Digital Radiography

Euclid Seeram

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Physical Principles and Quality Control

Second Edition

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This book is dedicated to my two smart, precious, and overall cute granddaughters, Claire and Charlotte, with love and blessings to you both forever.

Foreword

Planar or general radiography is the most common imaging examination in medicine. It is an important tool for clinicians to consider when making a diagnosis of an illness or injury for a patient.

Digital radiography is now the method to capture and display radiographic images. Digital radiography is a modality within the highly technological imaging world of computed tomography, magnetic resonance imaging, diagnostic ultrasound, positron emission tomography, and other complex digital imaging modalities. Digital radiographs require complex image processing to enable clinicians to fully visualize image detail. Digital images must be storable, transferrable, and recallable at distant locations and must meet quality standards to provide the required diagnostic patient information.

Radiographers/radiologic technologists and radiologists must understand the physical principles and technical details of digital radiography imaging systems such as computed radiography, flat-panel digital systems, digital fluoroscopy, and digital mammography in order to maximize image quality from the captured X-ray data. This text provides an insight into the understanding of digital radiography imaging modalities. It describes the acquisition of these images in the context of the digital environment through an explanation of the basic digital image processing, image storage, and transmission and explains the process of quality control in digital radiography.

The name Euclid Seeram has become synonymous with radiography education. Euclid has decades of experience in teaching all the areas of medical imaging. During this time he has gained worldwide respect as an educator and an author. Euclid has the gift of being able to explain difficult concepts in a way that students can grasp. This has been seen in his other texts. This book continues in this tradition and makes complex concepts easier to understand.

The success of the first edition is only part of the story of Euclid's contributions in the field. He continues to promote updated educational content for technologists, including a website of DR artifacts. By the time I met Euclid again at one of a series of CR and DR workshops that Larry Filipow, a Canadian pioneer in DR and PACS, Tony Seibert, an American pioneer in DR and PACS, and I were presenting across Canada, his work was well known throughout North America. Coincidentally, in individual conversations with Euclid, each of us said essentially the same thing: "we like what you're doing for the technologists!"

Through his efforts to provide practical and understandable information to the individuals who have the responsibility to produce the DR images, Euclid has made a broad positive impact on the quality of DR operations.

Students will appreciate the detail, ease of explanation, and breadth of treatment of the topics in digital radiography. His mother properly named him Euclid expecting him to complement this moniker for science and mathematics. Furthermore, Euclid has demonstrated a continual quest for knowledge in the medical imaging sciences field via his numerous lifelong education pursuits. Having completed courses in digital radiography from several notable experts in the field as well as a course on medical imaging informatics from Stanford University, he has also obtained a certificate of MRI Physics from the American Association of Physicists in Medicine summer school. He is a full member of the Health Physics Society and has been active in the field of Radiation Protection, which led to his PhD dissertation entitled "*Optimization of the Exposure Indicator of a Computed Radiography Imaging System as a Radiation Dose Management Strategy.*"

Euclid is willing to share this knowledge with the imaging community. These efforts continue to make him a successful author and educator. For those studying in the field of medical imaging or for those just wishing to gain a high level understanding of digital radiography, we highly recommend this book.

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Preface

The motivation for a second edition of this book stems from the continued *technical evolution* of digital radiographic imaging systems, as well as the introduction of new principles, issues, and ideas relating to digital imaging. With these considerations in mind, the book is now titled *Digital Radiography: Physical Principles and Quality Control.* Furthermore, technical advances have been a recurring feature in digital detector technology and the development of a standardized exposure indicator by the International Electrotechnical Commission (IEC), Picture Archiving and Communication Systems (PACS), and imaging informatics. The next era in imaging informatics will include topics such as enterprise imaging, cloud computing, big data, and artificial intelligence (AI) including subsets of AI such as machine learning and deep learning.

Furthermore, there has been a significant development of a technique referred to as digital tomosynthesis featuring two main application areas: radiographic tomosynthesis and digital breast tomosynthesis (DBT).

An important consideration from this new title is the lack of textbooks on this subject for radiologic technologists especially one that includes dose optimization principles, an essential ingredient that provides significant guiding principles to clinical practitioners to work within the ALARA (as low as reasonably achievable) philosophy, in an effort to protect not only the patient but personnel as well.

