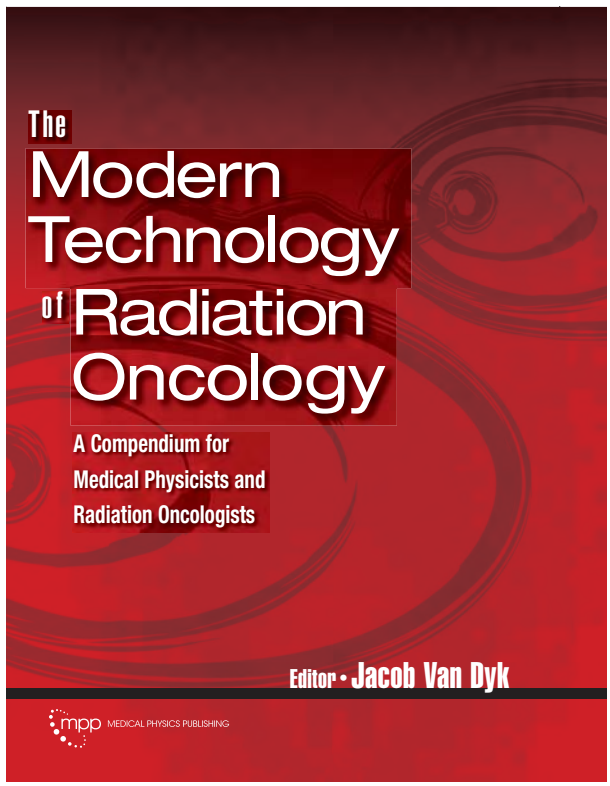

Here is a sample chapter from this book.

The Modern Technology of Radiation Oncology

A Compendium for Medical Physicists and Radiation Oncologists

Jacob Van Dyk
Editor

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Dedication

In my personal life:

> To my wife *Christine*, and my children *Tonia*, *Jon*, *Ben*, and *Amy*, who have unwittingly sacrificed family time due to my professional commitments but who have knowingly shared their love and support.

In my professional life:

> To *Jack Cunningham* who by example demonstrated that medical physics is much more than just a career.

Contents

Preface

Radiation Oncology is a very technology intensive discipline of medicine. Complex, sophisticated equipment is required to localize the tumor, to generate ionizing radiation, and to deliver a high radiation dose to a three-dimensional target volume while sparing normal tissues. A number of books have been written about the medical physics and clinical aspects of radiation oncology and treatment planning. The standard medical physics textbooks tend to discuss the basic concepts of radiation interactions and dosimetry, and some of the technical aspects as related to treatment machines and treatment planning. However, they generally do not address the design details of many of the practical tools that are required to prepare patients for treatment or that are used as part of the treatment process. Virtually no textbook addresses the details of acceptance, commissioning, and quality assurance of radiation therapy equipment.

The purpose of this book is to describe the details of the technology associated with radiation oncology. A special emphasis is placed on the **design** of all the equipment allied with radiation treatment. In addition, this book describes the procedures that are required to implement this equipment into clinical service (**needs assessment, purchase, acceptance, and commissioning**) and, once it is in use, the **quality assurance** that is required to keep the equipment operational at acceptable levels. In addition to describing all the tools that are used in "standard" radiation treatment centers, **this book addresses the less common or evolving technologies** and, thus, provides a comprehensive overview. Anyone embarking on any of these new procedures will be able to gain some basic insight as to what is required to make that procedure clinically viable.

Nowhere can all these technologies be found in one cancer therapy center. However, the staff of every cancer center is involved in improving procedures by either purchasing new equipment or by upgrading existing equipment. This book is intended to be a guide for those embarking on these procedures. While the body of each chapter is written at a level understandable by medical physicists and radiation oncologists, additional detailed information for medical physicists is provided in the appendices at the end of some of the chapters.

As the title indicates, the book is primarily intended for **medical physicists** and **radiation oncologists** although it will also benefit **radiation therapists (radiographers)** and **dosimetrists**, and to a lesser extent other allied professionals such as **engineering technologists, radiobiologists, and administrators**. It is intended to be both a reference text for those who have been working in the field for some years as well as an educational tool for those who are entering the field. It is assumed that the reader has a basic knowledge of medical physics as found in other standard medical physics textbooks.

Jacob Van Dyk

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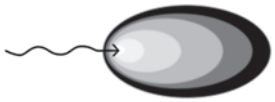
Chapter 8

Computerized Radiation Treatment Planning Systems



Jacob Van Dyk, Robin B. Barnett, and Jerry J. Battista

8.1 Introduction

The details of the steps in the overall treatment process have already been outlined in chapter 1. That part of the process known as *radiation treatment planning* consists of many steps including patient diagnosis, tumor staging, image acquisition for treatment planning, the localization of tumor and normal tissue volumes, optimal beam or source placement, and treatment simulation and optimization. This chapter deals very specifically with that component of the treatment planning process that makes use of the computer to generate optimal beam shapes and directions incident on the patient, thereby maximizing tumor control and minimizing normal tissue morbidity. Similarly, computers are used in the placement of brachytherapy sources. Dose optimization and verification of beam or source placement include, for example, the use of dose-volume histograms (DVHs) and digitally reconstructed radiographs (DRRs). As indicated in earlier chapters, especially chapter 4 on simulators, chapter 5 on CT simulators, and chapter 6 on simulator-CTs, the process of radiation therapy planning is undergoing rapid evolution. What used to be strictly a task associated with treatment planning computers can now be divided between the CT simulator, simulator-CT, and computerized radiation treatment planning systems (RTPS). The actual process used in a specific institution is dependent on the ease of access to these types of technologies. Thus, institutions with CT simulators will perform more of the planning process using the virtual simulation software of the CT simulator compared to institutions that have easy access to CT-scanning and 3-D treatment planning systems. The overlapping use of these various technologies can be seen in Table 8.1 where the steps in the radiation treatment planning process are summarized and the possible uses of different technologies are indicated.

A distinction is made between 2-D and 3-D treatment planning capabilities since the last ten years have seen an evolution of treatment planning towards a comprehensive 3-D approach, although not many institutions have full 3-D capabilities at the present time. It is clear from this table that there is a variety of combinations and permutations of dealing with the steps of the planning process dependent on the technology available and dependent on how the members of the treatment planning team implement this technology. The optimal integration of these technologies into an efficient and cost effective planning process is the new challenge for the professionals involved in treatment planning.

The emphasis in this chapter is on the use of computerized radiation treatment planning systems (RTPS), a description of their design, issues to consider when purchasing a new system, clinical commissioning, and routine quality assurance (QA). In view of the overlap of the various technologies for treatment planning, purchase considerations are not trivial and continue to evolve. This chapter can only provide a framework of issues to consider and cannot be fully prescriptive in view of the rapidly changing technologies. However, we will provide key practical guidance to be useful to the practicing clinical physicist and to other professionals involved in the purchase and clinical implementation process.

8.2 Historical Perspective

The first computers used in radiation therapy were actually "homemade," special purpose, analog computers developed with the aim of reducing the tedium of calculating 2-D dose distributions as well as improving their accuracy. The "Wheatley Integrator" [133] was the first reported computer to perform dose calculations for irregularly shaped fields. Tsien, at Memorial Hospital in New York, is generally credited as the first to use automatic computing machines for radiation dosage

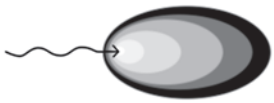


Table 8.1
The Steps of the Radiation Therapy Planning Process and the Possible Uses of Different Technologies for Each Step. (A direct comparison is made between conventional 2-D procedures and modern 3-D capabilities.)

	2-D OR 3-D	RTPS ALONE	CT SCANNING		CT SIMULATION		SIMULATION-CT	
STEPS IN THE RT PLANNING PROCESS			**ALONE**	**WITH RTPS**	**ALONE**	**WITH RTPS**	**ALONE**	**WITH RTPS**
Tumor	2-D	–	**	**	**	**	**	**
Localization	3-D	–	**	**	**	**	*	*
Normal Tissue	2-D	–	**	**	**	**	**	**
Localization	3-D	–	**	**	**	**	*	*
Virtual	2-D	–	–	*	**	**	*	*
Simulation	3-D	–	–	**	**	**	*	*
Dose	2-D	*	–	*	–	*	–	*
Calculation	3-D	*	–	**	–	**	–	*
Plan	2-D	*	–	*	*	*	*	*
Optimization	3-D	*	–	**	*	**	*	*
Verification	2-D	–	–	*	*	**	*	*
Information	3-D	–	–	**	**	**	*	*

** Complete, * Partial, – None, RTPS = Radiation Treatment Planning System

calculations [119]. He reduced the information contained in an isodose distribution to a matrix of numbers, which could be stored on punched cards. The resulting data were manipulated by card-reading equipment to produce summed dose distributions for multiple beams [31]. A similar approach was produced later, by Nelson and Meurk [94] also at Memorial in New York, for brachytherapy calculations. Aspin et al. [7] used a digital computer and a method of dose calculation that was originally developed for manual calculations by Clarkson [24]. This program generated many of the depth dose tables that appeared in the *British Journal of Radiology Supplement* 10 [57] and later in Supplement 11 [58]. A similar approach was used by Tsien and Cohen [120] to produce sets of isodose charts and depth dose tables for medium energy x-rays. Later, under the auspices of the International Atomic Energy Agency (IAEA), a manual procedure was used to digitize single beam isodose charts, but a computer was used to combine multiple single beams to generate an atlas of isodose distributions for arc and rotation therapy [60]. Subsequent years have seen the development of specialized treatment planning systems on minicomputers, on time-sharing systems [28], on graphics workstations, and today on personal computers. During each phase of the evolution of computer technology, treatment plans could be generated faster and more accurately, with improved image and graphic display capabilities. While automated optimization of treatment techniques has been under investigation since the 1960's [55,56], it is only in recent years that inverse treatment planning capabilities are actually being used in clinical practice with faster computers (see chapters 12 and 15).

