

Ahsan Habib Khandoker
Chandan Karmakar
Michael Brennan
Andreas Voss
Marimuthu Palaniswami

Poincaré Plot Methods for Heart Rate Variability Analysis

Poincaré Plot Methods for Heart Rate Variability Analysis

Ahsan Habib Khandoker • Chandan Karmakar
Michael Brennan • Andreas Voss
Marimuthu Palaniswami

Poincaré Plot Methods for Heart Rate Variability Analysis

 Springer

Ahsan Habib Khandoker
Department of Biomedical Engineering
Khalifa University, Abu Dhabi, UAE
Department of Electrical and Electronic
Engineering
The University of Melbourne, VIC, Australia

Michael Brennan
Electrical and Electronic Engineering
The University of Melbourne
Melbourne, VIC, Australia

Marimuthu Palaniswami
Electrical and Electronic Engineering
The University of Melbourne
Melbourne, VIC, Australia

Chandan Karmakar
Electrical and Electronic Engineering
The University of Melbourne
Melbourne, VIC, Australia

Andreas Voss
Department of Medical Engineering
and Biotechnology
University of Applied Sciences Jena
Jena, Germany

ISBN 978-1-4614-7374-9

ISBN 978-1-4614-7375-6 (eBook)

DOI 10.1007/978-1-4614-7375-6

Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2013939585

© Springer Science+Business Media New York 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

*Dedicated to students and researchers
of biomedical engineering.*

Preface

Heart rate variability is the study of autonomic nervous activity through the information provided by fluctuations in heart rate. Autonomic activity is responsible for regulating heart rate. By studying the beat-to-beat variability in the intervals between heartbeats, it is possible to form a representation of autonomic nervous activity. Alterations in this activity can thus be quantitatively measured with a non-invasive technique. Accordingly, heart rate variability has become a very active field of research and the most popular biological signal by which the autonomic nervous system is studied. Heart rate variability can measure the individual levels of parasympathetic and sympathetic modulation of heart rate, and from this information one can make predictions on the state of the autonomic nervous system. Moreover, a deeper exploration of the physiological basis of the autonomic nervous system can be investigated.

The study of the autonomic nervous system from the information contained in heart rate relies upon mathematical models and techniques and the power of digital computers to achieve reliable and accurate results. In the past only simplistic mathematical techniques have been brought to bear due to the limited ability of clinical investigators in this regard. Recently, mathematicians, physicists and engineers have worked alongside cardiologists and physiologists to develop sophisticated models and mathematical techniques for the analysis of heart rate data. The development of more accurate models of heart rate variability and robust analysis techniques that are immune to the large levels of noise and artefact found in all biological signals is an active field of research currently. Advances in this area have direct benefits to clinical and physiological studies that employ heart rate variability to study disease and physiology.

Many of the mathematical techniques are only approximations and have defects that are not obvious except when analysed carefully with a mathematical formulation. Mathematical analysis allows one to investigate the limitations of analysis techniques. Further, the full potential of the analysis techniques is often only revealed by a full mathematical treatment. The theoretical study of models of the autonomic system has similar characteristics, with the limitations and full descriptive power of a model being largely unknown until studied mathematically.

The study of models also allows the development of optimal analysis techniques. Many of the mathematical algorithms and models applied in HRV analysis remain uninvestigated. The problem is, how do we quantitatively characterize (linear and/or nonlinear) the heart rate time series to capture useful summary descriptions that are independent of existing HRV measures? Recent research on HRV has proven that Poincaré plot analysis (PPA) is a powerful tool to mark short-term and long-term HRV. Researchers have investigated a number of techniques: converting the two-dimensional plot into various one-dimensional views; the fitting of an ellipse to the plot shape; and measuring the correlation coefficient of the plot. In fact, they are all measuring linear aspects of the intervals which existing HRV indices already specify. The fact that these methods appear insensitive to the nonlinear characteristics of the intervals is an important finding because the Poincaré plot is primarily a nonlinear technique. This result motivates the search for better methods for Poincaré plot quantification. This provides the motivation for this book.

Chapter 1 gives an overview of the physiological concepts and necessary background in the field of heart rate variability, including the history, physiology, analysis techniques and the clinical significance of the field. This includes models of heart rate variability and the mathematical signals employed to characterize heart rate variability. Details of the time-domain and frequency-domain analysis of these signals are also covered.

