Phonocardiography Signal Processing

Synthesis Lectures on Biomedical Engineering

Editor
John D. Enderle, ***University of Connecticut***

Phonocardiography Signal Processing
Abbas K. Abbas and Rasha Bassam
2009

Landmarking and Segmentation of 3D CT Images
Shantanu Banik, Rangaraj M. Rangayyan, and Graham S. Boag
2009

Introduction to Biomedical Engineering: Biomechanics and Bioelectricity - Volume II
Douglas A. Christensen
2009

Introduction to Biomedical Engineering: Biomechanics and Bioelectricity - Volume I
Douglas A. Christensen
2009

Basic Feedback Controls in Biomedicine
Charles S. Lessard
2008

Understanding Atrial Fibrillation: The Signal Processing Contribution, Volume II
Luca Mainardi, Leif Sörnmon, and Sergio Cerutti
2008

Understanding Atrial Fibrillation: The Signal Processing Contribution, Volume I
Luca Mainardi, Leif Sörnmon, and Sergio Cerutti
2008

Introductory Medical Imaging
A. A. Bharath
2008

Lung Sounds: An Advanced Signal Processing Perspective
Leontios J. Hadjileontiadis
2008

An Outline of Information Genetics
Gérard Battail
2008

Neural Interfacing: Forging the Human-Machine Connection
Thomas D. Coates, Jr.
2008

Quantitative Neurophysiology
Joseph V. Tranquillo
2008

Tremor: From Pathogenesis to Treatment
Giuliana Grimaldi and Mario Manto
2008

Introduction to Continuum Biomechanics
Kyriacos A. Athanasiou and Roman M. Natoli
2008

The Effects of Hypergravity and Microgravity on Biomedical Experiments
Thais Russomano, Gustavo Dalmarco, and Felipe Prehn Falcão
2008

A Biosystems Approach to Industrial Patient Monitoring and Diagnostic Devices
Gail Baura
2008

Multimodal Imaging in Neurology: Special Focus on MRI Applications and MEG
Hans-Peter Müller and Jan Kassubek
2007

Estimation of Cortical Connectivity in Humans: Advanced Signal Processing Techniques
Laura Astolfi and Fabio Babiloni
2007

Brain-Machine Interface Engineering
Justin C. Sanchez and José C. Principe
2007

Introduction to Statistics for Biomedical Engineers
Kristina M. Ropella
2007

Capstone Design Courses: Producing Industry-Ready Biomedical Engineers
Jay R. Goldberg
2007

BioNanotechnology
Elisabeth S. Papazoglou and Aravind Parthasarathy
2007

Bioinstrumentation
John D. Enderle
2006

Fundamentals of Respiratory Sounds and Analysis
Zahra Moussavi
2006

Advanced Probability Theory for Biomedical Engineers
John D. Enderle, David C. Farden, and Daniel J. Krause
2006

Intermediate Probability Theory for Biomedical Engineers
John D. Enderle, David C. Farden, and Daniel J. Krause
2006

Basic Probability Theory for Biomedical Engineers
John D. Enderle, David C. Farden, and Daniel J. Krause
2006

Sensory Organ Replacement and Repair
Gerald E. Miller
2006

Artificial Organs
Gerald E. Miller
2006

Signal Processing of Random Physiological Signals
Charles S. Lessard
2006

Image and Signal Processing for Networked E-Health Applications
Ilias G. Maglogiannis, Kostas Karpouzis, and Manolis Wallace
2006

Phonocardiography Signal Processing

Abbas K. Abbas and Rasha Bassam

ISBN: 978-3-031-00509-1 paperback
ISBN: 978-3-031-01637-0 ebook

DOI 10.1007/978-3-031-01637-0

A Publication in the Springer series
SYNTHESIS LECTURES ON BIOMEDICAL ENGINEERING

Lecture #31
Series Editor: John D. Enderle, University of Connecticut

Series ISSN
Synthesis Lectures on Biomedical Engineering
Print 1930-0328 Electronic 1930-0336

