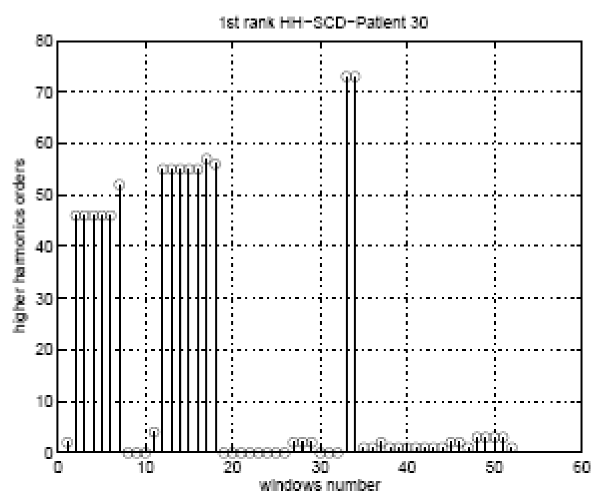

Fig. 4 HH in the first rank of the amplitude classification.

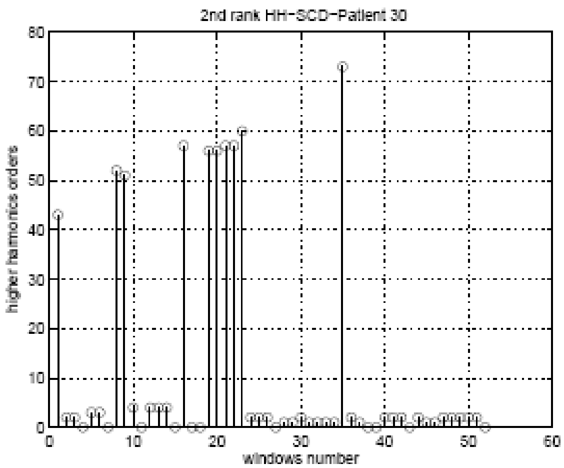

Fig. 5 HH in the second rank of the amplitude classification.

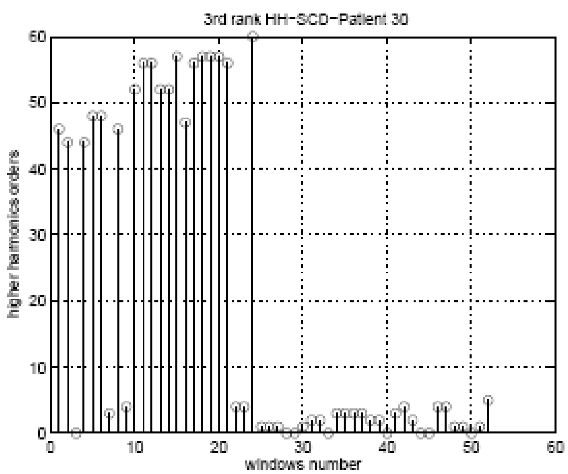

Fig. 6 HH in the third rank of the amplitude classification.

5. Discussion

The higher harmonic predominance is used in this study to characterize the ECGs dynamics of patient suffering from SCD. In [3] it was stated that patients at high risk of sudden cardiac death show evidence of nonlinear heart rate dynamics, including abrupt spectral changes and sustained low frequency (.01-.04 Hz) oscillations in heart rate rhythm. Approaching the SCD moment, the common phenomena observed in both records 30 and 47 is in the first hand, the higher harmonics laying in the low frequency range become progressively among the first ranks in the decreasing amplitude classification. In the second hand, the occurrence of peaks of HH amplitudes during the few minutes preceding the SCD. Therefore, Further information of primary interest emphasizing on the role of higher harmonics complement prediction tools focusing on amplitudes to contribute to design new SCD predictors.

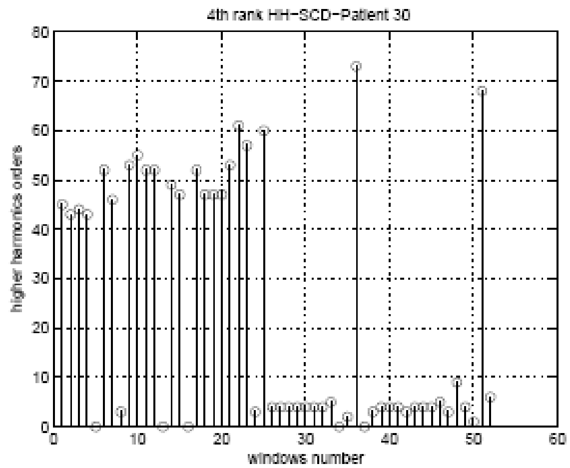

Fig. 7 HH in the fourth rank of the amplitude classification.

