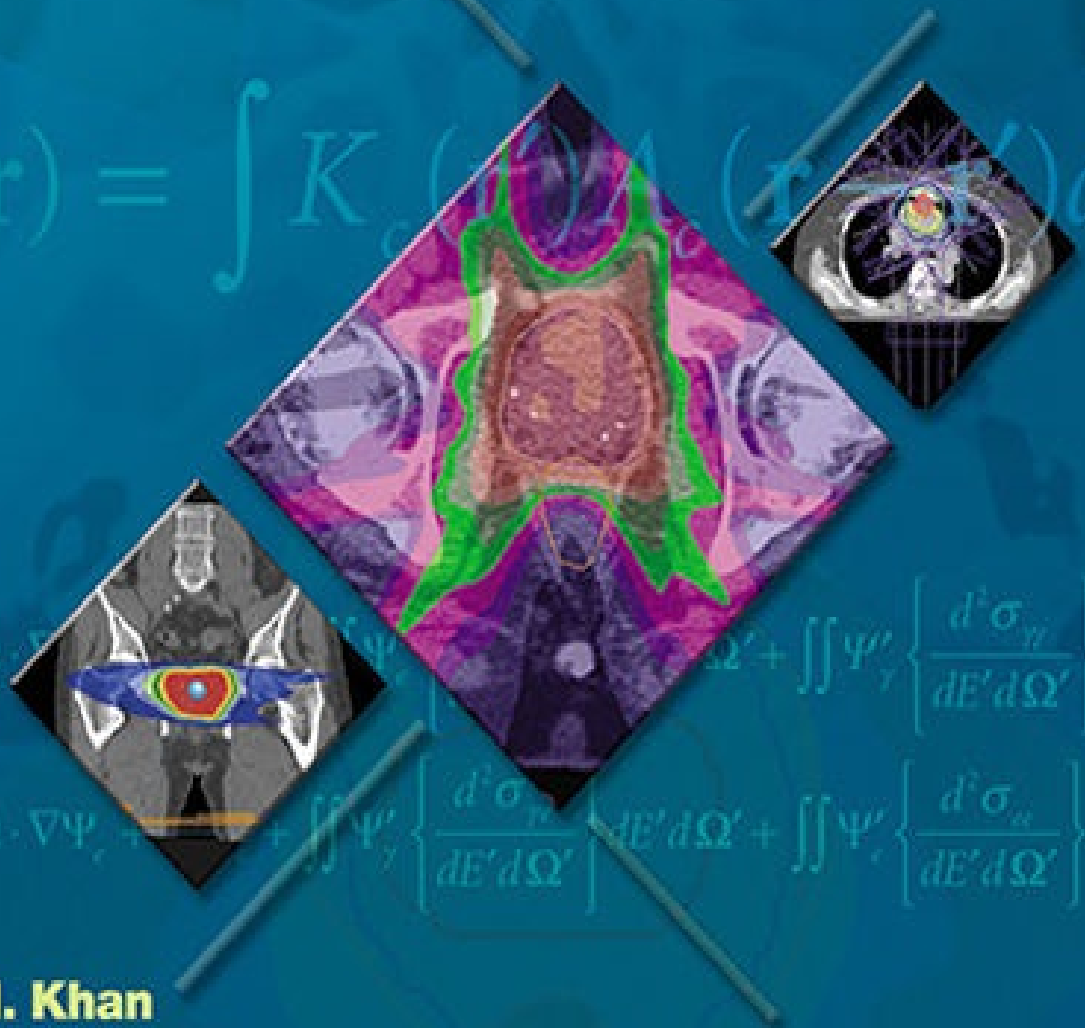
KHAN'S

Treatment Planning in Radiation Oncology



Faiz M. Khan
John P. Gibbons
Paul W. Sperduto

Fourth Edition

Wolters Kluwer

FOURTH EDITION

KHAN'S

Treatment Planning in Radiation Oncology

EDITORS

Faiz M. Khan, PhD
Professor Emeritus
Department of Radiation Oncology
University of Minnesota Medical School
Minneapolis, Minnesota

John P. Gibbons, PhD
Chief Medical Physicist
Department of Radiation Oncology
Ochsner Health System
New Orleans, Louisiana

Paul W. Sperduto, MD, MPP, FASTRO
Radiation Oncologist
Minneapolis Radiation Oncology
Minneapolis, Minnesota

Philadelphia · Baltimore · New York · London
Buenos Aires · Hong Kong · Sydney · Tokyo

Acquisitions Editor: Julie Goolsby
Senior Product Development Editor: Emilie Moyer
Editorial Assistant: Brian Convery
Production Project Manager: Alicia Jackson
Design Coordinator: Joan Wendt, Elaine Kasmer
Illustration Coordinator: Jennifer Clements
Manufacturing Coordinator: Beth Welsh
Marketing Manager: Rachel Mante Leung
Prepress Vendor: Aptara, Inc.

4th edition

9 8 7 6 5 4 3 2 1

Printed in China

Library of Congress Cataloging-in-Publication Data
Names: Khan, Faiz M., editor. | Gibbons, John P., Jr., editor. | Sperduto, Paul W., editor.
Title: Khan's treatment planning in radiation oncology / editors, Faiz M. Khan, John P. Gibbons, Paul W. Sperduto.
Other titles: Treatment planning in radiation oncology.
Description: Fourth edition. | Philadelphia : Wolters Kluwer [2016] | Preceded by Treatment planning in radiation oncology / editors, Faiz M. Khan, Bruce J. Gerbi. 3rd ed. c2012. | Includes bibliographical references and index.
Identifiers: LCCN 2016004611 | ISBN 9781469889979
Subjects: | MESH: Neoplasms—radiotherapy | Radiotherapy Planning, Computer-Assisted | Radiation Oncology—methods
Classification: LCC RC271.R3 | NLM QZ 269 | DDC 616.99/40642—dc23
LC record available at http://lccn.loc.gov/2016004611

patient. The publisher does not provide medical advice or guidance and this work is merely a reference tool. Healthcare professionals, and not the publisher, are solely responsible for the use of this work including all medical judgments and for any resulting diagnosis and treatments.

Given continuous, rapid advances in medical science and health information, independent professional verification of medical diagnoses, indications, appropriate pharmaceutical selections and dosages, and treatment options should be made and healthcare professionals should consult a variety of sources. When prescribing medication, healthcare professionals are advised to consult the product information sheet (the manufacturer's package insert) accompanying each drug to verify, among other things, conditions of use, warnings and side effects and identify any changes in dosage schedule or contraindications, particularly if the medication to be administered is new, infrequently used or has a narrow therapeutic range. To the maximum extent permitted under applicable law, no responsibility is assumed by the publisher for any injury and/or damage to persons or property, as a matter of products liability, negligence law or otherwise, or from any reference to or use by any person of this work.

LWW.com

To Kathy, my wife and companion of fifty years:
Happy Anniversary, My Love.

—Faiz M. Khan

To my wife Nicole, for her continued patience and support

—John P. Gibbons

To Jody, Luke, Maria, and Will for their love and laughter and my patients who provide me the privilege of caring for them in times of greatest need.

—Paul W. Sperduto

Contributors

Judy A. Adams, CMD
Director of Dosimetry
Department of Radiation Oncology
Massachusetts General Hospital Cancer Center
Boston, Massachusetts

Fiori Alite, MD
Department of Radiation Oncology
Stritch School of Medicine
Loyola University
Maywood, Illinois

John A. Antolak, PhD
Associate Professor & Consultant
Department of Radiation Oncology
Mayo Clinic
Rochester, Minnesota

James M. Balter, PhD
Professor
Radiation Oncology Department
University of Michigan
Ann Arbor, Michigan

Christopher Beltran, PhD
Mayo Clinic
Department of Radiation Oncology
Rochester, Minnesota

Rachel C. Blitzblau, MD, PhD
Assistant Professor
Department of Radiation Oncology
Duke University School of Medicine
Attending Physician, Radiation Oncology
Duke University Medical Center
Durham, North Carolina

Stefan Both, PhD
Associate Attending
Medical Physics Department
Memorial Sloan Kettering Cancer Center
New York, New York

Frank J. Bova, PhD, FACR, FAAPM, FAAPM
Albert E. and Birdie W. Professor of Computer-Assisted Stereotactic Neurosurgery
University of Florida College of Medicine
Gainesville, Florida

Jason Chan, MD
Resident in Training
Department of Radiation Oncology
University of California San Francisco
San Francisco, California

Albert Chang, MD, PhD
Assistant Professor in Residence
Departments of Radiation Oncology and Urology
University of California, San Francisco
San Francisco, California

George T. Y. Chen, PhD
Department of Radiation Oncology
Massachusetts General Hospital and Harvard Medical School
Boston, Massachusetts

Zhe (Jay) Chen, PhD
Professor
Department of Therapeutic Radiology
Yale University School of Medicine
Yale-New Haven Hospital
New Haven, Connecticut

Yen-Lin Evelyn Chen, MD
Instructor
Radiation Oncology
Massachusetts General Hospital
Boston, Massachusetts

James C. L. Chow, PhD
Assistant Professor
Department of Radiation Oncology
University of Toronto
Radiation Physicist
Radiation Medicine Program
Princess Margaret Cancer Center
Toronto, Ontario, Canada

Benjamin M. Clasie, MD
Resident Physician
Radiation Oncology
Rush University Medical Center

Chicago, Illinois

Brian G. Czito, MD
Gary Hock and Lyn Proctor Associate Professor
Department of Radiation Oncology
Duke University Medical Center
Durham, North Carolina

Thomas F. DeLaney, MD, FASTRO
Andres Soriano Professor of Radiation Oncology
Harvard Medical School
Radiation Oncologist
Department of Radiation Oncology
Medical Director, Francis H. Burr Proton Therapy Center
Co-Director, Center for Sarcoma and Connective Tissue Oncology
Massachusetts General Hospital
Boston, Massachusetts

Lei Dong, PhD
Director, Chief of Medical Physics
Scripps Proton Therapy Center
Professor, Department of Radiation Medicine and Applied Sciences
University of California—San Diego
San Diego, California

Bahman Emami, MD, FACR, FASTRO
Professor
Department of Radiation Oncology
Loyola University Medical Center
Chicago, Illinois

Robert L. Foote, MD, FASTRO
Professor of Radiation Oncology
Mayo Medical School
Chair
Department of Radiation Oncology
Mayo Clinic
Rochester, Minnesota

Ryan D. Foster, PhD
Medical Physicist
Department of Radiation Oncology
Carolinas HealthCare System/Levine Cancer Institute
Concord, North Carolina

