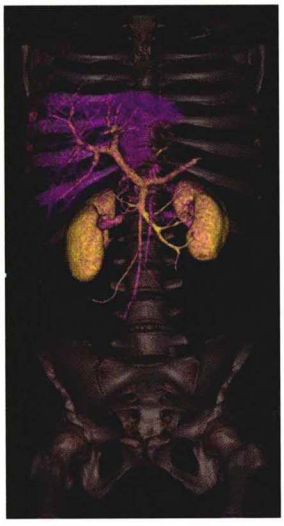
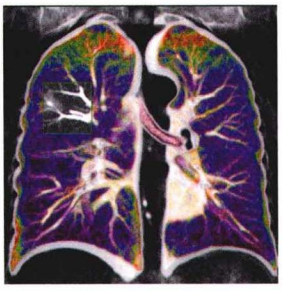
COMPUTED TOMOGRAPHY

Physical Principles, Clinical Applications, and Quality Control



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COMPUTED TOMOGRAPHY

Physical Principles, Clinical Applications, and Quality Control

FOURTH EDITION

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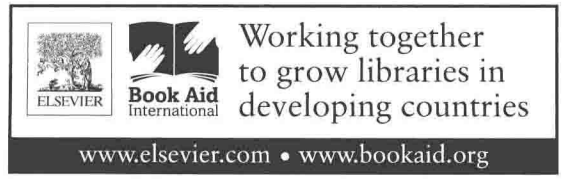

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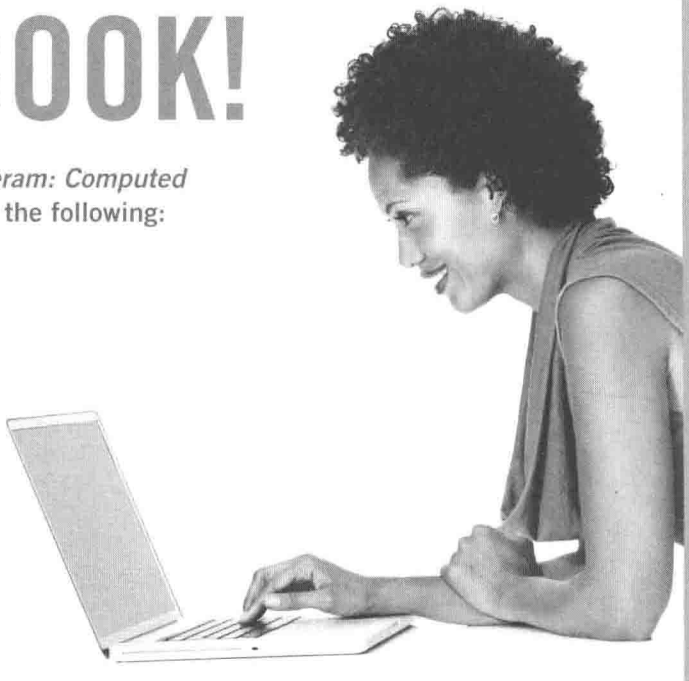

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This book is dedicated with love and affection to my beautiful, smart, and overall cute and witty granddaughter

