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The **BIOMEDICAL ENGINEERING** Series
Series Editor Michael Neuman

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Advanced Segmentation Techniques

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CRC PRESS

Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

Angiography and plaque imaging : a segmentation perspective / edited by
Jasjit S. Suri and Swamy Laxminarayan.
p. ; cm.- (Biomedical engineering series)
Includes bibliographical references and index.
ISBN 0-8493-1740-1 (alk. paper)
1. Angiography. 2. Atherosclerotic plaque. 3.
Blood-vessels–Diseases–Diagnosis. 4. Blood-vessels–Imaging.
[DNLM: 1. Blood Vessels-pathology. 2. Imaging,
Three-Dimensional–methods. 3. Magnetic Resonance Angiography-methods.
4. Vascular Diseases–diagnosis. WG 500 A5862 2003] I. Suri, Jasjit
S. II. Laxminarayan, Swamy. III. Series: Biomedical engineering series (Boca Raton, Fla.).
RC691.6.A53A54 2003
616.1'30754—dc21 2003046074

Direct all inquiries to CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.

International Standard Book Number 0-8493-1740-1
Library of Congress Card Number 2003046074
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

Dedication

Jasjit Suri would like to dedicate this book to his son, Harman, who led to a family bond; to his parents, especially his late mother for her immortal softness and encouragement; his sister Angela, his family, and his wife Malvika.

Swamy Laxminarayan would like to dedicate this book to the many distinguished peers with whom he had the privilege to interact and learn from and to all his students who gave him the opportunity to impart in some small measure the benefits of his research endeavors.

Preface

The art of imaging blood vessels in the human body is called angiography. Since its inception, physicians have benefited from the field of angiography imaging. This has helped them to diagnostically treat patients with various kinds of vascular diseases. Recently, because of the technology growth in fields of acquisition techniques, such as magnetic resonance, computer tomography, digital subtraction angiography, and ultrasound, the vascular imaging research community has become very interested. But acquisition is just one side of the coin. Given the high resolution acquired with angiographic volumetric data, the art of blood vessel extraction is another side of the coin. The recent growth in mathematical engineering and applied mathematics has opened the door to solve complex problems in angiographic imaging, such as detection, segmentation, tracking, display, and quantification of blood vessels. By fusing together different branches of engineering and medicine, such as physics, computer engineering, electrical engineering, biomedical engineering, and medicine, it has become possible to understand not only the needs of today's fast-growing technology, but also to solve difficult problems in angiographic imaging. This book is an attempt to present, for the first time, different medical imaging modalities such as MR, CT, x-ray, and ultrasound for performing angiography and its analysis.

The art of angiography imaging has penetrated several fields of medicine, such as ophthalmology, neurology, cardiology and pulmonology. Keeping this in mind, we address the state-of-the-art issues of angiography, pre- and post-angiographic imaging, and applications. This includes intravascular ultrasound (IVUS) and x-ray fusion, plaque imaging, and morphology analysis. The angiographic imaging covers different body parts such as retinal, neuro, renal, coronary, and run-off based on the above four medical imaging modalities.

Readers who will benefit from this book include researchers in the field of medicine, imaging sciences, biomedical engineering, physics, and applied mathematics, algorithmic developers, and researchers who are beginners in the field of image processing and graphics but are interested in shape analysis. This book is a collection of chapters in the area of angiography acquisition and postprocessing of angiography volumetric data sets and applications of vascular segmentation techniques.

The contributors to this book consist of pioneers in the field of engineering, imaging sciences, biomedical engineering, computer engineering, image processing, computer vision, deformable models, and partial differential equations. This book is also a classic example of a buffer between industry and academics, because the contributors are from both sides of engineering and mathematics.

Chapter 1 presents a long survey of vascular image processing techniques. It divides the techniques into two broad classes: skeleton vs. non-skeleton-based techniques. The major part of this chapter focuses on skeleton (indirect) and non-skeleton (direct) based techniques. We present more than five different skeleton or indirect techniques, along with their mathematical foundations, algorithms, and their pros and cons. Then, the chapter presents eight different techniques in the class of non-skeleton or direct methods. A full section is dedicated to a discussion of Fuzzy connectedness vs. geometric techniques, their pros and cons, skeleton versus non-skeleton approaches, and the major dominance of scale-spaces. This chapter concludes with a clinical discussion of automated vascular segmentation algorithms for MR data sets, possible extensions for improving the segmentation system, and the future of vascular segmentation techniques.