William A. Friedman, MD
Professor and Chair
Department of Neurosurgery

University of Florida College of Medicine
Gainesville, Florida

Yolanda I. Garces, MD, MS
Consultant
Assistant Professor of Radiation Oncology
Mayo Clinic
Rochester, Minnesota

John P. Gibbons Jr, PhD
Chief Medical Physicist
Department of Radiation Oncology
Ochsner Health System
New Orleans, Louisiana

Eli Glatstein, MD, FASTRO
Emeritus Professor
Department of Radiation Oncology
University of Pennsylvania
Philadelphia, Pennsylvania

Vinai Gondi, MD
Co-Director, Brain & Spine Tumor Center
Northwestern Medicine Cancer Center, Warrenville
Warrenville, Illinois

Aditya N. Halthore, MD
Resident
Department of Radiation Medicine
Hofstra North Shore-LIJ School of Medicine
North Shore-LIJ Health System
Lake Success, New York

Andrew Jackson, PhD
Associate Attending Physicist
Medical Physics Computer Service
Memorial Sloan-Kettering Cancer Center
New York, New York

Julian Johnson, MD
Resident in Training
Department of Radiation Oncology
University of California San Francisco
San Francisco, California

James A. Kavanaugh, MS
Department of Radiation Oncology
Washington University in St. Louis
Director of Satellite Services

Siteman Cancer Center
St. Louis, Missouri

Paul J. Keall, PhD
Professor and NHMRC Australian FellowDirector, Radiation Physics Laboratory
Central Clinical School
Sydney Medical School
The University of Sydney
New South Wales, Australia

Faiz M. Khan, PhD
Professor Emeritus
Department of Radiation Oncology
University of Minnesota Medical School
Minneapolis, Minnesota

Eric E. Klein, PhD
Professor
Department of Radiation Medicine
Northwell Health
Lake Success, New York

Jonathan P. S. Knisely, MD
Associate Professor
Department of Radiation Medicine
Northwell Health
Hofstra University School of Medicine
Lake Success, New York

Hanne M. Kooy, PhD
Associate Professor
Department of Radiation Oncology
Massachusetts General Hospital
Harvard Medical School
Boston, Massachusetts

Rupesh Kotecha, MD
Resident
Department of Radiation Oncology
Taussig Cancer Institute
Cleveland Clinic
Cleveland, Ohio

Gerald Kutcher, PhD
Professor
History Department
Binghamton University
State University of New York

Binghamton, New York

Guang Li, PhD, DABR
Associate Member and Associate Attending Physicist
Department of Medical Physics
Memorial Sloan Kettering Cancer Center
New York, New York

Tony Lomax, PhD
Professor
Centre for Proton Therapy
Paul Scherrer Institute
Switzerland

Shannon M. MacDonald, MD
Associate Professor of Radiation Oncology
Massachusetts General Hospital/Harvard Medical School
Francis H. Burr Proton Therapy Center
Boston, Massachusetts

Gig S. Mageras, PhD
Member, Memorial Hospital
Memorial Sloan Kettering Cancer Center
Attending Physicist
Department of Medical Physics
Memorial Hospital
New York, New York

Amit Maity, MD, PhD
Professor
Department of Radiation Oncology
University of Pennsylvania
Philadelphia, Pennsylvania

Charles Mayo, PhD
Department of Radiation Oncology
University of Michigan
Ann Arbor, Michigan

Minesh P. Mehta, MD, FASTRO
Professor
Department of Radiation Oncology
University of Maryland School of Medicine
Baltimore, Maryland

Loren K. Mell, MD
Associate Professor
Department of Radiation Medicine and Applied Sciences
University of California San Diego

La Jolla, California

Dimitris N. Mihailidis, PhD, FAAPM, FACMP, CAMC
Chief Medical Physicist
Cancer Center-Alliance Oncology
West Virginia University School of Medicine
Clinical Professor
Radiation Oncology
Charleston, West Virginia

Radhe Mohan, PhD
Professor
Department of Radiation Physics
University of Texas MD Anderson Cancer Center
Houston, Texas

Yvonne M. Mowery, MD, PhD
Resident Physician
Department of Radiation Oncology
Duke University School of Medicine
Resident Physician
Radiation Oncology
Duke University Medical Center
Durham, North Carolina

Arno J. Mundt, MD, FACRO, FASTRO
Professor and Chair
Department of Radiation Medicine & Applied Sciences
University of California San Diego
President, Radiating Hope Society Chair
American College of Radiation Oncology
San Diego, California

Sasa Mutic, PhD, FAAPM
Professor and Director of Medical Physics
Department of Radiation Oncology
Washington University School of Medicine
St. Louis, Missouri

Colin G. Orton, PhD
Professor Emeritus
Wayne State University
Detroit, Michigan

Manisha Palta, MD
Assistant Professor
Duke Cancer Institute
Department of Radiation Oncology

Duke University Medical Center
Durham, North Carolina

Niko Papanikolaou, PhD
Professor and Chief
Division of Medical Physics
University of Texas Health Science Center at San Antonio
San Antonio, Texas

Anthony Paravati, MD, MBA
Resident in Radiation Oncology
Department of Radiation Medicine and Applied Sciences
Moores Cancer Center
University of California, San Diego
La Jolla, California

Charles A. Pelizzari, PhD
Associate Professor
Department of Radiation and Cellular Oncology
The University of Chicago Medical Center
Chicago, Illinois

Bradford A. Perez, MD
Resident
Duke Cancer Institute
Department of Radiation Oncology
Duke University Medical Center
Durham, North Carolina

John P. Plastaras, MD, PhD
Associate Professor
Department of Radiation Oncology
University of Pennsylvania
Philadelphia, Pennsylvania

Ezequiel Ramirez, MSRS, CMD, RT(R)(T)
Department of Radiation Oncology
University of Texas Southwestern Medical Center
Dallas, Texas

Mark J. Rivard, PhD, FAAPM
Professor of Radiation Oncology
Tufts University School of Medicine
Boston, Massachusetts

Gregory C. Sharp, PhD
Assistant Professor
Department of Radiation Oncology
Massachusetts General Hospital

Boston, Massachusetts

Daniel R. Simpson, MD
Assistant Professor
Department of Radiation Medicine and Applied Sciences
Moores Cancer Center
UCSD School of Medicine
La Jolla, California

Chang W. Song, PhD
Professor Emeritus
Department of Radiation Oncology
University of Minnesota Medical School
Minneapolis, Minnesota

Paul W. Sperduto, MD, MPP, FASTRO
Medical Director, Minneapolis Radiation Oncology
Co-Director, University of Minnesota Gamma Knife Center
Minneapolis, Minnesota

Kevin L. Stephans, MD
Assistant Professor
Taussig Cancer Institute
Department of Radiation Oncology
Cleveland Clinic
Cleveland, Ohio

Kenneth R. Stevens Jr, MD
Professor Emeritus and Former Department Chair
Radiation Medicine Department
Oregon Health & Sciences University
Portland, Oregon

Alexander Sun, MD, FRCPC
Associate Professor
Department of Radiation Oncology
University of Toronto
Staff Radiation Oncologist
Princess Margaret Cancer Centre
Toronto, Canada

Nancy J. Tarbell, MD, FASTRO
CC Wang Professor of Radiation Oncology
Dean for Academic and Clinical Affairs
Harvard Medical School
Boston, Massachusetts

Bruce R. Thomadsen, PhD
Professor

Medical Physics
University of Wisconsin
Madison, Wisconsin

Robert Timmerman, MD
Professor, Vice Chair
Department of Radiation Oncology
University of Texas Southwestern Medical Center
Dallas, Texas

Wolfgang A. Tomé, PhD, FAAPM
Professor and Director of Medical Physics
Institute for Onco-Physics
Department of Radiation Oncology
Albert Einstein College of Medicine
Professor and Director
Division of Therapeutic Medical Physics
Department of Radiation Oncology
Montefiore Medical Center
Bronx, New York

Jordan A. Torok, MD
Resident Physician
Department of Radiation Oncology
Duke University School of Medicine
Duke Cancer Institute
Durham, North Carolina

Jan Unkelbach, PhD
Assistant Professor of Radiation Oncology
Harvard Medical School
Assistant Radiation Physicist
Department of Radiation Oncology
Massachusetts General Hospital
Boston, Massachusetts

Jacob (Jake) Van Dyk, BSc, MSc, FCCPM, FAAPM, FCOMP, DSc(hon)
Professor Emeritus
Oncology and Medical Biophysics
Western University
Former Manager/Head
Physics and Engineering
London Regional Cancer Program
London Health Sciences Centre
London, Ontario, Canada

Gregory M. M. Videtic, MD, CM, FRPC
Professor of Medicine

Cleveland Clinic Lerner College of Medicine
Staff Physician
Department of Radiation Oncology
Taussig Cancer Center
Cleveland Clinic
Cleveland, Ohio

Yi Wang, PhD
Instructor
Department of Radiation Oncology
Harvard Medical School
Medical Physicist
Radiation Oncology
Massachusetts General Hospital
Boston, Massachusetts

Kenneth J. Weeks, PhD
Medical Physicist
Federal Medical Center
Butner, North Carolina

Christopher G. Willett, MD, FASTRO
Professor and Chairman
Department of Radiation Oncology
Duke University
Durham, North Carolina

John A. Wolfgang, PhD
Physicist
Department of Radiation Oncology
Harvard Medical School
Massachusetts General Hospital
Boston, Massachusetts

Neil M. Woody, MD, MS
Resident
Department of Radiation Oncology
Taussig Cancer Institute
Cleveland Clinic
Cleveland, Ohio

Catheryn M. Yashar, MD, FACRO
Professor
Department of Radiation Medicine and Applied Sciences
University of California San Diego
San Diego, California

Fang-Fang Yin, PhD

Professor
Department of Radiation Oncology
Duke Clinics
Durham, North Carolina

Darwin Yip, MD
Clinical Fellow
Department of Radiation Oncology
Massachusetts General Hospital
Harvard Medical School
Boston, Massachusetts

Sua Yoo, PhD
Associate Professor
Department of Radiation Oncology
Duke University Medical Center
Durham, North Carolina

Ellen D. Yorke, PhD
Attending Physicist and Member
Memorial Sloan Kettering Cancer Center
Department of Medical Physics
New York, New York

Preface

The field of radiation oncology has advanced considerably since the advent of Intensity-Modulated Radiation Therapy (IMRT) and related technologies such as Image-Guided Radiation Therapy (IGRT), Volumetric-Modulated Arc Therapy (VMAT), and Stereotactic Body Radiotherapy (SBRT). As a result of maturation of these techniques in the past decade or so, their application in the treatment of various cancers has accelerated at a rapid pace. Also, parallel to these developments, proton beam therapy has gained widespread acceptance as an effective modality, especially in the treatment of pediatric tumors and other malignancies where greater conformity of dose distribution is required than possible with photons. Consequently, we invited some leading experts to write about these latest developments in the field. It is our hope that the fourth edition will bring our readers up-to-date with the state of the art in the physics, biology, and clinical practice of radiation oncology.

