HANDBOOK OF

Medical Imaging

Volume 2. Medical Image Processing and Analysis

Editorial Board

The images on the front cover are taken from figures in the text. *Top row:* left, Fig. 7.13(c), p. 430; middle, Fig. 2.14, p. 104; right, Fig. 6.10(b), p. 363 and color plate 1. *Middle row:* left, Fig. 11.27, p. 659; right, Fig. 13.28(d), p. 774, *Bottom:* Fig. 15.10(d), p. 937.

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Editors

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Preface to the Handbook of Medical Imaging

During the last few decades of the twentieth century, partly in concert with the increasing availability of relatively inexpensive computational resources, medical imaging technology, which had for nearly 80 years been almost exclusively concerned with conventional film/screen x-ray imaging, experienced the development and commercialization of a plethora of new imaging technologies. Computed tomography, MRI imaging, digital subtraction angiography, Doppler ultrasound-imaging, and various imaging techniques based on nuclear emission (PET, SPECT, etc.) have all been valuable additions to the radiologist's arsenal of imaging tools toward ever more reliable detection and diagnosis of disease. More recently, conventional x-ray imaging technology itself is being challenged by the emerging possibilities offered by flat panel x-ray detectors. In addition to the concurrent development of rapid and relatively inexpensive computational resources, this era of rapid change owes much of its success to an improved understanding of the information theoretic principles on which the development and maturation of these new technologies is based. A further important corollary of these developments in medical imaging technology has been the relatively rapid development and deployment of methods for archiving and transmitting digital images. Much of this engineering development continues to make use of the ongoing revolution in rapid communications technology offered by increasing bandwidth.

A little more than 100 years after the discovery of x rays, this three-volume *Handbook of Medical Imaging* is intended to provide a comprehensive overview of the theory and current practice of Medical Imaging as we enter the twenty-first century. Volume 1, which concerns the physics and the psychophysics of medical imaging, begins with a fundamental description of x-ray imaging physics and progresses to a review of linear systems theory and its application to an understanding of signal and noise propagation in such systems. The subsequent chapters concern the physics of the important individual imaging modalities currently in use: ultrasound, CT, MRI, the recently emerging technology of flat-panel x-ray detectors and, in particular, their application to mammography. The second half of this volume, which covers topics in psychophysics, describes the current understanding of the relationship between image quality metrics and visual perception of the diagnostic information carried by medical images. In addition, various models of perception in the presence of noise or "unwanted" signal are described. Lastly, the statistical methods used in determining the efficacy of medical imaging tasks, and

ROC analysis and its variants, are discussed.

Volume 2, which concerns Medical Image Processing and Image Analysis, provides descriptions of the methods currently being used or developed for enhancing the visual perception of digital medical images obtained by a wide variety of imaging modalities and for image analysis as a possible aid to detection and diagnosis. Image analysis may be of particular significance in future developments, since, aside from the inherent efficiencies of digital imaging, the possibility of performing analytic computation on digital information offers exciting prospects for improved detection and diagnostic accuracy.

Lastly, Volume 3 describes the concurrent engineering developments that in some instances have actually enabled further developments in digital diagnostic imaging. Among the latter, the ongoing development of bright, high-resolution monitors for viewing high-resolution digital radiographs, particularly for mammography, stands out. Other efforts in this field offer exciting, previously inconceivable possibilities, e.g., the use of 3D (virtual reality) visualization for surgical planning and for image-guided surgery. Another important area of ongoing research in this field involves image compression, which in concert with increasing bandwidth enables rapid image communication and increases storage efficiency. The latter will be particularly important with the expected increase in the acceptance of digital radiography as a replacement for conventional film/screen imaging, which is expected to generate data volumes far in excess of currently available capacity. The second half of this volume describes current developments in Picture Archiving and Communications System (PACS) technology, with particular emphasis on integration of the new and emerging imaging technologies into the hospital environment and the provision of means for rapid retrieval and transmission of imaging data. Developments in rapid transmission are of particular importance since they will enable access via telemedicine to remote or underdeveloped areas.