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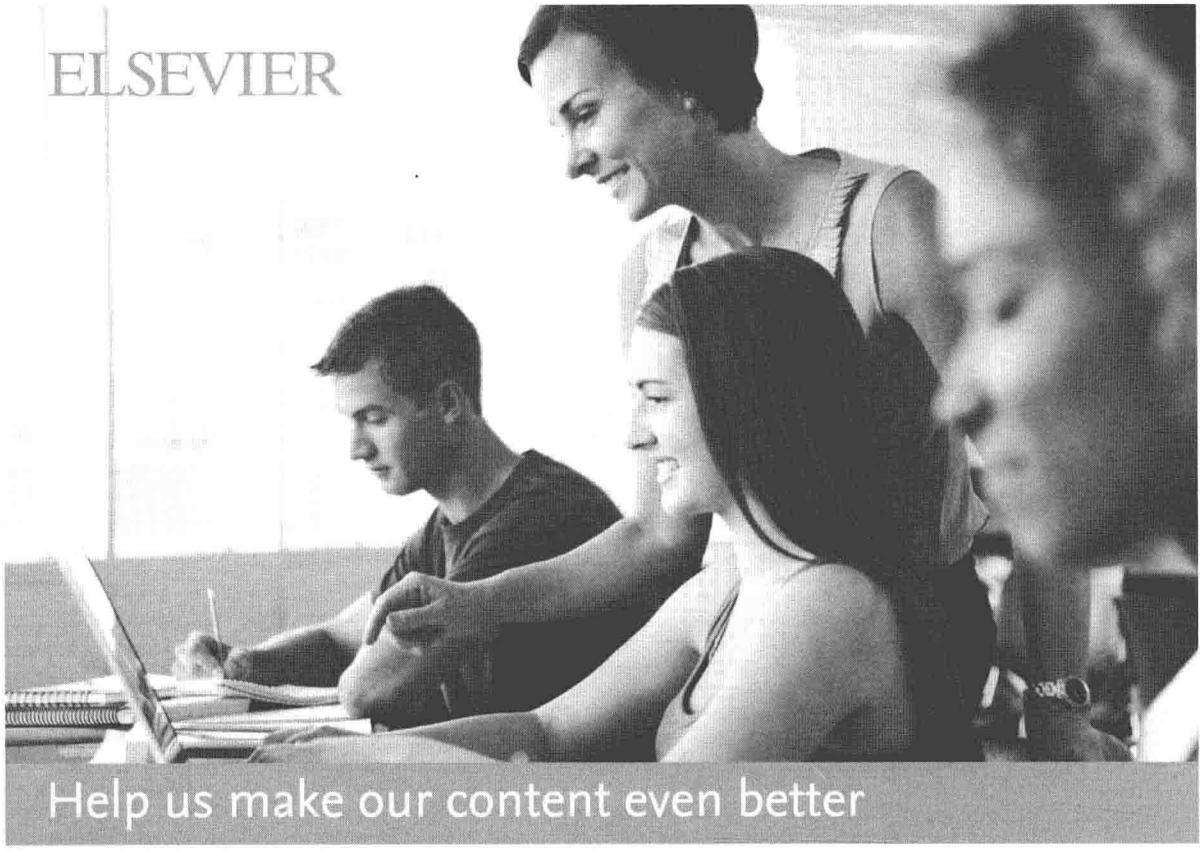

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FOREWORD

Computed tomography (CT) still remains one of the most important diagnostic tools in medicine and health. What is still amazing is that development of CT has not abated over recent years and the clinical applications continue to grow rapidly with increasing benefit for patients and clinicians. While CT is one of many diagnostic imaging tools, it will maintain its position in the forefront of radiologic departments.

Such an effective tool requires competent and reflective operators. Initially it would appear that the usability of radiologic equipment becomes easier with subsequent technological generations, but this appearance substantially undermines the responsibilities generated by the advancement in CT techniques. The plethora of data generated, the expectation of useful image reconstructions by clinical staff, the move to automated segmentation and quantification procedures, sophisticated quality assurance procedures, and the huge potential for excessive patient exposure requires that technological staff are highly efficient and knowledgeable about the opportunities that this device offers. Regarding the latter point, radiation dose, it has never been so necessary for clinicians and health professionals to have a solid and working knowledge of dose-reducing measures.

The name Euclid Seeram has become synonymous with learning and teaching in CT and other areas of medical imaging. This fourth edition of his very well-known text, *Computed Tomography—Physical Principles, Clinical Applications, and Quality Control*, expands on previous editions. This textbook still covers the topics of the previous editions and now brings the reader up to date with the latest technologies, including iterative reconstruction algorithms, detector and x-ray tube design and technologies, spectral imaging, and updates on SPECT/CT and PET/CT. Importantly, there is an increased focus on CT dose-optimization strategies and approaches. It also informs the reader of methods for ensuring that these new technologies are implemented for the patient's greatest benefit. The focus of the previous editions has been on educating students; now this text will serve as a fundamental reference to current radiographers and clinicians so that they can update their CT knowledge.

