STRATEGIES FOR RADIATION THERAPY TREATMENT PLANNING

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Strategies for Radiation Therapy Treatment Planning provides radiation oncologists, physicists, and dosimetrists with a step-by-step guide to implementing external beam treatment plans that meet clinical requirements for each major disease site. As a companion book to the Handbook of Treatment Planning in Radiation Oncology Second Edition, this book focuses on the technical aspects of treatment planning and the major challenges in creating highly conformal dose distributions, referenced to as treatment plans, for external beam radiotherapy. To overcome challenges associated with each step, leading experts at the Cleveland Clinic have consolidated their knowledge and experience of treatment planning techniques, potential pitfalls, and other difficulties to develop quality plans across the gamut of clinical scenarios in radiation therapy.

The book begins with an overview of external beam treatment planning principles, inverse planning and advanced planning tools, and descriptions of all components in simulation and verification. Following these introductory chapters are disease-site examples, including central nervous system, head and neck, breast, thoracic, gastrointestinal, genitourinary, gynecologic, lymphoma, and soft tissue sarcoma. The book concludes with expert guidance on planning for pediatric cancers and how to tailor palliative plans. Essential for all radiation therapy team members, including trainees, this book is for those who wish to learn or improve their treatment planning skills and understand the different treatment planning processes, plan evaluation, and patient setup.

KEY FEATURES:
• Provides basic principles of treatment planning
• Contains step-by-step, illustrated descriptions of the treatment planning process
• Discusses the pros and cons of advanced treatment planning tools, such as auto-planning, knowledge-based planning, and multi-criteria based planning
• Describes each primary treatment site from simulation, patient immobilization, and creation of various treatment plans to plan evaluations
• Includes instructive sample plans to highlight best practices
• Comes with access to the fully downloadable eBook

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I would like to dedicate this book to my dear mentor, Dr. Lynn Verhey. Twenty-three years ago, when I was a medical physics resident at the University of San Francisco, Dr. Verhey advised me to be involved in treatment planning, to be actively engaged in clinical practice, and to advance technology in radiation oncology by conducting research.

Ping Xia
## CONTENTS

Contributors ix  
Preface xiii  

Share Strategies for Radiation Therapy Treatment Planning  

1. **Overview of External Beam Treatment Planning Principles**  
   Ping Xia, Andrew Godley, Anthony Mastroianni, and John H. Suh  

2. **Inverse Planning and Advanced Treatment Planning Tools**  
   Jeremy Donaghue, Ping Xia, Naichang Yu, John Greskovich, and John H. Suh  

3. **Overview of Simulation and Verification**  
   Lisa Zickefoose, Andrew Godley, Andrew Vassil, and Chirag Shah  

4. **Central Nervous System**  
   Matt Kolar, John Potter, Salim Balik, Gennady Neyman, Joycelin Canavan, and John H. Suh  

5. **Head and Neck Planning**  
   Eric Murray, Ping Xia, Andrew Dorfmeyer, Nikhil Joshi, Daesung Lee, and Shlomo Koyfman  

6. **Breast Cancer**  
   Taoran Cui, Eric Murray, Eva Suarez, and Chirag Shah  

7. **Thoracic Cancer**  
   Michelle Sands, Carol Belfi, Tingliang Zhuang, Michael Weller, and Gregory M. M. Videtic  

8. **Gastrointestinal Radiotherapy**  
   Anthony Magnelli, Lisa Zickefoose, Jennifer Archambeau, Ehsan H. Balagamwala, and Gregory M. M. Videtic  

9. **Genitourinary Cancer**  
   Salim Balik, Radoslaw Szwedowski, Elaine Kunka, Cory Hymes, Omar Mian, George Engeler, and Chirag Shah
10. Gynecologic Cancer 201
   Susan Kost, Carol Belfi, D. Allan Wilkinson, Henry Blair, and Sudha Amarnath

11. Lymphoma 227
    Bingqi Guo, Cory Hymes, Sheen Cherian, and Gregory M. M. Videtic

12. Soft Tissue Sarcoma 235
    Kyle Verdecchia, Lama Muhieddine Mossolly, Matt Kolar, Eric Murray, Lanea Keller, and Chirag Shah

13. Pediatric Cancer 255
    Nicky Vassil, Andrew Godley, Mihir Naik, and Erin Murphy

14. Palliative Treatment 269
    Peng Qi, Kristan Pechatsko, Saju Rajan, and John H. Suh

Abbreviations 293
Index 297
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This book began when Dr. Gregory Videtic suggested that our physics and dosimetry groups develop a companion to his *Handbook of Treatment Planning in Radiation Oncology* second edition, for which he is the senior editor, to cover the strategies of treatment planning. After reviewing previous treatment planning texts, we realized that there is a lack of prescriptive instruction books for treatment planning in modern radiation therapy. Therefore, this book would not only be a partner for the current “Handbook,” but also a necessity on its own.