Phonocardiography Signal Processing

Abbas K. Abbas
RWTH Aachen University

Rasha Bassam
Aachen University of Applied Science

SYNTHESIS LECTURES ON BIOMEDICAL ENGINEERING #31

ABSTRACT

The auscultation method is an important diagnostic indicator for hemodynamic anomalies. Heart sound classification and analysis play an important role in the auscultative diagnosis. The term phonocardiography refers to the tracing technique of heart sounds and the recording of cardiac acoustics vibration by means of microphone-transducer. Therefore, understanding the nature and source of this signal is important to give us a tendency for developing a competent tool for further analysis and processing, in order to enhance and optimize cardiac clinical diagnostic approach. This book gives the reader an inclusive view of the main aspects in phonocardiography signal processing.

KEYWORDS

phonocardiography, auscultation technique, signal processing, signal filtering, heart sounds, stethoscope microphone, cardiac acoustic modeling, wavelets analysis, data classification, spectral estimation and analysis, PCG classification, phonocardiography calibration, intracardiac phonocardiography, cardiac acoustic imaging

To our great land, Mesopotamia,
To our great Iraq,
To our light in the darkness: our parents.

Contents

SYNTHESIS LECTURES ON BIOMEDICAL ENGINEERING iii

Contents xi

Preface xvii

List of Abbreviations xix

List of Symbols xxiii

1 Introduction to Phonocardiography Signal Processing 1

1.1 Introduction 1

1.2 Signal processing 2

1.2.1 Overview of signal processing 2

1.3 Application of signal processing in biomedical engineering 4

1.4 Cardiovascular physiology 4

1.5 Cardiac cycle 8

1.6 Cardiac pressure profile 9

1.7 Ventricular pressure-volume loops 10

1.8 Cardiac electrical conduction system 12

1.9 Physiology of the heart sound 13

1.10 Abnormal heart sound pattern 15

1.10.1 Heart sound as hemodynamic index 19

1.11 Auscultation technique 20

1.12 Summary 27

2 Phonocardiography Acoustics Measurement 29

2.1 Dynamics of phonocardiography 29

2.2 Vibratory PCG signal spectrum 34

2.3 Band-pass filter versus high-pass filter 37
2.3.1 Phonocardiography calibration 39
2.3.2 Investigation of normal cardiac cycle in multi-frequency band 39
2.3.3 High-frequency vibrations bands [500-1000 Hz and 1000-2000 Hz 45
2.3.4 Ultra-low frequency tracing (linear frequency band) 46
2.3.5 Medium-low frequency tracing [60-120 Hz] 46
2.3.6 Medium-high frequency band [120-240 Hz and 240-480 Hz] 46
2.3.7 The heart tones production mechanism 47
2.4 Stethoscope transducer modeling 48
2.4.1 Microphone transducer 48
2.4.2 Acoustic coupling 51
2.5 Summary 52

3 PCG Signal Processing Framework 53

3.1 Phonocardiography signal presentation 53
3.2 Denoising and signal filtering techniques 55
3.3 PCG signal presentation 55
3.4 Cardiac sound modeling and identification 56
3.4.1 S_1 cardiac sound modeling 57
3.4.2 S_2 cardiac sound modeling 58
3.4.3 Modeling abnormal heart sound S_3 and S_4 58
3.5 Model-based phonocardiography acoustic signal processing 61
3.6 Future perspectives 61
3.6.1 Pacemaker heart sound acoustic detection 62
3.6.2 Physiological monitoring of blood pressure with phonocardiography 63
3.6.3 Automated blood pressure-PCG based measurement 64
3.6.4 Transit times extraction and estimation 66
3.6.5 Hemodynamics and transit intervals modulation 66
3.7 Summary 66