Chapter 2 provides a mathematical analysis of a common heart rate variability technique known as the Poincaré plot. The Poincaré plot is an emerging analysis technique that takes a sequence of intervals between heartbeats and plots each interval against the following interval. The geometry of this plot has been shown to distinguish between healthy and unhealthy subjects in clinical settings by employing trained specialists to visually classify the plots. The Poincaré plot is a valuable HRV analysis technique due to its ability to display nonlinear aspects of the interval sequence. In particular we investigate the question of whether existing measures of Poincaré plot geometry reflect nonlinear features of heart rate variability. We show that methods of Poincaré quantification that summarize the geometrical distribution of the points with “moment-like” calculations, i.e. means and standard deviations, etc., are unlikely to be independent of existing linear measures of heart rate variability.

Chapter 3 of the book investigates Poincaré plot interpretation using a new oscillator model of heart rate variability. This chapter develops a physiologically plausible mathematical model of autonomic nervous control of heart rate based on a series of well-studied oscillations in heart rate. By employing the results described, the time series of intervals between heartbeats are able to be analytically determined. The properties of the Poincaré plot can then be derived. By analysing the Poincaré plot in terms of an underlying model of HRV, the theoretical basis of Poincaré plot morphology can be precisely related back to the model and therefore back to the physiological causes. This provides a deeper understanding of the Poincaré plot than has previously been possible. To validate the model, simulations of various autonomic conditions are compared to HRV data obtained from subjects under the prescribed conditions. For a variety of autonomic balances, the model generates

Poincaré plots that undergo morphological alterations strongly resembling those of actual heartbeat intervals.

Poincaré plot is valuable due to its ability to display nonlinear aspects of the data sequence. However, the problem lies in capturing temporal information of the plot quantitatively. The standard descriptors used in quantifying the Poincaré plot ($SD1$, $SD2$) measure the gross variability of the time series data. Determination of advanced methods for capturing temporal properties poses a significant challenge. Chapter 4 proposes a novel descriptor “Complex Correlation Measure (CCM)” to quantify the temporal aspect of the Poincaré plot. In contrast to $SD1$ and $SD2$, the CCM incorporates point-to-point variation of the signal.

The asymmetry in heart rate variability is a visibly obvious phenomenon in the Poincaré plot of normal sinus rhythm. It shows the unevenness in the distribution of points above and below the line of identity, which indicates instantaneous changes in the beat-to-beat heart rate. The major limitation of the existing asymmetry definition is that it considers only the instantaneous changes in the beat-to-beat heart rate rather than the pattern (increase/decrease). Chapter 5 describes a novel definition of asymmetry considering the geometry of a 2D Poincaré plot. Based on the proposed definition, traditional asymmetry indices—Guzik’s index (GI), Porta’s index (PI) and Ehlers’ index (EI)—have been redefined.

Chapter 6 of the book considers the segmented aspects of Poincaré plot remaining, on the one hand, the nonlinear properties of the system and, on the other hand, providing high resolution information about the time course and time correlations within a heart rate time series. These new approaches were successfully introduced in risk stratification.

This book should be of considerable help to researchers, professionals in medical device industries, academics and graduate students from a wide range of disciplines. The text provides a comprehensive account of recent research in this emerging field and we anticipate that the concepts presented here will generate further research in this field.

Melbourne, VIC, Australia
 Melbourne, VIC, Australia
 Melbourne, VIC, Australia
 Jena, Germany
 Melbourne, VIC, Australia

Ahsan Habib Khandoker
 Chandan Karmakar
 Michael Brennan
 Andreas Voss
 Marimuthu Palaniswami

Acknowledgements

The authors would like to gratefully acknowledge the contribution of Michael Brennan in Chaps. 2 and 3. The authors would also like to thank Claudia Fischer and Rico Schroeder of University of Applied Sciences Jena for their contributions in Chap. 6. The authors wish to gratefully acknowledge the financial support provided by the Australian Research Council and the Deutsche Forschungsgemeinschaft (DFG: Vo 505/8-1 and Vo 505/8-2) for the research presented in Chaps. 3–6, respectively.

Contents

1	Introduction	1
1.1	Heart Rate Variability Techniques in Cardiology	1
1.1.1	The RR Intervals	2
1.2	History of Heart Rate Variability	3
1.3	Physiological Basis of HRV Analysis	5
1.4	Analysis Methods	8
1.4.1	Time Domain	8
1.4.2	Frequency Domain	10
1.4.3	Nonlinear Dynamics	11
2	Quantitative Poincaré Plot	13
2.1	Introduction	13
2.2	Visualization of HRV Using Poincaré Plot	14
2.3	Quantification of Poincaré Plot of RR Interval	15
2.3.1	Ellipse-Fitting Technique	17
2.3.2	Histogram Techniques	21
2.4	Relationship Between Poincaré Shape and Linear HRV Measure	22
2.5	Conclusion	23
3	Poincaré Plot Interpretation of HRV Using Physiological Model	25
3.1	Introduction	25
3.2	Autonomous Nervous System and HRV Analysis	26
3.3	Physiological HRV Model	27
3.3.1	Sympathetic Oscillator	27
3.3.2	Parasympathetic Respiratory Oscillator	28
3.3.3	Sinus Oscillator	28
3.4	Mathematical Analysis of HRV Model Using Poincaré Plot	30
3.4.1	Length of Poincaré Plot Main Cloud	32
3.4.2	Width of the Poincaré Plot Main Cloud	35
3.4.3	Poincaré Plot Morphological Properties for the HRV Model	37