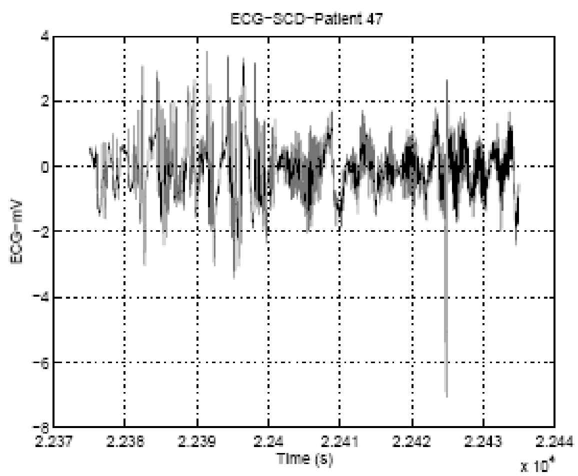

Fig. 8 1-minute ECG waveform for Patient 47.

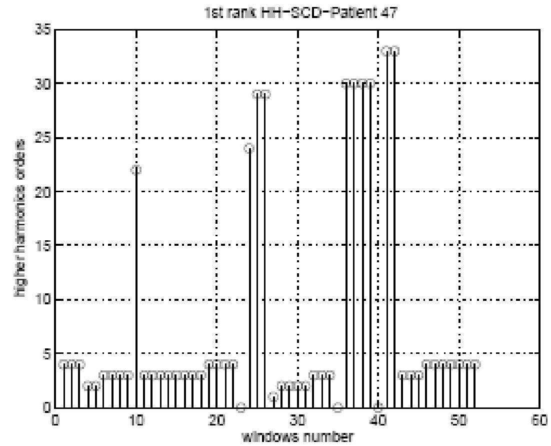

Fig. 9 HH in the first rank of the amplitude classification.

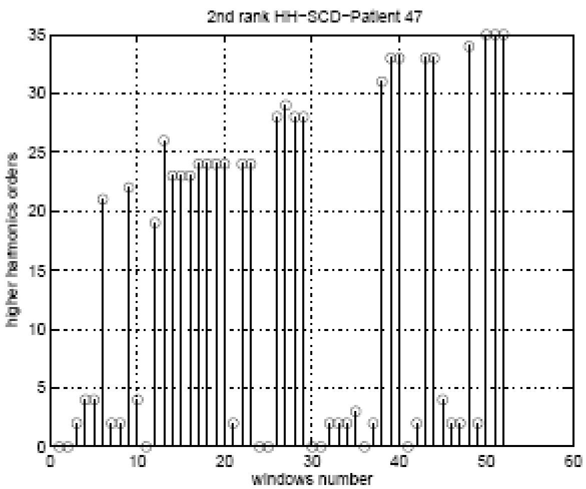

Fig. 10 HH in the first rank of the amplitude classification.

In tables 1 and 2 are given the peak amplitudes over a 1-minute interval and the mode harmonic value which is the harmonic that is frequently in the first rank.

Table 1: Largest HH in ECG Spectra: Patient 30.

Time	Largest HH in 1st rank	Peaks	Mode
SCD	0 1 2 3 4 46 52 55 56 57 73	1	0 1
-1mn	0 10 20 21 30 31	21 10	20 10
-2mn	0 1 20 21 29 30 31	0	0 20
-3mn	0 1 2 4 26	0	0
-4mn	0 1	0	1 0
-5mn	0 1 9 13 14 18	0	13 0
-6mn	0 9 13 14 27	0	0 13
-7mn	0 13 14	0	0 14

Table 2: Largest HH in ECG Spectra: Patient 47.