Dr Seeram is a distinguished and rigorous academic who has a proven track record in providing understandable and comprehensive radiologic manuscripts. A hallmark of his approach is the ability to convey complex topics in an easy-to-read and manageable way, and this work is no exception. He presents his topics in an organized, progressive, and comprehensive manner so that at the end of each clearly defined chapter, learning objectives are met and the reader comes away with a solid and supported knowledge of specific topics. Euclid has decades of experience in the teaching of CT and medical imaging and during this time has gained worldwide respect as an educator. Both clinicians and physicists in the field of medical imaging are in agreement with the high level of influence Euclid has on medical imaging education and on the profession as a whole. He is simply a global leader in his field, and policy makers, health service providers, the industry, and patients everywhere should be grateful for the impact Dr Seeram has had on radiologic science and technology education.

Euclid has the gift of being able to explain difficult concepts in a way that students can grasp. This ability has made the previous versions of this text highly desirable reading in the learning of CT. Earlier editions can be found on the syllabuses of all leading education institutions in the world that teach medical imaging; hence, the influence Euclid has had over a generation of CT users is immeasurable.

The previous text became essential reading within undergraduate and graduate curricula, and the fourth edition will be essential reading for students and should be an essential text for all CT departments globally. We again congratulate the author for adding another first-class tome to his already impressive collection. We would highly recommend this textbook to students studying medical imaging, those in allied fields where CT is becoming more important such as nuclear medicine and radiation therapy, and to those already in the field who need an update or just want a great reference text.

A great textbook by a great educator.

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PREFACE TO THE FOURTH EDITION

The motivation for the fourth edition of *Computed Tomography—Physical Principles, Clinical Applications, and Quality Control* stems from the continued technical evolution of computed tomography (CT) to meet the needs of the clinical environment.

The continued evolution of CT is marked by the refinement of current physical principles, the introduction of new principles, and the development of engineering tools to make these scanners perform at such high levels. Such performance meets the needs of various clinical imaging requirements. One such notable technical evolution is the introduction of iterative reconstruction algorithms for use in routine practice. These algorithms play a role in the improvement of image quality and reduced radiation dose to the patient. All CT manufacturers offer iterative reconstruction algorithms for implementation on their scanners. The fourth edition, of course, adds more scope to the content of the third edition by elaborating on new elements of the evolution and deleting elements that some may consider "obsolete." This is mandatory to bring the textbook "up to date."

NEW TO THIS EDITION

The chapters in this book have been updated to address the continued technical evolution and major technology trends in CT. Furthermore, a set of updated articles have been cited to support the inclusion of the following:

- The design and implementation of *iterative reconstruction (IR) algorithms*. A new chapter has been added to the contents of this book and addresses the concepts that are important to the CT technologist such as the assumptions made to derive the filtered back-projection (FBP) algorithm, noise reduction techniques, IR without modeling, modeling approaches in IR, examples of IR algorithms, and the performance evaluation studies on IR algorithms. Today all major CT manufacturers have implemented IR algorithms on their scanners.
- *Design innovations in CT detector technology* such as the NanoPanel Prism Detector (Philips Healthcare), the Gemstone Clarity Detector (GE Healthcare), the Stellar Detector (Siemens Healthcare), and PureVISION and the Quantum Vi detectors (Toshiba Medical Systems) are described. In addition, detector technologies are discussed such as *new scintillation crystals* (such as, for example, GE's Gemstone garnet of the type $(Lu,Gd,Y,Tb)_3(Ga,Al)_5O_{12}$ detector) and *miniaturized detector electronics* through the use of *integrated microelectronic circuitry* such as the *application-specific integrated circuit* (ASIC) for analog-to-digital conversion. Furthermore, detectors are described in the categories of the conventional energy integration (EI) detector, the dual-layer detector, and the direct conversion detector (photon counting detector). *Detector-based spectral CT*, the purpose of which is to exploit the transmitted x-ray photons through the patient using energy weighting and material decomposition approaches, is also briefly described.
- *Alternative x-ray tube designs* for multislice CT (MSCT), such as the recent directly cooled x-ray tubes (direct anode cooling)
- *The use of graphics processing unit (CPU) computing in CT* for image reconstruction, image processing, dose calculations, and treatment plan optimization in imaging and radiation therapy
- *Medical image fusion overview* (definitions, medical image fusion areas of studies, steps in medical image fusion, major medical image fusion algorithms, and clinical applications)
- *Single-photon emission computed tomography (SPECT/CT)* has been added to the PET/CT chapter.
- RSNA and ACR statements on the *future of CT screening*
- *Increased focus on CT dose optimization strategies and approaches*
- CT Dose Index Registry, Image Wisely, and Image Gently
- Use of *bismuth shields* in CT including the AAPM Position Statement on the Use of Bismuth Shielding
- Equipment and *phantoms for QC testing, the ACR CT accreditation QC tests, and QC concepts from the International Atomic Energy Agency (IAEA)*