4 Phonocardiography Wavelets Analysis 67

4.1 Wavelets 67
4.1.1 Historical perspective 67
4.2 Fourier analysis 68
4.2.1 Wavelets versus fourier analysis 70
4.2.2 Haar wavelet 71
4.2.3 Debauchies (Db) wavelet 73
4.2.4 Subband coding 76
4.3 Wavelets decomposition 77
4.3.1 Continuous Wavelet Transform 78
4.3.2 Discrete wavelet transform 79
4.4 Pattern detection based on adaptive wavelets analysis 79
4.5 Summary 83

5 Phonocardiography Spectral Analysis 85

5.1 PCG signal spectral analysis 85
5.1.1 Energy spectral density of deterministic signals 87
5.1.2 PCG spectral estimation 89
5.2 Nonparametric method for phonocardiography spectral estimation 90
5.2.1 Effect of signal sampling 92
5.2.2 Windowing, periodic extension, and extrapolation 92
5.2.3 Periodogram method 94
5.2.4 Modified periodogram method 95
5.3 Parametric method for phonocardiography spectral estimation 97
5.3.1 PCG ARMA spectral estimation 97
5.3.2 ARMA modeling approach 99
5.3.3 Phonocardiography ESPRIT method 100
5.4 Spectral-window method for PCG-signal processing 102
5.5 Digital stethoscope system (DS) 104
5.5.1 Visual electronic stethoscope 105
5.6 Summary 106

6 PCG Pattern Classification 109

6.1 Introduction 109
6.2 PCG pattern classification methods 110
6.3 K-means clustering method 111
6.4 Fuzzy c-means classification algorithm 113
6.5 Principal component analysis (PCA) 114
6.6 Higher-order statistics PCG classification PCG-HOS 116
6.7 Independent component analysis (ICA) method 118
6.8 PCG classification based on artificial neural network (ANN) 122
6.8.1 General concept of ANN 124
6.8.2 Neural network topologies 125
6.8.3 PCG diagnosis with self-organizing mapping (SOM) 127
6.8.4 Self-organization principle 128
6.9 Bayes classifier 131
6.9.1 PCG signal Bayesian parameter estimation 132
6.10 Phonocardiography hemodynamic identification 134
6.11 PCG pattern classification application example 137
6.11.1 Delimitation of systoles and diastoles Assessment 138
6.11.2 Time and frequency decomposition of systoles and diastoles 138
6.11.3 Extraction of PCG power and frequency feature vectors 139
6.11.4 Correction of feature vectors for S_1/S_2 remnants 139
6.12 Future trends in phonocardiography pattern classification 139
6.13 Summary 140

7 Special Application of Phonocardiography 143

7.1 Introduction 143
7.2 Fetal phonocardiography signal processing 143
7.2.1 Fetal sound detection medical sensors 145
7.2.2 Challenges and motivation 146
7.3 Intracardiac phonocardiography (ICP) signal processing 147
7.3.1 ICP measurement device 149
7.3.2 ICP signal processing 149

7.3.3 ICP acoustic transmission properties 150
7.4 Separation of phonocardiography from phonospirography signal 152
7.5 Phonocardiogram cardiac pacemaker driven system 157
7.6 Basis of cardiac supportive device 158
7.7 Summary 161

8 Phonocardiography Acoustic Imaging and Mapping 163

8.1 Introduction 163
8.2 Motivation and problem formulation 164
8.3 PATI-experimental setup and system prototyping 167
8.4 Acoustic array signal processing 169
8.4.1 Adaptive beam-forming in cardiac acoustic imaging 170
8.4.2 Adaptive beam former with minimum-variance distortionless response 173
8.4.3 Heart sounds physiological modeling based on PATI method 174
8.5 Summary 175

Feedback from Clinical and Biomedical Aspects 179

Bibliography 181

Contributors 191

About the Authors 193

Preface

In modern health care, auscultation has found its main role in personal health care and in decision making of particular and extensive clinical examination cases. Making a clinical decision based on auscultation is a double-edged sword: a simple tool which is able to screen and assess murmurs is imprecise, yet it would be both time- and cost-saving while also relieving many patients of needless apprehension. The instructions found in this book provide both a constructive and supportive background for students and biomedical engineers, because they provide not only the facts about the phonocardiography (PCG) signal but also the interaction between the heart sounds and PCG analysis platform, through advanced PCG signal processing methods. This approach will assist in identifying and obtaining useful clinical and physiological information. Although these PCG acquisition techniques are plain, noninvasive, low-cost, and precise for assessing a wide range of heart diseases, diagnosis by auscultation requires good experience and considerable observation ability.