As evidenced by the variety of the research described in these volumes, medical imaging is still undergoing very rapid change. The editors hope that this publication will provide at least some of the information required by students, researchers, and practitioners in this exciting field to make their own contributions to its ever increasing usefulness.

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Introduction to Volume 2: Medical Image Processing and Analysis

The subject matter of this volume, which is well described by its name, *Medical Image Processing and Analysis*, has not until now been the focus of a rigorous, detailed, and comprehensive book. While there are many such books available for the more general subjects of image processing and image analysis, their broader scope does not allow for a thorough examination of the problems and approaches to their solution that are specific to medical applications. It is the purpose of this work to present the ideas and the methods of image processing and analysis that are at work in the field of medical imaging.

There is much common ground, of course. Image processing, whether it be applied to robotics, computer vision, or medicine, will treat imaging geometry, linear transforms, shift-invariance, the frequency domain, digital versus continuous domains, segmentation, histogram analysis, morphology, and other topics that apply to any imaging modality and any application. Image analysis, regardless of its application area, encompasses the incorporation of prior knowledge, the classification of features, the matching of models to subimages, the description of shape, and many of the generic problems and approaches of artificial intelligence. However, while these classic approaches to general images and to general applications are important, the special nature of medical images and medical applications requires special treatment. This volume emphasizes those approaches that are appropriate when medical images are the subjects of processing and analysis. With the emphasis placed firmly on medical applications and with the accomplishments of the more general field used as a starting point, the chapters that follow are able, individually, to treat their respective topics thoroughly, and they serve, collectively, to describe the current state of the field of medical image processing and analysis in great depth.

The special nature of *medical* images derives as much from their method of acquisition as it does from the subjects whose images are being acquired. While surface imaging is used in some applications, for example for the examination of the properties of skin in Chapter 19, medical imaging has been distinguished primarily by its ability to provide information about the volume beneath the surface, a capability that sprang first from the discovery of x radiation some one hundred years ago. Indeed, images are obtained for medical purposes almost exclusively to probe the otherwise invisible anatomy below the skin. This information may be in the form of the two-dimensional projections acquired by traditional radiography, the two-dimensional slices of B-mode ultrasound, or full three-dimensional mappings, such as those provided by computed tomography (CT), magnetic resonance (MR) imaging, single photon emission computed tomography (SPECT), positron emission tomography (PET), and 3D ultrasound. Volume 1 in this series provides a detailed look at the current state of these modalities.

In the case of radiography, perspective projection maps physical points into image space in the same way as photography, but the detection and classification of objects is confounded by the presence of overlying or underlying tissue, a problem rarely considered in general works on image analysis. In the case of tomography, three-dimensional images bring both complications and simplifications to processing and analysis relative to two-dimensional ones: The topology of three dimensions is more complex than that of two dimensions, but the problems associated with perspective projection and occlusion are gone. In addition to these geometrical differences, medical images typically suffer more from the problems of discretization, where larger pixels (voxels in three dimensions) and lower resolution combine to reduce fidelity. Additional limitations to image quality arise from the distortions and blurring associated with relatively long acquisition times in the face of inevitable anatomical motion – primarily cardiac and pulmonary, and reconstruction errors associated with noise, beam hardening, etc. These and other differences between medical and nonmedical techniques of image acquisition account for many of the differences between medical and nonmedical approaches to processing and analysis.

The fact that medical image processing and analysis deal mostly with living bodies brings other major differences in comparison to computer or robot vision. The objects of interest are soft and deformable with three-dimensional shapes whose surfaces are rarely rectangular, cylindrical, or spherical and whose features rarely include the planes or straight lines that are so frequent in technical vision applications. There are however major advantages in dealing with medical images that contribute in a substantial way to the analysis design. The available knowledge of what is and what is not normal human anatomy is one of them. Recent advances in selective enhancement of specific organs or other objects of interest via the injection of contrast-enhancing material represent others. All these differences affect the way in which images are effectively processed and analyzed.