Computers also led to a revolution in diagnostic imaging procedures especially during the 1970's when computerized tomography (CT) scanning become readily available for clinical usage. CT scanning was ideally suited for radiation therapy planning, since it provided, for the first time, an easy ability to localize the tumor and surrounding normal tissues on a patient-specific basis. Furthermore, it provided an ability of placement of the radiation beams on the CT images and the calculation of dose distributions, which actually accounted for the real tissue densities within the patient [9,10,49,124].

Today, treatment planning has evolved such that full 3-D planning capabilities are possible including patient data from a variety of different imaging sources. The image data from CT and magnetic resonance (MR) can be used with image registration techniques to improve the definition of planning target volumes (PTV) in 3-D with very high precision. The use of ultrasound imaging for prostate brachytherapy treatment planning is gaining prominence at a very rapid rate [51,102] and is described in detail in chapter 7. In some institutions, single photon emission tomography (SPECT) and positron emission tomography (PET) are being used in combination with other imaging modalities, typically with CT, for the determination of clinical target volumes (CTV). Digital angiography (DSA) is used to aid the planning process for stereotactic radiosurgery (see chapter 16).

The modern 3-D treatment planning system allows for virtual simulation of the patient by the superposition of radiation beam geometries at any orientation on any image or combination of images combined with a beam's eye view of the anatomy. Furthermore, plan analysis tools such as DVHs and biological objectives are assisting the choice of techniques and providing a tool for plan optimization. Calculation routines are being developed for enhanced quantitative analysis of all the uncertainties associated with patient setup and treatment and these will provide an additional aid for treatment optimization [50,121,127]. In the future, we can look forward to further enhancements of functional imaging and radiobiological predictive assays to provide additional information on tumor bulk, tumor oxygen concentrations, and microscopic tumor extension to aid in the development of 3-D treatment plans and altered fractionation schemes. These approaches may even be applied to different parts of individual tumors [71].

8.3 Process of Clinical Implementation of Dose Calculation Algorithms

Dose calculation algorithms generally undergo a series of evolutionary steps before they can be used in routine clinical practice. It is informative to look at the steps of this process and to understand that there are components of this development process that are *not* under the control of the user. Recognition of this will aid the development of the QA process that is needed and implemented by the user. These steps are summarized in Table 8.2.

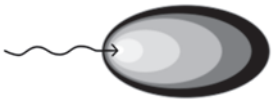


Table 8.2
Steps Involved in the Clinical Implementation of Treatment Planning Calculation Algorithms (Adapted from reference [126].)*

PROCESS	USER CONTROL
Development of dose calculation algorithm —Based on model of radiation interactions —Physics is complex, incorporates approximations —Model contains inherent uncertainties —Works over a limited range of conditions	Not under user control
Algorithm is coded into software —Includes input/output routines —Includes image display/ manipulation routines —Includes treatment technique options —Includes plan evaluation/ optimization routines —Developer must ensure that the code is correct	Not under user control
Entry of radiation data required by algorithm —Data obtained over a limited range of conditions —Data have inherent uncertainties —Data may contain relative or absolute doses	Under user control
Clinical use of programs —Enter patient data (e.g., CT, MR, contours) —Perform beam placement —Perform dose calculation —Evaluate/review/optimize —Output on display or hardcopy	Under user control

*"Quality Assurance" by J. Van Dyk in *Treatment Planning in Radiation Oncology*, F. M. Khan and R. A. Potish (Eds.), 1997, Williams and Wilkins, Baltimore, MD.

8.3.1 Development of dose calculation algorithms

The intent of a dose calculation algorithm is to predict, with as much accuracy as possible, the dose delivered to any point within the patient. Due to the complexity of radiation interactions with human tissues and due to the practical need for rapid calculation times, such dose calculation algorithms have inherent limitations due to the approximations used in the physical models. The result is that these algorithms provide reasonably accurate calculations over a limited range of commonly used conditions but may have substantial uncertainties under other conditions. Usually the more complex algorithms have fewer uncertainties compared to the simpler algorithms although this is usually at the expense of longer calculation times. The commonly used dose calculation algorithms are discussed in more detail below (section 8.4). Dose algorithm preference is one of the more important factors in the selection of a computerized treatment planning system. Some manufacturers will provide a choice of more than one algorithm for some types of calculations.

8.3.2 Development of software using dose calculation algorithm

Once the mathematical formulation has been developed, the algorithm must be converted into computer code. This coding will require software: (1) to accept patient-related image or contour data, (2) to allow the contouring of target volumes and normal tissues, (3) to define the beam geometry and the field shapes, (4) to allow for the addition of relevant ancillary devices such as wedges, shields, or multileaf collimators (MLCs), (5) to perform an accurate dose calculation accounting for the relevant machine and patient-related parameters, (6) to provide easy evaluation and optimization of treatment plans, (7) to provide plan display on the video monitor, and (8) to provide both hardcopy or digital output of the plan on a color printer or through the network. Indeed, the vast majority of code goes into the management of information and only a very small percentage of the code is used for the actual dose calculation mathematics. While the purchaser has a choice of the algorithm by purchasing a particular system, the purchaser does not have control over how well the algorithm has actually been coded. In the interest of computational speed, software "shortcuts" are sometimes introduced beyond the original mathematical formulation.

8.3.3 Entry of radiation data required by the dose calculation algorithm

All algorithms require input radiation data of some form. For conventional treatment planning systems, radiation data need to be measured for each beam quality available in the clinic. The accuracy and quality of the input data are dependent on the measured or calculated data that are produced by the user. For practical reasons, the data are generally determined over a limited range of conditions, e.g., limited depths and field sizes. Whenever calculations extend beyond the range of measured data, the output results should be scrutinized since the algorithms can perform inaccurate extrapolations. In addition, the measured data have their own inherent uncertainties or inconsistencies which depend on the care taken by the person generating the data, the types and sizes of the detectors that are used (see chapter 19), as well as on the stability of the machine producing the radiation beam (e.g., variations in flatness and symmetry with gantry angle or with time).

Generally both relative data and absolute data need to be determined—relative data in the form of dose ratios, and absolute data (e.g., Gy) in terms of the machine output calibration. The latter is a requirement of the treatment planning system if it is used for monitor unit or time calculations.

8.3.4 Clinical use of programs

Once the system is accepted and commissioned, the user needs to enter patient-specific information such as external contours or digital images. Treatment planning can then be performed to yield optimized dose distributions and absolute monitor unit calculations. The determination of the optimal treatment plan is entirely under the user's control, and subject to the dose or biological constraints specified by the radiation oncologist.

8.4 Dose Calculation Algorithms

Most treatment planning systems are very similar in the software modules that allow digital images, contours, treatment beams and sources, and dose distributions to be displayed. Any software differences are due mainly to implementation, ergonomics, and to streamlining of the treatment planning process. The dose algorithm, on the other hand, *is the most unique, critical, and complex piece of software in a computerized planning system.* The dose algorithm underpins many clinical decisions taken on the basis of dose distributions and dose-volume histograms. In this section we provide an overview of the physics of dose calculation algorithms and some implementation considerations. Special emphasis is placed on the user's need to be able to ask the right questions at the time of purchase of a new treatment planning system. Furthermore, the user needs to understand the limitations of his/her particular algorithm when advising radiation oncologists on the accuracy of

the calculated dose under various clinically relevant situations.

8.4.1 The dose calculation problem

It is very important to distinguish the *3-D display* of dose distributions from the *3-D calculation* of the dose distribution [8,12]. We define a true 3-D calculation as one in which the primary and scattered radiation components are followed independently throughout the volume of tissue irradiated. Primary radiation originates in the radiation source and reaches the proximity of a point of interest without any prior interaction in the patient. The scatter component reaches the destination point by indirect routes along multiple pathways within the patient. This is shown for a simplified case in Figure 8.1 where only single-scatter events are considered. In reality, the situation is much more complex because the primary source is generally composed of a spectrum of different particles which do not originate from a single point [104,109]. In the patient, multiple-scattering of the shower of scattered photons and electrons is equally complex. Thus the 3-D computational burden is large and some compromise between dose accuracy and computational speed is inevitable in practical dose algorithms.

