Preface

Background and Motivation

The establishment of the clinical electrocardiograph (ECG) by the Dutch physician Willem Einthoven in 1903 marked the beginning of a new era in medical diagnostic techniques, including the entry of electronics into health care. Since then, electronics, and subsequently computers, have become integral components of biomedical signal analysis systems, performing a variety of tasks from data acquisition and preprocessing for removal of artifacts to feature extraction and interpretation. Electronic instrumentation and computers have been applied to investigate a host of biological and physiological systems and phenomena, such as the electrical activity of the cardiovascular system, the brain, the neuromuscular system, and the gastric system; pressure variations in the cardiovascular system; sound and vibration signals from the cardiovascular, the musculo-skeletal, and the respiratory systems; and magnetic fields of the brain, to name a few.

The primary step in investigations of physiological systems requires the development of appropriate sensors and instrumentation to transduce the phenomenon of interest into a measurable electrical signal. The next step of analysis of the signals, however, is not always an easy task for a physician or life-sciences specialist. The clinically relevant information in the signal is often masked by noise and interference, and the signal features may not be readily comprehensible by the visual or auditory systems of a human observer. Heart sounds, for example, have most of their energy at or below the threshold of auditory perception of most humans; the interference patterns of a surface electromyographic (EMG) signal are too complex to permit visual

analysis. Some repetitious or attention-demanding tasks, such as on-line monitoring of the ECG of a critically ill patient with cardiac rhythm problems, could be uninteresting and tiring for a human observer. Furthermore, the variability present in a given type of signal from one subject to another, and the inter-observer variability inherent in subjective analysis performed by physicians or analysts make consistent understanding or evaluation of any phenomenon difficult, if not impossible. These factors created the need not only for improved instrumentation, but also for the development of methods for objective analysis via signal processing algorithms implemented in electronic hardware or on computers.

Processing of biomedical signals, until a few years ago, was mainly directed toward filtering for removal of noise and power-line interference; spectral analysis to understand the frequency characteristics of signals; and modeling for feature representation and parameterization. Recent trends have been toward quantitative or objective analysis of physiological systems and phenomena via signal analysis. The field of biomedical signal analysis has advanced to the stage of practical application of signal processing and pattern analysis techniques for efficient and improved non-invasive diagnosis, on-line monitoring of critically ill patients, and rehabilitation and sensory aids for the handicapped. Techniques developed by engineers are gaining wider acceptance by practicing clinicians, and the role of engineering in diagnosis and treatment is gaining much-deserved respect.

The major strength in the application of computers in biomedical signal analysis lies in the potential use of signal processing and modeling techniques for quantitative or objective analysis. Analysis of signals by human observers is almost always accompanied by perceptual limitations, inter-personal variations, errors caused by fatigue, errors caused by the very low rate of incidence of a certain sign of abnormality, environmental distractions, and so on. The interpretation of a signal by an expert bears the weight of the experience and expertise of the analyst; however, such analysis is almost always subjective. Computer analysis of biomedical signals, if performed with the appropriate logic, has the potential to add objective strength to the interpretation of the expert. It thus becomes possible to improve the diagnostic confidence or accuracy of even an expert with many years of experience. This approach to improved health care could be labeled as *computer-aided diagnosis*.

Developing an algorithm for biomedical signal analysis, however, is not an easy task; quite often, it might not even be a straightforward process. The engineer or computer analyst is often bewildered by the variability of features in biomedical signals and systems, which is far higher than that encountered in physical systems or observations. Benign diseases often mimic the features of malignant diseases; malignancies may exhibit a characteristic pattern, which, however, is not always guaranteed to appear. Handling all of the possibilities and degrees of freedom in a biomedical system is a major challenge in most applications. Techniques proven to work well with a certain system or set of signals may not work in another seemingly similar situation.

The Problem-solving Approach

The approach I have taken in presenting material in this book is primarily that of development of algorithms for problem solving. Engineers are often said to be (with admiration, I believe) problem solvers. However, the development of a problem statement and gaining of a good understanding of the problem could require a significant amount of preparatory work. I have selected a logical series of problems, from the many case-studies I have encountered in my research work, for presentation in the book. Each chapter deals with a certain type of a problem with biomedical signals. Each chapter begins with a statement of the problem, followed immediately with a few illustrations of the problem with real-life case-studies and the associated signals. Signal processing, modeling, or analysis techniques are then presented, starting with relatively simple "textbook" methods, followed by more sophisticated research approaches directed at the specific problem. Each chapter concludes with one or more applications to significant and practical problems. The book is illustrated copiously with real-life biomedical signals and their derivatives.

