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Heart Rate Variability–A Bibliographical Survey

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The study of heart rate variability (HRV) provides a mean for observing the heart's ability to respond to normal regulatory signals that affect its rhythm. The HRV analysis has proven useful in diagnosis, treatment and monitoring of various pathologies. The modern field of HRV processing is extremely diverse, involving many areas like spectral estimation, system modeling, nonlinear dynamics and chaotic analysis, etc. With the recognition of significant relationship between the autonomic nervous system and cardiovascular mortality, efforts for development of autonomic activity have led to the use of HRV as one of the most promising markers. Thus, there is an urgent need to keep a track of advancements and activities taking place in this emerging field. This paper gives a bibliographical survey and general backgrounds of research and development in the field of HRV based on over 83 published articles. The collected literature has been divided into many sections so that new researchers do not face any difficulty for obtaining literature in this field.

Indexing terms: Autonomic nervous system, Cardiovascular control, Heart rate variability, RR interval, Biomedical signal processing.

1. INTRODUCTION

BEAT-TO-BEAT fluctuations of cardiac rhythm, referred to as heart rate variability (HRV) provides a noninvasive tool to monitor the autonomic control on the heart both in normal and pathological subjects in understanding cardiovascular regulation in a range of conditions, including heart failure, diabetes, and hypertension. Pharmacological tests have established that the high frequency and low frequency components of HRV signal are modulated by parasympathetic and, combined sympathetic and parasympathetic branches of autonomic nervous system respectively [1-4].

As early as 1973, Sayers and others focused attention on the existence of inherent rhythms embedded in beat-to-beat heart-rate (HR) and blood-pressure (BP) signals [5]. In 1977, Rompelman *et al* [6] discussed the use of HRV in clinical applications and the neural cardiovascular research; and evaluated four different signals for describing HRV. In 1980, Rompelman *et al* [7] analyzed HRV in relation to psychological factors and McDonald [8,ch-1] considered the mechanisms affecting the heart-rate. In 1985, DeBoer *et al* [9] presented a survey of techniques, which transform HRV data into a signal that is both visually informative and accessible for analysis. In 1986, Pagani *et al* [10] established power spectrum of heart and arterial pressure variabilities as a marker of sympathovagal interaction in man and conscious dog.

In 1989, Malik *et al* [11] proposed the automated filtering of long-term ECG data for HRV analysis. In January 1990, Merri *et al* [12] quantified the error introduced into the RR-interval measurement by too low-sampled ECG and minimum sampling rate of 250 Hz has been recomended [1]. In April 2001, Malpas *et al* [13] studied the role played by the sympathetic nervous system in regulating blood pressure variability (BPV). In 2002, Malpas [14] reviewed the fundamental origin of variability associated with respiration and a slow oscillation at 0.1 Hz in the human. In March 2003, Mateo and Laguna [15] described the power spectral density (PSD) estimation of the HRV by means of heart timing signal in the presence of ectopic beats.

2. METHODOLOGIES AND ANALYSIS

Recent progress in technology has offered new tools for a more selective identification of specific variability components and increasing application of

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these methods in a clinical setting has provided the demonstration of diagnostic and prognostic relevance of several parameters derived from analysis of blood pressure and heart rate dynamics [16].

In 1980, Sayers [7, ch-3] described the nature of the heart-rate signal, through the analysis of both its long-term and its short-term properties. At the same time, Kitney [7, ch-5] described the thermoregulatory influence on HRV reflected in very low frequency band. In July 1981, Akselrod *et al* [17] reported that HRV power spectrum reflect beat-to-beat cardiovascular control. In 1984, DeBoer *et al* [18] evaluated the interval spectrum and spectrum of counts and established their equivalence. In September 1986, Berger *et al* [19] gave an improved algorithm for the derivation of a heart rate signal from the ECG. In 1986, Baselli *et al* [20] analyzed the parametric methods for HRV quantification. In February 1989, Shin *et al* [21] explored the HRV by using complex demodulation.