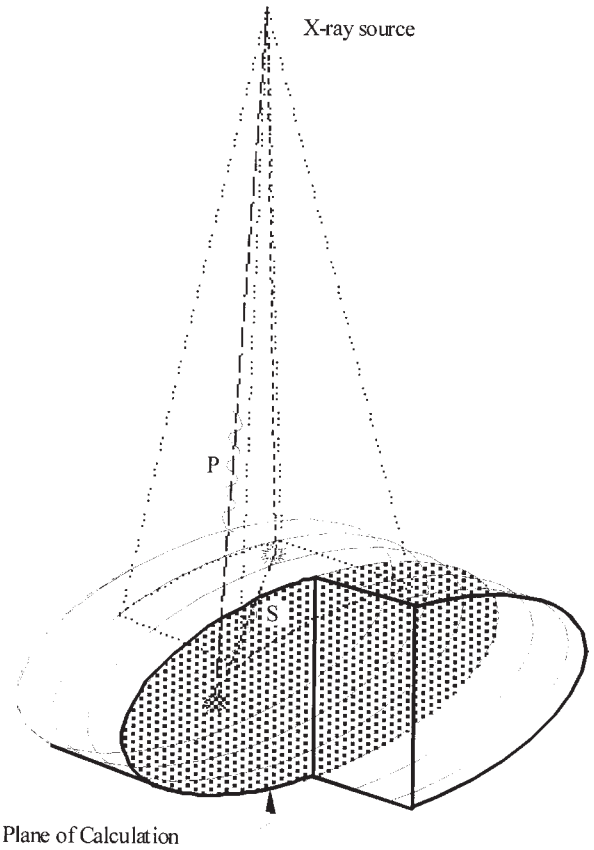


Figure 8.1
Schematic of a radiotherapy beam incident on a patient. The shaded slice represents the plane of dose calculation. Each point in this plane receives primary radiation (P) directly from the source and scattered radiation (S) which originates in any slice of the patient. A true 3-D calculation includes the effects of inter-slice scattering on total dose. [Adapted with permission from reference [8].]

8.4.2 A generic algorithm using the superposition principle

A major advance in dose calculation methods occurred when radiation was decomposed into its primary and scatter components. In fact, *the evolution of algorithms has been marked by a steady progressive decomposition of the dose components.* The advantage is that each component can be adjusted independently for beam shape, beam intensity, surface topology of the patient, and internal tissue densities. In Figure 8.2a, the total scatter from a broad beam of radiation reaches a destination point, P(x,y,z) within a water phantom. Scatter contributions from various subvolumes of different shape can, however, be isolated if data are available for a variety of depths and field sizes [30]. One can determine the contributions from regions in the form of a slab (Figure 8.2b), pencil beam (Figure 8.2c), or point (Figure 8.2d).

We define the *pattern of spread* of energy from such entities as "scatter kernels," illustrated conceptually in Figure 8.3. Figure 8.4 displays actual point kernels calculated for Compton scattering events in a uniform water absorber exposed to Cobalt-60 radiation [14,76,113]. The kernels can be interpreted from two points of view: (1) as iso-contributions from upstream scattering points to a destination point of interest (i.e., a receiver's viewpoint) or (2) as the energy spread from a scattering point to downstream voxels (i.e., a sender's viewpoint). Figure 8.5 shows point kernels for 5 MeV mono-energetic photons (equivalent to about a 15 MV beam), decomposed into contributions from primary Compton electrons, singly-scattered Compton photons, twice-scattered Compton photons, multiply-scattered Compton photons and radiative photons due to the slowing down of charged particles [8].

During the execution of a dose algorithm, the dose at a point is calculated by summing the effects from scattering elements. The level of summation required, however, is dictated by the problem and boundary conditions at hand. If the incident radiation is changing in only one direction (e.g., wedged photon field), then there are speed advantages to using a slab kernel and performing only a one-dimensional superposition. If

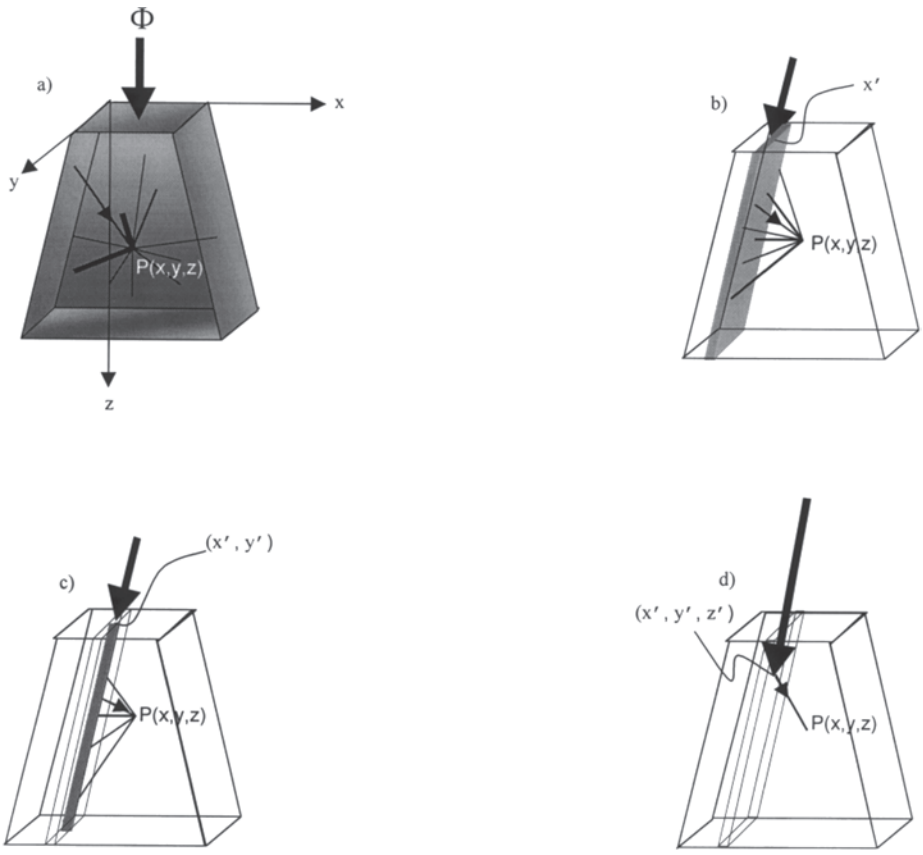


Figure 8.2
The summation of dose contribution from various scatter kernels, K. (a) Beam kernel, (b) Slab kernel, (c) Pencil beam kernel, (d) Point kernel. [Adapted with permission from reference [12].]

the incident beam intensity is intentionally varied in two directions using tissue compensators or intensity modulation, then the pencil beam approach is more suitable [4,22,23,65,87]. If the beam fluence is also changing in a complex way throughout the absorber, then the point kernel must be known and a full 3-D integration is necessary. Mathematically [1,12,34] the dose distribution, D(x,y,z) for situations depicted in Figure 8.2b, 8.2c, and 8.2d, respectively, is:

$$D(x,y,z) = \int \Phi_{1D}(x')K_{slab}(x';x,y,z)dx' \tag{8.1}$$

$$D(x,y,z) = \iint \Phi_{2D}(x',y')K_{pen}(x',y';x,y,z)dx'dy' \tag{8.2}$$

$$D(x,y,z) = \iiint \Phi_{3D}(x',y',z') \times K_{pt}(x',y',z';x,y,z)dx'dy'dz' \tag{8.3}$$

where Φ is proportional to the primary source fluence (particles per cm^2) incident upon the surface of each scatter kernel, and K can be either a point, pencil, or slab kernel. In this general discussion, the kernels are not assumed identical for each combination of scattering element (x′,y′,z′) and dose point (x,y,z), i.e., the kernels are not assumed to be invariant throughout the irradiated volume. In heterogeneous tissue, these equations allow for local changes in pimary fluence, Φ, as well as changes in the spread of energy due to local scattering conditions [1–3,73,87,141] (Figure 8.6). This general approach is known as the *superposition* principle.

Under special circumstances, including mono-energetic nondivergent sources incident on a homogeneous absorber, the scatter kernels are identical or "spatially-invariant" at each point (x′,y′,z′) in the absorber. The dose integrals then simplify to *convolution* integrals, with relative positions (x – x′, y – y′, z – z′) substituted into the arguments of K in the superposition equations. The advantage is that the integrals can then be evaluated efficiently using fast Fourier transforms (FFTs)