This book provides a comprehensive discussion of the physical, biologic, and clinical aspects of treatment planning. Because of its primary focus on treatment planning, it covers this subject at a much greater depth than is the case with other books on medical physics or radiation oncology. Like the previous editions, it is written for the benefit of the entire treatment planning team—namely the radiation oncologist, medical physicist, dosimetrist, and radiation therapist. A distinctive feature of this edition is the inclusion of Key Points and Study Questions at the end of each chapter. This is intended to make the book useful not only for the practitioners but also residents preparing for their board examinations.

We acknowledge Julie Goolsby, Acquisitions Editor, Emilie Moyer, Senior Product Development Editor, and other editorial staff of Wolters Kluwer for their support in the development and production of this book.

Last but not the least, we wish to acknowledge the contributing authors whose expertise and efforts are greatly appreciated. Their valuable contributions have made this publication possible.

Faiz M. Khan
John P. Gibbons
Paul W. Sperduto

Preface to First Edition

Traditionally, treatment planning has been thought of as a way of devising beam arrangements that will result in an acceptable isodose pattern within a patient's external contour. With the advent of computer technology and medical imaging, treatment planning has developed into a sophisticated process whereby imaging scanners are used to define target volume, simulators are used to outline treatment volume, and computers are used to select optimal beam arrangements for treatment. The results are displayed as isodose curves overlaid on multiple body cross-sections or as isodose surfaces in three dimensions. The intent of the book is to review these methodologies and present a modern version of the treatment planning process. The emphasis is not on what is new and glamorous, but rather on techniques and procedures that are considered to be the state of the art in providing the best possible care for cancer patients.

Treatment Planning in Radiation Oncology provides a comprehensive discussion of the clinical, physical, and technical aspects of treatment planning. We focus on the application of physical and clinical concepts of treatment planning to solve treatment planning problems routinely encountered in the clinic. Since basic physics and basic radiation oncology are covered adequately in other textbooks, they are not included in this book.

This book is written for radiation oncologists, physicists, and dosimetrists and will be useful to both the novice and those experienced in the practice of radiation oncology. Ample references are provided for those who would like to explore the subject in greater detail.

We greatly appreciate the assistance of Sally Humphreys in managing this lengthy project. She has been responsible for keeping the communication channels open among the editors, the contributors, and the publisher.

Faiz M. Khan
Roger A. Potish

Contents

SECTION II

Treatment Planning for Specific Cancers

SECTION I

Physics and Biology of Treatment Planning

1 Introduction: Process, Equipment, and Personnel

Faiz M. Khan

Every patient with cancer must have access to the best possible care regardless of constraints such as geographic separation from adequate facilities and professional competence, economic restrictions, cultural barriers, or methods of healthcare delivery. Suboptimal care is likely to result in an unfavorable outcome for the patient, at greater expense for the patient and for society.

—Blue Book (1)

INTRODUCTION

Radiotherapy procedure in itself does not guarantee any favorable outcome. It is through meticulous planning and careful implementation of the needed treatment that the potential benefits of radiotherapy can be realized. The ideas presented in this book pertain to the clinical, physical, and technical aspects of procedures used in radiotherapy treatment planning. Optimal planning and attention to details will make it possible to fulfill the goal of the Blue Book, namely, to provide the best possible care for every patient with cancer.

TREATMENT PLANNING PROCESS

Treatment planning is a process that involves the determination of treatment parameters considered optimal in the management of a patient's disease. In radiotherapy, these parameters include target volume, dose-limiting structures, treatment volume, dose prescription, dose fractionation, dose distribution, patient positioning, treatment machine settings, online patient monitoring, and adjuvant therapies. The final product of this activity is a blueprint for the treatment, to be followed meticulously and precisely over several weeks.

TARGET VOLUME ASSESSMENT

Treatment planning starts right after the therapy decision is made and radiotherapy is chosen as the treatment modality. The first step is to determine the tumor location and its extent. The *target volume,* as it is called, consists of a volume that includes the tumor (demonstrated through imaging or other means) and its occult spread to the surrounding tissues or lymphatics. The determination of this volume and its precise location is of paramount importance. Considering that radiotherapy is basically an agent for local or regional tumor control, it is logical to believe that errors in target volume assessment or its localization will cause radiotherapy failures.

Modern imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, single photon emission computed tomography (SPECT), and

positron emission tomography (PET) assist the radiation oncologist in the localization of target volume. However, what is discernible in an image may not be the entire extent of the tumor. Sufficient margins must be added to the demonstrable tumor to allow for uncertainty in the imaging as well as microscopic spread, depending upon the invasive characteristics of the tumor.

Next in importance to localization of the target volume is the localization of critical structures. Again, modern imaging is greatly helpful in providing detailed anatomic information. Although such information is available from standard anatomy atlases, its extrapolation to a given patient is fraught with errors that are unacceptable in precision radiotherapy.

Assessment of the target volume for radiotherapy is not as easy as it may sound. The first and foremost difficulty is the fact that no imaging modality at the present time is capable of revealing the entire extent of the tumor with its microscopic spread. The visible tumor, usually seen through imaging, represents only a part of the tumor, called the *gross tumor volume* (GTV). The volume that includes the entire tumor, namely, GTV, and the invisible microscopic disease can be estimated only clinically and is therefore called the *clinical target volume* (CTV).

The estimate of CTV is usually made by giving a suitable margin around the GTV to include the occult disease. This process of assessing CTV is not precise because it is subjective and depends entirely on one's clinical judgment. Because it is an educated guess at best, one should not be overly tight in assigning these margins around the GTV. The assigned margins must be wide enough to ensure that the CTV thus designed includes the entire tumor, including both the gross and the microscopic disease. If in doubt, it is better to be more generous than too tight because missing a part of the disease, however tiny, would certainly result in treatment failure.

Added to the inherent uncertainty of CTV are the uncertainties of target volume localization in space and time. An image-based GTV, or the inferred CTV, does not have static boundaries or shape. Its extent and location can change as a function of time because of variations in patient setup, physiologic motion of internal organs, patient breathing, and positioning instability. A planning target volume (PTV) is therefore required, which should include the CTV plus suitable margins to account for the above uncertainties. PTV, therefore, is the ultimate target volume—the primary focus of the treatment planning and delivery. Adequate dose delivered to PTV at each treatment session presumably assures adequate treatment of the entire disease-bearing volume, the CTV.

Because of the importance of accurate determination of PTV and its localization, the International Commission on Radiation Units and Measurements (ICRU) has come up with a systematic approach to the whole process, as illustrated in Figures 1.1 and 1.2. The reader is referred to ICRU Reports 50, 62, and 71 for the underlying concepts and details of the system (2–4).

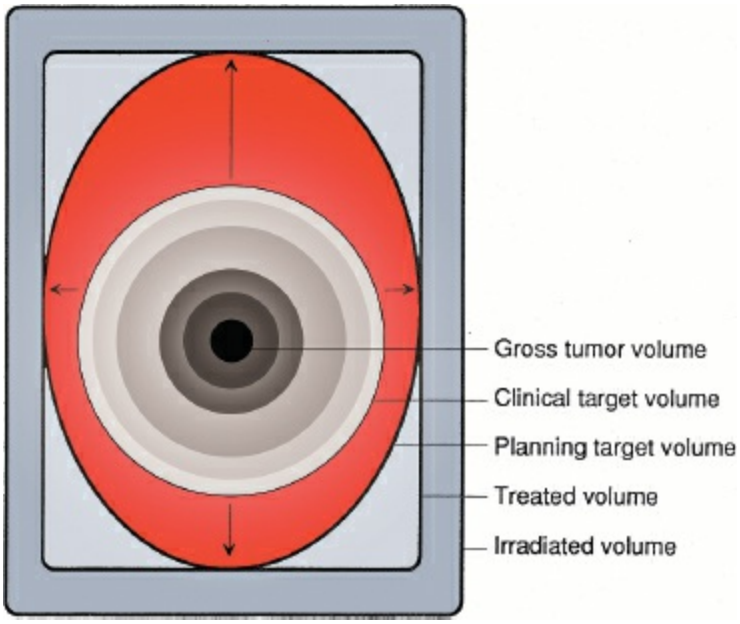


FIGURE 1.1 Schematic illustration of ICRU volumes. (From ICRU. *Prescribing, Recording, and Reporting Photon Beam Therapy. ICRU Report 50*. Bethesda, MD: International Commission of Radiation Units and Measurements; 1993.)