In 1990, Parati and others [22] demonstrated that BP and pulse interval oscillations of 0.025-0.35 Hz occur in ambulatory subjects. In February 1993, Bianchi and colleagues [23] described time-variant power spectrum analysis for the detection of transient episodes in HRV signal. In March 1993, Novak and Novak [24] assessed Wigner distribution for the analysis of blood pressure, respiratory, and beat-to-beat fluctuations. In 1993, Kamath and Fallen [25] presented a detailed literature review on methodological issues relevant to signal processing, computational and clinical applications of power spectrum analysis of HRV. In 1995, Parati *et al* [26] presented a critical appraisal of the commonly used spectral analysis techniques. They also provided the insight into the problems that still affect the physiological and clinical interpretations of the data provided by spectral analysis of BP and HRV. In 1996, Pola and others [27] assessed the role of time-frequency representations in the estimation of PSD in non-stationary cardiovascular time series. At the same time Keselbrener and Akselrod [28] applied the selective discrete Fourier transform for time-frequency distribution.

In 1997, Karemaker [29] highlighted the theoretical considerations in BP and HRV analysis and described the usefulness of frequency-domain analysis of HRV for patho-physiologic research into cardiovascular regulation. In the same year, Wiklund and colleagues [30,31] characterized the HRV signal using wavelet transform. In June 1998, Laguna *et al* [32] studied the frequency behavior of a least-square method to estimate the PSD of unevenly sampled signals. In April 2001, DiReinzo *et al* [33] examined the advancements in estimating the baroreflex function and Head *et al* [34] provided a comparison of modern and traditional techniques for the evaluation of arterial baroreflex. In November 2001, Brennan *et al* [35] gave a detailed analysis of Poincaré plot geometry as applied to HRV. Kallio *et al* in 2002 [36] gave systematic comparison of time domain, frequency domain, non-linear, geometrical and statistical analyses of HRV for revealing HRV differences between untreated patients with Parkinson's disease and healthy controls. In 2002, Monti *et al* [37] proposed that smoothed pseudo Wigner-Ville distrbution and complex demodulation method together provide a reliable algorithm to assess instantaneous spectral parameters in non-stationary cardiovascular time series. Boardman *et al* [38] studied the optimum order selection of autoregressive models for HRV recommended that the order should not be less than 16.

In 2000, Attapattu and Mitrani [39] suggested a telemedicine application to remotely track the heart rate variability of patients in a clinical research environment. In December 2002, Virone *et al* [40] suggested a system for the automatic measurement of the circadian activity deviations in telemedicine in order to ensure the security and quality of life for patients who need home based medical monitoring. In 2004, Singh *et al* [41,42] suggested an RR-interval sampling frequency of 4 Hz with segment length of 256 samples and 50% overlapping provides a smoothed spectral estimate with clearly outlined peaks in low- and high-frequency bands. Further, in 2005 Singh *et al* [43] devised an improved windowing technique for HRV spectral estimation. In May 2007, Brittain *et al* [44], proposed a single-trial coherence analysis method. For mobile applications, in August 2007, Salahuddin *et al* [45] performed the HRV analysis on short term ECG measurement. As for mobile applications, short term ECG measurement may be used for HRV analysis since the conventional five minute long recordings might be inadequately long. This performance of this method is reliably good for monitoring mental stress in mobile settings. In August 2007, Shafqat *et al* [46] performed the analysis of two different algorithms of detrending the RR-interval before HRV analysis. The first algorithm is based on the Smoothness Prior Approach (SPA) and the second algorithm is implemented using Wavelet Packet (WP) analysis. The WP method provided more attenuation of the slow varying trend and was able to preserve the other signal components better than the SPA method. Also, the SPA method was computationally slower and it might be not appropriate with long signals. In September 2007, Ding *et al* [47] proposed a method for the analysis nonstationary heart rate dynamics based on three processes: (*i*) a recurrence quantification analysis (RQA) to quantify the dynamic patterns, (*ii*) the use of mutual information and the entropy to characterize the variation of non-linear dynamic pattern, and (*iii*) linear discriminant analysis to exploit the associations within MI and EN measures. Mathematically, it overcomes the nonstationary interference on the quantification of nonlinear properties in heart rate dynamic series as compared to the RQA analysis method. In October 2007, Kumar *et al* [48] proposed an HRV analysis method for mental stress assessment using fuzzy clustering and robust identification techniques. This approach exploited fuzzy clustering and fuzzy identification techniques to render robustness in HRV analysis against uncertainties due to individual variations. In January 2008, Chen and Mukkamala [49], derived new indexes for PNS and SNS by the autonomically mediated transfer functions relating fluctuations in instantaneous lung volume and fluctuations in arterial blood pressure so as to eliminate the input contributions to HR and then separate each estimated transfer function in the time domain into PNS and SNS indexes using physiological knowledge. These indexes were better than those provided by the traditional high-frequency (HF) power, LF-to-HF ratio, and normalized LF power of HR variability.