In addition to updated content, a set of learning outcomes and key terms to watch for and remember have been added to the beginning of each chapter. Ten multiple choice questions are provided at the end of each chapter for students to check their understanding of the materials studied.

The fourth edition keeps up with the latest advances in CT imaging where each chapter from the previous edition has been expanded and updated to include state-of-the-art technology and the most up-to-date information on physical principles, instrumentation, clinical applications, and quality control. The addition of numerous new images demonstrates the achievements of these technological advances. New line drawings provide a better representation of important concepts in the text, and a new page layout makes it easier to locate information. 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 CT 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

Multislice CT has revolutionized CT scanning and has resulted in a wide range of new clinical applications that are examined in this book. This growth of CT technology and its clinical applications have resulted in a new, expanded edition of *Computed Tomography—Physical Principles, Clinical Applications, and Quality Control* that reflects the current state of CT technology.

Ancillaries

New ancillaries have also been added to this edition (available online on Evolve), including:

- A test bank of approximately 600 questions available in ExamView format
- A practice test to help students reinforce what they have learned and prepare for the ARRT CT Registry Examination
- An image collection of the figures from the book

PURPOSE

The fourth edition has grown by including descriptions of new technology and elaboration of some previous content to accommodate all the recent advances in CT, and in this regard, the text remains dedicated to its original manifold purposes:

1. To provide comprehensive coverage of the physical principles of CT and its clinical applications for both adults and children
2. To lay the theoretical foundations necessary for the clinical practice of CT scanning
3. To enhance communication between the CT technologist and other related personnel, such as radiologists, medical physicists, and CT vendors
4. To promote an understanding of 2D and 3D anatomic images as they relate to CT

CONTENT AND ORGANIZATION

The content and organization of the book has 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 third edition, Chapter 2, an Introduction to Computers, has been deleted; however, some relevant content from this chapter has been used and included in the new Chapter 7. Chapters 11 and 12 have been combined to create the new Chapter 11. A completely new chapter (Chapter 6) on IR algorithms has been added to the fourth edition. Chapter 15 has been included in the new Chapter 13.

The content and organization of the fourth edition are as follows:

Chapter 1 lays the foundations of computed tomography by reviewing its history, including the introduction of the CT scanner as a diagnostic medical imaging tool. Chapter 2 examines the topic of image processing and representation and explores the relevancy of CT to the technology of digital image processing.

Chapter 3 begins with a discussion of the limitations of radiography and conventional tomography followed by a more in-depth examination of the physical principles of CT, radiation attenuation, the meaning of CT numbers, and other technological considerations and concludes with a list of the advantages and limitations of CT. Chapter 4 addresses the concepts of data acquisition and the first step in image production and also includes a description of CT detectors. Chapter 5 focuses on what the CT technologist needs to know to understand the process of image reconstruction and introduces the notion of cone-beam reconstruction. Chapter 6 is the new chapter on IR algorithms and deals with not only the basic principle of an IR algorithm but also provides examples of several IR algorithms from the major CT manufacturers. Furthermore, performance evaluation studies on IR algorithms from 2012 to 2015 are included in this chapter.