Chapter 2 focuses on scale-space filtering of the white- and black-blood angiography imaging. This chapter presents a system where the raw MR angiographic volume is first converted to isotropic volume, followed by three-dimensional, higher-order, separable Gaussian derivative convolution with known scales to generate edge volume. The edge volume is then run by the directional processor at each voxel where the eigenvalues of the three-dimensional ellipsoid are computed. The vessel score per voxel is then estimated based on these three eigenvalues, which suppress the nonvasculature and background structures yielding the filtered volume. The filtered volume is ray-cast to generate the maximum intensity projection images for display. This chapter then presents the performance evaluation system by computing the mean, variance, signal-to-noise ratio, and contrast-to-noise ratio images. The system shows the results of 20 patient studies from different areas of the body, including the brain, abdomen, kidney, knee, and ankle. This chapter also discusses the timing issues and compares its strategy with other MR filtering algorithms.

Chapter 3 focuses on segmentation tools from an industrial point of view. Vessel View is an interactive postprocessing application for three-dimensional magnetic resonance angiography (MRA) and computed tomography angiography (CTA) images. The application provides simple interactive point-and-click localization and quantification of vessels. Behind the scenes, there are several robust and efficient segmentation algorithms that operate at interactive speeds. For three-dimensional localization of vessels, a variant of Dijkstra's algorithm grows a segmenting surface from initial seeds and connects them with a minimal path computation. The technique is local and does not require any preprocessing of the volume. The propagation is controlled by iterative computation of border probabilities. As expanding regions meet, the statistics collected during propagation are passed to an active minimal-path generation module that links the associating points through the vessel tree. Once the vessel tree is obtained, local, high-precision segmentation techniques, employing mean-shift-modulated ray propagation, are used for quantifying selected pathologies, such as aneurysm and stenosis. This chapter describes in detail these algorithms and also explains why these particular techniques were chosen based on clinical workflow. The costliest element of the diagnosis is the time spent by doctors and technicians. Optimization of user time leads to a simple set of design criteria: algorithms must be fast, robust, give immediate visual feedback, and respond intuitively to user guidance. These demands require a system in which visualization and segmentation are tightly coupled. Integral visualization and navigation techniques are developed in conjunction with the content extraction methods.

Chapter 4 focuses on black-blood angiography. It introduces different kinds of masking strategies such as Bayesian, fuzzy, recursive mathematical morphology, and connected components analysis for mask generation for black-blood angiographic volumes. One section of the chapter presents the filtering/segmentation algorithms for black-blood angiography. Here is discussed the role of scale-spaces for vessel detection and display techniques for black-blood vessels. The last section of this chapter presents a clinical discussion on automated vascular segmentation algorithms for MR data sets, possible extensions for improving the black-blood segmentation system, and the future of black-blood vascular segmentation techniques.

Chapter 5 reports on techniques for automatic analysis of retinal angiographic images. In particular, we focus on the segmentation of the blood vessels in these images and subsequent shape analysis of the segmented branching structures. We describe a recently proposed approach based on the continuous wavelet transform using the Morlet wavelet. The main advantage of the latter, with respect to retinal images, relies on its capability of tuning to specific frequencies, thus allowing noise filtering and blood vessel enhancement in a single step. Furthermore, because of the importance of using shape analysis techniques for the detection and quantitative characterization of the blood vessel vascular branching pattern in the retina, the wavelets can also be explored to extract shape features for image analysis. The chapter concludes with an exploration of the fractal analysis of the segmented vessels for characterization of the branching pattern using the correlation dimension.

Chapter 6 focuses on retinal vascular image processing. This chapter provides a detailed review of algorithms for extracting the retinal vasculature from clinical instruments such as the fundus microscope. Also described are methods for extracting key points, such as bifurcations and crossovers, and methods for performing vessel morphometry. Tracing of retinal vessels has a number of applications, including support for clinical trials, real-time instrumentation for computer-assisted surgery, computer-assisted diagnosis, and fundamental science. Examples of applications are provided. Depending on the intended application, different algorithmic and implementation choices can be made. This chapter describes the rationale behind these choices, using several examples.

