

HANDBOOK OF

# Medical Imaging

---

Volume 1. Physics and Psychophysics

## Editorial Board

---

**Jacob Beutel**  
*Consultant*

**J. Michael Fitzpatrick**  
*Vanderbilt University*

**Steven C. Horii**  
*University of Pennsylvania Health Systems*

**Yongmin Kim**  
*University of Washington*

**Harold L. Kundel**  
*University of Pennsylvania Health Systems*

**Milan Sonka**  
*University of Iowa*

**Richard L. Van Metter**  
*Eastman Kodak Company*

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.

HANDBOOK OF

# Medical Imaging

---

Volume 1. Physics and Psychophysics

Jacob Beutel  
Harold L. Kundel  
Richard L. Van Metter  
*Editors*

**SPIE**  
PRESS

Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Handbook of medical imaging / [edited by] Jacob Beutel, Harold L. Kundel,  
and Richard L. Van Metter

p. cm.

Includes bibliographical references and index.

Contents: v. 1. Progress in medical physics and psychophysics.

ISBN 978-0-8194-3621-6 (hardcover: alk. paper)

1. Diagnostic imaging—Handbooks, manuals, etc. 2. Imaging systems in  
medicine—Handbooks, manuals, etc. I. Beutel, Jacob. II. Kundel, Harold L.  
III. Van Metter, Richard L.

[DNLM: 1. Diagnostic Imaging—Handbooks. 2. Health Physics—Handbooks.

3. Image Processing, Computer-Assisted—Handbooks. 4. Psychophysics—  
Handbooks. 5. Technology, Radiologic—Handbooks. WN 39 H2363 2000]

RC78.7.D53 H36 2000

616.07'54—dc21

99-054487

CIP

Vol. 1 ISBN 978-0-8194-7772-9 (Softcover)

*Physics and Psychophysics*, edited by Richard L. Van Metter, Jacob Beutel, and Harold L. Kundel.

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: +1 360 676 3290

Fax: +1 360 647 1445

Email: [Books@SPIE.org](mailto:Books@SPIE.org)

Web: <http://spie.org>

Copyright © 2000 Society of Photo-Optical Instrumentation Engineers

All rights reserved. No part of this publication may be reproduced or distributed  
in any form or by any means without written permission of the publisher.

The content of this book reflects the thought of the authors. Every effort has been  
made to publish reliable and accurate information herein, but the publisher is not  
responsible for the validity of the information or for any outcomes resulting from  
reliance thereon.

Printed in the United States of America.



# Contents

**Preface / xi**

## **PART I. PHYSICS**

**Introduction / xv**

### **Chapter 1. X-ray Production, Interaction, and Detection in Diagnostic Imaging / 1**

*John M. Boone*

- 1.1 X-ray production / 3
- 1.2 X-ray interactions / 17
- 1.3 X-ray spectra / 40
- 1.4 X-ray dosimetry / 58
- 1.5 X-ray detection / 64
- References / 77

### **Chapter 2. Applied Linear-Systems Theory / 79**

*Ian A. Cunningham*

- 2.1 Introduction / 82
- 2.2 Background concepts / 83
- 2.3 Introduction to linear-systems theory / 91
- 2.4 The spatial-frequency domain / 100
- 2.5 Stochastic processes in linear systems / 108
- 2.6 Metrics of system performance / 115
- 2.7 Noise transfer in cascaded imaging systems / 126
- 2.8 Cascaded DQE and quantum sinks / 131
- 2.9 Metrics of digital-system performance / 137
- 2.10 Analysis of a simple digital detector array / 145
- 2.11 Summary / 155
- References / 156

**Chapter 3. Image Quality Metrics for Digital Systems / 161**

*James T. Dobbins, III*

- 3.1 Introduction / 163
- 3.2 Global parameter assessment / 163
- 3.3 Spatial-frequency assessment / 178
- 3.4 Image-processing assessment / 203
- 3.5 Observer assessment / 211
- References / 219