Chapter 7 is devoted to basic CT instrumentation and includes a description of the data acquisition, computer, and image display, storage, and communication systems. In addition this chapter has essential elements from Chapter 2 in the third edition, including an overview of computer systems, computer applications in radiology, and finally the components of picture archiving and communication systems (PACS) and three-dimensional (3D) imaging. The discussion of image manipulation and visualization tools continues in Chapter 8, which includes an introduction to multiplanar reconstruction and 3D imaging. Chapter 9 describes the essentials on image

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quality and includes a discussion of image artifacts in CT. Chapter 10, on the other hand, deals with radiation dose in CT and provides an increased focus on CT dose optimization strategies and approaches, including examples of several dose optimization research studies.

Chapters 11 through 13 are devoted to the physical concepts of volume CT scanning. Chapter 11 details the evolution and fundamentals of multislice spiral/helical CT (also called *volume CT*). This chapter is considered a pivotal chapter in the book, since most of the recent developments in multislice CT are described here. Chapter 12 furthers the discussion by presenting other technical applications of multislice spiral/helical CT and includes a description of CT angiography (CTA), CT fluoroscopy, applications of radiation therapy, medical image fusion, flat-detector CT (FD-CT), CT screening, breast CT imaging, quantitative CT, and portable multislice CT scanning. Chapter 13 examines in-depth three-dimensional concepts in CT imaging, since the advances in spiral/helical CT have resulted in an increased use of 3D display of sectional anatomy. Additionally, virtual reality imaging concepts are included in this chapter. Chapter 14 presents a description of single-photon emission computed tomography/CT (SPECT/CT) as well as positron emission tomography CT (PET/CT).

The next three chapters include coverage of the clinical applications of CT: Chapter 15, "CT of the Head, Neck, and Spine"; Chapter 16, "CT of the Body"; and Chapter 17, "Pediatric CT." Included are a set of updated references that are key to these chapters.

The final chapter in the book, Chapter 18, presents updated information on CT quality control, including a description of CT phantoms and the ACR CT Accreditation QC Tests. Three appendices summarize some of the historical and technical developments in CT, the use of the terms *spiral* and *helical,* a detailed description of the physics of cardiac CT imaging.

USE AND SCOPE

This comprehensive text is written to meet the wide and varied requirements of its users, students and instructors alike, and meets the many different educational and program needs. *Computed Tomography—Physical Principles, Clinical Applications, and Quality Control* can be used as the primary text for introductory CT courses at the diploma, associate, and baccalaureate degree levels; it serves as a resource for continuing education programs; it functions as a reference text for the CT technologist and other imaging personnel; and it provides the necessary overview of the physical and clinical aspects of CT, which is a prerequisite for graduate-level (Master's Degree) courses in CT.

The content is intended to meet the educational requirements of various radiologic technology professional associations including the American Society of Radiologic Technologists, the American Registry for Radiologic Technologists, the Canadian Association of Medical Radiation Technologists, and the College of Radiographers in the United Kingdom and those in Africa, Asia, Australia, and continental Europe.

CT has become an integral part of the education of radiologic technologists who play a significant role in the care and management of patients undergoing sophisticated CT imaging procedures.

Read on, learn, and enjoy. *Your patients will benefit from your wisdom.*

Euclid Seeram, PhD, MSc, BSc, FCAMRT
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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 for use of materials from *Radiographics* and *Radiology*; Springer Science and Business Media for materials from *European Radiology*; and Elsevier for figures from *Physica Medica*. Furthermore, I must acknowledge the assistance of Yeon Hyeon Choe, MD, Editor-in-Chief, of the *Korean Journal of Radiology*; as well as the American Association of Physicists in Medicine, for materials from *Medical Physics*; Wiley-Blackwell Publishers Inc., for materials from *Australian Radiology*; ImPACT Scan from the United Kingdom, especially Sue Edyvean; and the American Thoracic Society. There are several radiologists who graciously gave their permission as well, and I would like to list some of their names here: Dr Dalrymple, Dr Silva, Dr Kalra, and Dr Van der Molen. Furthermore, I am grateful to the following authors for the use of their illustrations: Alex Pappachen James,

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