The PCG signal is traditionally analyzed and characterized by morphological properties in time domain, by spectral properties in the frequency domain, or by non-stationary properties in a combined time-frequency domain. Besides reviewing these techniques, this book will cover recent advancement in nonlinear PCG signal analysis, which has been used to reconstruct the underlying cardiac acoustics model.

This processing step provides a geometrical interpretation of the signal's dynamics, whose structure can be used for both system characterization and classification, as well as for other signal processing tasks such as detection and prediction. In addition, it will provide a core of information and concepts necessary to develop modern aspects for an intelligent computerized cardiac auscultation, as a smart stethoscope module.

Particularly, this book will focus on classification and analysis of patterns resulting from PCG signal by using adaptive signal processing methods. System identification and modeling of main acoustic dynamics for a cardiac system based on different methods, such as autoregressive moving average ARMA, Páde approximation, and recursive estimation, are addressed. The PCG variation detection of several clinical-oriented diseases, such as mitral valve insufficiency and aortic regurgitation, is based on recurrence time statistics in combination with nonlinear prediction to remove obscuring heart sounds from respiratory sound recordings in healthy and patient subjects.

This book also lights up advanced aspects in the field of phonocardiography pattern classification and other higher-order data clustering algorithm. The application of artificial intelligence in PCG classification and data mining was discussed through artificial neural networks (e.g., Perceptron classifier and self-organized mapping (SOM) and fuzzy-based clustering method like fuzzy c-mean algorithm.

A special topic in PCG-related application was presented as fetal phonocardiography (fPCG) signal acquisition and analysis, PCG driven-rate responsive cardiac pacemaker, intracardiac phonocardiography instrumentation and processing aspects, in addition to selected topics in physiological-derived signal with synchronization of PCG signal.

Finally, in this book, nonlinear PCG processing, as well as precise localization techniques of the first and second heart sound by means of ECG-gating method, are discussed and presented. Specifically learning objectives of each chapter will provide the students, physicians, and biomedical engineers with a good knowledge by introducing nonlinear analysis techniques based on dynamical systems theory to extract precise clinical information from the PCG signal.

Abbas K. Abbas and Rasha Bassam
Aachen, Germany
March 2009

List of Abbreviations

Abbreviation	Description
AV	Aortic valve
AVN	Atrioventricular node
AWD	Adaptive wavelet decomposition
ASD	Aortic stenosis disease
AHA	American Heart association
ARMA	Auto regressive moving average
ACOD	Audio Codecs
ACF	Auto –Correlation Function
ADC	Analogue-to-Digital Conversion
AKM	Adaptive K-mean Clustering Algorithm
ANN	Artificial neural network
BAD	Bradycardia arterial disease
BW	Bandwidth (of waveform)
BPF	Band pass filter
CAD	Congestive aortic disease
CM	Cardiac Microphone
CDS	Clinical Diagnosis System
CHD	Congestive heart disease
CWT	Continuous wavelet decomposition
DAQ	Data Acquitsion System
DbW	Debauchies wavelet
DCT	Discrete Cosine Transform
DFT	Discrete Fourier Transform
DS	Digital stethoscope
DVI	Pacemaker mode (Dual sensed, ventricular paced, inhibited mode)
DVT	Pacemaker mode (Dual sensed, ventricular paced, triggered mode)
DWT	Discrete wavelet decomposition
ECG	Electrocardiography
ePCG	Esophageal phonocardiography
ESD	Early systolic disease
ESPRIT	Estimation of Signal Parameters via Rotational Invariance Techniques

