HANDBOOK OF
Medical Imaging
Volume 1. Physics and Psychophysics
The cover illustration shows views of a knee obtained after trauma in which the conventional x-ray images show only minimal abnormality of the bone while the MRI shows more extensive injury to the bone and ligaments. See Chapter 12, p. 671, Effects of Anatomical Structure on Signal Detection, Ehsan Samei, William Eyler and Lisa Baron.
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Preface

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, pro-
vides descriptions of the methods currently being used or developed for enhanc-
ing 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 di-
gnosis. Image analysis may be of particular significance in future developments, 
since, aside from the inherent efficiencies of digital imaging, the possibility of per-
forming 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 mam-
mography, stands out. Other efforts in this field offer exciting, previously incon-
ceivable possibilities, e.g., the use of 3D (virtual reality) visualization for surgi-
cal planning and for image-guided surgery. Another important area of ongoing re-
search 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 accep-
tance of digital radiography as a replacement for conventional film/screen imaging, 
which is expected to generate data volumes far in excess of currently available ca-
pacity. The second half of this volume describes current developments in Picture 
Archiving and Communications System (PACS) technology, with particular em-
phasis on integration of the new and emerging imaging technologies into the hos-

torial 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.

Jacob Beutel
J. Michael Fitzpatrick
Steven C. Horii
Yongmin Kim
Harold L. Kundel
Milan Sonka
Richard L. Van Metter
Introduction to Part I

During the last half of the twentieth century, Medical Imaging has undergone a series of revolutionary changes. These have not only been driven by advances in the underlying science and technology, but by changes in the needs of health care providers. The diagnostic quality of images available to physicians as well as the variety and scope of available imaging technologies has expanded beyond what could have been imagined fifty years ago. The pace of this change is still accelerating. In part this revolution is attributable to advances in our fundamental understanding of the physical phenomena on which the imaging technologies are based. But the useful application of this understanding has been enabled by an increasing availability of computational power and high-speed data communications. Networked computational resources have been harnessed to support both the increasing pace of scientific research and, more importantly, to handle the vast amounts of data that digital imaging technologies require.

The best-known advances in medical imaging have applied digital imaging technology to previously unexploited physical measurables. Here the fortuitous combination of physical understanding and ever-increasing, widely available computational power have enabled the development and widespread adoption of ultrasound imaging, tomography, and magnetic resonance imaging. Further improvements and extensions of the scope of these imaging modalities are the subject of many ongoing research and development efforts. More speculative efforts are aimed toward discovering new “signals” that can be utilized for diagnostic purposes.

Even as new imaging technologies have found their place in medical diagnosis, classical x-ray projection radiography itself is undergoing a revolution. This began with the development of commercial Computed Radiography systems in the 1980s. At first large and expensive, technological advances have steadily reduced size and cost, while the usefulness of digital images has increased due to the ever-expanding information technology infrastructure in medicine. Here technological advances and the challenges of providing health care to a greater number of people more efficiently than ever before are driving revolutionary change. Research is now concentrated on the development of flat panel digital detectors whose possible applications range from digital mammography to conventional diagnostic radiography and fluoroscopy. Ultimately these detectors will lower the cost and increase
the availability of diagnostic imaging thereby completing the transition to a totally digital medical imaging environment where image information will be better utilized to guide patient care.

Concurrent with all of these changes, our understanding of imaging science, largely derived from information theoretic considerations developed during the 1950s, has developed to the point where it can effectively guide system optimization. This initially allowed conventional x-ray imaging systems to be optimized well beyond their prior capabilities. Now with the separation between image capture and image display enabled by digital imaging technology, we pursue the heretofore unavailable opportunity of independently optimizing these two subsystems. This will bring image quality closer than ever before to the currently understood fundamental limits.

As we begin the new century, this volume provides a snapshot of our current understanding of the physics of medical imaging written by authors who have contributed significantly to its development. The first three chapters describe the fundamental physics and imaging science on which x-ray projection radiography is based. Together these provide the basis for the ongoing improvements and new developments aimed at optimizing the performance of these imaging systems. The unifying signal-to-noise concepts described are now accepted as the technology-independent absolute criteria by which progress is measured for all imaging modalities. These lead naturally to a discussion of the exciting developments in detector technology for digital radiography. Therefore, the next two chapters describe the most recent developments in flat panel detectors for digital mammography and general projection x-ray imaging. The most exciting imaging technologies to emerge in this information age allow us to fully visualize the three-dimensional structure of human anatomy. They are the focus of the final three chapters in Part I. Of these, the first two describe current practices incorporating the latest developments in magnetic resonance imaging and computed tomography. They are followed, in the final chapter, by a description of recent developments in volume ultrasound imaging.

Jacob Beutel
Richard L. Van Metter
Introduction to Part II

Human observers are an integral part of any imaging system. Image quality can be described in purely physical terms, but optimal image quality can only be described with reference to the performance of an imaging task. The relation between physical image quality and diagnostic performance is the borderland between physics and psychology known as psychophysics. The first three chapters in the perception section deal with the current state of the art in the development and testing of psychophysical models for predicting human observer performance. Myers provides an overview of ideal observer models, Abbey and Buchod describe linear models, Eckstein, Abbey and F. O. Buchod provide an overview of available models and a roadmap for future model development. The chapter by Wilson, Jabri, and Manjeshwar shows how human observer models can actually be used to improve the design of dynamic fluoroscopic imaging systems. The chapter by Samei, Eyler and Baron on the effect of anatomical backgrounds on perception provides a bridge between the hardcore psychophysics and the softer studies of human image perception by considering the problems of moving from statistically defined images to real images of real people. Rolland summarizes the progress in the simulation of realistic yet mathematically definable backgrounds for use in the models.

The methodology for assessing human performance is very important because there is wide variability both within and between human observers even when they perform relatively simple visibility and detection tasks. The receiver operating characteristic (ROC) analysis has emerged as one of the major statistical analytical tools available to characterize human performance. It can correct for variability in the application of decision criteria. It is an active area of research in imaging. The chapter by Metz updates this very important methodology and elaborates its strengths and weaknesses, while the chapter by Chakraborty describes some of the variants of classical ROC analysis and their application to special problems in diagnostic imaging. There is also a need to go beyond the limitations imposed by the use of the ROC analysis. One approach is to evaluate observer agreement rather than the accuracy. The chapter by Polansky reviews the classical method for measuring agreement in imaging and describes an alternative methodology based on mixture distribution analysis.

Human performance even on simple tasks such as detecting tumors or fractures is complicated by the need to locate abnormalities embedded in the complex patterns of anatomical details on images. The chapter by Kundel deals with the role of
visual search in detection tasks. Human performance also depends upon expertise-the combination of talent, training, and experience. Nodine and Mello-Thoms review the status of studies of expertise in radiology and stress the implications for training and certifying radiologists.

In the final chapter Krupinski reviews the contributions that have been made by image perception research to the field of medical imaging.

It is the hope of the editor that these chapters mark just the beginnings of our knowledge about the perception of medical images. They provide summaries, reviews, and comprehensive bibliographies. What a place to start learning.

Harold L. Kundel