New to This Edition

The chapters in this book have been updated to address the continued technical evolution and major technology trends in digital radiographic imaging. Furthermore, a set of updated articles have been cited to support the inclusion of major new technical areas of current interest in clinical practice such as the following: the standardized exposure indicator, digital tomosynthesis, and enterprise imaging, including vendor neutral archives (VNAs), cloud computing, big data (BG), and artificial intelligence (AI) including subsets of AI such as machine learning and deep learning. The addition of numerous new images illustrates the fundamental principles of these new technologies, and new line drawings serve to enhance and provide important concepts in the text. Last but not least, a reasonable effort has been

made to keep the cited literature current. These references are important since they serve a twofold purpose:

1. To validate the statements made in the textbook regarding digital radiography physical principles and applications
2. To guide the student to the primary and secondary sources of information that serve as the fundamental basis for pursuing their own research and presentations

Purpose

The purpose of this textbook is fourfold as follows:

1. To provide a comprehensive coverage of the physical principles of digital radiography imaging systems and associated technologies, such as Picture Archiving and Communication Systems (PACS), VNAs, and new topics in medical imaging informatics, such as cloud computing, VNAs, BG, digital tomosynthesis, and AI and its subsets
2. To lay the theoretical foundations necessary for the effective use of digital radiography in clinical practice
3. To enhance communication among radiology personnel such as technologists, radiologists, medical physicists, biomedical engineers, and between radiology personnel and vendors
4. To meet the educational requirements of various radiologic technology professional organizations including the American Society of Radiologic Technologists, the American Registry of Radiologic Technologists, the Canadian Association of Medical Radiation Technologists, the College of Radiographers in the United Kingdom, as well as those in Africa, Asia, Australia, and continental Europe

Content and Organization

The content and organization of the book have not been changed significantly; however, certain chapters have been deleted completely, and some content has been reshaped and added to "new" chapters. For example, in the first edition, *Chap. 4*, *Effective Use of Computed Radiography (CR)*, has been deleted. This chapter was written by a dear friend of mine Barry Burns, MS, RT (R), DABR. Barry was a Professor—Division of Radiologic Science, School of Medicine, University of North Carolina, Chapel Hill, North Carolina. Barry passed away in 2016 (God bless him).

Another chapter, Chap. 10, *Quality Control for Digital Radiography*, that was part of the first edition, was written by Dr. Charles Willis, PhD, DABR, Associate Professor, Department of Imaging Physics, University of Texas, MD Anderson Cancer Center, Houston, Texas. In this chapter, several topic areas have been included, in particular Sections Sect. 11.4 "Understanding Processes and Errors in Digital Radiography" and Sect. 11.7 "Responsibilities

for DR QC." Such materials are attributed to Dr. Charles Willis, PhD. I am grateful to Dr. Willis, who graciously gave his permission to reuse these materials. This chapter is Chap. 11 in this book, and the new title is *Continuous Quality Improvement for Digital Radiography.* Furthermore *three new chapters have been added, Chaps. 5, 8, and 12*.

The content and organization of the book are based on the following structures:

- Brief historical developments of digital radiography imaging systems
- Digital image processing fundamentals
- Physical principles and technological aspects of digital radiography imaging modalities
- Effective use of technologies that are integral components of digital imaging systems, for example, tomosynthesis including DBT, PACS, imaging informatics, and quality control procedures

Chapter 1 presents an *Overview of the Technologies* that constitute the subject matter of this book including a discussion of the limitations of film-based radiography and the major structural components of digital radiography imaging systems as well as brief description of the image acquisition detectors, PACS, and imaging informatics.

Chapter 2 provides a detailed description of the topic of *Digital Image Processing*, a topic that is of particular importance in today's digital clinical imaging practice.

Chapter 3 deals with the basic physics and technology of *Computed Radiography* (CR) and describes, specifically, the physics of photostimulable luminescence, CR technical components, image processing, exposure control in CR, and image quality descriptors for CR and presents an overview of artifacts. Finally the chapter concludes with a brief introduction of selected quality control tests for CR, using quality criteria for assessment.

Chapter 4 is devoted to *Flat-Panel Digital Radiography* imaging systems and includes a description of the different types of flat-panel digital imaging systems, design characteristics, operating principles, image processing, and imaging performance characteristics such as spatial resolution, modulation transfer function, dynamic range, detective quantum efficiency, image lag, and image artifacts. Wireless digital detectors are briefly introduced.

Chapter 5 is a new chapter focusing on details of the *Standardized Exposure Indicator* (EI) through a description of the conditions for the IEC standardized EI, various definitions, determination of the standardized EI, interpretation of deviation index (DI) values, factors affecting EI values, responsibilities, and an objective approach for establishing target EI values.

Chapter 6 provides a description of the technical aspects and image processing for *Digital Fluoroscopy Systems*, based on image intensifiers and flat-panel digital detectors, as well as the fundamental physical principles of digital subtraction angiography.