Chapters 7, 8, and 9 discuss the MRI of atherosclerosis. These three chapters describe the imaging techniques, morphologic index, and tissue characterization approaches for the visualization and characteristics of atherosclerosis. Noninvasive magnetic resonance imaging is ideally suited for such purposes. Plaque characteristics may be useful in determining high risk, or "vulnerable" plaques. Chapter 7 focuses on plaque imaging techniques useful in imaging basic plaque tissues and specific plaque features with magnetic resonance imaging.

Traditionally, the degree of lumen stenosis is used as a marker for high-risk (vulnerable) plaques. Clinically, x-ray, CT, ultrasound, and MR angiography are used to determine lumen stenosis. Stenosis, however, is just one simple feature in morphology analysis. We believe that complex morphology markers can provide more information for vulnerable plaques. A set of carotid shape descriptors developed to distinguish the different types of plaque morphology based on carotid wall thickness to assist in determining the vulnerable plaque is presented in Chapter 8.

Knowing the composition and distribution of atherosclerotic plaque components within the walls of arteries can be valuable for surgical planning, assessing disease severity, and monitoring response to treatment. Chapter 9 details techniques for the segmentation of artery walls into distinct tissue regions, measurement of compositional indexes, and three-dimensional display of plaque distribution. The methods focus on magnetic resonance images of the carotid arteries, but can be extended for use in other vessels and with other methods for vessel wall imaging.

Chapter 10 addresses the problem of constructing volumetric dynamic models of coronary vessels. The growing appreciation of the pathophysiological and prognostic importance of arterial morphology has led to the realization of the importance of volumetric analysis of coronary vessels for a reliable diagnosis and choice of therapeutic procedure. The problem of real three-dimensional reconstruction of dynamic vessels is a complex task that needs to incorporate data from different medical image modalities. Today, angiograms represent the most-used image modality for diagnosis during clinical practice. However, due to the projective nature of x-ray images, direct quantitative measurements are prone to errors. A three-dimensional reconstruction of the vessels could estimate vessel lesions and aid in the process of determining the reliable therapy more precisely (length of stent, etc.). In this chapter, different computer vision approaches for two-dimensional analysis and three-dimensional reconstruction of vessels on (biplane) angiogram systems is discussed, focusing on their performance and need for user interaction.

On the other hand, angiograms, visualizing just the vessel lumen, are inherently limited in defining the distribution and extension of coronary wall disease. As a perfect complement, intravascular ultrasound (IVUS) images represent a unique interoperative image modality that allows physicians to obtain a picture of the composition of the vessel in detail. IVUS images contain valuable geometric information (diameters, area, etc.) about plaque, vessel lumen, mutual position with stent, etc. Given the huge amount of IVUS data, the problem of (semi)-automatic segmentation and extraction of geometric measurements arouses increasing interest by cardiac caregivers in order to avoid the tedious and time-consuming process of manual segmentation. Moreover, image processing and computer vision techniques allow for an automatic texture characterization of vessel morphology (plaque, calcium deposits, etc.), which represents essential help to cardiologists during the process of diagnosis and therapy. Chapter 10 discusses the current state-of-the-art of automatic analysis (segmentation, statistical description of vessel composition, dynamics, etc.) of IVUS images. The chapter finishes with current work on fusing IVUS and angiogram data to obtain a real volumetric vessel model, thereby making easier the arduous task of mental conceptualization of vessel shape and analysis of real spatial extension, distribution, and treatment of the coronary diseases.

Chapter 11 presents the issues and problems that computer-assisted analysis of images of vasculature pose to medical image processing researchers. Methods that are appropriate for the analysis of images of tissues are not always appropriate for vascular images. For example, vessels generally form sparse networks in which each vessel's cross-section is nearly circular and varies smoothly along its tortuous path. If ignored, these geometric properties confound standard image segmentation and registration methods. However, if these geometric properties are specifically exploited, the resulting vascular image processing methods can gain accuracy, consistency, and ease-of-use. In this chapter we review several prominent methods for characterizing and viewing vascular images for surgical planning as well as methods for registering vascular images for surgical guidance and treatment monitoring. These reviews focus on the current and potential clinical use of the methods. Special attention is given to the role of vascular image processing methods for neurosurgical planning, liver transplant planning, liver shunt placement, and liver lesion ablation guidance. The utility of these and other clinical applications are shown to often be related to the degree to which the underlying image processing methods exploit the geometric properties of vessels.

Chapter 12 focuses on the future aspects of vasculature image processing. Here we summarize the acquisition of MR, CT, and ultrasound modalities. Postprocessing issues such as separation are also presented.