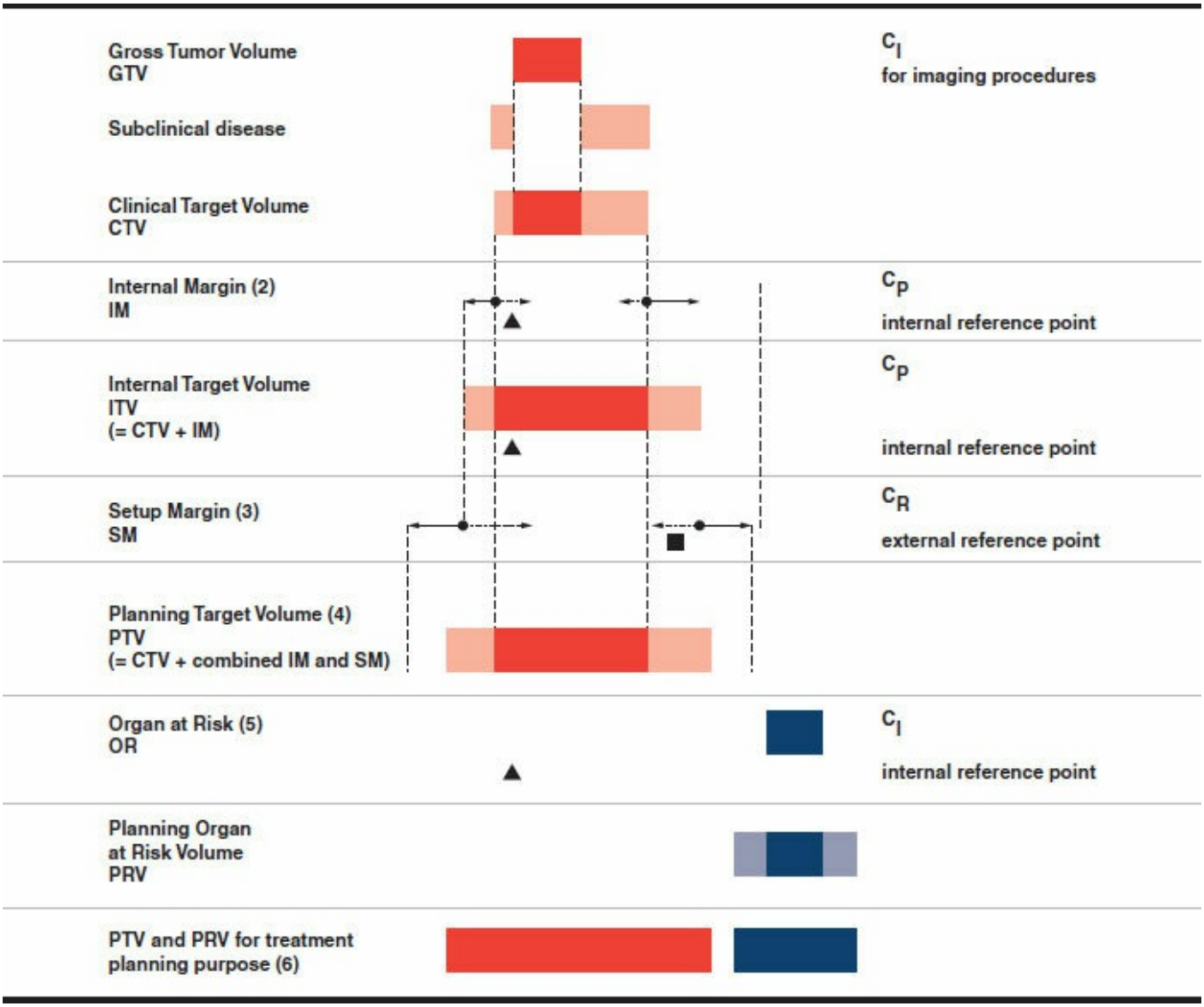


FIGURE 1.2 Schematic representation of ICRU volumes and margins. (From ICRU. *Prescribing, Recording, and Reporting Photon Beam Therapy [Supplement to ICRU Report 50]. ICRU Report 62*. Bethesda, MD: International

Commission on Radiation Units and Measurements; 1999.)

Although sophisticated treatment techniques such as intensity-modulated radiation therapy (IMRT) and image-guided radiation therapy (IGRT) are now available, which account for organ motion and positional uncertainties as a function of time, the basic problem still remains: How accurate is the CTV? Unless the CTV can be relied upon with a high degree of certainty, various protocols to design PTV from it and the technical advances to localize it precisely in space and time would seem rather arbitrary, illusory, or even make-believe. Therefore, the need for technologic sophistication (with its added cost and complexity) must be balanced with the inherent uncertainty of CTV for a given disease.

However, the above, seemingly pessimistic view of the process should not discourage the development or the use of these technologies. It should rather be taken as a cautionary note for those who may pursue such technologies with a blind eye to their limitations. Technologic advances must ultimately be evaluated in the context of biologic advances. “Smart bombs” are not smart if they miss the target or, worse yet, produce unacceptable collateral damage.

Treating the right target volume conformally with the right dose distribution and fractionation is the primary goal of radiotherapy. It does not matter if this objective is achieved with open beams or uniform-intensity wedged beams, compensators, IMRT, or IGRT. As will be discussed in the following chapters, various technologies and methodologies are currently available, which should be selected on the basis of their ability to achieve the above radiotherapy goal for the given disease to be treated. In some cases, simple arrangements such as a single beam, parallel-opposed beams, or multiple beams, with or without wedges, are adequate, while in others IMRT or IGRT is the treatment of choice.

EQUIPMENT

Treatment planning is a process essentially of optimization of therapeutic choices and treatment techniques. This is all done in the context of available equipment. In the absence of adequate or versatile equipment, optimization of treatment plans is difficult, if not impossible. For example, if the best equipment in an institution is a cobalt unit or a traditional low-energy (4 to 6 MV) linear accelerator, the choice of beam energy for different patients and tumor sites cannot be optimized. If a good-quality simulator (conventional or CT) is not available, accurate design of treatment fields, beam positioning, and portal localization are not possible. Without modern imaging equipment, high accuracy is not possible in the determination of target volumes and critical structures, so that techniques that require conformal dose distributions in three dimensions cannot be optimized. Accessibility to a reasonably sophisticated computerized treatment planning system is essential to plan isodose distributions for different techniques so as to select the one that is best suited for a given patient. Therefore, the quality of treatment planning and the treatment itself depend on how well equipped the facility is with regard to treatment units, imaging equipment, and treatment planning computers.

External Beam Units

Low-Energy Megavoltage X-ray Beams

Low-energy megavoltage beams without IMRT capability (e.g., cobalt-60 and/or 4–6-MV

x-rays) are principally used for relatively shallow or moderately deep tumors such as in the head and neck, breast, and extremities. For treatments using parallel-opposed beams, the body thickness in the path of these beams should not exceed approximately 17 cm. This is dictated by the ratio of maximum peripheral dose to the midline dose (5).

In addition to the beam energy, it is also important to have machine specifications that improve beam characteristics as well as accuracy of treatment delivery. Some of the major specifications, for example, are isocentric capability with source-to-axis distance of 100 cm (not less than 80 cm for cobalt-60), field size of at least 40 × 40 cm, versatile and rigid treatment couch, asymmetrical collimators, MLCs, and other features that allow optimization of treatment techniques.

For IMRT or IGRT techniques, a 6-MV x-ray beam is sufficient so far as the energy is concerned. However, the unit must be equipped with a special collimator having dynamic MLC or apertures suitable for these techniques. Its operation must be computer controlled to allow for intensity-modulated beam delivery in accordance with the IMRT or IGRT treatment plans.

Medium- or High-Energy Megavoltage X-ray Beams

X-ray beams in the energy range of 10 to 25 MV allow treatment techniques for deep-seated tumors in the thorax, abdomen, or pelvis. For parallel-opposed beam techniques, the deeper the tumor, the higher the energy required to maximize the dose to the tumor, relative to the normal tissue. Again, the ratio of the maximum peripheral dose to the midline dose is an important consideration (5). In addition, the dose buildup characteristics of these beams allow substantial sparing of normal subcutaneous tissue in the path of the beams.

One may argue that the degree of normal tissue sparing achieved by x-ray beams of 10 MV energy can also be achieved by lower megavoltage beams using more than two beam directions, as in multiple isocentric fields, rotation therapy, or IMRT. However, for deep-seated tumors, high-energy beams offer greater tissue sparing for all techniques, including IMRT.

Charged-Particle Beams

1. Electrons. Electron beams in the range of 6 to 20 MeV are useful for treating superficial tumors at depths of 5 cm. They are often used in conjunction with x-ray beams, either as a boost or a mixed-beam treatment, to provide a particular isodose distribution. The principal clinical applications include the treatment of skin and lip cancers, chest wall irradiation, boost therapy for lymph nodes, and the treatment of head and neck cancers.

Depth–dose characteristics of electron beams have unique features that allow effective irradiation of relatively superficial cancers and almost complete sparing of normal tissues beyond them. The availability of this modality is essential for optimizing treatments of approximately 10% to 15% of cancers managed with radiotherapy.

2. Protons. Proton beam therapy has been used to treat almost all cancers that are traditionally treated with x-rays and electrons (e.g., tumors of the brain, spine, head and neck, breast, lung, gastrointestinal malignancies, prostate, and gynecologic cancers). Because of the ability to obtain a high degree of conformity of dose distribution to the target volume with practically no exit dose to the normal tissues, the proton radiotherapy is an excellent option for tumors in close proximity of critical structures such as tumors of the brain, eye, and spine. Also, protons give significantly less integral dose than photons and, therefore, should be a preferred modality in the

treatment of pediatric tumors where there is always a concern for a possible development of secondary malignancies during the lifetime of the patient.

3. Carbon ions. Efficacy of charged particles heavier than protons such as nuclei of helium, carbon, nitrogen, neon, silicon, and argon has also been explored. Although carbon ions or heavier charged particles have the potential to be just as good as protons, if not better, it is debatable whether the benefits justify the high cost of such machines. As it stands, for most institutions, even the acquisition of protons is hard to justify over the far less expensive but very versatile megavoltage x-ray and electron accelerators.

Protons and heavier charged particles no doubt have unique biologic and physical properties, but "Are they clinically superior to x-rays and electrons with IMRT and IGRT capabilities?" The answer awaits more experience. Clinical superiority of heavy charged particles needs to be demonstrated by carefully conducted clinical trials.

Patient Load Versus Treatment Units

The number of patients treated on a given unit can be an important determinant of the quality of care. Overloaded machines and overworked staff often give rise to suboptimal techniques, inadequate care in patient setup, and a greater possibility of treatment errors. As in any other human activity, rushed jobs do not yield the best results. In radiotherapy, in which the name of the game is accuracy and precision, there is simply no room for sloppiness, which can easily creep in if the technologist's primary concern is to keep up with the treatment schedule. An assembly line type of atmosphere should never be allowed in a radiotherapy facility because it deprives the patients of their right to receive the best possible care that radiotherapy has to offer.

A report like the Blue Book is the best forum for setting up guidelines for equipment use. The recommendation of this document is that the load for a given megavoltage unit should not exceed 6,000 standard treatments (single patient visit equivalent) per year. Depending upon the complexity of procedures performed on a machine, its calibration checks, and quality assurance, the patient load per megavoltage machine for full use can vary from 20 to 30 patients treated per day. Details of calculating realistic load for a megavoltage unit and criteria for replacing or acquiring additional equipment are given in the Blue Book (1).

Brachytherapy Equipment

Brachytherapy is an important integral part of a radiotherapy program. Some tumors are best treated with brachytherapy, alone or in conjunction with an external beam. It is therefore important to have this modality available if optimal treatment planning is the goal. Although electrons are sometimes used as an alternative, brachytherapy continues to have an important role in treating certain tumors such as gynecologic malignancies, oral cancers, sarcomas, prostate cancer, and brain tumors.

Currently, the sources most often being used are cesium-137 tubes, iridium-192 seeds contained in ribbons, iodine-125 seeds, and palladium-103 seeds. These isotopes can be used in after-loading techniques for interstitial as well as intracavitary implantation. Numerous applicators and templates have been designed for conventional LDR brachytherapy. The institution must follow a particular system consistently with all its hardware, rules of implantation, and dose specification schemes. Remote after-loading units, LDR as well as HDR, are becoming increasingly popular, especially among institutions with large patient loads for brachytherapy. Brachytherapy hardware,

software, and techniques are discussed in later chapters.

Imaging Equipment

Modern treatment planning is intimately tied to imaging. Although all diagnostic imaging equipments have some role in defining and localizing target volumes, the most useful modalities currently are the CT, MRI, and PET.