The original “Handbook” provides indications and requirements for clinical treatment planning aspects. Our book details the technical aspects of how to achieve those requirements, including patient positioning, creation of patient-specific bolus, beam angle configurations, and inverse planning optimization approaches. Our book is written for everyone involved in treatment planning, whether they are looking to commence or enhance their skills, including dosimetrist, physicists, and physicians. This book is organized as the original “Handbook” was, by body site or system; however, planning strategies for one treatment site can be applied to others. For example, the Head and Neck chapter has the most comprehensive approach to inverse planning optimization, but this can be applied to all sites.

For each site, there is a description of patient simulation, including immobilization, setup, isocenter placement, and any special considerations such as motion management. The plan goals for each treatment site are tabulated, followed by recipes to achieve them from the simplest planning technique to the most advanced planning technique. For simple 3D conformal plans, the recipes include the field arrangement and portal shape design (both with many figures), beam weighting, and selection of dose normalization point. For advanced techniques such as intensity-modulated radiation therapy, volumetric modulated radiation therapy, and stereotactic body radiation therapy, the recipes provide details of creation of optimization structures and multiple stage optimizations. Each chapter concludes with plan evaluation, comparing achieved doses to the clinical planning goals. There are three introductory chapters. The first describes the types of treatment plans and the general process of treatment planning. The second chapter explains the principles and limitations of current inverse planning optimization algorithms, and discusses the application of auto-planning, knowledge-based planning, and multi-criteria optimization to overcome these limitations. Although
each chapter has site-specific simulation details, a chapter on simulation is included to cover the available immobilization equipment and general principles of simulation, including patient safety procedures.

This book was a team effort from the entire Cleveland Clinic Radiation Oncology Department, including dosimetrists, physicists, radiation oncologists, and therapists, even though they may not all be listed as co-authors. What we described in this book reflects our current practice at Cleveland Clinic. Our experiences are based on a particular treatment planning system, but no specific planning system of therapy equipment is being endorsed, and the methods described to achieve the quality plans are agnostic to the planning system used. We would like to acknowledge Peng Qi, PhD, medical physicist, who generously offered to generate all the dose volume histograms used in the book. Lastly, we would like to thank our co-editors Dr. Chirag Shah, Dr. Gregory Videtic, and Dr. John Suh, who encouraged us and carefully reviewed each chapter.

Ping Xia
Andrew Godley
Share
Strategies for Radiation Therapy Treatment Planning
OVERVIEW OF EXTERNAL BEAM TREATMENT PLANNING PRINCIPLES

Ping Xia, Andrew Godley, Anthony Mastroianni, and John H. Suh

What Is Treatment Planning? .................................................................1
The Importance of Treatment Planning .....................................................2
Treatment Plan Preparation ......................................................................2
SSD Versus SAD Treatment Planning .......................................................2
Treatment Target Volumes and Planning Margins ...................................5
Treatment Plan Types ..............................................................................5
Prescription and Normalization Methods .................................................7
Open Field, Wedged Field, and Field-in-Field .........................................7
Forward Planning Versus Inverse Planning .............................................9
Boost: Sequential Versus Integrated .......................................................9
IMRT and VMAT Delivery Methods .......................................................10

WHAT IS TREATMENT PLANNING?

- Treatment planning consists of two components: clinical treatment planning and technical treatment planning.
- Clinical treatment planning refers to the treatment intent, treatment modality, and treatment dose scheme (total prescription dose and number of fractions).
- Technical treatment planning refers to the details of patient positioning, placement of radiation beams, and the aperture shapes of radiation beams designed to achieve highly conformal radiation dose distributions to the treatment target volumes (delineated by radiation oncologists in the clinical planning process) while protecting the critical organs.
- This book focuses on technical treatment planning, especially for external beam treatments. Throughout the book, we refer to the technical component of treatment planning as the treatment plan.
THE IMPORTANCE OF TREATMENT PLANNING