Acknowledgments

This book is the result of collective endeavours from several noted engineering and computer scientists, mathematicians, physicists, and radiologists. The authors are indebted to all of their efforts and outstanding scientific contributions. The editors are particularly grateful to Drs. Sameer Singh, Petia Reveda, James Williams, Roberto M.Cesar, Jr., Badrinath Roysam, Chun Yuan, Stephen Alyward, and all their team members for working with us so closely in meeting all of the deadlines of the book.

We would like to express our appreciation to CRC Press for helping create this book. We are particularly thankful to Susan Farmer, Helena Redshaw, and Susan Fox for their excellent coordination of the book at every stage.

Dr. Suri would like to thank Philips Medical Systems, Inc., for the MR data sets and encouragement during his experiments and research. Special thanks are due to Dr. Larry Kasuboski and Dr. Elaine Keeler from Philips Medical Systems, Inc., for their support and motivation. Thanks are also due to past Ph.D. committee research professors, particularly Professors Linda Shapiro, Robert M. Haralick, Dean Lytle, and Arun Somani, for their encouragement.

We extend our appreciation to Dr. George Thoma, Chief, Imaging Science Division from the National Institutes of Health; and Dr. Sameer Singh, University of Exeter, U.K. for their motivation. Special thanks go to Michael Neuman, Series Editor of the Biomedical Engineering Series, for advising us on all aspects of the book.

We thank IEEE Press, Academic Press, Springer-Verlag Publishers, and several medical and engineering journals for permitting us to use some of the images previously published in these journals.

Finally, Jasjit Suri would like to thank his wife Malvika Suri for all the love and support she has shown over the years and our baby Harman whose presence is always a constant source of pride and joy. Dr. Suri also expresses his gratitude to his father, a mathematician, who inspired him throughout his life and career, and to his late mother, who passed away a few days before his Ph.D. graduation. Special thanks to Pom Chadha, a true salesperson, who taught me that life is not just books. He is one of my best friends. I would like to also thank my in-laws who have a special place for me in their hearts and have shown lots of love and care for me.

Swamy Laxminarayan would like to express his profound appreciation to the senior author, Dr. Jasjit Suri, for his highest level of collaborative spirit and warm scientific interactions during the course of editing this book. A book of this complexity and content is a collective venture with excellent contributions by authors whose scholarly work will always be an intellectual reference resource to the biomedical community. We are most grateful to them. I have had the pleasure of numerous technical and scientific discussions with Dr. Beth Stamm and Dr. Neil Piland of the Institute of Rural Health at the Idaho State University. This has been especially important to the critical evaluation of the book, for which I owe them and my colleagues at the Institute of Rural Health a great debt of gratitude and thanks. Two mathematical scientists, Lakshminarayan Rajaram and Ramanath Laxminarayan, have served as "non-imaging" oriented gold standards by providing feedback about the worth and value of the book to the non-medical applied scientific community. These are important considerations and I thank them. My active participation over the years in the technical programs of the IEEE Engineering in Medicine and Biology Society and especially my tenure as the Founding Editor-in-Chief of the IEEE Transactions on Information Technology has had a significant influence on my in-depth appreciation of the practical applications of diagnostic imaging. I want to recognize the Society, some of the medical imaging gurus in the Society and other leaders such as Charles Robinson, Yongmin Kim, Michael Vannier, Willis Tompkins, Christian Roux, Joseph Bronzino, Jean Louis Coatrieux, Banu Onaral, Jerry Harris, and others. To Joe Bronzino, our special thanks for his ever encouraging words of wisdom. I also want to recognize the deep sense of sacrifice of our families, during all the long hours we spent on the book. My loving thanks to my wife, Marijke, and my children, Vinod and Malini, for sharing with me the frustrations of my long absences from the regular schedule of life. Projects like this always remind me of my sister Ramaa, a musical genius, whose death at the tender age of 16 from epileptic complications inspired my biomedical engineering career.

The Editors

Jasjit S. Suri, Ph.D., received a B.S. in computer engineering with distinction from Maulana Azad College of Technology, Bhopal, India, an M.S. in computer sciences from the University of Illinois, Chicago, and a Ph.D. in electrical engineering from the University of Washington, Seattle. He has been working in the field of computer engineering/imaging sciences for more than 19 years. He has published more than 100 papers in the area of image sciences and medical engineering and has filed several U.S. patents.