Validation of the developed medical image processing and analysis techniques is major part of any medical imaging application. While validating the results of any methodology is always important, the scarcity of accurate and reliable independent standards creates yet another challenge for the medical imaging field.

Medical image processing deals with the development of problem-specific approaches to the enhancement of raw medical image data for the purposes of selective visualization as well as further analysis. Medical image analysis then concentrates on the development of techniques to supplement the mostly qualitative and frequently subjective assessment of medical images by human experts with a variety of new information that is quantitative, objective, and reproducible. Of course, a treatment of medical image processing and analysis without a treatment of the methods by which images are acquired, displayed, transmitted, and stored would provide only a limited view of the field. The two accompanying volumes of this handbook complete the picture with complementary information on all of these topics. Image acquisition approaches are presented in Volume 1, and image visualization, virtual reality, image transmission, compression, and archiving are dealt with in Volume 3.

The volume you hold in your hands is a result of the work of a dedicated team of researchers in medical image processing and analysis. The editors have worked very closely with the authors of individual chapters to produce a coherent volume with a uniformly deep treatment of all its topics, as well as to provide a comprehensive coverage of the field. Its pages include many cross references that further enhance the usability of the nineteen chapters, which treat separate but frequently interrelated topics. The book is loosely divided into two parts: Generally applicable theory is provided in Chapters 1–10 with the remaining chapters devoted more specifically to separate application areas. Nevertheless, many general approaches are presented in the latter group of chapters in synergy with information that is pertinent to specific applications. Each of the chapters is accompanied by numerous figures, example images, and abundant references to the literature for further reading.

The first part of this volume, which emphasizes general theory, begins with a rigorous treatment of **statistical image reconstruction** in Chapter 1. Author, *J. Fessler*, deals with the problems of tomographic reconstruction when the number of detected photons is so low that Poisson statistics must be taken into account. In this regime standard back-projection methods fail, but maximum likelihood methods, if properly applied, can still produce good images. Fessler gives a rigorous presentation of optimization methods for this problem with assessments of their practical implementation, telling us what works and what does not. The focus is on attenuation images, but the simpler problem of emission tomography is treated as well.

Image segmentation, which is the partitioning of an image into regions that are meaningful for a specific task, is one of the first steps leading to image analysis and interpretation. Chapter 2, which presents this subject, was written by *B. Dawant* and *A. Zijdenbos* and deals with the detection of organs such as the heart, the liver, the brain, or the lungs in images acquired by various imaging modalities.

Image **segmentation using deformable models** is the topic of Chapter 3, written by *C. Xu, D. L. Pham*, and *J. L. Prince*. Parametric and geometric deformable models are treated in a unifying way, and an explicit mathematical relationship between them is presented. The chapter also provides a comprehensive overview of many extensions to deformable models including deformable Fourier models, deformable superquadrics, point distribution models, and active appearance models.

Chapter 4, prepared by *J. Goutsias* and *S. Batman*, provides a comprehensive treatment of binary as well as gray-scale **mathematical morphology**. The theoretical concepts are illustrated on examples demonstrating their direct applicability to problems in medical image processing and analysis.

Chapter 5 is devoted to the **extraction of description features** from medical images and was written by *M. Loew*. The text summarizes the need for image features, categorizes them in several ways, presents the constraints that may determine which features to employ in a given application, defines them mathematically, and gives examples of their use in research and in clinical settings.

A. Guéziec authored Chapter 6, which describes methods for extracting **surface models of the anatomy** from medical images, choosing an appropriate surface representation, and optimizing surface models. This chapter provides detailed algorithms for surface representation and evaluates and compares their performance on real-life examples.