- The quality of a treatment plan can vary drastically, primarily depending on the following technical parameters:
  - The radiation beam orientation (or beam angles) in combination with the treatment couch angles
  - The number of beams
  - Radiation beam energies
  - Beam shapes (portals) or number of sub-shapes (apertures or segments)

TREATMENT PLAN PREPARATION

- This section covers the initial planning steps after simulation (discussed in Chapter 3) is completed.
- Define the isocenter of a plan by either directly importing the coordinates of the isocenter from the CT simulation or locate the three markers (called BBs) in the planning CT and place the isocenter in the center of the axis defined by the three markers.
- Remove the CT couch from the CT scan, which often contains metal and does not reflect the treatment couch. Immobilization devices on the CT couch, which will be used in treatment, should not be removed.
- If the planning CT is acquired with oral contrast, manually override the contrast density with the tissue density since the contrast will not be administered during daily treatment.
- If a large metal implant (such as hip prostheses), which may introduce image artifacts, is present, manually override the artifact region with a uniform tissue density of 1 gm/cm$^3$.
- Verify all contours to ensure there are no small holes inside or dots outside of any contours due to the use of contouring tools.
- Table 1.1 (A and B) lists the standard names for all organs at risk (OAR) used at the Cleveland Clinic. Use of standard OAR names is important for plan evaluation (see discussion in subsequent chapters) and for future outcome studies.

SSD VERSUS SAD TREATMENT PLANNING

- The SSD treatment method sets the source-to-skin (patient) distance (SSD) to a defined integer: 100 cm, 105 cm, or 110 cm.
- The SAD treatment method sets the source-to-axis (isocenter) distance (SAD) to an accelerator dependent integer: 100 cm.
- For treatment simplicity and efficiency, most modern treatments with photon beams use the SAD treatment method.
### TABLE 1.1
(A) Standard Names for Brain and Head and Neck Sites

<table>
<thead>
<tr>
<th>Brain</th>
<th>Head and Neck</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTV_{XXXX}* OPTIC_{NRV_L}</td>
<td>PET_MTV LIPS</td>
</tr>
<tr>
<td>CTV_{XXXX}* OPTIC_{NRV_R}</td>
<td>MR_GT V MANDIBLE</td>
</tr>
<tr>
<td>PTV_{XXXX}* PITUITARY</td>
<td>CT_GT V OPTIC_{NRV_L}</td>
</tr>
<tr>
<td>GTV_{YYYY}* RETINA_L</td>
<td>GTV_{XXXX} OPTIC_{NRV_R}</td>
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<tr>
<td>CTV_{YYYY}* RETINA_R</td>
<td>CTV_{XXXX} ORAL_CAVITY</td>
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<td>PTV_{YYYY}* SPINAL_{CORD}</td>
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<tr>
<td>BRAIN</td>
<td>SPINAL_{CORD_PRV5}</td>
</tr>
<tr>
<td>BRAINSTEM</td>
<td>TEMP_LOBE_L</td>
</tr>
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<td>BRAINSTEM_{PRV5}</td>
<td>TEMP_LOBE_R</td>
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<td>CHIASM</td>
<td>HIPPO_{L} BRAIN SKIN</td>
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<td>COCHLEA_{R}</td>
<td>HIPPO_{L_PRV5} BRAINSTEM_{PRV5}</td>
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<td>HIPPO_{R_PRV5} CHIASM SUBMANDIBULAR_{L}</td>
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<td>GLOBE_{R}</td>
<td>COCHLEA_{L} SUBMANDIBULAR_{R}</td>
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<td>HYPOTHALMUS</td>
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*GTV_{XXXX} and GTV_{YYYY} where XXXX and YYYY are the prescription doses in cGy. If there are more prescription dose levels, add GTV, CTV, and PTV in the same fashion.

(continued)
### TABLE 1.1 (continued)
(B) Standard Names for Breast, Thorax, Pelvis, Prostate, and GYN Sites

<table>
<thead>
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<th>Breast</th>
<th>Thorax</th>
<th>Pelvis</th>
<th>Prostate</th>
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<td>LYMPH_</td>
<td>BONE</td>
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<td>FEMUR_L</td>
<td>PENILE_</td>
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*GTV_XXXX and GTV_YYYY where XXXX and YYYY are the prescription doses in cGy. If there are more prescription dose levels, add GTV, CTV, and PTV in the same fashion.