The methods presented in the book are at a fairly high level of technical sophistication. A good background in signal and system analysis [1, 2, 3] as well as probability, random variables, and stochastic processes [4, 5, 6, 7, 8, 9] is required, in order to follow the procedures and analysis. Familiarity with systems theory and transforms such as the Laplace and Fourier, the latter in both continuous and discrete versions, will be assumed. We will not be getting into details of the transducers and instrumentation techniques essential for biomedical signal acquisition [10, 11, 12, 13]; instead, we will be studying the problems present in the signals after they have been acquired, concentrating on how to solve the problems. Concurrent or prior study of the physiological phenomena associated with the signals of specific interest, with a clinical textbook, is strongly recommended.

Intended Readership

The book is directed at engineering students in their final year of undergraduate studies or in their graduate studies. Electrical Engineering students with a rich background in signals and systems [1, 2, 3] will be well prepared for the material in the book. Students in other engineering disciplines, or in computer science, physics, mathematics, or geophysics should also be able to appreciate the material in the book. A course on digital signal processing or digital filters [14] would form a useful link, but a capable student without this topic may not face much difficulty.

Practicing engineers, computer scientists, information technologists, medical physicists, and data-processing specialists working in diverse areas such as telecommunications, seismic and geophysical applications, biomedical applications, and hospital information systems may find the book useful in their quest to learn advanced techniques for signal analysis. They could draw inspiration from other applications of signal processing or analysis, and satisfy their curiosity regarding computer applications in medicine and computer-aided medical diagnosis.

Teaching and Learning Plan

The book starts with an illustrated introduction to biomedical signals in Chapter 1. Chapter 2 continues the introduction, but with emphasis on the analysis of multiple channels of related signals. This part of the book may be skipped in the teaching plan for a course if the students have had a previous course on biomedical signals and instrumentation. In such a case, the chapters should be studied as review material in order to get oriented toward the examples to follow in the book.

Chapter 3 deals exclusively with filtering for removal of artifacts as an important precursive step before signal analysis. Basic properties of systems and transforms as well as signal processing techniques are reviewed and described as and when required. The chapter is written so as to facilitate easy comprehension by those who have had a basic course on signals, systems, and transforms [1, 2, 3]. The emphasis is on the application to particular problems in biomedical signal analysis, and not on the techniques themselves. A large number of illustrations are included to provide a visual impression of the problem and the effectiveness of the various filtering methods described.

Chapter 4 presents techniques particularly useful in the detection of events in biomedical signals. Analysis of waveshape and waveform complexity of events and components of signals is the focus of Chapter 5. Techniques for frequency-domain characterization of biomedical signals and systems are presented in Chapter 6. A number of diverse examples are provided in these chapters. Attention is directed to the characteristics of the problems one faces in analyzing and interpreting biomedical signals, rather than to any specific diagnostic application with particular signals.

The material in the book up to and including Chapter 6 will provide more than adequate material for a one-semester (13-week) course at the senior (fourth-year) engineering level. My own teaching experience indicates that this material will require about 36 hours of lectures, augmented with about 12 hours of tutorials (problem-solving sessions) and 10 laboratory sessions.

Modeling biomedical signal-generating processes and systems for parametric representation and analysis is the subject of Chapter 7. Chapter 8 deals with the analysis of nonstationary signals. The topics in these chapters are of higher mathematical complexity than suitable for undergraduate courses. Some sections may be selected and included in a first course on biomedical signal analysis if there is particular interest in these topics. Otherwise, the two chapters could be left for self-study by those in need of the techniques, or included in an advanced course.

Chapter 9 presents the final aspect of biomedical signal analysis, and provides an introduction to pattern classification and diagnostic decision. Although this topic is advanced in nature and could form a graduate-level course on its own, the material is introduced so as to draw the entire exercise of biomedical signal analysis to its concluding stage of diagnostic decision. It is recommended that a few sections from this chapter be included even in a first course on biomedical signal analysis so as to give the students a flavor of the end result.