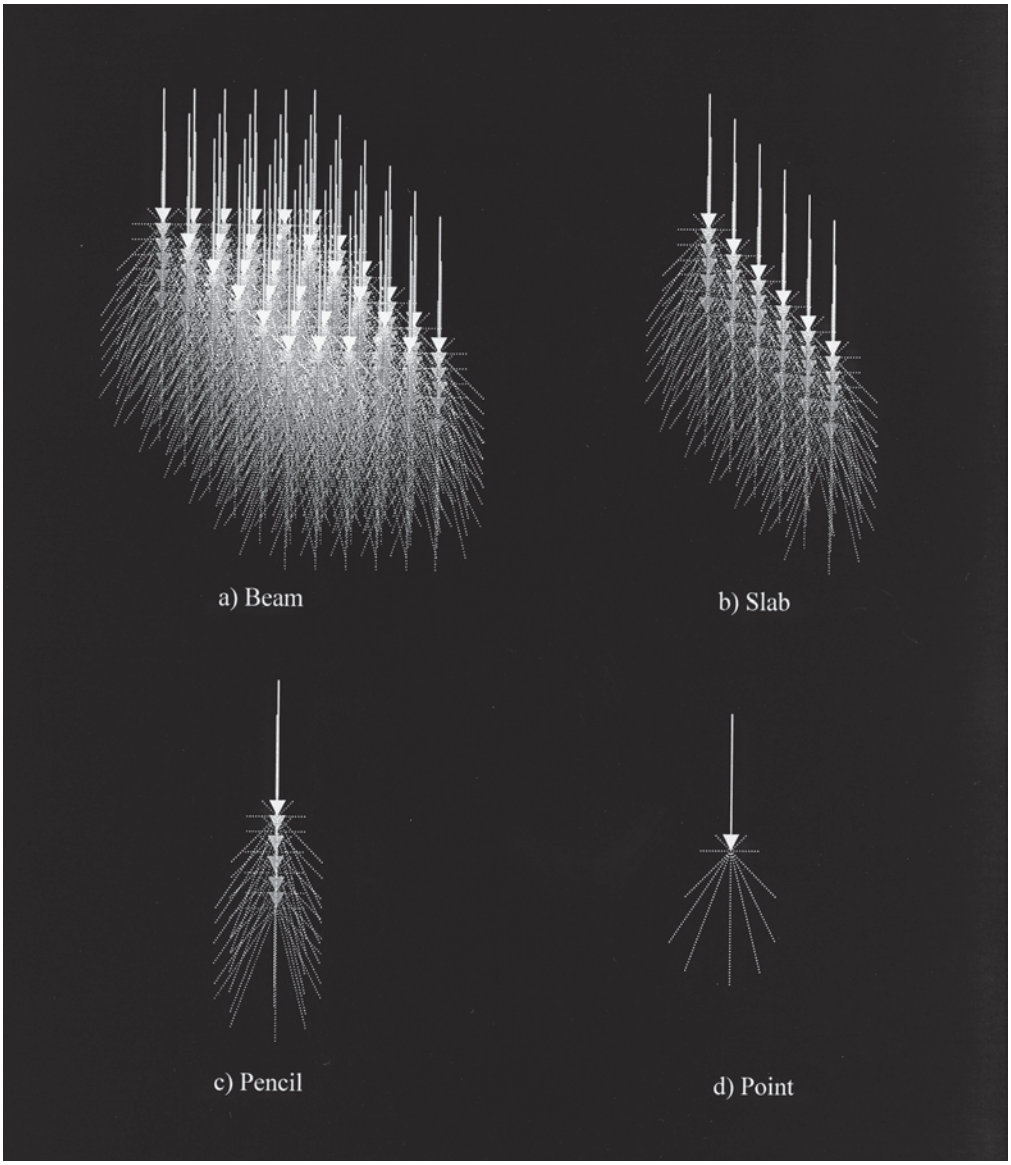


Figure 8.3
Scatter kernels of different dimension.

[15,44,88,96,136]. When applied to the case of a polyenergetic divergent beam incident on a heterogeneous absorber, some approximations are introduced in order to maintain the Fourier speed advantage, but at the expense of accuracy [16,17,136,146]. The effects of lateral electron transport can also be included in the FFT approach [137].

The universality of the applicability of the superposition method is illustrated in Figure 8.7 for a photon beam, for an electron beam and for an array of brachytherapy sources. For photon beams (Figure 8.7a), every point in the absorber is a source of scattered radiation, with the source intensity being modulated by exponential attenuation of primary photons. For electron beams (Figure 8.7b), the primary fluence of electrons is limited to the surface of the absorber and pencil beam kernels are generally used. For brachytherapy, the fluence, Φ, is a discontinuous function propor

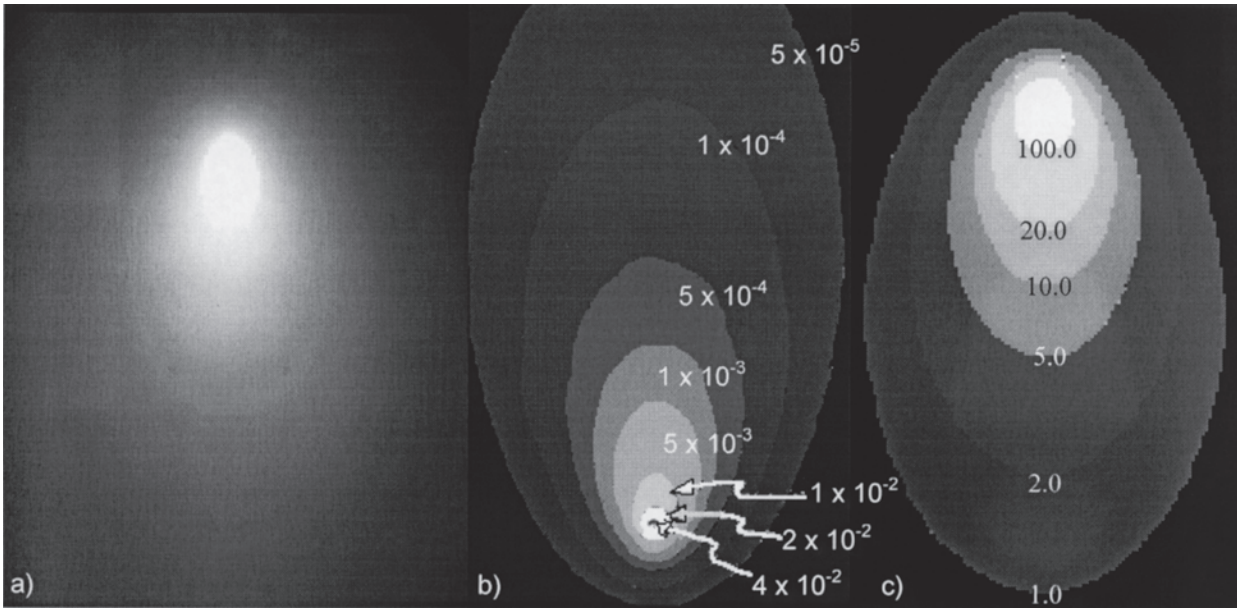


Figure 8.4
Cobalt-60 first-scatter kernels obtained by: (a) Monte Carlo method; (b) Analytical method, showing iso-contributions as dSAR values. [Adapted with permission from reference [113]]; (c) Analytical method, isodoses labeled in units of eV/g per photon interaction at the origin. [Adapted with permission from reference [14]]. Figures (a) and (c) are displayed from the "sender's" perspective. Figure (b) is inverted and displayed from the "receiver's" perspective.

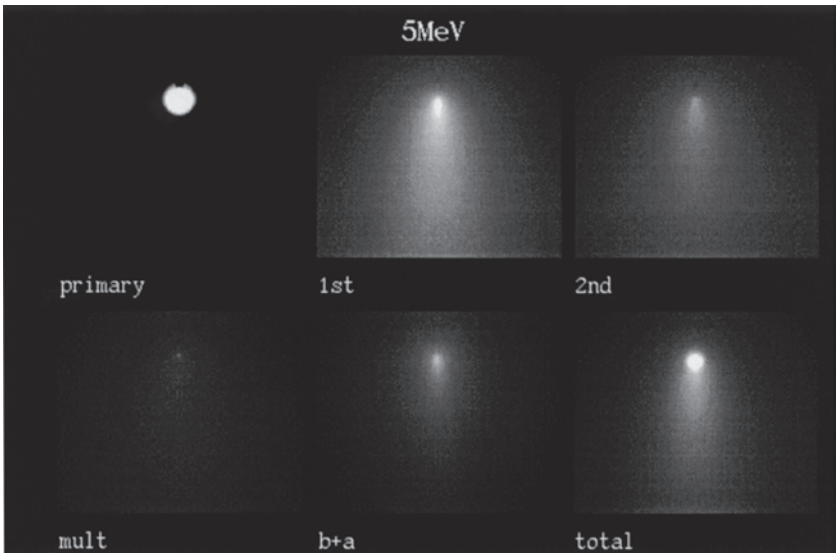


Figure 8.5
5.0 MeV dose spread kernels representing the energy distributed away from a primary interaction site in water by primary electrons and positrons set in motion by incident photon interactions (primary), once-scattered photons (1st), twice-scattered photons (2nd), multiply-scattered photons (mult), Bremsstrahlung and annihilation photons (b+a), and the sum of all interactions (total). [Adapted with permission from reference [8].]

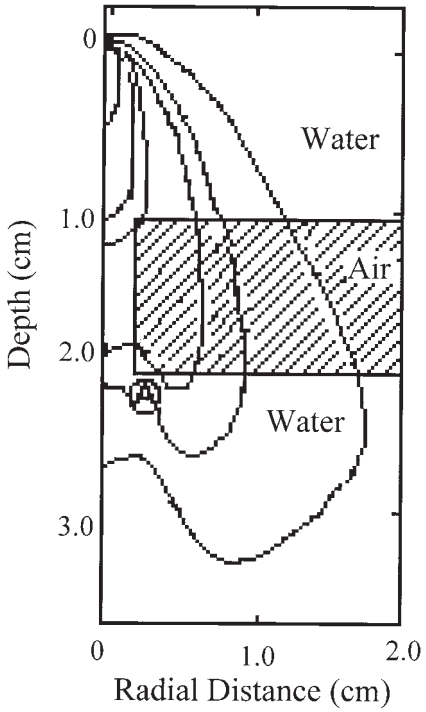


Figure 8.6
Photon point kernel at 6 MeV, corrected for tissue density changes using the density scaling method. [Adapted from reference [141].]