3.5	Simulation Results in Clinical Examples	38
3.5.1	Complete Autonomic Blockade	38
3.5.2	Unopposed Sympathetic Activity–Parasympathetic Blockade	38
3.5.3	Sympathetic-Parasympathetic Balance	41
3.5.4	Data Set Acquisition	42
3.5.5	Data Set Analysis	43
3.5.6	Poincaré Plot Morphology for Real Data	45
3.6	Conclusion	45
4	Poincaré Plot in Capturing Nonlinear Temporal Dynamics of HRV	47
4.1	Introduction	47
4.2	Nonlinear Dynamics	48
4.3	Limitation of Standard Descriptors of Poincaré Plot	48
4.4	Complex Correlation Measures in Poincaré Plot: A Novel Nonlinear Descriptor	50
4.5	Mathematical Analysis of <i>CCM</i>	53
4.5.1	Sensitivity Analysis	53
4.6	Physiological Relevance of <i>CCM</i> with Cardiovascular System	57
4.6.1	Subjects and Study Design	57
4.6.2	Results	58
4.6.3	Physiological Relevance of <i>CCM</i>	60
4.7	Clinical Case Studies Using <i>CCM</i> of Poincaré Plot	62
4.7.1	HRV Studies of Arrhythmia and Normal Sinus Rhythm	62
4.7.2	HRV Studies of Congestive Heart Failure and Normal Sinus Rhythm	63
4.8	Critical Remarks on <i>CCM</i>	65
4.9	Conclusion	68
5	Heart Rate Asymmetry Analysis Using Poincaré Plot	69
5.1	Introduction	69
5.2	Existing Indices of HRA	70
5.2.1	Guzik’s Index	71
5.2.2	Porta’s Index	71
5.2.3	Ehlers’ Index	72
5.3	New Definition of Asymmetry in RR Interval Time Series	73
5.4	Modified HRA Indices Using Poincaré Plot	75
5.4.1	Guzik’s Index (GI_p)	76
5.4.2	Porta’s Index (PI_p)	77
5.4.3	Ehlers’ Index (EI_p)	77
5.5	Application of HRA in Clinical Research	77
5.5.1	Presence of HRA in Healthy Subjects	77
5.5.2	Correlation Between HRA and Parasympathetic Activity	83
5.6	Conclusion	91

6 Segmented Poincaré Plot Analysis and Lagged Segmented Poincaré Plot Analysis	93
6.1 Introduction	93
6.2 Segmented Poincaré Plot Analysis	95
6.2.1 SPPA Method	95
6.2.2 Applying SPPA on Simulated BBI Time Series	96
6.2.3 The Ability of SPPA to Obtain Nonlinear Behaviour in Time Series When Applying Surrogate Data Analysis	101
6.2.4 Application of SPPA for Risk Stratification in Dilated Cardiomyopathy Patients	103
6.2.5 Investigating the Influence of Rectangle Size	106
6.2.6 Investigating Age Dependencies in Healthy Subjects	107
6.3 Application of SPPA to Blood Pressure Signals	110
6.3.1 SPPA Adaptation to Blood Pressure (BP)	110
6.3.2 Application to Hypertensive Pregnancy Disorders	113
6.4 Lagged Segmented Poincaré Plot Analysis	115
6.4.1 Method	115
6.4.2 Application of LSPPA to Determine Risk Stratification in Patients Suffering from Dilated Cardiomyopathy	117
6.4.3 LSPPA in Comparison to Traditional Time and Frequency Domain Analysis	119
6.5 Perspective	122
6.5.1 Application of SPPA and LSPPA to Respiratory Signals	122
6.5.2 Application of SPPA to Two-Dimensional Analysis of Signal Couplings (2D SPPA)	123
6.5.3 Application of SPPA to Three-Dimensional Analysis of Signal Couplings (3D SPPA)	126
6.6 Conclusions	128
References	131
Index	143