The topic of data compression has deliberately been left out of the book. Advanced topics such as nonlinear dynamics, time-frequency distributions, wavelet-based anal-

ysis, chaos, and fractals are not covered in the book. Adaptive filters and nonstationary signal analysis techniques are introduced in the book, but deserve more attention, depth, and breadth. These topics will form the subjects of a follow-up book that I intend to write.

Each chapter includes a number of study questions and problems to facilitate preparation for tests and examinations. A number of laboratory exercises are also provided at the end of each chapter, which could be used to formulate hands-on exercises with real-life signals. Data files related to the problems and exercises at the end of each chapter are available at the site

ftp://ftp.ieee.org/uploads/press/rangayyan/

MATLAB programs to read the data are also provided where required.

It is strongly recommended that the first one or two laboratory sessions in the course be visits to a local hospital, health sciences center, or clinical laboratory to view biomedical signal acquisition and analysis in a practical (clinical) setting. Signals acquired from fellow students and professors could form interesting and motivating material for laboratory exercises, and should be used to supplement the data files provided. A few workshops by physiologists, neuroscientists, and cardiologists should also be included in the course so as to provide the students with a non-engineering perspective on the subject.

Practical experience with real-life signals is a key element in understanding and appreciating biomedical signal analysis. This aspect could be difficult and frustrating at times, but provides professional satisfaction and educational fun!

RANGARAJ MANDAYAM RANGAYYAN

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September, 2001

About the Author

Rangaraj (Raj) Mandayam Rangayyan was born in Mysore, Karnataka, India, on 21 July 1955. He received the Bachelor of Engineering degree in Electronics and Communication in 1976 from the University of Mysore at the People's Education Society College of Engineering, Mandya, Karnataka, India, and the Ph.D. degree in Electrical Engineering from the Indian Institute of Science, Bangalore, Karnataka, India, in 1980. He was with the University of Manitoba, Winnipeg, Manitoba, Canada, from 1981 to 1984.

He is, at present, a Professor with the Department of Electrical and Computer Engineering (and an Adjunct Professor of Surgery and Radiology) at the University of Calgary, Calgary, Alberta, Canada. His research interests are in the areas of digital signal and image processing, biomedical signal analysis, medical imaging and image analysis, and computer vision. His current research projects are on mammographic image enhancement and analysis for computer-aided diagnosis of breast cancer; region-based image processing; knee-joint vibration signal analysis for noninvasive diagnosis of articular cartilage pathology; and analysis of textured images by cepstral filtering and sonification. He has lectured extensively in many countries, including India, Canada, United States, Brazil, Argentina, Uruguay, Chile, United Kingdom, The Netherlands, France, Spain, Italy, Finland, Russia, Romania, Egypt, Malaysia, Thailand, China, and Japan. He has collaborated with many research groups in Brazil, Spain, France, and Romania.

He was an Associate Editor of the *IEEE Transactions on Biomedical Engineering* from 1989 to 1996; the Program Chair and Editor of the Proceedings of the IEEE Western Canada Exhibition and Conference on "Telecommunication for Health Care:

Telemetry, Teleradiology, and Telemedicine", July 1990, Calgary, Alberta, Canada; the Canadian Regional Representative to the Administrative Committee of the IEEE Engineering in Medicine and Biology Society (EMBS), 1990–1993; a Member of the Scientific Program Committee and Editorial Board, International Symposium on Computerized Tomography, Novosibirsk, Siberia, Russia, August 1993; the Program Chair and Co-editor of the *Proceedings of the 15th Annual International Conference of the IEEE EMBS*, October 1993, San Diego, CA; and Program Co-chair, 20th Annual International Conference of the IEEE EMBS, Hong Kong, October 1998.

He is the winner of the 1997 and 2001 Research Excellence Awards of the Department of Electrical and Computer Engineering, and the 1997 Research Award of the Faculty of Engineering, University of Calgary. He was awarded the Killam Resident Fellowship and a Sabbatical Fellowship by the University of Calgary in support of writing this book. He was recognized by the IEEE with the award of the Third Millennium Medal in 2000, and was elected as a Fellow of the IEEE in 2001.

Photo by Trudie Lee.

Acknowledgments

To write a book on my favorite subject of biomedical signal analysis has been a long-cherished ambition of mine. Writing this book has been a major task with many facets: challenging, yet yielding more knowledge; tiring, yet stimulating the thirst to understand and appreciate more; difficult, yet satisfying when a part was brought to a certain stage of completion.