Image interpretation is one of the ultimate goals of medical imaging and utilizes techniques of image segmentation, feature description, and surface representation. It is heavily dependent on a priori knowledge and available approaches for pattern recognition, general interpretation, and understanding. It is also a frequent prerequisite for highly automated quantitative analysis. This topic is treated in Chapter 7 by *M. Brown* and *M. McNitt-Gray*.

Chapter 8 was authored by *J. M. Fitzpatrick, D. L. G. Hill,* and *C. R. Maurer, Jr.* and presents the field of **image registration**. The goal of registration, which is simply to map points in one view into corresponding points in a second view, is important when information from two images is to be combined for diagnosis or when images are used to guide surgery. This chapter presents the theoretical as well as experimental aspects of the problem and describes many approaches to its solution, emphasizing the highly successful application to rigid objects.

One of the promising directions of medical image analysis is the potential ability to perform **soft tissue characterization** from image-based information. This topic is treated in Chapter 9 by *M. Insana, K. Myers,* and *L. Grossman.* Tissue characterization is approached as a signal processing problem of extracting and presenting diagnostic information obtained from medical image data to improve classification performance, or to more accurately describe biophysical mechanisms. This chapter discusses in detail the difficulties resulting from the lack of accurate models of image signals and provides an insight into tissue modeling strategies.

Validation of the image analysis techniques is a necessity in medical imaging. In Chapter 10, *K. Bowyer* focuses on the problem of measuring the performance of medical image processing and analysis techniques. In this context, performance relates to the frequency with which an algorithm results in a correct decision. The chapter provides an overview of basic performance metrics, training and testing methodologies, and methods for statistical testing, as well as it draws attention to commonly occurring flaws of validation.

Chapter 11 opens the second part of this volume, which emphasizes applications, by providing detailed information about cardiac anatomy in the context of **echocardiographic imaging and analysis**. The chapter was written by *F. Sheehan, D. Wildon, D. Shavelle,* and *E. C. Geiser* and consists of sections devoted to echocardiographic imaging including 3-D echocardiography, echocardiographic assessment of ventricular volume, mass, and function, and their clinical consequences. Separate sections are devoted to imaging and analysis of valvular morphology and function as well as to an overview of available automated analysis approaches and their validation.

Ventricular motion and function is a topic of Chapter 12, which was contributed by *X. Papademetris* and *J. Duncan*. This chapter further explores the diagnostic utility of estimating **cardiac motion and deformation** from medical images. The authors focus primarily on the use of 3D MR image sequences, while also discussing the applications to ultrafast CT and 3D ultrasound. Description of magnetic resonance tagging, tag detection, and phase-contrast methods are all included and motion assessment is discussed in the context of the corresponding image data.

The following chapter, Chapter 13, is authored by *J. H. C. Reiber, G. Koning, J. Dijkstra, A. Wahle, B. Goedhart, F. Sheehan,* and *M. Sonka* and deals with minimally invasive approaches to **imaging the heart and coronary arteries** using contrast angiography and intravascular ultrasound. This chapter summarizes the preprocessing of angiography images, geometric correction techniques, and analysis approaches leading to quantitative coronary angiography as well as quantitative left ventriculography. Approaches for three-dimensional reconstruction from biplane angiography projections are discussed. Later sections deal with quantitative intravascular ultrasound techniques and introduce methodology for image data fusion of biplane angiography and intravascular ultrasound to achieve a geometrically correct representation of coronary lumen and wall morphology.

Chapter 14 treats ultrasound, MR, and CT approaches to non-invasive **vascular imaging** and subsequent image analysis. The chapter, written by *M. Sonka, A. Stolpen, W. Liang,* and *R. Stefancik*, covers the determination of intima–media thickness using carotid ultrasound, assessment of brachial artery endothelial function, as well as the imaging of peripheral and brain vasculature via MR angiography and x-ray CT angiography. The chapter contains methods for determining the topology and morphology of vascular structures and demonstrates how X-ray CT can be used to determine coronary calcification. Overall, facilitating early diagnosis of cardiovascular disease is one of the main goals of the methodologies presented.