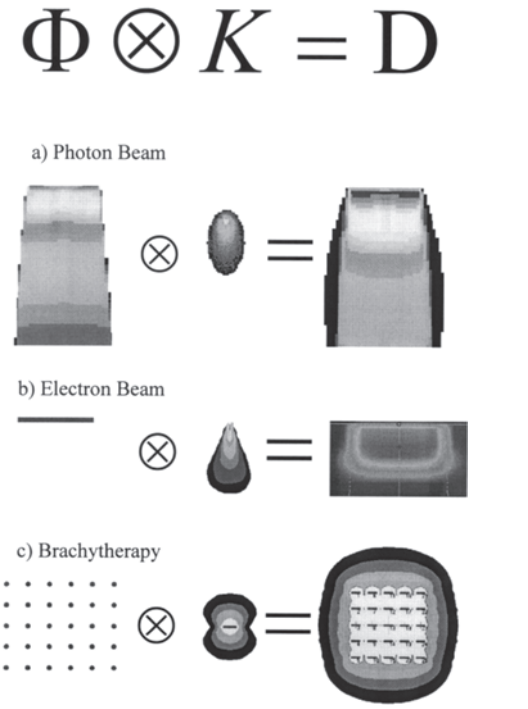


Figure 8.7
Universality of the superposition principle. (a) photon beams, (b) electron beams, and (c) brachytherapy sources. Each uses a fluence distribution (F) and a kernel (K) specific to the clinical application.

tional to the source strength (or activity) at discrete locations of source placement. The point kernel for brachytherapy is the dose pattern surrounding each radioactive seed [91];

$$K_{pt}(r,\theta) = S_k \, \Lambda \, [G(r,\theta) / G(r_0,\theta_0)] \, g(r) \, F(r,\theta) \tag{8.4}$$

where S_k is the air kerma strength of the source (units U = μGy m^2 h^{-1}), and is related to source radioactivity; Λ is the dose rate constant (cGy h^{-1} U^{-1}), which yields the dose rate at a reference point, usually at 1 cm along the perpendicular to the seed axis (i.e., 90°); $G(r_0,\theta_0)$ is the geometry factor, related to the distribution of radioactivity within a seed; this term is different for point sources and for line sources; $g(r)$ is the radial depth-dose curve, related to the attenuation and scatter within water; and $F(r,\theta)$ is the anisotropy function, related to the attenuation and scatter within the seed encapsulation materials and is normalized to 1.00 at coordinate (r, 90°).

8.4.3 The Monte Carlo method

Integration can also be performed by the random-sampling technique known as the Monte Carlo method [6,75]. This technique simulates a large number of individual particle tracks and as they traverse the tissue voxels, the energy absorbed is scored in voxels traversed by charged particles (see Figure 8.8). After approximately 10^6–10^7 primary photon histories are simulated, the dose value, D(x,y,z), in each voxel converges to a statistically-acceptable result. This integration method is less efficient than the kernel-based methods but it allows a wider range of complexities to be taken into account, especially within inhomogeneous tissue. The EGS4 Monte Carlo code [63,95] has been an invaluable tool in generating scatter kernel data, providing benchmark data for testing the performance of approximate algorithms, and simulating the radiation emerging from linear accelerators to serve as input data for algorithms [104]. Progress is being made towards using the Monte Carlo method directly for treatment planning [39,52,77,142].

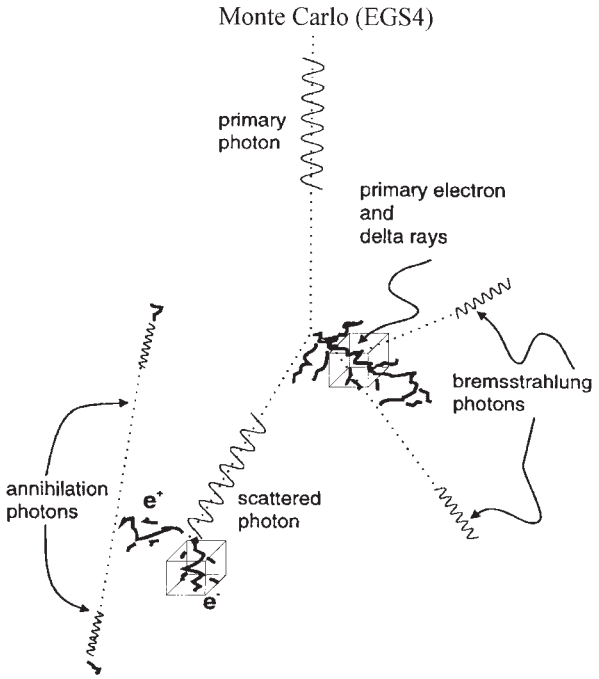


Figure 8.8
Single photon history. Each primary photon interaction releases a shower of secondary electrons and photons. The energy deposited by charged particles (e-, e+) is scored in voxels. [Adapted with permission from reference [8].]

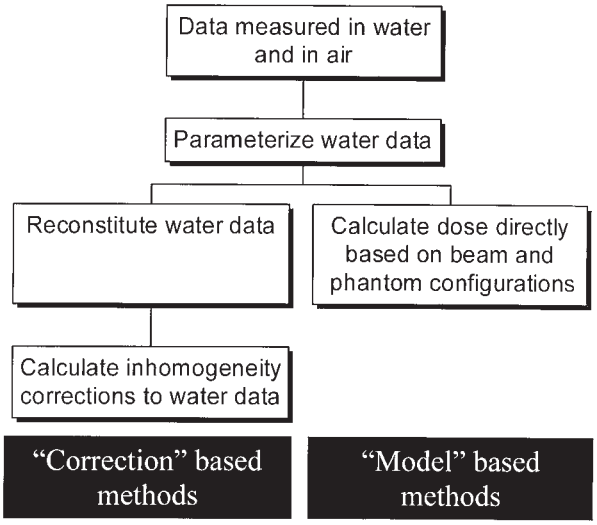


Figure 8.9
Two approaches to dose calculation algorithms. [Adapted with permission from reference [78].]

8.4.4 Specific dose algorithms

Historically, two approaches have been taken [32, 90,139], as summarized in Figure 8.9 [78]. In correction-based methods, the starting point is always the dose distribution for an all-water absorber, with secondary corrections introduced to account for tissue density. In the model-based methods, there is much greater reliance on the fundamental physics of scattering and the dose distribution in water is no longer a prerequisite.

Correction-Based Methods

The dose distribution, corrected for tissue inhomogeneity, is given by:

$$D_{in\,\mathrm{hom}}(x,y,z) = ICF(x,y,z) \infty D_{H20}(\mathrm{x,y,z}) \tag{8.5}$$

where D_{inhom} is the dose distribution within inhomogeneous tissue; *ICF* is the inhomogeneity correction factor; and D_{H2O} is the reference dose distribution in a homogeneous water absorber.

The advantage of this approach is that the dose distribution can be calculated via two independent algorithms used in tandem. A fast method can be used to predict the dose distribution in water—a "first-order" approximate solution to the calculation problem. A perturbation method is then used to correct the water distribution using the local ICF factors. The details of various methods for calculating these factors on the basis of tissue contours and average density are summarized in Figure 8.10. These techniques rely principally on a water-equivalent or effective pathlength (d'). The use of an effective pathlength adjusts the primary fluence of the radiation reaching a dose point correctly. However, this approach indirectly adjusts the scatter component and this is a fundamental limitation of these early methods. The Power-Law method [112] also considered the proximity of an inhomogeneity to the point of interest (d_1, d_2) and greatly improved the accuracy of dose calculations in lung regions.

Kappas and Rosenwald [67] developed a 3-D beam subtraction method for inhomogeneity corrections. Sontag and Cunningham [114] introduced the Equivalent Tissue Air Ratio (ETAR) algorithm as a modification to the ratio of TAR algorithm by accounting for variation in tissue density both in the plane of calculation as well as in the third dimension. The original implementation was characterized as a "2.5-D" method due to the compression of the heterogeneous volume into a virtual scattering slice positioned at a mean lat

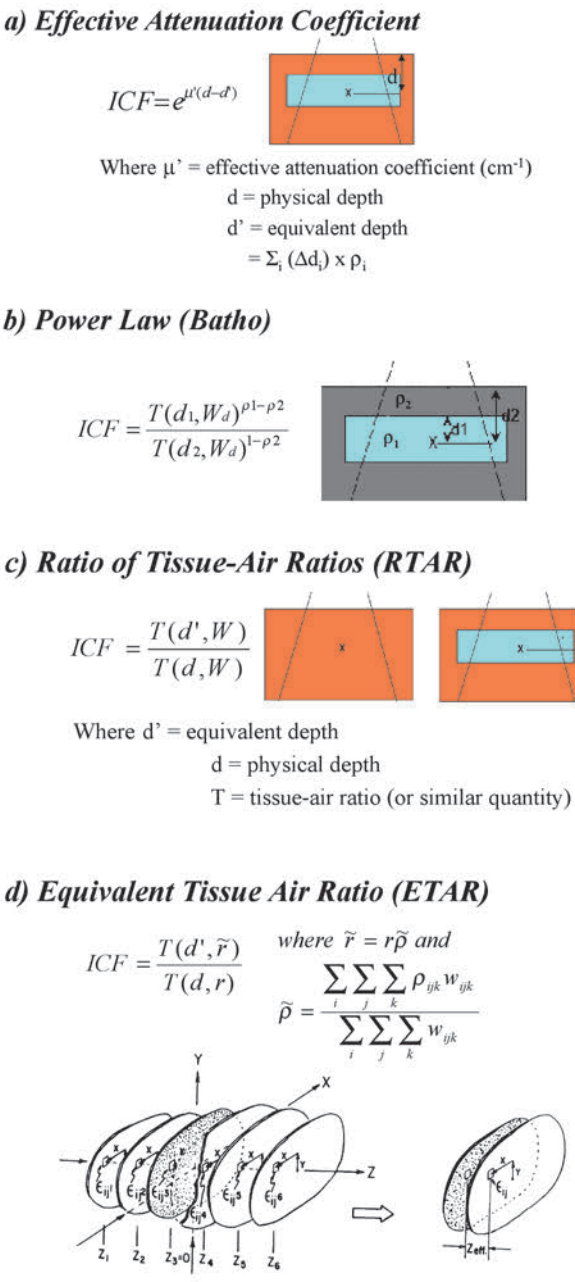


Figure 8.10
Some correction-based algorithms for photon beams. Figure 8.10d is adapted with permission from reference [114] and the Radiological Society of North America.

eral distance (Z_{eff}) from the plane of interest. In recent implementations, the slice collapsing procedure has been avoided and Fourier convolution has been applied to perform the scatter integration more efficiently, assuming an invariant scatter kernel, W_{ijk} [144].