3. MODELING AND SIMULATION

Having access to realistic artificial modulated series of event times may facilitate evaluation of the new biomedical signal processing algorithms. This section deals with publications related to modeling and simulation of cardiovascular system.

Kitney and others [50] in 1985 described the application of computer modeling to the study of transient interactions in cardiorespiratory control. In 1987, DeBoer *et al* [51] developed a beat-to-beat model of cardiovascular system to study the short-term variability in arterial BP and HR data from humans at rest. In December 1988, Baselli *et al* [52] introduced a complex structure in order to have a closely related model to the physiological aspects. In 1994, TenVoorde *et al* [53] analyzed the influence of pulse-frequency modulation on the spectral estimation of the pulse amplitude modulation process in IPFM model for cardiac pacemaker. In 1997, Yang and Liao [54] built a simulated model of an HRV signal based on a wavelet transform. In August 2000, Mateo and Laguna [55] introduced the heart timing signal and demonstrated improved HRV analysis according to the IPFM model. In September 2000, Stanley *et al* [56] presented a physiologically inspired stochastic model describing HRV. In April 2001, Barbieri *et al* [57] proposed a mathematical model for the closed-loop assessment of arterial baroreflex function and Chiu and Kau [58] illustrated a mathematical model for autonomic control of HRV. In July 2003, Leor-Librach and colleagues [59] developed a computerized system for the controlled increase of HR, with which several level of stabilized HR can be gradually obtained. In June 2003, Pyetan and Akselrod [60] presented IPFM approach to sino-atrial node physiology in order to obtain a close set of equations for mean heart rate and respiratory sinus arrhythmia.

In Jan 2008, McNames, and Aboy [61], proposed a state-space model of cardiovascular signals such as arterial blood pressure, pulse oximetry and intracranial pressure that can be used with the generalizations of the Kalman filter to decompose cardiovascular signals into clinically meaningful components. In Jan 2008, Lewicke *et al* [62], proposed a model to incorporate reliability in the classification model in its design and training in order to improve classification performance using learning vector quantization neural network, multilayer perceptron neural network, and support vector machines as the classifiers. In Jan 2008, Tiinanen *et al* [63], proposed an adaptive LMS-based filter for removing the respiration effect from the baroreflex sensitivity (BRS) estimates. This adaptive filter reduces the distorting effect of respiration on BRS values, which enables more accurate estimation of BRS as compare to the simple and widely applied open-loop models and hence the usage of spontaneous breathing as a measurement protocol.

4. STANDARD GUIDELINES

In 1996, the Task Force of the ESC/NASPE published guidelines in HRV analysis proposing several time and frequency domain parameters [1]. It covers measurement of HRV; technical requirements for recording and analysis; physiologic correlates of HRV; clinical use of HRV and future possibilities. A review of physiological origins and mechanisms can be found in Committee Report [3]. In 2000, Lombardi *et al* [64] discussed several unrecognized technical and methodological problems in relation to HRV analysis.

5. BLOOD PRESSURE AND HRV

The cross-spectral analysis of BPV and HRV signals could contribute in the description of (*i*) power interchanged between the signals, (*ii*) the delay by which the rhythm propagate and (*iii*) the role of respiration [20].

In July 1985, DeBoer *et al* [65] discussed the relationships between short-term blood pressure fluctuations and HRV in resting subjects by spectral analysis approach. In 1989, DiRienzo *et al* [66] developed a procedure for the 24-h HRV and BPV tracking in ambulant subjects. Censi and others [67] in 2000 investigated the intermittent Phase Locking phenomena between respiration, HR and BP variability signals during cardiorespiratory synchronization experiments, using the following time-domain techniques: Poincare maps, recurrence plots, time-space separation plots and frequency tracking locus.

In 2002, Baumert *et al* [68] presented a study of joint symbolic dynamics as a new short-term non-linear analysis method to investigate the interactions between HR and systolic blood pressure.