A number of very important personalities have shaped me and my educational background. My mother, Srimati Padma Srinivasan Rangayyan, and my father, Sri Srinivasan Mandayam Rangayyan, encouraged me to keep striving to gain higher levels of education and to set and achieve higher goals all the time. I have been very fortunate to have been taught and guided by a number of dedicated teachers, the most important of them being Professor Ivaturi Surya Narayana Murthy, my Ph.D. supervisor, who introduced me to the topic of this book at the Indian Institute of Science, Bangalore, Karnataka, India. It is with great respect and admiration that I dedicate this book as a humble offering to their spirits.

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My association with the IEEE Engineering in Medicine and Biology Society (EMBS) in many positions has benefited me considerably in numerous ways. In particular, the period as an Associate Editor of the *IEEE Transactions on Biomedical Engineering* was very rewarding, as it provided me with a wonderful opportunity to work with many leading researchers and authors of scientific articles. I thank IEEE EMBS for lending professional support to my career on many fronts. I am grateful to the IEEE Press, in particular, Metin Akay, Series Editor, IEEE Press Series in Biomedical Engineering, for inviting me to write this book.

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It is my humble hope that this book will assist those who seek to enrich their lives and those of others with the wonderful powers of biomedical signal analysis. Electrical and Computer Engineering is indeed a great field in the service of humanity!

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Contents

Dedication vii

Preface ix

About the Author xiv

Acknowledgments xvii

Symbols and Abbreviations xxix

1 Introduction to Biomedical Signals 1
1.1 The Nature of Biomedical Signals 1
1.2 Examples of Biomedical Signals 5
1.2.1 The action potential 5
1.2.2 The electroneurogram (ENG) 9
1.2.3 The electromyogram (EMG) 11
1.2.4 The electrocardiogram (ECG) 14
1.2.5 The electroencephalogram (EEG) 28
1.2.6 Event-related potentials (ERPs) 30
1.2.7 The electrogastrogram (EGG) 31
1.2.8 The phonocardiogram (PCG) 34
1.2.9 The carotid pulse (CP) 38

1.2.10 Signals from catheter-tip sensors 40
1.2.11 The speech signal 40
1.2.12 The vibromyogram (VMG) 46
1.2.13 The vibroarthrogram (VAG) 46
1.2.14 Oto-acoustic emission signals 48
1.3 Objectives of Biomedical Signal Analysis 48
1.4 Difficulties in Biomedical Signal Analysis 52
1.5 Computer-aided Diagnosis 55
1.6 Remarks 57
1.7 Study Questions and Problems 58
1.8 Laboratory Exercises and Projects 59

2 Concurrent, Coupled, and Correlated Processes 61
2.1 Problem Statement 62
2.2 Illustration of the Problem with Case-studies 62
2.2.1 The electrocardiogram and the phonocardiogram 62
2.2.2 The phonocardiogram and the carotid pulse 63
2.2.3 The ECG and the atrial electrogram 64
2.2.4 Cardio-respiratory interaction 66
2.2.5 The electromyogram and the vibromyogram 67
2.2.6 The knee-joint and muscle vibration signals 67
2.3 Application: Segmentation of the PCG 69
2.4 Remarks 71
2.5 Study Questions and Problems 71
2.6 Laboratory Exercises and Projects 71

3 Filtering for Removal of Artifacts 73
3.1 Problem Statement 73
3.1.1 Random noise, structured noise, and physiological interference 74
3.1.2 Stationary versus nonstationary processes 81
3.2 Illustration of the Problem with Case-studies 85
3.2.1 Noise in event-related potentials 85
3.2.2 High-frequency noise in the ECG 85
3.2.3 Motion artifact in the ECG 85
3.2.4 Power-line interference in ECG signals 87
3.2.5 Maternal interference in fetal ECG 88
3.2.6 Muscle-contraction interference in VAG signals 90
3.2.7 Potential solutions to the problem 92