Model-Based Methods

Model-based methods (Figure 8.11) have the potential to calculate the dose, D(x,y,z), directly from first principles without the prerequisite dose distribution in water. Assuming the characteristics of the incident primary radiation are known, the transport of radiation through the tissue voxels is more explicitly considered. The differential scatter-air ratio method (dSAR) was proposed almost four decades ago for the calculation of dose in the presence of small tissue inhomogeneities [29,68]. The scattering "strength" of each voxel was based on differential scatter-air ratios measured in water, but a single-scatter ray-tracing model applied to the *total* scatter led to unacceptable accuracy. The DeltaVolume method [138] is a descendant of the dSAR method, although it was developed much later. In this technique, the influence of an individual air-filled voxel was precisely measured in water using specialized dosimetry instrumentation. Because of the computational burden of ray-tracing between pairs of voxels, and need for a radiation database which could not easily be measured, this method has not been implemented widely.

The paradigm shift in model-based calculations occurred when it was realized that (1) scatter kernels could be treated as "response functions" and (2) this impulse-response analysis also applied to the *primary electrons* launched by photons (Figure 8.5). This opened the possibility of solving a long-standing fundamental limitation of all previous (non-Monte Carlo) methods, the inability to correct for lateral disequilibrium of electrons in narrow photon beams or at the edge of any beam or density discontinuity.

Lateral Electronic Disequilibrium

In most photon algorithms, electrons set-in-motion by primary photons are assumed to be absorbed "on the spot." This assumption weakens for higher energy x-rays which launch electrons that travel several centimeters, especially in lower density tissue. For example, the dose in lung exposed to a narrow (5 cm) x-ray beam is actually *reduced* by almost 10%, compared with an *increase* of 10% predicted by traditional methods [42,53,84,85,122,145]. This effect is illustrated in Figure 8.12, which demonstrates a substantial difference between total dose and primary fluence, at times moving in the opposite direction as predicted by conventional methods. There is a substantial advantage to using algorithms, which clearly distinguish the primary

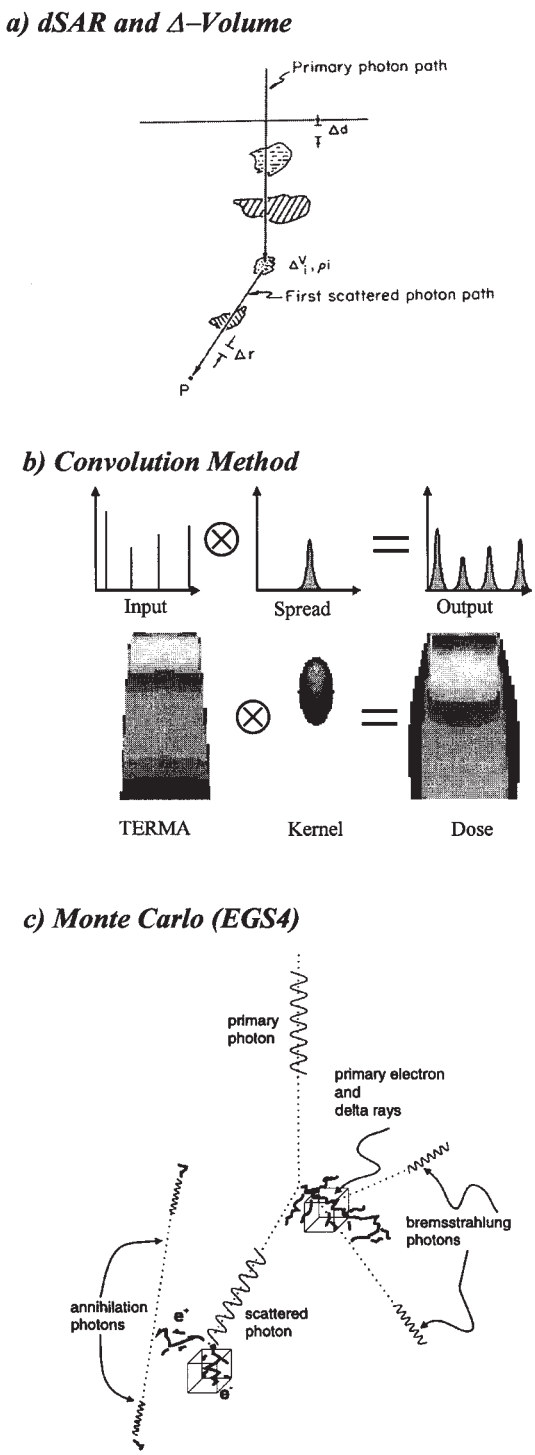


Figure 8.11
Some model-based algorithms for photon beams. [Adapted with permission from references [8] and [138].]

photon fluence, Φ, and the primary scatter kernel, K. Without this distinction, discrepancies between the primary photon fluence and the absorbed dose in build-up regions, build-down regions, at tissue interfaces [41,85,108,129,130] can only be remedied by empiricism.

8.4.5 Electron dose algorithms

Pencil Beam Method

For electron calculations, a pencil kernel need only be integrated over the 2-D surface of the patient as in Figure 8.7b, provided the kernel can be adjusted in shape with penetration depth. Pencil beam kernels have been derived from analytical theory [64,82,98,106], Monte Carlo simulations [20], or from empirical data [33,123]. Correction of the kernel for tissue inhomogeneity, including the strong effects of atomic number, is based on converting CT image data to scattering power data [54,100,143].

Phase Space Evolution

In the phase space evolution technique, the pencil beam is constantly redefined with successive layers of penetration depth [59,82]. The superposition technique then becomes more similar to the 3-D superposition method used in photon beams (Figure 8.2d). The kernel is based on the statistical distributions of location, energy, and direction of a cohort of electrons after traversing a small layer of material. The distributions are then propagated in an evolutionary manner until all the electron energy is expended. The evolution of the beam must be recorded in a multi-dimensional space, and this bookkeeping requires significant computer resources [105].

Macro Monte Carlo Methods

Individual electron histories can be followed but on a coarser grid spacing, compatible with the size of image voxels. In one implementation [95], the history of an electron is followed along a sequence of abutting spherical voxels (Figure 8.13). The scattering effects of these spheres, which can each be viewed as scatter kernels, are predetermined by detailed Monte Carlo simulations, thereby achieving the savings in computational time. The Voxel Monte Carlo (VMC) algorithm [69] uses simplifications of general Monte Carlo codes for the specialized application to electron beam calculations. Firstly, the domain of validity of the theories underlying Monte Carlo code was restricted to the energy range of 1–30 MeV and to the materials of clinical relevance, leading to simpler probability functions for all physical processes. Secondly, the step size for generating an electron history is maximized with a minimal loss of accuracy. Thirdly, the number of electron histories is reduced by recycling histories in different regions of a patient through density scaling of electron

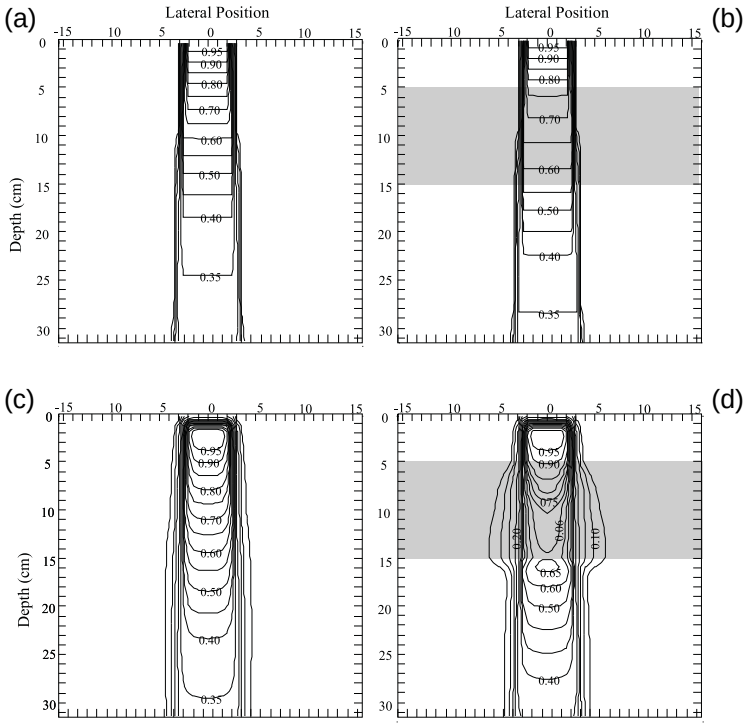


Figure 8.12
FLUENCE and DOSE distributions for a beam of 5.0 MeV photons (5 x 5 cm^2 field) incident on a water phantom (a & c) and a slab phantom with a cork insert (b & d). FLUENCE distribution in a water phantom (a). FLUENCE distribution in a water-cork-water phantom (b). DOSE distribution in a water phantom (c). DOSE distribution in a water-cork-water phantom (d). Note the dose reduction in the central region of the cork and the penumbral flaring of the beam. [Adapted with permission from reference [8].]

path lengths. In brief, these variants of the microscopic Monte Carlo method adopt a macroscopic scale, compatible with today's imaging capabilities.