Time	Largest HH in 1st rank	Peaks	Mode
SCD	0 1 2 3 4 22 24 29 30 37	1	3 4
-1mn	0 3 4	3 4	4
-2mn	0 1 3 4	0 1	4 0 4
-3mn	0 2 3 4 7 11 13 15	11 15	0 4
-4mn	0 1 2 4 5 6 7 8	1 2	0 1
-5mn	0 1 2 3 4 5 6 7	0	0
-6mn	0 1 2 3 4 6 7	1	0 1
-7mn	0 1 3 4 6 7	0	0

The dc Fourier constant is omnipresent among the four largest amplitudes of the descending order classification, besides many peaks correspond to such dc component in the case of patient 30. Focusing on the 1-minute intervals just before the SCD one can observe certain similarities between the two studied cases. The Higher harmonics in first ranks (0, 3, 4) for record 47 and (0 10, 20, 21, 30, 31) for record 30 have relatively closer higher amplitudes. The spectra of first intervals just before the SCD of patient 30 exhibit the abrupt occurrence of higher frequencies 46 52 55 56 57 (5.6 - 6.95 Hz). For the patient 47 the higher frequencies which appear mainly in the second rank (1-5 Hz), during the 7 minutes foregoing the SCD the spectra show the predominance of lower order higher harmonics (0.122-0.6 Hz).

The major changes may affect the amplitude, the ranks and the orders or frequencies of higher harmonic forming the spectra of ECG. The peak amplitudes which may coincide with premature ventricular contractions is the common features revealed from the spectra of 7-minute interval preceding SCD for both patients 30 and 47.Such peak amplitudes correspond mainly to the lower order higher harmonics.

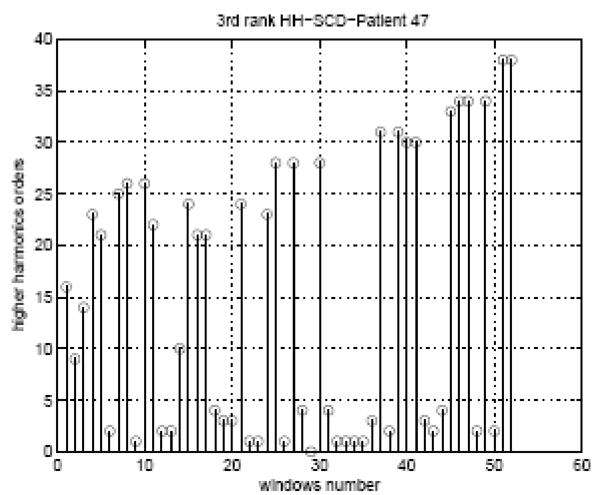

Fig. 11 HH in the first rank of the amplitude classification.

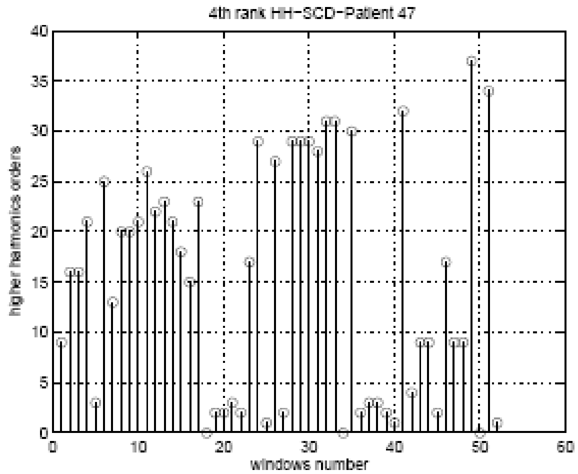

Fig. 12 HH in the fourth rank of the amplitude classification.

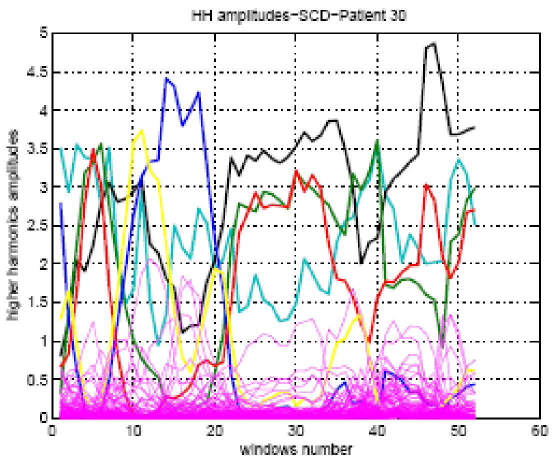

Fig. 13 HH amplitude variation along a 1-minute interval just before SCD (Patient 30).