He is a lifetime member of various research engineering societies including Tau Beta Pi, and Eta Kappa Nu, Sigma Xi, New York Academy of Sciences, Engineering in Medicine and Biology Society (EMBS), SPIE, ACM, and also a Senior Member of IEEE. He is on the editorial board/reviewer of several international journals, including *Real Time Imaging, Pattern Analysis and Applications, Engineering in Medicine and Biology Society, Radiology, Journal of Computer Assisted Tomography, IEEE Transactions on Information Technology in Biomedicine*, and *IASTED*. He has chaired image processing sessions at several international conferences and has given more than 40 international presentations.

Dr. Suri has published two books; the first book is in the area of medical imaging covering cardiology, neurology, pathology, and mammography imaging, primarily in collaboration with University of Exeter, England. The second book is in the area of mathematical imaging techniques applied to static and motion imagery. Dr. Suri has been listed in Who's Who five times (World, Executive, and Mid-West), is a recipient of the President's Gold Medal in 1980, and has been awarded more than 50 scholarly and extra-curricular awards during his career.

Dr. Suri has worked with Siemens and Philips. Currently, Dr. Suri is also completing his EMBA from Weatherhead School of Management, Case Western Reserve University, Cleveland, Ohio. He is also working as a Senior Research Scientist/Associate at Case Western Reserve University, Professor of Computer Science at University of Exeter, Exter, UK, and a Director of Biomedical Engineering Division, Jebra Wells and Technology, Inc., Cleveland, Ohio. Dr. Suri's major interests are imaging sciences, various fields in biomedical engineering, engineering management, software engineering, and the role of engineering in medicine management.

Swamy Laxminarayan is currently on the faculty of the Idaho State University and serves as the Chief of Biomedical Information Engineering at the Institute of Rural Health. Prior to joining ISU, he held several senior positions in both industry and academia. These have included serving as the Chief Information Officer at the National Louis University in Chicago, Director of the Pharmaceutical and Health Care Information Services at NextGen Internet (the premier Internet organization that spun off from the NSF-sponsored John von Neuman National Supercomputer Center in Princeton, NJ), Program Director of Biomedical Engineering and Research Computing at the University of Medicine and Dentistry in New Jersey, Director of Computational Biology, Vice-Chair of Advanced Medical Imaging Center, and Director of Clinical Computing at the Montefiore Hospital and Medical Center and the Albert Einstein College of Medicine in New York, Director of the VocalTec High Tech Corporate University in New Jersey, and the Director of the Bay Networks Authorized Center in Princeton. Prior to his immigration to the U.S., he was a faculty member as a Senior Research Investigator at the Physiology Laboratory of the Free University in Amsterdam, and at the Thorax Center of the Erasmus University in Rotterdam, the Netherlands. He also served as a Research Physicist at the Christian Medical College in Vellore and later became an Aerodynamicist and a Flight Test Engineer in Germany before he switched careers to biomedical engineering. Dr. Laxminarayan has had a long tenure as an Adjunct Professor of Biomedical Engineering at the New Jersey Institute of Technology, a Clinical Associate Professor of Health Informatics, a Visiting Professor at the University of Brno in the Czech Republic and an Honorary Professor of Health Sciences at Tsinghua University in China.

As an educator, researcher, technologist, and executive, Dr. Laxminarayan has been involved in biomedical engineering and information technology applications in medicine and healthcare for over 25 years and has published over 250 articles in international journals, books, and conferences. He has had the privilege of giving invitational keynote addresses at a number of international conferences. His expertise is in the areas of biomedical information technology, high performance computing, digital signals and image processing, bioinformatics, and physiological systems analysis. He has been actively involved in the technical activities of the IEEE Engineering in Medicine and Biology Society for over 20 years. He is the Founding Editor-in-Chief and an Editor Emeritus of the *IEEE Transactions on Information Technology in Biomedicine*. He also currently serves as an elected member at large on the IEEE Publications and Products Board. His technical and scientific contributions to the field of biomedical engineering and information technology have earned him numerous national and international awards. He is a Fellow of the American Institute of Medical and Biological Engineering, a recipient of the IEEE 3rd Millennium Medal, and a recipient of the Purkynje Award, one of the highest awards in Europe given to an American scientist by the Czech Academy of Medical Societies. Dr. Laxminarayan can be reached at s.n.laxminarayan@ieee.org.

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