continues

Abbreviation	Description
continued	
FFT	Fast Fourier transform
FIR	Finite impulse response
FCM	Fuzzy C-mean classifier system
FHR	Fetal Heart rate
fPCG	Fetal phonocardiography
HBF	High pass filter
HMM	Hidden markov's model
HOS	Higher-order statistics
HT	Hilbert Transform
ICP	Intracardiac phonocardiography signal
ICSP	Intracardiac sound pressure signal
ICD	Intracardiac defibrillator
ICA	Independent Component Analysis
IEEE	Institute of Electrical and Electronic Engineering
IIR	Infinite impulse response filter
IABP	Intra-Aortic Balloon Pump
IRS	Image reconstruction system
KLM	Kalman linear model
LCD	Liquid crystal display
LVPV	Left ventricular Pressure Volume
LVP	Left ventricular Pressure
LVV	Left ventricular volume
LPF	Low pass filter
LTI	Linear-Time invariant system
LSE	Least-squares estimation
MSM	Mitral stenosis disease
MR	Mitral stenosis disease
MCU	Microcontroller unit
MI	Myocardial infarction
MV	Mitral Valve
OP	Operational point (Blood pressure curve)
ODE	Ordinary differential equation
PCA	Principal component Analysis
PCG	Phonocardiography
continues	

Abbreviation	Description
continued	
PDE	Partial differential equation
PET	Positron emission tomography imaging
PSG	Phonospirography signal
PATI	Phonocardiography acoustic tomography imaging
PSD	Power Spectral Density
P-wave	ECG cycle segment represent atrial depolarization phase
QRS-complex	ECG cycle segment represent ventricular depolarization phase
RBANN	Radial Basis Artificial Neural Network
RTF	Radial transformation
SOM	Self-Organized mapping
STFT	Short-time Fourier transform
SPECT	Single Photon Emission Computerized tomography imaging
SNR	Signal-to-noise ratio
SAN	Sino-Atrial node
S1	First heart sound
S2	Second heart sound
S3	Third heart sound
S4	Fourth heart sound
T-wave	ECG cycle segment represents ventricular repolarization phase
TAD	Tricuspid arterial disease
VVT	Pacemaker mode (ventricular sensed, ventricular paced, triggered mode)
VES	Visual electronic stethoscope
WAV	File format for audio-waveform data
WDE	Wavelet density estimation

List of Symbols

α	angle of fourier transformation
S_1	First heart sound
S_2	Second heart sound
S_3	Third heart sound
S_4	Fourth heart sound
θ_{PCG}	PCG pattern vector
V_s	microphone voltage source
R_s	microphone source impedance
ω	angular frequency
C_0	microphone output capacitance
V_0	microphone voltage output
Z_{ch}	acoustic impedance
A_2	Atrial component of PCG signal
P_2	Pulmonary component of PCG signal
$f(t)$	Fourier transform of PCG signal
E_t	PCG signal Energy
$\Phi(t)$	Haar Wavelet transform function
$\Psi(t)$	Haar scaling factor of PCG signal
Φ_2^D	Db-wavelet transformation of PCG signal
p_{2k}	two scale frequency-wavelet domain
Φ_{PCG}	Entropy value of PCG signal
$\gamma(s, \tau)$	continuous-wavelet transformation (CWT) of PCG signal
$\Psi(s, \tau)$	Scaling factor of (CWT) PCG signal
$S(t, w)$	Wavelet decomposition vector of PCG signal
$Mj - PCG(t)$	Spectral mean estimate of PCG signal
x_{PCG}	PCG signal data array
$\hat{R}_{PCG}(s)$	Power spectral density of PCG signal
$\hat{R}_B(w)$	PCG signal periodigram estimator
$H(z)$	Density transfer function of PCG signal
$A(z)$	Density transfer function zeros of PCG signal
$B(z)$	Density transfer function poles of PCG signal
X_{pcg}^T	PCG transfer matrix signal
f_{LO}	Microphone center frequency
w_f	Fundamental frequency