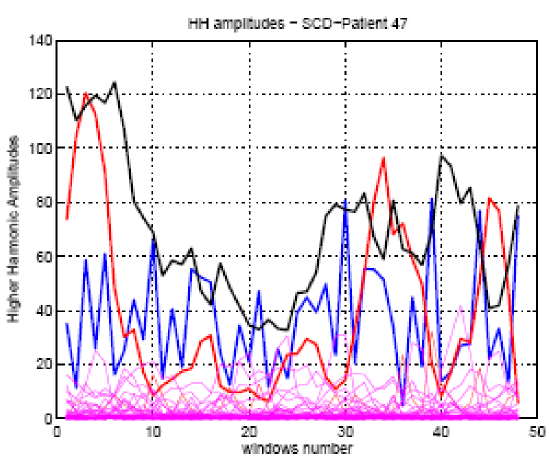

Fig. 14 HH amplitude variation along a 1-minute interval just before SCD (Patient 47).

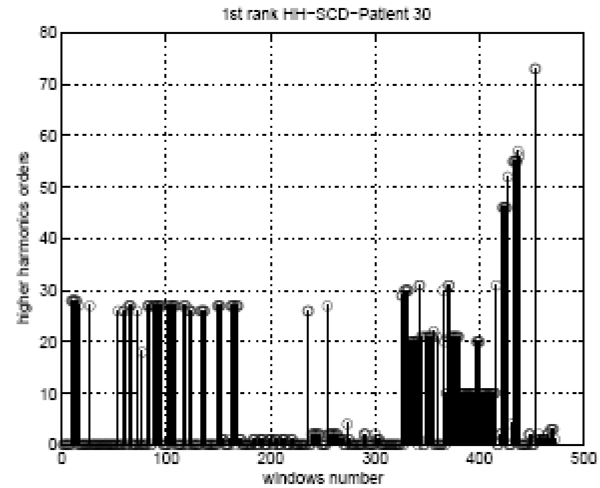

Fig. 15 HH in the first rank of the amplitude classification along a 7-minutes interval just before SCD (Patient 30).

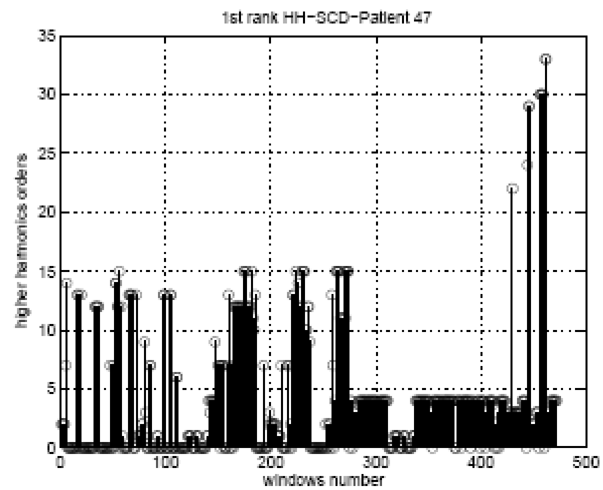

Fig. 16 HH in the first rank of the amplitude classification along a 7-minutes interval just before SCD (Patient 47).

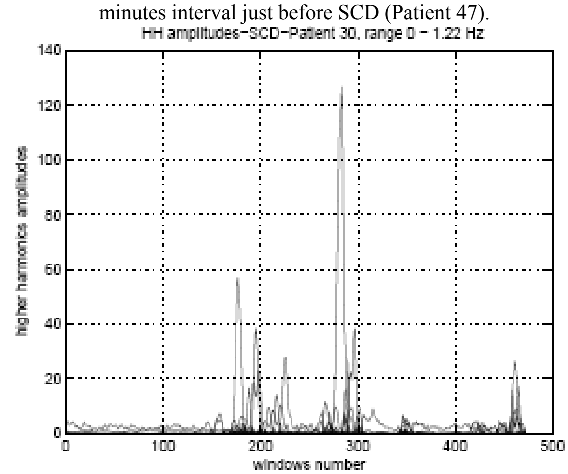

Fig. 17 Evolution of the lower order HH (0 – 1.22 Hz) during an interval of 7-minutes forgoing SCD (Patient 30).