Chapter 7 describes the essential technological aspects of *digital mammography*. Topics include types of detectors, digital image processing, and

various applications such as digital tomosynthesis and computer-aided detection and diagnosis.

Chapter 8 is a *new chapter* dealing *Digital Tomosynthesis*. Topics include definition and principles (image acquisition and system components, image acquisition parameters, image reconstruction, image display and communication), radiation dose considerations, synthesized 2D digital mammography, and clinical applications.

Chapter 9 examines the major components, and *core technologies of PACS* are described in detail followed by an outline of the bare essentials of information systems and communication standards for digital radiology, including DICOM (Digital Imaging and Communications in Medicine), HL-7 (Health Level-7), and the technical framework of IHE (Integrating the Healthcare Enterprise). Furthermore the concepts relating to vendor neutral archives (VNAs) and enterprise imaging (EI), including a definition of EI and the major elements of an enterprise imaging system, are presented.

Chapter 10 outlines the major components of medical *imaging informatics*, an evolving field for the digital radiography community. Examples of these components include the health information systems, electronic health record, systems integration, information technology (IT) security fundamentals, and skills and certification of a PACS technologist. Additionally *new topics* that are considered emerging topics in imaging informatics are introduced in this chapter. In particular, these topics include *cloud computing*, *big data*, *artificial intelligence*, *machine learning*, and *deep learning*.

Chapter 11 presents a detailed description of the elements of *Continuous Quality Improvement in Digital Radiography*. Major topics described include significant elements of continuous quality improvement (CQI) such as definitions of quality assurance (QA) and quality control (QC), dose optimization, parameters for QC monitoring in digital radiography, and tolerance limits or acceptance criteria. The next important section of this chapter reviews the processes and errors in digital radiography, responsibilities for digital radiography QC, and an overview of digital mammography QC (topics that were addressed in detail in the first edition of this book and written by Dr. Charles Willis, PhD, as mentioned above, under the topics of "Content and Organization"). In addition, four QC tests for digital radiography have been described in a manner that students can conduct them in a radiography laboratory.

Chapter 12 is a *new chapter* and the final chapter in this book. It deals primarily with *Dose Optimization in Digital Radiography*, through a description of topics such as dose optimization approaches (optimization of kVp, optimization of mAs, optimization of the exposure indicator (EI)) and dose optimization tools and methods for image quality assessment. Finally the chapter concludes with an overview of the method of visual grading of normal anatomy and optimization of the EI as a dose management strategy.

Use and Scope

The purpose of this comprehensive text is to meet the wide and varied requirements of its users, students, and educators alike. Therefore this book can meet many different educational and program needs. *Digital Radiography: Physical Principles and Quality Control* can be used as the primary text for introductory digital imaging courses at the diploma, associate, and baccalaureate degree levels. Additionally, it can be used as a resource for continuing education programs; it functions as a reference text for others working in radiology, for example, biomedical engineering professionals. Finally it provides the required overview of the physical principles and technological considerations and may be viewed as providing the needed prerequisites for graduate-level (master's degree) courses in digital radiography.

The content is intended to meet the educational requirements of various radiologic technology professional associations including the *American Society of Radiologic Technologists* (ASRT), the *American Registry of Radiologic Technologists* (ARRT), the *Canadian Association of Medical Radiation Technologists* (CAMRT), the *College of Radiographers* in the United Kingdom, as well as those professional medical imaging organizations in Africa, Asia, Australia, and continental Europe.

Digital radiography has become an integral part of the education of radiologic technologists and related professionals who play a significant role in the care and management of patients undergoing both routine and other sophisticated imaging procedures.

Enjoy the pages that follow, and remember that with your knowledge and skills in digital radiography, your patients will benefit from your wisdom.

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Acknowledgments

The single most important and satisfying task in writing a book of this nature is to acknowledge the help and encouragement of those individuals who perceive the value of its contribution to the medical imaging sciences literature. It is indeed a pleasure to express sincere thanks to several individuals whose time and efforts have contributed tremendously to this third edition.

First and foremost, I am indebted to Dr. Charles Willis, PhD, Department of Imaging Physics, University of Texas, MD Anderson Cancer Center, Houston, Texas, who provided his support for me to reuse a section of his chapter in the first edition of this book. Thanks Chuck. Indeed I have learned a great deal from you attending your workshops and through your educative published papers in the literature.