CTV, clinical target volume; GTV, gross tumor volume; MTV, metabolic target volume; PTV, planning target volume; PTVN, planning target volume of lymph nodes.

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TREATMENT TARGET VOLUMES AND PLANNING MARGINS

- The goal of treatment planning is to achieve the required dose coverage of the planning target volume (PTV). Typically, adequate PTV dose coverage means 95% of the PTV receiving the prescription dose.
- The PTV is expanded from the gross tumor volume (GTV), clinical target volume (CTV), and the internal target volume (ITV), which is the GTV or CTV plus motion.
- The amount of the expansion is called the planning margin. This expansion can be uniform in three dimensions or nonuniform, depending on the clinical treatment planning intent.
- The planning margins account for subclinical involvement, the variations inherent in patient setup, and inter- and intra-treatment motion.

TREATMENT PLAN TYPES

- From simple to complex, treatment plan types include 2D, 3D, conformal arc, dynamic conformal arc, intensity modulated radiation therapy (IMRT), and volumetric modulated arc therapy (VMAT).
- A 2D plan is based on 2D images, obtained from a conventional simulator. This type of plan is rarely used today.
- A 3D plan is based on CT images from a CT simulator, typically consisting of one to four beams with either square or rectangular beam shapes (open beams) or simply modified beam shapes from the open field. Figure 1.1 shows a typical four-field box plan for a whole pelvis treatment.
- A conformal arc plan typically uses a number of cones (in 4, 5 to 17.5 mm diameter with an increment of every 2.5 mm for Varian TrueBeam SRS package and other vendor specific cone sizes) and delivers these conically shaped beams in full or partial arcs. Conventional linear accelerator (linac)-based stereotactic radiosurgery (SRS) plans typically use numerous conformal arcs to create highly conformal dose distributions.
- A dynamic conformal arc plan uses the multi-leaf collimator (MLC) to shape each aperture of an arc beam. These apertures conform to the PTV (with a defined margin) that is projected on the discretized angles (every 2°–4°) of the arc beam.
- IMRT plans typically use multiple fixed-angle beams (seven to nine beams). Each IMRT beam consists of multiple segments with variable beam intensities measured by monitor units (MU). The composite fluence from the segments of an IMRT beam comprises the intensity modulation. Figure 1.2 shows individual segment shapes and a composite fluence from these segments.
FIGURE 1.1 Dose distributions of a typical four-field box plan. Note the hot spot of 49 Gy in blue. The hot spot is defined as the areas that are encompassed by the isodose lines greater than the prescription dose (45 Gy in this case).

FIGURE 1.2 A composited fluence map and individual segment shapes.
VMAT plans consist of one or more arcs. The difference between the VMAT plans and dynamic conformal arc plans is that the aperture shape for each discrete angle (every 2°–4°) does not simply encompass the entire PTV, enabling better protection of critical OARs while still providing conformal dose coverage to the PTV.

PRESCRIPTION AND NORMALIZATION METHODS

- Prescription is the intent of the treatment while normalization is the scaling of the plan required to achieve the prescription dose.
- The plan can be normalized to a point or a volume. The intent is typically to achieve the adequate dose coverage to a target volume of 90% to 100%, which should be specified in the prescription or in institutional protocols.
- Point-based normalizations are typically used for simple 3D plans, but also for highly conformal SRS or stereotactic body radiation therapy (SBRT) plans.
- The normalization point is commonly the isocenter. When the isocenter falls in or near a heterogeneous region (bone, metal, air), a new calculation point in a homogeneous region (tissue) is needed to normalize the plan.
- For SRS or SBRT, the maximum dose point can also be the normalization point. This has the advantage that the prescription isodose line indicates the plan homogeneity.
- Volume-based normalization can represent a mean dose to a target, or the volume covered by a required dose (e.g., dose to 95% of the treatment target).

OPEN FIELD, WEDGED FIELD, AND FIELD-IN-FIELD

- An open field is a radiation aperture consisting of uniform intensity where the field shape may be constructed to block critical structures while still exposing the PTV to radiation. Figure 1.3 is a typical lateral open field shape for whole brain treatment.
- A wedged field decreases linearly the radiation intensity from one side of an open field to the other. Figure 1.4 shows dose distributions from an anterior posterior/posterior anterior (AP/PA) plan with a wedge added to the AP beam to compensate for non-flat anterior sternum.
- A wedged field can be achieved by inserting a physical wedge in the beam, or by sweeping an upper jaw from one side of the field to the other.
- A segment is an incomplete radiation portal because it is not fully opened to expose the entire projection of the PTV from a specific beam angle. A simple intensity modulated field can be created by manually constructing a few segments with different intensities. This is done to reduce high dose regions. Figure 1.5 shows multiple segments manually created for one of the tangential fields of a whole breast treatment. This is also termed field-in-field.
FIGURE 1.3  A typical lateral open field shape for whole brain treatment.