**Chapter 4. Flat Panel Detectors for Digital Radiography / 223**

*John A. Rowlands and John Yorkston*

- 4.1 Introduction / 225
- 4.2 X-ray detection media / 234
- 4.3 Flat-panel array technology / 253
- 4.4 Configuration and operation of a flat-panel x-ray imager / 276
- 4.5 Methods of evaluating performance / 286
- 4.6 Clinical applications of complete systems / 300
- 4.7 Future prospects / 312
- References / 313

**Chapter 5. Digital Mammography / 329**

*Martin J. Yaffe*

- 5.1 Introduction / 331
- 5.2 Digital mammography / 336
- 5.3 X-ray detectors for digital mammography / 345
- 5.4 Display of digital mammograms / 359
- 5.5 Clinical status of digital mammography / 362
- 5.6 Applications of digital mammography / 362
- 5.7 Tele mammography / 363
- 5.8 Tomosynthesis / 365
- 5.9 Quantitative image analysis: Risk assessment / 365
- 5.10 Dual-energy mammography / 366
- 5.11 Contrast-uptake imaging of the breast / 366
- 5.12 Conclusion / 366
- References / 367

**Chapter 6. Magnetic Resonance Imaging / 373**

*David Pickens*

- 6.1 Introduction / 375
- 6.2 Basic principles / 376
- 6.3 Magnetic resonance imaging / 388
- 6.4 Common artifacts / 419
- 6.5 Hardware and software components / 427

- 6.6 Current techniques and areas of research / 440
- 6.7 Conclusions: What does the future hold? / 457
- References / 458

## **Chapter 7. Three-Dimensional Ultrasound Imaging / 463**

*Aaron Fenster, Donal B. Downey*

- 7.1 Introduction / 465
- 7.2 Limitations of ultrasonography addressed by 3D imaging / 466
- 7.3 Three-dimensional ultrasound scanning techniques / 467
- 7.4 Reconstruction of the 3D ultrasound images / 481
- 7.5 Effects of errors in 3D ultrasound image reconstruction / 483
- 7.6 Viewing of 3D ultrasound images / 487
- 7.7 Three-dimensional ultrasound system performance / 491
- 7.8 Trends and future developments / 498
- 7.9 Conclusions / 501
- References / 501

## **Chapter 8. Tomographic Imaging / 511**

*David J. Goodenough*

- 8.1 Introduction / 512
- 8.2 Overview of CT as an image device / 512
- 8.3 Scanner design / 513
- 8.4 Reconstruction techniques / 523
- 8.5 CT image quality / 527
- 8.6 Other artifacts in CT / 537
- 8.7 Multislice CT / 537
- 8.8 CT scanner performance / 543
- 8.9 Developments in other modalities / 550
- 8.10 Conclusions / 552
- References / 552

## **PART II. PSYCHOPHYSICS**

### **Introduction / 557**

## **Chapter 9. Ideal Observer Models of Visual Signal Detection / 559**

*Kyle J. Myers*

- 9.1 Introduction / 561
- 9.2 The Bayesian or ideal observer / 568
- 9.3 Calculation of ideal-observer performance: examples / 572
- 9.4 Comparison with human performance / 582
- 9.5 Estimation of ideal observer performance from finite samples / 585

viii Contents

- 9.6 Estimation tasks / 585
- 9.7 Closing remarks / 586
- References / 587

**Chapter 10. A Practical Guide to Model Observers for Visual Detection in Synthetic and Natural Noisy Images / 593**

*Miguel P. Eckstein, Craig K. Abbey and François O. Bochud*

- 10.1 Introduction / 595
- 10.2 Key components for the use of model observers / 596
- 10.3 Visual tasks for model observers / 596
- 10.4 Signals and backgrounds / 598
- 10.5 Model observers / 602
- 10.6 Calculation of figures of merit / 614
- 10.7 Comparing model to human performance / 620
- 10.8 Concluding remarks / 622
- References / 623

**Chapter 11. Modeling Visual Detection Tasks in Correlated Image Noise with Linear Model Observers / 629**

*Craig K. Abbey, François O. Bochud*

- 11.1 Introduction / 630
- 11.2 Mathematical preliminaries / 631
- 11.3 Modeling signal-detection tasks / 635
- 11.4 Linear model observers / 643
- 11.5 Summary / 650
- References / 651