Most radiotherapy institutions have access to these machines through diagnostic departments. The only problem with this kind of arrangement is that the fidelity of imaging data obtained under diagnostic conditions is quite poor when used for treatment planning. This is caused primarily by the lack of reproducibility in patient positioning. Besides appropriate modifications in the scanner equipment (e.g., flat tabletop, patient positioning aids), the patient setup should be supervised by a member of the treatment planning staff. With the growing demand for CT, 4-dimensional (4D) CT (respiration-correlated), and MRI in radiotherapy and the large number of scans that 3-dimensional (3D) treatment planning requires, dedicated scanners in radiotherapy departments are becoming the norm.

Simulator

There is still a role for conventional simulators in a radiation therapy department although their presence is becoming less common. It is important that the simulator has the same geometric accuracy as the treatment machine. In addition, it should allow the simulation of various treatment techniques that is possible with modern treatment machines.

With the advent of 3D treatment planning, conformal field shaping, MLCs, 4D CTs, and electronic portal imaging, it is logical to move into CT simulation. A conventional simulator may be useful for final verification of the field placement, but with the availability of good-quality DRRs and special software for CT simulation, this need no longer exists. Final field verification before treatment can be obtained with the portal imaging system available on modern linacs.

CT scanners have been used for treatment planning for many years because of their ability to image patient anatomy and gross tumor, slice by slice. These data can be processed to view images in any plane or in three dimensions. In addition, CT numbers can be correlated with tissue density, pixel by pixel, thereby allowing heterogeneity corrections in treatment planning. The only drawback of diagnostic CT scans is that of geometric accuracy of localization needed in radiotherapy. Diagnostic CT units, with typically narrow apertures and curved tabletops, cannot reproduce patient positions that would be used for treatment. Although variations due to positioning can be minimized by using flat tabletops and units with wide aperture (e.g., 70 cm or larger diameter), the personnel operating diagnostic equipment are not trained to set up patients accurately to reproduce radiation therapy conditions. In addition, diagnostic simulation units are usually too busy to allow sufficient time for therapy simulations. Because of these technical and logistic problems, a dedicated CT scanner for radiation therapy has gained wide acceptance.

A dedicated radiation therapy CT scanner, with accessories (e.g., flat table identical with those of the treatment units, lasers for positioning, immobilization, and image registration devices, etc.) to accurately reproduce treatment conditions, is called a *CT-simulator*. Many types of such units are commercially available. Some of them are designed specifically for radiation therapy with wide apertures (e.g., 85 cm diameter) to provide flexibility in patient positioning for a variety of treatment setups. The CT image data set thereby obtained, with precise localization of patient anatomy and tissue

density information, is useful not only in generating an accurate treatment plan, but also in providing a reference for setting up treatment plan parameters. This process is sometimes called *virtual simulation*.

Positron Emission Tomography/Computed Tomography

The physics of PET is based on the positron–electron annihilation into photons. For example, a radiolabeled compound such as fluorodeoxyglucose (FDG) incorporates ^{18}F as the positron-emitting isotope. FDG is an analog of glucose that accumulates in metabolically active cells. Because tumor cells are generally more active metabolically than normal cells, an increased uptake of FDG is positively correlated with the presence of tumor cells and their metabolic activity. When the positron is emitted by ^{18}F, it annihilates a nearby electron, with the emission of two 0.511-MeV photons in opposite directions. These photons are detected by ring detectors placed in a circular gantry surrounding the patient. From the detection of these photons, computer software (e.g., filtered back projection algorithm) reconstructs the site of the annihilation events and the intervening anatomy. The site of increased FDG accumulation, with the surrounding anatomy, is thereby imaged with a resolution of about 4 mm.

Combining PET with CT scanning has several advantages:

1. Superior quality CT images with their geometric accuracy in defining anatomy and tissue density differences are combined with PET images to provide physiologic imaging, thereby differentiating malignant tumors from the normal tissue on the basis of their metabolic differences.
2. PET images may allow differentiation between benign and malignant lesions well enough in some cases to permit tumor staging.
3. PET scanning may be used to follow changes in tumors that occur over time and with therapy.
4. By using the same treatment table for a PET/CT scan, the patient is scanned by both modalities without moving (only the table is moved between scanners). This minimizes positioning errors in the scanned data sets from both units.
5. By fusing PET and CT images, the two modalities become complementary.

Although PET provides physiologic information about the tumor, it lacks correlative anatomy and is inherently limited in resolution. CT, on the other hand, lacks physiologic information but provides superior images of anatomy and localization. Therefore, PET/CT provides combined images that are superior to either PET or CT images alone.

Accelerator-Mounted Imaging Systems

After the treatment planning and simulation comes the critical step of accurate treatment delivery of the planned treatment. Traditionally, patients are set up on the treatment couch with the help of localization lasers and various identification marks on the patient, for example, ink marks, tattoos, or palpable bony landmarks. Sometimes identification marks are drawn on the body casts worn by the patient for immobilization. These procedures would be considered reasonable, if only the patient would not move within the cast and the ink or tattoo marks did not shift with the stretch of the skin. Bony landmarks are relatively more reliable, but their location by palpitation cannot be pinpointed to better than a few millimeters. Good immobilization devices are critical in minimizing setup variations and are discussed later in the book.

With the introduction of 3D conformal radiation therapy (CRT), including IMRT and

IGRT, it has become increasingly apparent that the benefit of these technologies cannot be fully realized if the patient setup and anatomy do not match the precision of the treatment plan within acceptable limits at every treatment session. As the treatment fields are made more conformal, the accuracy requirements of patient setup and the PTV coverage during each treatment accordingly have to be made more stringent. These requirements have propelled advances in the area of patient immobilization and dynamic targeting of PTV through imaging systems mounted on the accelerators themselves. Thus began the era of IGRT.

Each of the three major linear accelerator manufacturers, Varian, Elekta, and Siemens, provide accelerator-mounted imaging systems allowing online treatment plan verification and correction (adaptive radiation therapy) and dynamic targeting, synchronized with the patient's respiratory cycles (gating). The commercial names for the systems are Trilogy (www.varian.com), Synergy (www.elekta.com), and ONCOR (www.siemens.com). These products come with various options, some of which may be works in progress or currently not FDA approved. The reader can get the updated information by visiting the corresponding Web sites.

The important consideration in acquiring any of these systems is dictated by the desire to provide state-of-the-art radiation therapy. Such a system is expected to have the following capabilities:

1. 3D CRT with linac-based megavoltage photon beam(s) of appropriate energy (e.g., 6 to 18 MV)
2. Electron beam therapy with five or six different energies in the range of 6 to 20 MeV
3. IMRT, IGRT, and gated radiation therapy capabilities
4. Accelerator-mounted imaging equipment to allow the treatment techniques mentioned earlier (such as IMRT and IGRT)

Typically, such a system consists of an electronic portal imaging device (EPID), a kVp source for radiographic verification of setup, an online fluoroscopic mode to permit overlaying of treatment field aperture on to the fluoroscopy image, and cone-beam CT capability for treatment plan verification. Many of these devices and their use in modern radiotherapy such as IGRT are discussed in the following chapters.

Treatment Planning Computers

Commercial treatment planning computers became available in the early 1970s. Some of the early ones such as the Spear PC, the Artronix PC-12, Rad-8, Theratronics Theraplan, and ADAC were instant hits and provided a quantum jump from manual to computerized treatment planning. They served their purpose well in providing fast and reasonably accurate 2-dimensional (2D) treatment plans. Typically, they allowed the input (through the digitizer) of external patient contours, anatomic landmarks, and outlines of the target volume and of the critical structures in a specified plane (usually central). Beams were modeled semiempirically from the stored beam data obtained in a water phantom. Various corrections were used to apply the water phantom data to the patient situation, presenting irregular surfaces, tissue inhomogeneities, and multiple beam angles. However, from today's standards, the old systems would be considered very limited in capability and rudimentary in the context of modern 3D treatment planning.

With the explosion of computer and imaging technologies in the last 20 years or so, the treatment planning computers and their algorithms have accordingly become more powerful and sophisticated. Systems that are currently available allow 3D treatment

planning in which patient data obtained from CT scanning, MRI, PET, and so on, are to be input electronically. Beams are modeled with sophisticated computational algorithms, for example, pencil beam, convolution–superposition, semi Monte Carlo, or full Monte Carlo. These algorithms for photons, electrons, and brachytherapy sources are discussed in later chapters.

Besides major improvements in dose computational methods, there have been revolutionary advances in software, which allow planning of complex treatments such as 3D CRT, IMRT, IGRT, and HDR brachytherapy. One of the most powerful treatment planning algorithms is called *inverse planning,* which allows the planner to specify the desired dose distribution and let the computer generate a plan as close to the input specifications as possible. Again, these techniques and algorithms are topics of discussion later in the book.

Major 3D treatment planning systems that are commercially available are Pinnacle (www.medical.philips.com), Eclipse (www.varian.com), and Computerized Medical Systems (CMS; www.cms.stl.com). As these systems are constantly evolving and undergoing revisions, the reader should be mindful of the fact that an older version of any given system may not carry much resemblance to the newest version. Therefore, anyone in the market for such a system needs to do some researching and check out each system with its most current version. Also, because these systems and their software are frequently revised and updated, the user is advised to carry a service contract for maintenance as well as the option of receiving future updates as they come along.

Staffing

The 1991 Blue Book has been updated by ASTRO to a new document, entitled *Safety Is No Accident: A Framework for Quality Radiation Oncology and Care* (6). This book was published in 2012 and is available online at **https://www.astro.org/Clinical-Practice/Patient-Safety/Blue-Book/bfp/index.html#/60.** The new document provides a blueprint for modern radiation oncology facilities in terms of structure, process, and personnel requirements.

The basis for these recommendations is the fundamental principle that radiation oncology practice requires a team of personnel with appropriate educational and training background. Besides the physician specialists, the radiation oncologists, radiotherapy requires the services of medical physicists, dosimetrists, therapists, and nurses. The minimum level of staffing recommended is shown in Table 1.1. In the specific areas of treatment planning, the key personnel are radiation oncologists, medical physicists, and dosimetrists. The quality of treatment planning largely depends on the strength of this team.

TABLE 1.1 **Minimum Personnel Requirements for Clinical Radiation Therapy**[a]

Category	Staffing (See important comments below)
Chief Radiation Oncologist	One per facility
Chief Medical Physicist	One per facility
Department Manager	One per facility (in some departments this function may be filled by a member of the team)
Medical Dosimetrist[b]	As needed, approximately one per 250 patients treated annually
Radiation Therapist[b]	As needed, approximately one per 90 patients treated annually
Brachytherapy Technologist[b]	As needed, approximately one per 100 brachytherapy patients treated annually
Mold Room Technologist	As needed to provide service
Social Worker/Dietician	As needed to provide service

[a]It is recommended that a minimum of two qualified individuals be present for any routine external beam patient treatment.