8.4.6 Judging the capability of a dose algorithm

A good understanding of the underlying radiation physics as it applies to a wide variety of irradiation conditions is necessary in order to ensure a dose result which can be trusted for clinical decision-making. Unfortunately, dose algorithms are often the most hidden elements of the treatment planning software because of proprietary reasons. Furthermore, the implementation of an algorithm is usually a modification of published procedures, with pre-processing of the radiation data base or additional approximations introduced to accelerate the computational speed. A qualified medical physicist must therefore investigate the methods actually used by the manufacturer, understand the radiation database requirements, and review the software implementation details, including source code if it is made available.

Algorithm Classification

We list here some key questions, which help to define the nature of an algorithm. They are complementary to other questions which form part of the tender document for purchasing computerized treatment planning systems (section 8.8).

- What is the name of the algorithm used?
- What publications is the algorithm based on?
- What deviations from the published methods were used during software implementation?
- What radiation data base and anatomy database is required as input?

Having defined the general features of the algorithm, more specific details can be determined, using the checklist suggested for photon beams of Table 8.3.

The arrows denote the direction towards greater intrinsic capability usually with a penalty in speed performance. Similar tables can be developed for electron

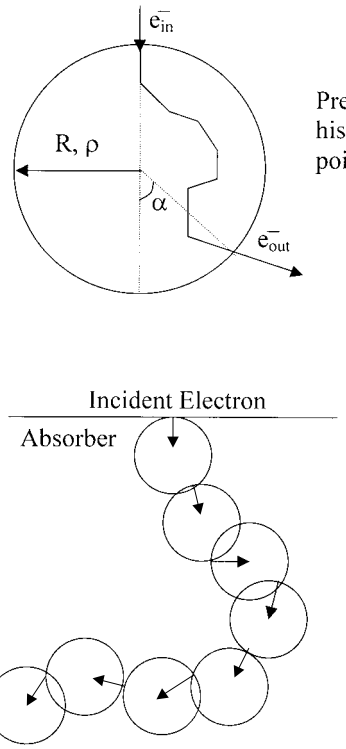


Figure 8.13
Macro Monte Carlo method using spherical scatter kernels. Each incident electron travels along a series of abutting spheres. [Adapted with permission from reference [95] and IOP Publishing Limited, Bristol, UK.]

beams and for brachytherapy. The table emphasizes the utilization of digital anatomy density data for inhomogeneity corrections, the relationships to the core superposition principle, and the computational speed. The speed specification should be carefully reviewed since a "fast" method may entail less detailed radiation physics, a limited volume of dose computation, or a coarser dose grid. All of these can lead to dose inaccuracies and may be of concern especially with dose escalation in 3-D conformal radiation therapy.

Algorithm Testing

Experimental testing protocols (section 8.10) for in-water dose distributions and for inhomogeneity corrections will help to screen algorithms, especially those with poor intrinsic physics, for dose accuracy. The dose accuracy results obtained should correlate well with the expected performance based on the criteria listed in Table 8.3. After acceptance testing of the planning system, it is always instructive to compute dose distributions for a set of clinical test cases. These can be compared with those obtained from previously used treatment planning methods, and any differences resolved on the basis of new algorithm capabilities. After clinical commissioning, quality assurance of the dose algorithm and its associated utilities must be repeated, especially after major software upgrades that can directly or indirectly impact the dose accuracy.

8.5 Design and Architecture

8.5.1 Basic components

A treatment planning system is a combination of hardware and software components that allow the user to produce and display calculated dose distributions from which a physician will prescribe a patient's radiation treatment. The basic components of a treatment planning system include:

Software

- Utility software for entering external beam treatment unit and measured absorbed dose data
- Utility software for entering brachytherapy radioisotope data
- Utility software for accessing and printing selected treatment unit or source data
- Software for creating and organizing patient data files
- Contouring software for entering the external contour of the patient, internal contours, target volumes and landmarks pertinent to the treatment
- Utility software for transferring patient CT data and converting to relative electron densities
- Video display software for interactive beam placement, shaping, sizing, and filtering
- Dose calculation initialization software for establishing calculation grid and method of calculation (e.g., contour correction included, inhomogeneity correction included)
- Dose calculation software
- Isodose display software including relative normalization and beam weighting
- Hardcopy software for producing scaled isodose distributions
- Archiving software for storing non-current patient data
- Backup software for protecting operating system and application programs

Hardware

- Central processor with memory to accommodate operating and application software
- High resolution graphics capability

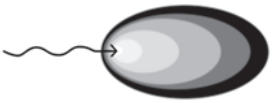


Table 8.3
Checklist of Key Features of Photon Dose Algorithms. Arrows Indicate Progression Toward More Desirable Features

FEATURE	CHARACTERISTIC TO CONSIDER
Sensing of anatomy voxels during scatter calculations	1-D rayline → 2-D slice → 3-D volume
Scatter kernel dimension	beam → slab → pencil → point
Scatter kernel content	total → S_1 photons → $S_{>1}$ photons → P electrons
Scatter kernel source	Empirical or theoretical
Scatter kernel – corrected for tissue inhomogeneity	No → density-scaled → atomic number correction of total? S_1 photons? or $S_{>1}$ photons? P electrons?
Dimension of scatter integral	0-D → 1-D → 2-D → 3-D
Computational speed (CPU time per dose point per beam)	slow → medium → fast

S_1 = first scatter of photons
$S_{>1}$ = higher order scatter of photons, in addition to S_1
P = primary knock-on electrons, in addition to S_1 and $S_{>1}$

- Mass storage (hard disk) capacity sufficient to easily retain all current patients on treatment
- Floppy disk and CD ROM
- Keyboard and mouse
- High resolution graphics monitor
- Digitizer
- Laser printer
- Color plotter
- DAT tape for archiving and backup
- Ethernet card for acquiring CT data and remote access

Various components of a typical treatment planning system are pictured in Figure 8.14.

8.5.2 Stand-alone system

Stand-alone treatment planning systems contain the basic components described above and would meet the requirements of a smaller cancer treatment facility where access to the system is limited to a few people and where a single centralized planning facility is adequate. The components of a stand-alone system are shown schematically in Figure 8.15. The management of a stand-alone system is relatively straightforward with only a few user accounts/passwords and less restricted access to the system components. One CPU carries the burden of running all system resources.

Stand-alone planning systems are sometimes purchased for dedicated applications such as brachytherapy or stereotactic radiosurgery. Specialty planning systems of this type typically offer features not available through the larger systems but do not provide the capability to export or merge patient data. Furthermore, they require additional management overhead.

8.5.3 Multi-station system

Multi-station planning systems are required in larger cancer treatment facilities where medical physicists, dosimetrists, and physicians need to access the system simultaneously. The components and architecture of a multi-station system are shown in Figure 8.16. A multi-station planning system is typically distributed over a local area network (LAN) and sometimes a large area network. Workstations can be located in several places and are distributed to facilitate commissioning, clinical treatment planning, security, and system management.

8.5.4 Ancillary components

A multi-station planning system typically requires a central file server for printing and file handling and also facilitates system management. A separate server is required for efficient electronic transfer of digital images [e.g., CT in DICOM (Digital Imaging and