**Chapter 12. Effects of Anatomical Structure on Signal Detection / 655**

*Ehsan Samei, William Eyer, Lisa Baron*

- 12.1 Introduction / 656
- 12.2 Anatomical structure as noise / 656
- 12.3 Perceptual effects of anatomical structure / 660
- 12.4 Effects of anatomical structure in selected clinical applications / 666
- 12.5 Methods for reducing the effects of anatomical structure / 673
- 12.6 Conclusions / 677
- References / 678

**Chapter 13. Synthesizing Anatomical Images for Image Understanding / 683**

*Jannick P. Rolland*

- 13.1 Introduction / 685
- 13.2 Computer-simulated angiograms / 686
- 13.3 Synthesizing lumpy backgrounds / 694



- 13.4 Modeling liver scans / 701
- 13.5 Synthesizing ultrasound B-scan images / 706
- 13.6 Texture synthesis / 710
- 13.7 Conclusion and future work / 715
- References / 717

#### **Chapter 14. Quantitative Image Quality Studies and the Design of X-Ray Fluoroscopy Systems / 721**

*David L. Wilson, Kadri N. Jabri, Ravindra M. Manjeshwar*

- 14.1 Introduction / 723
- 14.2 Modeling / 725
- 14.3 Methods / 728
- 14.4 Results and discussion / 733
- 14.5 Implications for x-ray system design / 741
- 14.6 Conclusions / 745
- References / 745

#### **Chapter 15. Fundamental ROC Analysis / 751**

*Charles E. Metz*

- 15.1 Introduction / 752
- 15.2 The ROC curve as a description of diagnostic accuracy / 752
- 15.3 Independent variables and sources of bias / 753
- 15.4 ROC indices / 753
- 15.5 Confidence-rating scales / 754
- 15.6 Other issues in experimental design / 755
- 15.7 Comments on forced-choice methodology / 759
- 15.8 ROC curve fitting / 761
- 15.9 Statistical tests for differences between ROC estimates / 762
- 15.10 Ordinal regression techniques / 763
- 15.11 An overview / 764
- References / 764

#### **Chapter 16. The FROC, AFROC and DROC Variants of the ROC Analysis / 771**

*Dev P. Chakraborty*

- 16.1 FROC methodology / 772
- 16.2 DROC methodology / 789
- References / 793

#### **Chapter 17. Agreement and Accuracy Mixture Distribution Analysis / 797**

*Marcia Polansky*

- 17.1 Introduction / 798
- 17.2 Kappa coefficient and Aickens's Alpha / 801

x Contents

- 17.3 Other models for agreement / 811
- 17.4 Mixture distributions of binomials / 816
- 17.5 Summary / 832
- References / 833

**Chapter 18. Visual Search in Medical Images / 837**

*Harold L. Kundel*

- 18.1 Introduction / 838
- 18.2 The organization of the visual system / 839
- 18.3 Visual scanning as a method for studying visual search / 847
- 18.4 Current problems in visual search / 852
- References / 855

**Chapter 19. The Nature of Expertise in Radiology / 859**

*Calvin F. Nodine, Claudia Mello-Thoms*

- 19.1 Introduction / 860
- 19.2 Plan of the chapter / 861
- 19.3 Expertise roots / 862
- 19.4 Expertise, acquired or innate? / 863
- 19.5 What is learned from reading medical images? / 867
- 19.6 Connectionism—another approach to information processing / 881
- 19.7 Conclusions / 889
- References / 891

**Chapter 20. Practical Applications of Perceptual Research / 895**

*Elizabeth A. Krupinski*

- 20.1 Introduction / 896
- 20.2 Bridging the gap between research and clinical practice / 896
- 20.3 Image display and workstation design / 899
- 20.4 Prompting/cueing to improve diagnostic performance / 912
- 20.5 Color applications in radiology / 917
- 20.6 Conclusions / 918
- References / 920

**Index / 931**

## 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, 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.

**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**