[b]This number may be higher or lower depending upon the complexity of patients treated by an individual physician or by the complexity of technology.

From American Society for Radiation Oncology (ASTRO). *Safety is No Accident*.

[https://www.astro.org/clinical-practice/patient-safety/safety-book/safety-is-no-accident.aspx]; 2012, with permission

Radiation Oncologist

The radiation oncologist, who has the ultimate responsibility for the care of the patient, heads the treatment planning team. It is his or her responsibility to formulate the overall plan for the treatment, including dose prescription to tumor-bearing sites of the body. Details of the actual treatment technique, beam energies, beam directions, and other specific details of the treatment are finalized after a number of isodose plans have been calculated and an optimal plan has been selected. The final plan must meet the approval of the radiation oncologist in charge of the patient.

The ACR standards require that the radiation oncologist be board-certified to practice radiation oncology. In addition, the number of radiation oncologists in a given institution must be in proportion to the patient load (Table 1.1). No more than 25 to 30 patients should be treated by a single physician. It is important to ensure that each patient receives adequate care and attention from the physician and that the treatments are not compromised because of the physician's lack of time.

Medical Physicist

No other medical specialty draws as much from physics as radiation oncology. The science of ionizing radiation is the province of physics, and its application to medicine

requires the services of a physics specialist, the medical physicist. It is the collaboration between the radiation oncologist and the medical physicist that makes radiotherapy an effective treatment modality for cancer. Ralston Paterson (7), emphasizing this relationship, stated in 1963: "In radiotherapy the physicist who has given special study to this field is full partner with the therapist, not only in the development of the science, but in the day-to-day treatment of patients. The unit team, therefore, even for the smallest department, consists of a radiotherapist and a physicist."

The unit team of radiation oncologist and medical physicist must have a supporting cast to provide radiotherapy service effectively to all patients referred to the department. Dosimetrists, radiation therapists (previously called technologists), nurses, and service engineers are the other members of the team. It must be recognized by all concerned that without this infrastructure and adequate staffing in each area of responsibility, radiotherapy is reduced to an ineffective, if not unsafe, modality of treatment.

Adequacy of the support of physics has been spelled out in the ASTRO document (6). The number of physicists required in a radiotherapy institution depends not only on the number of patients treated per year but also on the complexity of the radiotherapy services offered. For example, special procedures such as stereotactic radiotherapy, HDR brachytherapy, total-body irradiation for bone marrow transplantation, 3D CRT, IMRT, IGRT, SBRT, respiratory gating, TomoTherapy, CyberKnife treatments, and intraoperative radiotherapy are all physics-intensive procedures and therefore require more physicists as recommended by ASTRO.

According to the American Association of Physicists in Medicine (AAPM), a medical physicist involved with clinical services must have a PhD or MS degree and be board certified in the relevant specialty; in this case, radiation oncology physics. Also, most physicists in an academic setting teach and do research, and therefore a doctorate degree is more desirable for them. Such research plays a key role in the development of new techniques and in bringing about new advances to radiation oncology. Paterson (7) emphasized this role by stating "While the physicist has a day-to-day routine task in this working out or checking of cases, it is important that he has time for study of special problems. These may include the development of new x-ray techniques, the devising of special applicators to simplify or assist treatment, the critical analysis of existing techniques, or research work of a more fundamental nature."

TABLE 1.2 Roles and Responsibilities of Physicists

Equipment (teletherapy, brachytherapy, simulator)	Treatment planning (teletherapy and brachytherapy)	Dosimetry	Radiation protection	Academic, administrative
Selection, specifications	Management, QA of treatment planning computer	Dose calculation formalism	Regulatory	Teaching
Acceptance testing	Beam data management	Special treatment techniques	Radiation survey	Research
Commissioning, beam data measurement	Simulation consultation	Special dosimetry	Personnel monitoring	Developmental
Calibration	Patient data for treatment planning	In vivo dosimetry	Facility design	Administrative
Quality assurance	Technique optimization, isodose planning; plan analysis, evaluation; treatment aids; beam modifiers			

QA, quality assurance.

From Khan FM. Residency training for medical physicists. *Int J Radiat Oncol Biol Phys*. 1992;24:853–855.

A medical physicist's role in radiotherapy is summarized in Table 1.2. Specifically in treatment planning, the physicist has the overall responsibility of ensuring that the

treatment plan is accurate and scientifically valid. That means that the physicist is responsible for testing the computer software and commissioning it for clinical use. He or she is also responsible for proper interpretation of the treatment plan as it relates to the dose distribution and calculation of treatment duration or monitor units.

One important role of a medical physicist that is often overlooked is that of a consultant to radiation oncologists in the design of the treatment plan. Physicians working directly with dosimetrists to generate a treatment plan without any significant input from the physicist can often be seen. This process may be operationally smooth and less costly but can be risky if serious errors go undetected and the final plan is not optimal. It must be recognized that a qualified medical physicist, by virtue of education and training, is the only professional on the radiotherapy team who is familiar with the treatment planning algorithm and can authenticate the scientific validity of a computer treatment plan. It is important that he or she be actively involved with the treatment planning process and that the final plan receives his or her careful review. Because of the tendency of some physicians to bypass the physicist, some institutions have developed the policy of having the physicist present during simulation and doing the treatment planning either personally or closely working with the dosimetrist in the generation and optimization of the treatment plan.

Dosimetrist

Historically, dosimetrists were classified as physics personnel with a Bachelor of Science degree in the physical sciences. They assisted physicists in routine clinical work such as treatment planning, exposure time calculations, dosimetry, and quality assurance. They could be called a *physicist assistant,* analogous to physician assistant.

Today the dosimetrist's role is not much different, but the educational requirements have been formalized to include certification by the Medical Dosimetrist Certification Board (MDCB), in addition to a Bachelor's Degree and graduation from an accredited Medical Dosimetry training program.

As discussed earlier, the role of a dosimetrist is traditionally to assist the physicist in all aspects of physics service. However, in some institutions, dosimetrists substitute for physicists, and/or the treatment planning procedure is made the sole responsibility of the dosimetrist with no supervision from the physicist. Whether it is done for economic or practical reasons, leaving out the physicist from the treatment planning process is not appropriate and definitely not in the best interest of the patient. The dosimetrist's role is to assist the physicist, not to replace him or her. The radiation oncologist must understand that a computer treatment plan necessitates the physicist's input and review just as much as it necessitates consultation of other medical specialists in the diagnosis and treatment of a patient.

REFERENCES

1. ISCRO. *Radiation Oncology in Integrated Cancer Management: Report of the Inter-Society Council for Radiation Oncology (Blue book).* Reston, VA: American College of Radiology; 1991.
2. ICRU. *Prescribing, Recording, and Reporting Photon Beam Therapy. ICRU Report 50.* Bethesda, MD: International Commission on Radiation Units and Measurements; 1993.
3. ICRU. *Prescribing, Recording, and Reporting Photon Beam Therapy (Supplement to ICRU Report 50). ICRU Report 62.* Bethesda, MD: International Commission on Radiation

Units and Measurements; 1999.
4. ICRU. *Prescribing, Recording, and Reporting Electron Beam Therapy. ICRU Report 71.* Bethesda, MD: International Commission on Radiation Units and Measurements; 2004.
5. Khan FM, Gibbons JP. *The Physics of Radiation Therapy.* 5th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2014:179–180.
6. American Society for Radiation Oncology (ASTRO). *Safety is No Accident: A Framework for Quality Radiation Oncology and Care.* Fairfax, VA: American Society for Radiation Oncology; 2012. https://www.astro.org/clinical-practice/patient-safety/safety-book/safety-is-no-accident.aspx
7. Paterson R. *The Treatment of Malignant Disease by Radiotherapy.* 2nd ed. Baltimore, MD: Williams & Wilkins; 1963:527.

2 Imaging in Radiotherapy

George T.Y. Chen, Gregory C. Sharp, John A. Wolfgang, and Charles A. Pelizzari

INTRODUCTION

Imaging is the basis of modern radiotherapy; it plays a major role in disease localization, treatment planning, guiding radiation delivery, and monitoring response. While projection radiography was the backbone of medical imaging in the first 75 years of its existence, transformative imaging advances in the 1970s led to visualizing patient anatomy through computer assisted tomography. Soft tissue tumors can alter the spatial relationships of normal organs, and with transverse 3-dimensional (3D) maps radiation oncologists could assess target extent and proximity to sensitive organs at risk for collateral damage. Shortly after the introduction of computed tomography (CT) scanning in diagnostic radiology departments, radiation oncologists explored its potential use in therapeutic radiology. Initial studies found tumor coverage was marginal or inadequate in nearly one-half of patients studied (1). Advances in volumetric imaging have continued to evolve, and today multimodality imaging provides insight into tumor biochemistry and microenvironment normal organ function as well as structure.

In parallel, advances in radiation delivery such as intensity modulated, charged-particle-beam, and stereotactic body radiotherapy provided the capability to deliver highly conformal doses to the 3D target using personalized anatomical maps (2–4). Such delivery advances in turn increased the interest in the development of more accurate methods to image and treat moving targets. Advances in treatment-room imaging have further provided the capability of image-guided radiotherapy, where images obtained on a daily basis before or during treatment can be used to correct for variations in setup and organ motion. With advances in imaging and radiation treatment, dose conformation has provided an opportunity to safely increase tumor dose, thereby increasing the probability of tumor control, while minimizing dose to normal radiation sensitive organs below thresholds of serious complications.

The general principles of medical image formation and clinical oncologic imaging are described elsewhere (5,6). Observance of the centennial anniversary of the discovery of x-rays has resulted in historical reviews (7,8). This chapter provides an overview of the imaging modalities and image processing relevant to conformal external beam radiotherapy.

IMAGE ACQUISITION

Volumetric Imaging

Imaging in radiotherapy is broadly categorized into acquired and processed images. Figure 2.1 diagrammatically summarizes imaging modalities used in radiotherapy. Imaging in radiotherapy is dominated by volumetric data sets from multiple modalities. The modalities probe the body noninvasively, utilizing different physical interactions of tissues and the probe modality. Each modality has its strengths and applications, and

complements the strengths of other imaging techniques. Volumetric image acquisition is emphasized, although projection radiography has an important role in the clinic. Use of advanced imaging technologies was surveyed and reported in 2009 (9).