Furthermore I am grateful to my good friend and colleague Anthony Chan, MEng, MSc, PEng, CEng, CCE, at the British Columbia Institute of Technology (BCIT), a Canadian award-winning Biomedical Engineer, who provided good explanations of the engineering aspects of making digital detectors and other technical aspects of PACS, such as DICOM and HL-7. In addition, I must also thank Bruno Jaggi, DiplT, BASc, MASc, PEng, an expert Biomedical Engineer in the Faculty of Applied Sciences at the University of British Columbia. Bruno has always been supportive in teaching me about the Fourier transform and its applications in medical imaging. Additionally his course and regular discussions on digital image processing provided me with the theoretical background for a better understanding of image post-processing operations.

The content of this book is built around the works and expertise of several noted medical physicists, radiologists, computer scientists, and biomedical engineers who have done the original research. In reality, they are the tacit authors of this text, and I am truly grateful to all of them. In this regard, I owe a good deal of thanks to Dr. Anthony Siebert, PhD, of the University of California at Davis and Dr. Charles Willis, PhD, of the University of Texas, MD Anderson Cancer Center, two expert physicists in digital radiography and from whom I have learned the physics and technical aspects of digital radiography through their seminars and workshops that I have attended. Furthermore I am also grateful to several other physicists from whom I have learned much about digital imaging physics through their published writings. These include Dr. Perry Sprawls, PhD (Emory University); Dr. Kerry Krugh, PhD (Medical Physicist, University of Toledo Medical Center, Toledo, Ohio); Dr. John Yorkston, PhD (Senior Research Scientist, Clinical Applications

Research, Carestream Health Inc., Rochester, NY); Dr. Martin Spahn, PhD (Siemens AG, Medical Solutions); Dr. Ehsan Samei, PhD (Medical Physicist and Associate Professor at Duke University); Dr. Beth Schueler, PhD (Medical Physicist, Mayo Clinic); and Jeff Shepard, MS (Senior Medical Physicist, MD Anderson Cancer Center). One more medical physicist to whom I owe thanks is Dr. John Aldrich, PhD, Vancouver General Hospital, University of British Columbia, whose seminars on digital radiography and other topics have taught me quite a bit. Thanks John. Furthermore, I owe a good deal of thanks to my good friend and colleague Dr. Rob Davidson, PhD, MAppSc (MI), BBus, FIR, Professor of Medical Imaging, University of Canberra, Australia. Rob's advice on the inclusion of digital breast tomosynthesis was much appreciated.

I must acknowledge the efforts of all the individuals from digital radiography vendors who have assisted me generously with technical details and photographs of their systems for use in the book. In particular, I am grateful to Joanne Muldoon of Hologic® and Senior Scientist Dr. Andrew Smith, PhD, at Hologic®. Thanks so much for this assistance. Other vendors are acknowledged in respective figure legends.

In this book I have used several illustrations and quotes from original papers published in the professional literature, and I am indeed thankful to all the publishers and the authors who have done the original work and have provided me with permission to reproduce them in this textbook. I have purposefully used several quotes so as not to detract from the authors' original meaning. I personally believe that these quotes and illustrations have added significantly to the clarity of the explanations. In this regard, I am appreciative of the Radiological Society of North America (RSNA) and Jamie Dulkowski, Manager of Informatics at the RSNA; *Academic Radiology*; Wolters Kluwer Health; the American Association of Physicists in Medicine (AAPM), for materials from *Medical Physics*; Wiley-Blackwell Publishers Inc.; and Manning Publications Co., Shelter Island, NY.

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Thanks for taking such excellent care of our two granddaughters, to whom this book is dedicated. I love you all.

Last but not least, I must thank my students who have diligently completed my courses on digital imaging modalities, PACS, and digital image processing in radiology, at both the diploma and degree levels. Thanks for all the challenging questions.

Keep on learning and enjoy the pages that follow.

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Contents

About the Author

Euclid Seeram is a full member of the Health Physics Society. He is currently an Honorary Senior Lecturer at the Faculty of Health Sciences, University of Sydney; Adjunct Associate Professor of Medical Imaging and Radiation Sciences at Monash University, Australia; Adjunct Professor at the Faculty of Science, Charles Sturt University, Australia; and Adjunct Associate Professor of Medical Radiation Sciences at the University of Canberra.

His current research interests are focused on radiation dose optimization in CT and digital radiography imaging systems, topics on which he has published several papers in professional and peer-reviewed radiologic technology journals. He has published numerous books on CT, computers in radiology, radiographic instrumentation, digital radiography, and radiation protection. Presently, he serves on the editorial boards for the *Biomedical Imaging and Intervention Journal*, *Radiography*, *International Journal of Radiology and Medical Imaging*, *Open Journal of Radiology*, and the *Journal of Allied Health*. He is on the international advisory panel for the *Journal of Medical Radiation Sciences* and serves as an invited peer reviewer for the *Journal of Medical Imaging and Radiation Sciences*.