3.3 Time-domain Filters 94
3.3.1 Synchronized averaging 94
3.3.2 Moving-average filters 99
3.3.3 Derivative-based operators to remove low-frequency artifacts 106
3.4 Frequency-domain Filters 117
3.4.1 Removal of high-frequency noise: Butterworth lowpass filters 118
3.4.2 Removal of low-frequency noise: Butterworth highpass filters 128
3.4.3 Removal of periodic artifacts: Notch and comb filters 130
3.5 Optimal Filtering: The Wiener Filter 139
3.6 Adaptive Filters for Removal of Interference 147
3.6.1 The adaptive noise canceler 148
3.6.2 The least-mean-squares adaptive filter 150
3.6.3 The recursive least-squares adaptive filter 152
3.7 Selecting an Appropriate Filter 158
3.8 Application: Removal of Artifacts in the ECG 162
3.9 Application: Maternal – Fetal ECG 165
3.10 Application: Muscle-contraction Interference 166
3.11 Remarks 171
3.12 Study Questions and Problems 171
3.13 Laboratory Exercises and Projects 175

4 Event Detection 177
4.1 Problem Statement 177
4.2 Illustration of the Problem with Case-studies 178
4.2.1 The P, QRS, and T waves in the ECG 178
4.2.2 The first and second heart sounds 179
4.2.3 The dicrotic notch in the carotid pulse 180
4.2.4 EEG rhythms, waves, and transients 180
4.3 Detection of Events and Waves 182
4.3.1 Derivative-based methods for QRS detection 183
4.3.2 The Pan-Tompkins algorithm for QRS detection 187
4.3.3 Detection of the dicrotic notch 191
4.4 Correlation Analysis of EEG channels 191
4.4.1 Detection of EEG rhythms 193
4.4.2 Template matching for EEG spike-and-wave detection 200

4.5 Cross-spectral Techniques 200
4.5.1 Coherence analysis of EEG channels 200
4.6 The Matched Filter 204
4.6.1 Detection of EEG spike-and-wave complexes 204
4.7 Detection of the P Wave 205
4.8 Homomorphic Filtering 212
4.8.1 Generalized linear filtering 212
4.8.2 Homomorphic deconvolution 213
4.8.3 Extraction of the vocal-tract response 216
4.9 Application: ECG Rhythm Analysis 222
4.10 Application: Identification of Heart Sounds 225
4.11 Application: Detection of the Aortic Component of S2 227
4.12 Remarks 231
4.13 Study Questions and Problems 233
4.14 Laboratory Exercises and Projects 234

5 Waveshape and Waveform Complexity 237
5.1 Problem Statement 237
5.2 Illustration of the Problem with Case-studies 238
5.2.1 The QRS complex in the case of bundle-branch block 238
5.2.2 The effect of myocardial ischemia and infarction on QRS waveshape 238
5.2.3 Ectopic beats 238
5.2.4 EMG interference pattern complexity 239
5.2.5 PCG intensity patterns 239
5.3 Analysis of Event-related Potentials 240
5.4 Morphological Analysis of ECG Waves 240
5.4.1 Correlation coefficient 240
5.4.2 The minimum-phase correspondent and signal length 241
5.4.3 ECG waveform analysis 248
5.5 Envelope Extraction and Analysis 249
5.5.1 Amplitude demodulation 251
5.5.2 Synchronized averaging of PCG envelopes 252
5.5.3 The envelogram 255
5.6 Analysis of Activity 256
5.6.1 The root mean-squared value 259
5.6.2 Zero-crossing rate 259
5.6.3 Turns count 260
5.6.4 Form factor 262

5.7 Application: Normal and Ectopic ECG Beats 263
5.8 Application: Analysis of Exercise ECG 265
5.9 Application: Analysis of Respiration 266
5.10 Application: Correlates of Muscular Contraction 269
5.11 Remarks 269
5.12 Study Questions and Problems 272
5.13 Laboratory Exercises and Projects 274

6 Frequency-domain Characterization 277
6.1 Problem Statement 278
6.2 Illustration of the Problem with Case-studies 279
6.2.1 The effect of myocardial elasticity on heart sound spectra 279
6.2.2 Frequency analysis of murmurs to diagnose valvular defects 280
6.3 The Fourier Spectrum 282
6.4 Estimation of the Power Spectral Density Function 287
6.4.1 The periodogram 288
6.4.2 The need for averaging 289
6.4.3 The use of windows: Spectral resolution and leakage 291
6.4.4 Estimation of the autocorrelation function 297
6.4.5 Synchronized averaging of PCG spectra 298
6.5 Measures Derived from PSDs 302
6.5.1 Moments of PSD functions 305
6.5.2 Spectral power ratios 307
6.6 Application: Evaluation of Prosthetic Valves 308
6.7 Remarks 310
6.8 Study Questions and Problems 311
6.9 Laboratory Exercises and Projects 312