FIGURE 1.4  An anterior wedge was used to shape the dose distribution.

FIGURE 1.5  Four manually created segments for one of the tangential fields for a whole breast treatment.
FORWARD PLANNING VERSUS INVERSE PLANNING

- In forward planning, beam apertures are created for all beam directions with their relative weights adjusted to obtain the desired dose distributions. 2D, 3D, conformal arc, and conformal dynamic arc plans are created using forward planning.
- In inverse planning, the desired dose objectives are first entered (more discussion in Chapter 2) and then computer optimization derives the required dose distribution from either multiple fixed angle beams or arcs. In a 3D plan, the dose distribution is fairly uniform, while in inverse planning, the dose per beam is deliberately nonuniform, or intensity modulated.
- The inverse planning optimization can either be two-step or direct. In two-step optimization, the fluence of each beam or arc is first determined, then converted into multiple segments using a leaf sequencing algorithm. In this two-step optimization, the beam fluence is an ideal intensity profile, which does not consider constraints of the deliverability of each treatment machine. The second step of leaf sequencing incorporates the constraints of deliverability, which reduces the quality of the fluence plan.
- In direct optimization, the beam or arc segments are optimized directly to obtain the desired dose distribution while taking into account treatment machine parameters, thus ensuring a deliverable plan, with no loss of quality.
- Fixed gantry IMRT (see following discussion) and VMAT plans are created using inverse planning.

BOOST: SEQUENTIAL VERSUS INTEGRATED

- The prescription doses to the primary tumor, lymph nodes, and other intended targets may differ, depending on the clinical treatment intent. Typically, the lymph nodes and other targets may be prescribed a lower dose compared to the primary tumor.
- To deliver a higher dose to the primary tumor, either a sequential boost or simultaneously integrated boost (SIB) method can be used.
- The sequential boost method requires two or more plans, depending on the number of planned boosts. This method delivers the same daily dose to both primary tumor and other targets that are planned to receive a lower total dose.
- The SIB method requires one plan, delivering different daily doses to the different target volumes simultaneously. Typically, the SIB method produces more conformal dose distributions than delivering the boost sequentially. Logistically, the SIB method is simpler.
- The sequential boost is advantageous when the desired prescription doses to different tumor volumes differ significantly.
IMRT AND VMAT DELIVERY METHODS

- Typically, an IMRT plan is delivered by a linear accelerator equipped with an MLC. It is the MLC that creates the complex segments to deliver the optimized dose distribution. Although it is possible to deliver IMRT with rectangular jaw fields only, it is much slower.
- Dynamic delivery or sliding window refers to the segments of a fixed gantry angle IMRT field being delivered by sweeping MLC leaves from one side of the field to the other while the radiation beam remains “on.”
- Step-and-shoot refers to the segments of a fixed angle IMRT field being delivered in a sequence of moving MLC leaves (step) and then radiation beam on (shoot).
- VMAT delivery is achieved with the gantry continually rotating during delivery. The MLC leaves are also constantly moving as in dynamic IMRT delivery.
- Depending on the capabilities of the accelerator, the rate of gantry rotation may be constant or variable, and the dose rate may also vary during delivery.
- By varying the gantry rotation and dose rate, a more modulated plan can be delivered. Variable gantry rotation speed can also quicken the delivery.
- During IMRT and VMAT delivery, some linear accelerators require the secondary jaws (both x and y jaws) to remain open at the largest open field projection of an IMRT beam or a VMAT arc. Therefore, the jaws are not following (or conformal) to each segment. Leakage through MLC leaves, particularly for a VMAT plan, can be non-negligible. Modern accelerators allow the jaws to track the MLC position at each segment to block this leakage.
- To minimize the leakage from MLC during VMAT delivery, non-zero collimator angles (typically greater than 10°) should be used to minimize dose from any remaining MLC leakage.
- A special linear accelerator called TomoTherapy delivers IMRT plans with intensity modulated, rotating fan beams while the patient slides through the accelerator, delivering radiation slice-by-slice similar to how CT images are acquired.