6. INSIGHTS FROM HRV

Heart rate variability assessment has become a widely used technique for noninvasive study of sympatho-vagal modulation of heart rate in a broad spectrum of cardiovascular disorders. To date, clinical studies in this area are limited both in number as well as in sample size and thus, only suggestions on potential clinical utility can be made [1].

In April 1986, Myers *et al* [69] proved the efficacy of HRV analysis by PSD in categorizing cardiac patients according to risk of sudden cardiac death. In 1989, Malik and others [11] described the prognostic value of HRV after myocardial infarction. In May 1990, Bianchi *et al* [70] proposed new indices for the assessment of sympathovagal balance in diabetic subjects with or without neuropathy. In 1991, Freeman and others [71] supported the role of HRV as a clinical test of autonomic function in patients with known or suspected autonomic failure, which is a frequent complication of diabetes. In 1995, Malik and Camm [72] compiled an exhaustive treatment on clinical implications and use of HRV. In 1999, Hilton and colleagues [73] evaluated HRV as a diagnostic marker of the sleep apnea syndrome. In the same year, Huikuri *et al* [74] provided a critical review of the prospective reasons for increased mortality in abnormal HRV, appraisal of traditional and new methods of measuring HRV and future directions of HRV research and Stein *et al* [4] and Lombardi [75] gave a detailed review on the clinical insights from the study of heart rate variability.

In 2002, Boardman *et al* [76] developed a technique for detecting asphyxia based on monitoring the ECG and estimating the HRV and Schumann *et al* [77] reviewed the potential of feature selection methods in HRV for the classification of different cardiovascular diseases. Recently, reduced HRV is also reported in HIV-seropositive individuals in early stages of infection as well without any clinical evidence of autonomic dysfunction [78]. In 2006, Singh *et al* [79] established that as age increases, HRV diminishes, central frequencies of HRV bands shift and baroreflex sensitivity increases.

7. RECENT TRENDS IN HRV

In 2006, Singh and Vinod [80] explored the HRV dynamics under autonomic test battery using time-scale analysis. In 2007, Chan *et al* [81] studied the sympathovagal balance during supine, sitting, standing and walking postures. The use of Poincar'e plot in HRV assessment has been coming up as an alternative tool [82]. Further, Porta *et al* [83] analyzed the changes in complexity and nonlinearity for short-term HRV.

8. CONCLUSION

Heart rate variability has become in the last 30 years one of the most challenging topics in physiological signal analysis. During this period, more than 7,000 papers on different aspects of HRV are included in Medline covering various aspects of HRV. This paper is an effort for an overview of HRV concept, with a bibliographic survey of relevant background, practical requirements, the present state, and techniques. The citations listed in this bibliography provide a representative sample of current thinking pertaining to heart rate variability. Periodic bibliographic updates on this topic will be useful as the research continue to evolve. Despite the intensive research efforts, clinical use of HRV analysis is still limited. This is largely due to the general complexity of the human physiology, which is reflected in the signals. This complexity gives rise to large inter-subject variability and disposes the signal to the measurement artifacts and noise due to physiological activities. Hence, no consensus or clear definitions for the analysis methods have been found and Guidelines of the Task Force of ESC & NASPE [1] is just a step in this direction. However the current clinical applications are limited in use and the task of finding simple but effective parameters is yet to be accomplished.

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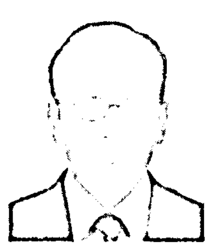
AUTHORS



Dilbag Singh was born in Adyana (Panipat), on February 26, 1969. He received the BE (Hons.) degree in Electrical Engineering from Punjab Engineering College, Chandigarh, and ME degree in Control & Guidance from the University of Roorkee, and the PhD degree in Engineering from the Indian Institute of Technology Roorkee in 1991, 1993, and 2004 respectively. The PhD degree thesis was developed at the Instrumentation & Signal Processing Laboratory of the Electrical Engineering Department under the direction of Vinod Kumar, S C Saxena and K K Deepak (AIIMS).

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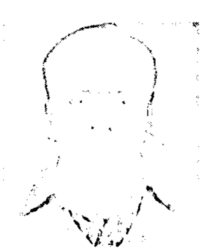

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