IJCSI International Journal of Computer Science Issues, Vol. 9, Issue 1, No 2, January 2012
ISSN (Online): 1694-0814
www.IJCSI.org

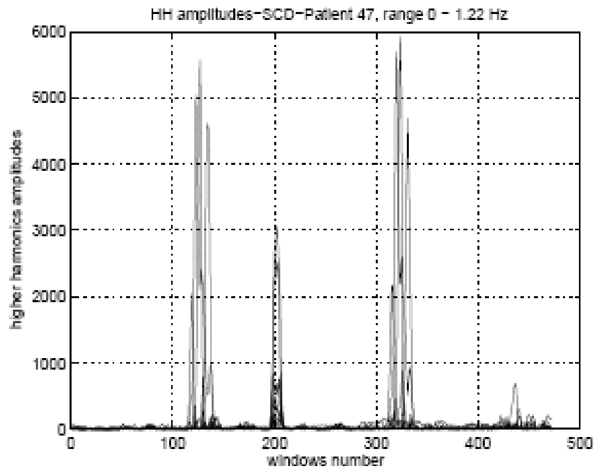

Fig. 18 Evolution of the lower order HH (0 – 1.22 Hz) during an interval of 7-minutes forgoing SCD (Patient 47).

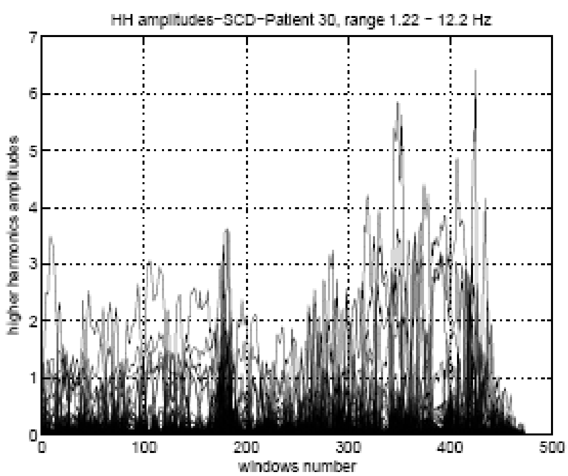

Fig. 19 Evolution of the higher order HH (0 – 1.22 Hz) during an interval of 7-minutes forgoing SCD (Patient 30).

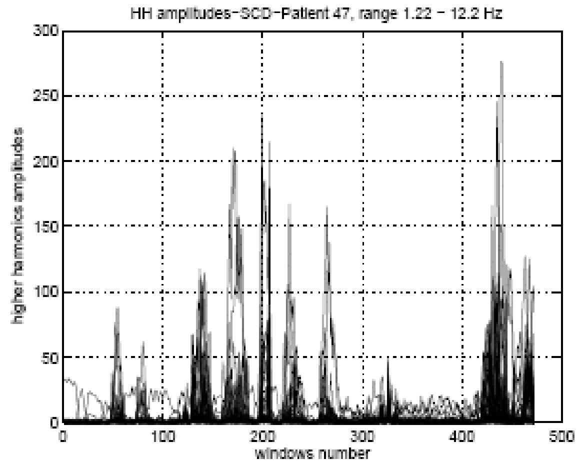

Fig. 20 Evolution of the lower order HH (0 – 1.22 Hz) during an interval of 7-minutes forgoing SCD (Patient 47).

6. Conclusion and future work

To the best of our knowledge, this study is the first to characterize the time preceding SCD through the higher harmonic interaction based on a descending order classification of their amplitudes. Spectral analysis of ECG signal of a patient who experienced SCD permits to put evidence into a complex spectral line reorganization that occurs before the SCD instant. Approaching the sudden cardiac death, the spectral composition of ECG signal undergoes quantitative changes which affect the amplitudes and the ranks of the spectral lines. The progressive occurrence of lower order harmonics and the peak amplitudes of harmonics from the same range in the few minutes preceding SCD, are common features observed for two different patients suffering from Sudden Cardiac Death. Further work might involve spectral analysis based on several human subjects with underlying Sudden Cardiac Death in order to broaden the scope of harmonic classification in descending order amplitudes to heart rate variability (HRV) regarding the R-R intervals.

Acknowledgments

We thank Physionet.org for providing sudden cardiac death ECG data.

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Hedi KHAMMARI, PhD. He was born in Kairouan, Tunisia in 1963. He received the engineer diploma and the Master degree from National Engineering School of Tunis in 1988 and 1990 respectively. He received PhD in Electrical Engineering in 1999. He is currently Associate Professor at Taif University, Saudi Arabia. His research interests are mainly in the area of nonlinear dynamics and the application of chaos theory in different fields namely communication, electric systems and bioinformatics.