Computed Tomography

CT is the primary imaging modality used in radiation oncology. The history and basic principles of CT image formation are discussed elsewhere (5,10). Briefly, CT measures the linear attenuation coefficient of each pixel in the transverse imaging plane. A fan beam of diagnostic energy x-rays passes through the patient, and the transmitted radiation is measured. Multiple projection views are acquired as the x-ray source rotates around the patient. From these projections, image reconstruction algorithms generate a transverse digital image. Each pixel value is a measurement of μ_x, the linear attenuation coefficient (relative to water μ_w) at an effective diagnostic x-ray energy. At diagnostic energies, the dominant photon/tissue interactions are the photoelectric and Compton effects. Pixel values are quantified in Hounsfield units (HU):

$$\text{CT pixel value (HU)} = 1{,}000\ (\mu_x - \mu_w)/\mu_w$$

For a single energy scan, the HUs associated with various body components are: air, -1,000 HU; water, 0 HU; fat, ~-80 HU; muscle, ~30 HU, and bone variable up to or greater than 1,000 HU. HUs of different tissues at diagnostic energies can be approximately extrapolated to electron density values used for dose calculations (11). Tissue characterization to separately unfold the atomic composition and electron density per pixel can be performed with dual energy scanning (12), although most radiotherapy planning scans are performed at a single x-ray potential. A possible need for dual energy scanning is the calculation of charged particle stopping powers used in proton and heavy ion radiotherapy.

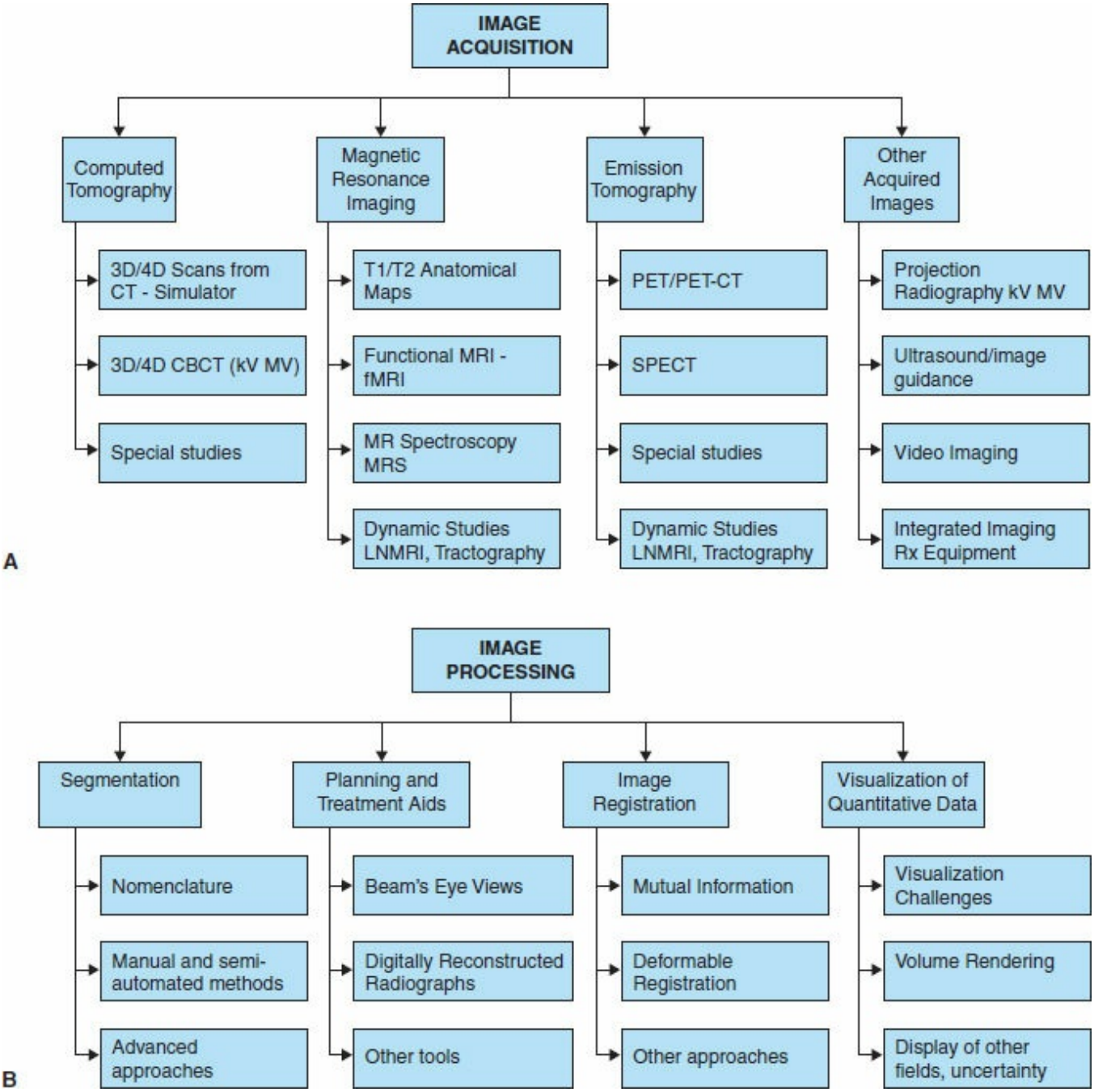


FIGURE 2.1 **A:** Imaging modalities acquired in radiation therapy; **B:** Image processing performed on acquired images to extract and integrate information needed for treatment.

Figure 2.2 shows a human abdominal cadaver section compared to the corresponding CT image (13). While delineation of an organ on CT will not exactly correspond to photographic ground truth (14,15), CT can be geometrically very accurate. Early CT scanners produced a single transaxial slice; 3D volumes were constructed by stacking images. Multiplanar reconstruction of CT data provides the user with sagittal, coronal, and oblique views.

Volumetric CT studies are acquired on CT-simulators within the department. These devices are essentially diagnostic quality scanners with a slightly larger gantry opening to accommodate treatment accessories. The resulting images are nearly the same quality as those used in diagnosis, and provide images usually more than adequate for radiation therapy planning.

CT Scan Acquisition for Treatment Planning

The volumetric CT scans are input into treatment planning, with the goal of calculating

the dose delivered at treatment. Thus, care is taken to position the patient as he/she will be treated on the linear accelerator. Flat treatment couches are used rather than the diagnostic scanner curved table-tops to ensure that internal organs closely approximate their shape and location at treatment. Treatment immobilization devices are used during the scan. High-speed scanning reduces motion artifacts and can capture a bolus of contrast before dissipation.

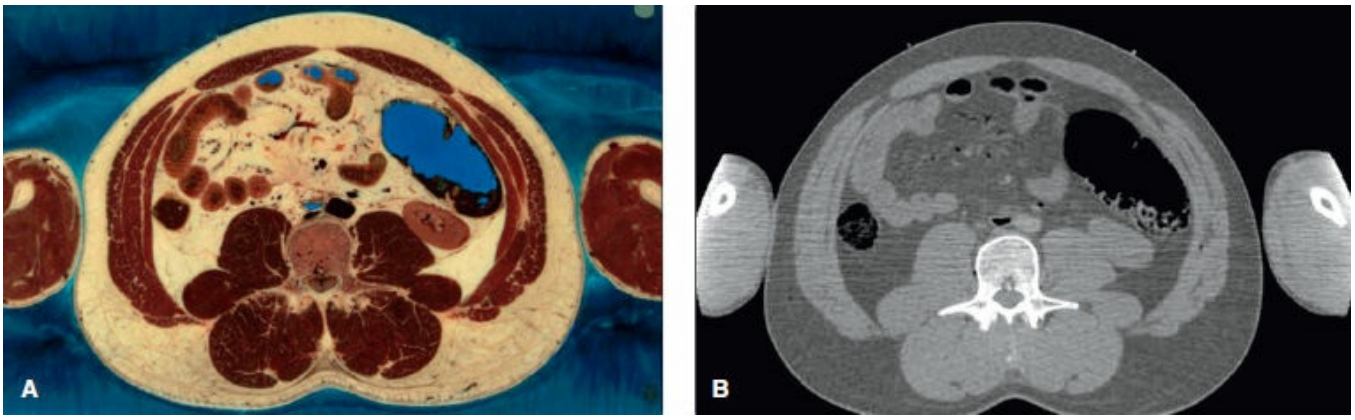


FIGURE 2.2 **A:** Photographic transaxial section of a human abdomen from a cadaver. **B:** Corresponding CT scan (courtesy Visible Human Project).

Three-dimensional CT acquisition modes include (a) axial and (b) helical mode. In axial mode, the patient support assembly is static an image slice is acquired, the x-ray source is then gated off, and the couch is advanced to the next longitudinal position. The procedure is repeated to build a 3D image volume. In helical mode, the couch is continuously advanced while the x-ray tube continuously rotates, leading to faster volumetric scan acquisitions. The time to complete one rotation is ~0.5 seconds. Tagging the x-ray longitudinal coordinate with the image projection data and resorting as the patient advances into the gantry provides the information needed for helical scan image reconstruction.

A scan field of view (FOV) is selected to permit visualization of the external skin contour, data needed for dose calculations. For sites such as head and neck, often two FOVs are used: a smaller FOV for the neck, and a larger FOV to fully image the shoulders. Longitudinal scan limits are chosen to capture both the tumor extent and longitudinal extent of organs at risk. Slice thickness of 3 mm and a total of 200 slices per scanning study are typical in planning scans.

Convention dictates that cross-sectional images are displayed as viewed from below; for a patient in the supine position on the table, head first into the scanner gantry, the image left is the patient's right side. Icons and alphanumeric information imprinted on the scan image provide details of pixel size, slice thickness, and radiographic parameters used during imaging.

CT Artifacts

Artifacts can degrade CT planning studies (16). Artifacts may originate within the patient. Beam hardening results in streaks when the photon beam crosses particularly opaque regions, such as the bone in the posterior fossa of the brain, or metallic fillings in teeth. Physiologic motion can also cause streak artifacts. Intravenous or oral contract can artificially elevate HUs. These artifacts can perturb the calculation of radiographic path length leading to inaccurate dose calculations. Artifacts can also originate within the scanner hardware or by choice of imaging parameters. Partial volume sampling is an artifact resulting from choice of slice thickness; too thick a slice influences the

detectability of small lesions. Other artifacts are introduced in helical or cone-beam reconstructions.

Limitations of 3D Imaging of Moving Anatomy

Imaging organ motion is essential in conformally irradiating moving targets. Quantifying motion can ensure adequate tumor coverage and unnecessary irradiation of adjacent normal tissues. Conventional 3D imaging of moving anatomy may result in an inaccurate depiction of organ shape and location. A motion artifact can frequently be seen in a thoracic CT scan of a patient breathing lightly during a scan (17). Figure 2.3 is an example of such an artifact, where the lung/diaphragm interface is distorted.