Mammography accounts for one of the most challenging, as well as most promising, recent additions to the set of highly automated applications of medical imaging. In Chapter 15 authors, *M. L. Giger, Z. Huo, M. A. Kupinski,* and *C.*

J. Vyborny, provide a comprehensive treatment of computer-aided diagnosis as a second opinion for the mammographer. The entire process of image acquisition, segmentation, lesion extraction, and classification is treated in this comprehensive chapter along with a careful look at the important problem of clinical validation.

Pulmonary imaging and analysis is the topic of Chapter 16, prepared by *J. Reinhardt, R. Uppaluri, W. Higgins,* and *E. Hoffman*. After a brief overview of pulmonary anatomy and a survey of methods and clinical applications of pulmonary imaging, the authors discuss pulmonary image analysis leading to the segmentation of lungs and lobes, vascular and airway tree segmentation, as well as the role of virtual bronchoscopy. Approaches for the characterization of pulmonary tissue are discussed followed by sections devoted to pulmonary mechanics, image-based perfusion and ventilation, and multi-modality data fusion.

Chapter 17, authored by *P. M. Thompson, M. S. Mega, K. L. Narr, E. R. Sowell, R. E. Blanton,* and *A. W. Toga*, presents the subjects of **brain imaging, analysis, and atlas construction**. The authors describe brain atlases that fuse data across subjects, imaging modalities, and time, storing information on variations in brain structure and function in large populations. The chapter then reviews the main types of algorithms used in brain image analysis, including approaches for non-rigid image registration, anatomical modeling, tissue classification, cortical surface mapping, and shape analysis. Applications include the use of atlases to uncover disease-specific patterns of brain structure and function, and to analyze the dynamic processes of brain development and degeneration.

Chapter 18, by *M. W. Vannier*, is devoted to **tumor imaging, analysis, and cancer treatment planning**. The chapter summarizes the use of imaging in diagnosis and treatment of solid tumors. It emphasizes current imaging technologies and image processing methods used to extract information that can guide and monitor interventions after cancer has been detected leading to initial diagnosis and staging.

Chapter 19, the concluding chapter of this volume, deals with light imaging of **soft tissue movement and its finite element modeling**. It was contributed by *L. V. Tsap, D. B. Goldgof,* and *S. Sarkar*. The main topic is the analysis of soft tissue motion descriptors not easily recoverable from visual observations. The descriptors include strain and initially unknown (or hard to observe) local material properties. New methods for human tissue motion analysis from range image sequences using the nonlinear finite element method are provided, and their practical utility is demonstrated, using assessment of burn scar tissue severity and the extent of repetitive motion injury.

Medical image processing and analysis has, over the last thirty years or so, evolved from an assortment of medical applications into an established discipline. The transition has been achieved through the cooperation of a large and growing number of talented scientists, engineers, physicians, and surgeons, many of whose ideas and accomplishments are detailed by the authors of these chapters. We have produced this volume in order to make these achievements accessible to researchers both inside and outside the medical imaging field. It is our hope that its publication will encourage others to join us in the common goal of improving the diagnosis and treatment of disease and injury by means of medical imaging.

Acknowledgments

This volume was prepared using the $\LaTeX\,2_\varepsilon$ publishing tool. All communication between the editors and authors was carried out over the Internet via E-mail, FTP, and the Web. All the authors, who contributed the individual chapters and agreed to adhere to strict deadlines and the demanding requirements of common formatting and cross referencing across chapter boundaries, share in the credit for the final product as you see it. Their enthusiasm, patience, and cooperation helped us to overcome all the obstacles that we encountered during preparation of this publication.

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