7 Modeling Biomedical Systems 315
7.1 Problem Statement 315
7.2 Illustration of the Problem 316
7.2.1 Motor-unit firing patterns 316
7.2.2 Cardiac rhythm 317
7.2.3 Formants and pitch in speech 317
7.2.4 Patello-femoral crepitus 319
7.3 Point Processes 320
7.4 Parametric System Modeling 327

7.5 Autoregressive or All-pole Modeling 333
7.5.1 Spectral matching and parameterization 339
7.5.2 Optimal model order 342
7.5.3 Relationship between AR and cepstral coefficients 346
7.6 Pole-zero Modeling 355
7.6.1 Sequential estimation of poles and zeros 358
7.6.2 Iterative system identification 360
7.6.3 Homomorphic prediction and modeling 366
7.7 Electromechanical Models of Signal Generation 371
7.7.1 Sound generation in coronary arteries 371
7.7.2 Sound generation in knee joints 374
7.8 Application: Heart-rate Variability 377
7.9 Application: Spectral Modeling and Analysis of PCG Signals 380
7.10 Application: Coronary Artery Disease 386
7.11 Remarks 386
7.12 Study Questions and Problems 389
7.13 Laboratory Exercises and Projects 390

8 Analysis of Nonstationary Signals 391
8.1 Problem Statement 392
8.2 Illustration of the Problem with Case-studies 392
8.2.1 Heart sounds and murmurs 392
8.2.2 EEG rhythms and waves 393
8.2.3 Articular cartilage damage and knee-joint vibrations 393
8.3 Time-variant Systems 396
8.3.1 Characterization of nonstationary signals and dynamic systems 397
8.4 Fixed Segmentation 399
8.4.1 The short-time Fourier transform 400
8.4.2 Considerations in short-time analysis 402
8.5 Adaptive Segmentation 405
8.5.1 Spectral error measure 408
8.5.2 ACF distance 413
8.5.3 The generalized likelihood ratio 414
8.5.4 Comparative analysis of the ACF, SEM, and GLR methods 416
8.6 Use of Adaptive Filters for Segmentation 419
8.6.1 Monitoring the RLS filter 420

8.6.2 The RLS lattice filter 421
8.7 Application: Adaptive Segmentation of EEG Signals 431
8.8 Application: Adaptive Segmentation of PCG Signals 438
8.9 Application: Time-varying Analysis of Heart-rate Variability 438
8.10 Remarks 444
8.11 Study Questions and Problems 444
8.12 Laboratory Exercises and Projects 444

9 Pattern Classification and Diagnostic Decision 445
9.1 Problem Statement 446
9.2 Illustration of the Problem with Case-studies 446
9.2.1 Diagnosis of bundle-branch block 446
9.2.2 Normal or ectopic ECG beat? 447
9.2.3 Is there an alpha rhythm? 448
9.2.4 Is a murmur present? 448
9.3 Pattern Classification 449
9.4 Supervised Pattern Classification 450
9.4.1 Discriminant and decision functions 450
9.4.2 Distance functions 451
9.4.3 The nearest-neighbor rule 452
9.5 Unsupervised Pattern Classification 453
9.5.1 Cluster-seeking methods 453
9.6 Probabilistic Models and Statistical Decision 457
9.6.1 Likelihood functions and statistical decision 457
9.6.2 Bayes classifier for normal patterns 460
9.7 Logistic Regression Analysis 462
9.8 The Training and Test Steps 463
9.8.1 The leave-one-out method 463
9.9 Neural Networks 464
9.10 Measures of Diagnostic Accuracy and Cost 466
9.10.1 Receiver operating characteristics 469
9.10.2 McNemar's test of symmetry 472
9.11 Reliability of Classifiers and Decisions 473
9.12 Application: Normal versus Ectopic ECG Beats 474
9.13 Application: Detection of Knee-joint Cartilage Pathology 480
9.14 Remarks 483
9.15 Study Questions and Problems 485
9.16 Laboratory Exercises and Projects 487

References 489

Index 509