Phantom studies under controlled conditions illustrate this temporal aliasing artifact (18). The first column in Figure 2.4 is a photograph of test objects embedded in a foam block. An initial scan is taken with the phantom stationary. Surface rendering of the scan shows life-like realism, as seen in the second column. The phantom is then set into motion simulating respiration, and scans are acquired in standard scan mode. The resulting images of test objects are strikingly distorted, as shown in the next three columns. For scale, the largest ball is 6 cm in diameter. With a motion amplitude of 1 cm (2 cm peak to peak), this sphere may be imaged with an inaccurate longitudinal axis dimension as small as 4 cm. The distortion visualized is dependent on both scan and object motion parameters as well as the respiratory phase at the instant the imaging planes intersect the test object, which explains why distortions vary.

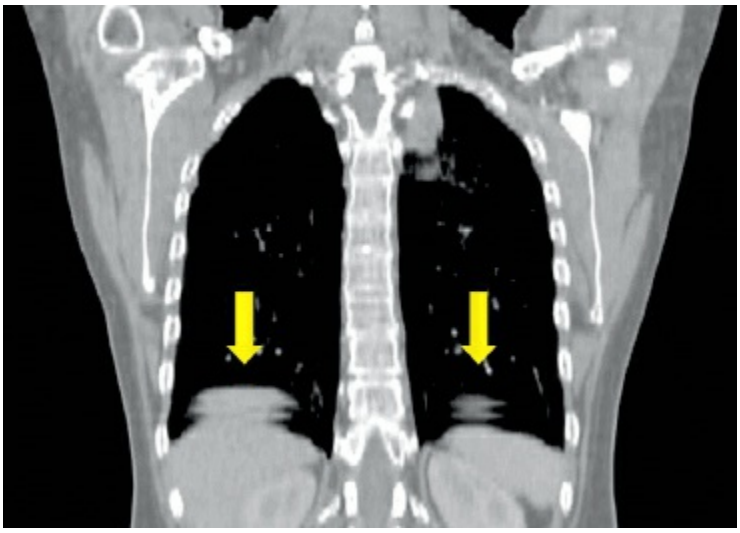


FIGURE 2.3 Temporal aliasing artifacts when scanning a patient during respiration. Note distortion at the lung/diaphragm interface, indicated by yellow.

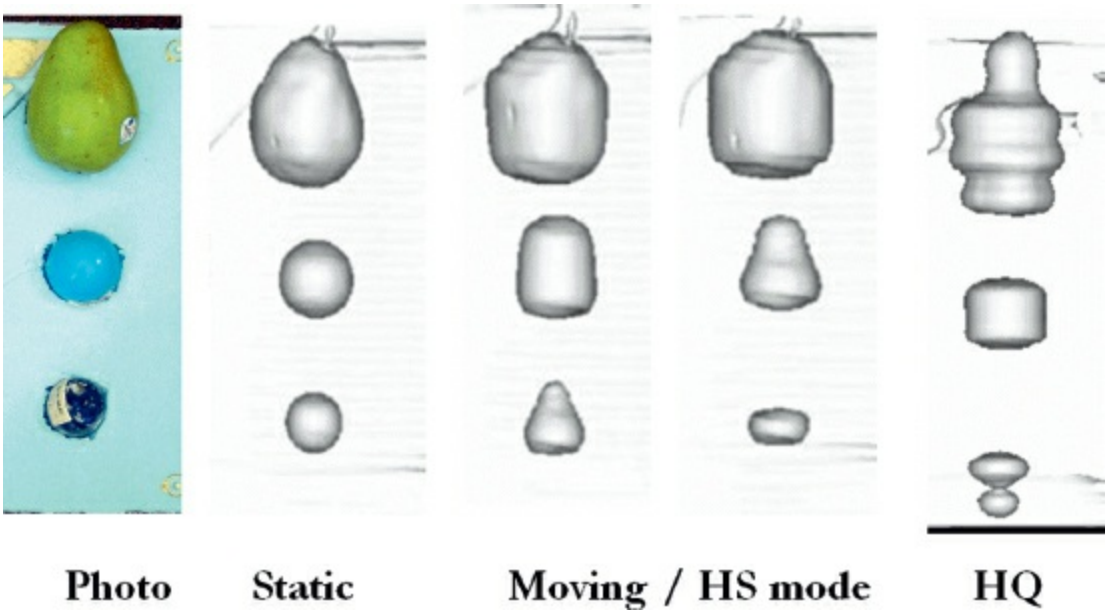


FIGURE 2.4 Imaging test objects in a phantom. The objects are surface rendered when the phantom is static and undergoing respiration simulated motion. Note the geometric distortions of the pear and balls.

4D CT Scanning

Four-dimensional (4D) CT scanning here is defined as CT acquisition at a respiratory time scale. The objective of 4D CT scanning is to capture the shape and trajectory of moving organs during breathing. The motion data can then be used to design an aperture to encompass the observed motion, or to apply motion mitigation strategies such as beam gating. Proof of principle of 4D scanning was initially prototyped on single-slice scanners in 2003 (19–21). A multislice 4D CT simulator system became commercially available shortly thereafter and rapidly became the scanner of choice for radiation therapy (22).

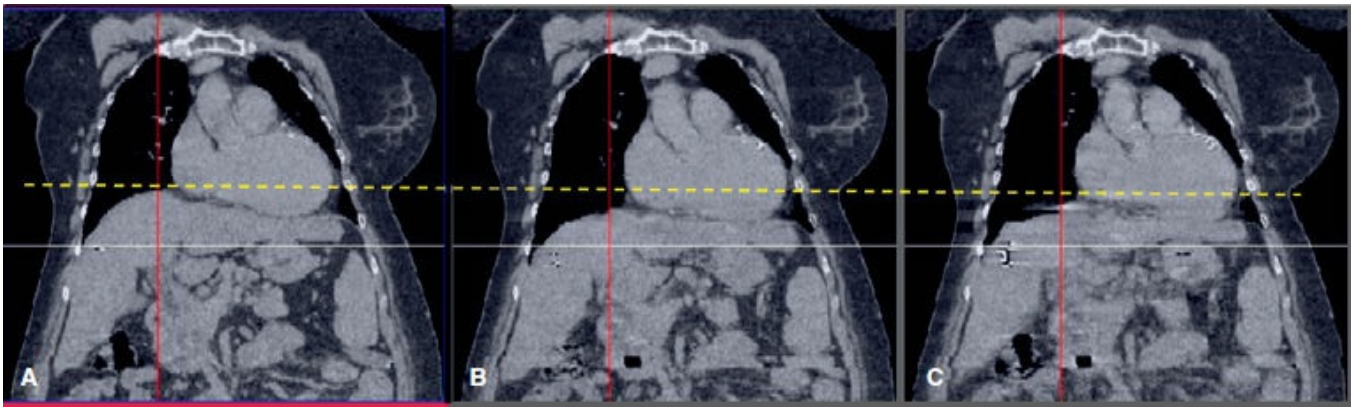


FIGURE 2.5 Coronal MPRs of 4D liver tumor scan. Organs move craniocaudally (*yellow reference line*) at exhale (**A**); at inhale (**B**); residual artifacts due to irregular breathing (**C**).

Respiration-correlated CT uses the motion of the abdominal surface, volume of air measured by spirometry, or other respiratory surrogate signal to correlate the respiratory state during CT acquisition of each slice. The signals are used to re-sort the approximately 1,500 slices of reconstructed image data to a set of coherent spatiotemporal CT data set corresponding to specific time points of the respiratory cycle. A 4D CT acquisition requires a few minutes, and produces 10 static CT volumes, each with a temporal separation of ~one-tenth of the respiratory period (~0.4 seconds). Details of the 4D CT acquisition methods and applications are described elsewhere (22–24). Dose during a 4D CT scan is approximately five times that of a

conventional treatment planning scan, although studies have shown that this may be reduced by altering the radiographic technique without significant reduction of motion information (25).

Figure 2.5 displays coronal images of a 4D CT scanned for a liver tumor. The first two images represent anatomy at exhale and inhale, showing a caudal movement of the dome of the liver by several centimeters.

A 4D capable CT-simulator is suited for assessing organ motion at ~1 second time scale, but has insufficient temporal resolution to image cardiac motion. Ultrahigh-speed cardiac scanners have shown that vessels and tumors near the heart can move by >1 cm (26) due to cardiac pulsation.

While an important advance, 4D CT acquisition can still have residual artifacts. Phase resorting neglects variability of lung tidal volume during free breathing. Figure 2.5C shows an example of an artifact from phase-based 4D CT resorting where breathing amplitude was irregular. Respiratory variations in amplitude, periodicity, and trajectory can perturb 4D scans. Strategies to coach breathing during 4D scanning have included voice prompts and visual feedback but with variable success. Physical breathing control has been attempted through abdominal compression or active breathing control, where the patient breathes through a regulated valve and is forced to hold his breath at a specific respiratory phase. This interventional approach reduces the 4D problem to a static scenario, where both imaging and treatment are performed with minimal motion (27,28).

Volumetric Imaging in the Treatment Room

The interest in precision radiotherapy spurred x-ray volumetric image acquisition in the treatment room. As this topic is covered in detail in the chapter on Image Guided Radiotherapy, we briefly cover selected highlights of image-guided therapy.

CT scanning in the treatment room was extensively used to study prostate and seminal vesicle volume over a protracted treatment regimen (29). The study acquired over 360 CT scans in 15 patients at a 3-scan-per-week rate. The patient is initially set up on the treatment couch and CT scanned in room (with the scanner advancing along the patient's longitudinal axis by translating on rails). After tumor localization, the patient support assembly is rotated into treatment position. This solution provided a stopgap volumetric imaging capability in the treatment room while other imaging solutions were developed and refined.

The most common implementation in use today involves adding tomographic imaging capability to the treatment machine. Much of the interest was spurred by investigators at William Beaumont Hospital (30). An x-ray tube and flat panel detector are mounted orthogonal to the treatment axis. The imaging approach is known as cone-beam computed tomography (CBCT) because the imaging beam is divergent along the longitudinal axis. Projection images for volumetric reconstruction are acquired at multiple angles as the gantry is rotated around the patient in ~1 minute. Reconstruction algorithms optimized for CBCT are used to generate volumetric anatomical maps. While diagnostic CT scanners still set the image quality standard, CBCT images provide clinically useful information even in the presence of motion during acquisition, radiation scatter, and mechanical isocenter wobble during scans. An advance in in-room CBCT imaging was the development of 4D CBCT (31). Time-resolved data can be obtained by sorting the acquired projection data into different temporal bins according to respiratory motion phase in an approach similar to standard 4D CT.

A third approach to treatment room tomographic imaging is to use the MV treatment beam itself. The therapeutic beam serves as the radiation source and a flat panel