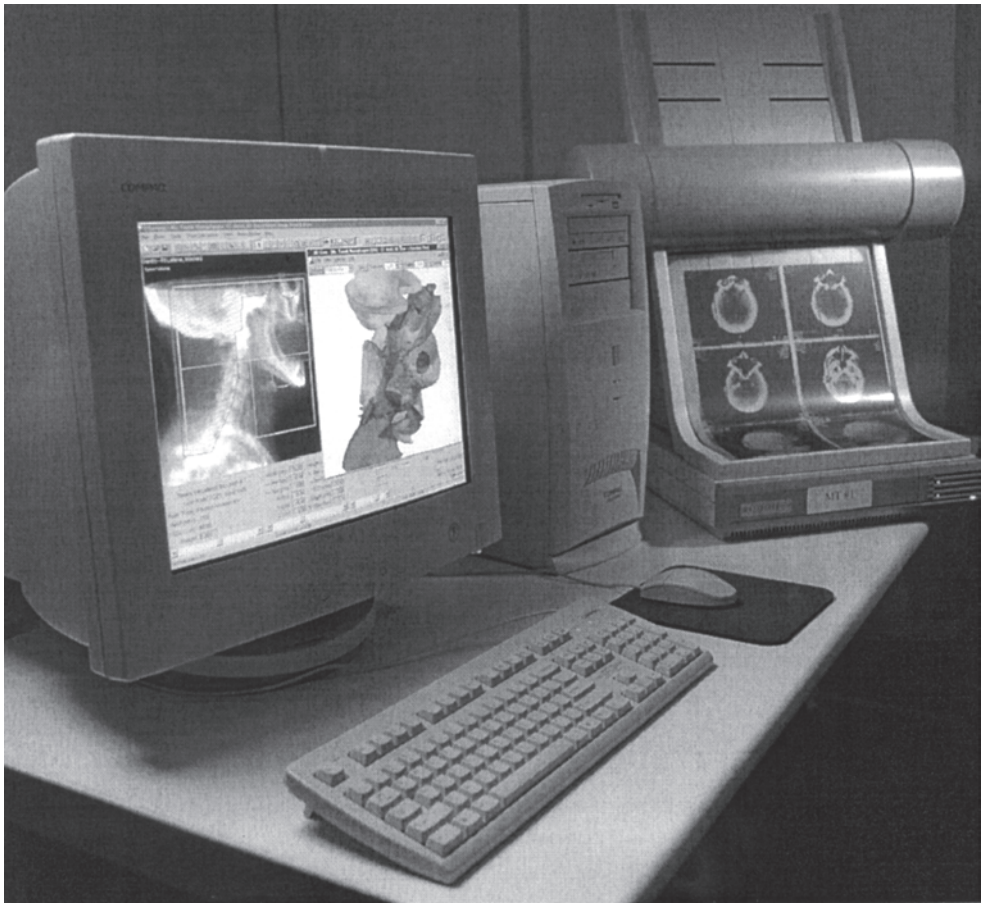


Figure 8.14
Basic components of a modern 3-D radiation treatment planning system. From left to right: video monitor and keyboard, computer tower, film digitizer. [Courtesy of Theratronics International Ltd.]

Communications in Medicine) format] to the planning system and an optical storage facility is needed to house and provide access to large volume image data sets. Image data sets are usually acquired from a CT scanner or CT simulator but could originate from any device provided they are in DICOM format and software is available for importation/fusion.

Network infrastructure for a multi-station planning system requires multiple hubs (10baseT) and typically one switch with 100 Mb/s access (100baseT) for image transfer. Virtual LAN optimization is a useful option. A centralized computer room facilitates environmental control, system management and security, and can be used to locate noisy printing and plotting peripherals.

Architectural overhead for a multi-station planning system is significant and could require a full-time-equivalent support specialist. User accounts must be organized to protect patient data and at the same time allow shared access when required. For example, physicians contour or enter volumetric data on an image data set, which is then accessed by dosimetrists for treatment planning. In addition, when someone is absent, dosimetrists and physicists routinely access each other's plans for editing. Users must also be able to sign on at any workstation and have access to the required resources without much difficulty.

Backup must be organized to protect both the operating software and the application. Ideally, the operating system would be located on a mirrored disk set on the server and the application on a separate redundantly (e.g., RAID 5) configured disk set with "hot swap" capability. Archiving must be organized to retrieve eas-

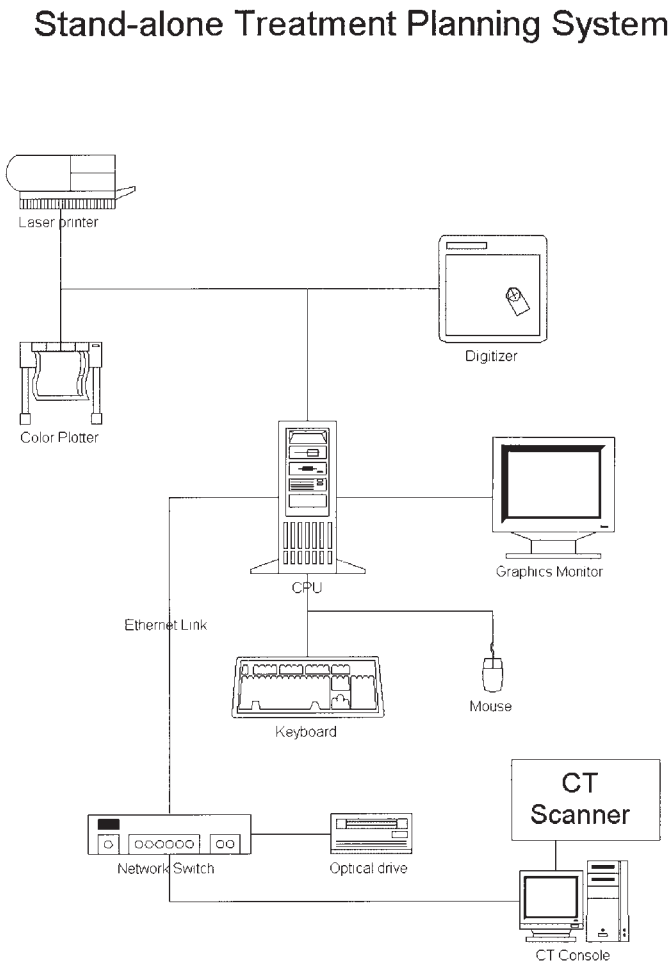


Figure 8.15
Schematic of stand-alone treatment planning computer configuration.

ily old patient plans or special planning cases. Acceptance, original commissioning, and re-commissioning all require extensive system testing and associated data archiving.

8.5.5 Third party software

A reality of current treatment planning systems is the need to develop and extend the capabilities of the software. This is typically required to match existing treatment equipment or existing clinical practice with the planning system. In this situation, qualified personnel develop software locally at the cancer center. One example is the exportation and conversion of a planned multileaf collimator (MLC) field to leaf coordinate positions for a particular linear accelerator. Another example is the development of software to transfer electronically planning data for clinical trial protocol participation (e.g., Radiation Therapy Oncology Group (RTOG) clinical trials). These applications require the use of commercial software tools and also access to the planning system software. Access to the planning system software may require the availability of the source code in which case the vendor must communicate closely with the developer and establish a liability agreement. Alternatively, the vendor may supply commercial tools, which allow access to the planning system without the need to obtain the source code.

Modern treatment planning systems often come with embedded third party software either within the treatment planning programs or separate from these programs. Thus, spreadsheet software can be used to

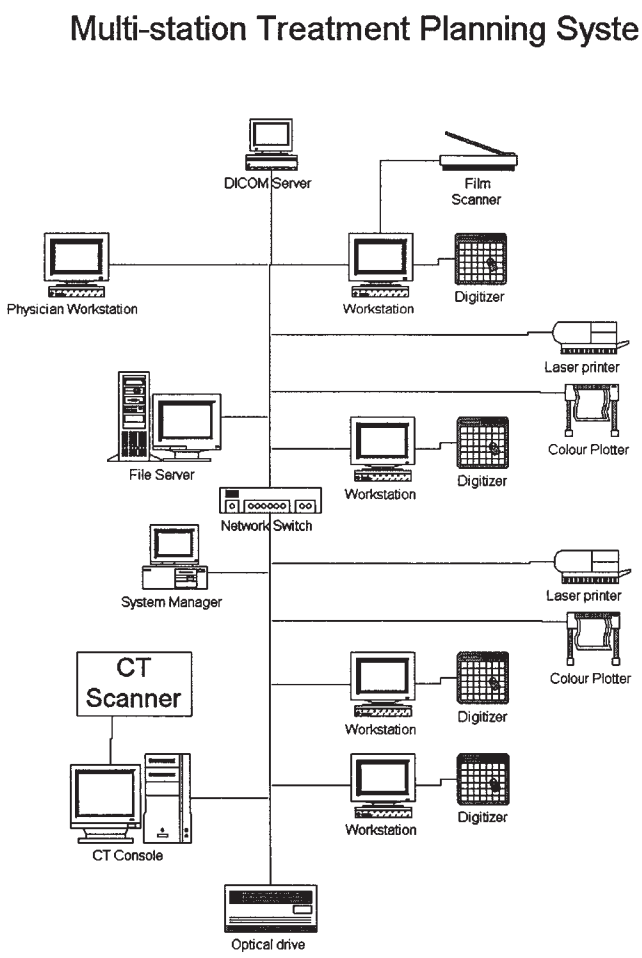


Figure 8.16
Schematic of the components and architecture of a multi-station treatment planning system.

develop a series of macros, which allow for a series of "automated" operations within the treatment planning system. These macros can be used for running a series of consecutive plans to generate an optimized plan or they can be used as a template to run a standard plan. Furthermore, data generated by a water phantom can be "cut" and "pasted" into the spreadsheet for the database of the treatment planning system. Similarly, data base programs can also be used for generating and storing data for later analysis. These data could be used for workload measures, for clinical studies, and any other analysis deemed appropriate.

8.5.6 Evolution of treatment planning systems

Although the basic components of a computerized planning system have not changed considerably, the technical capabilities have. Recent developments in computerized linear accelerator control, field collimation technology (e.g., asymmetric diaphragms, dynamic wedge, MLC), and electronic portal imaging have driven the development of planning systems toward providing 3-D conformal capability for both dose calculation and display. The current focus in this area is on the implementation of intensity modulated radiation therapy (IMRT), which requires planning capabilities for dynamic MLC operation.

While CT has been an integral part of computerized treatment planning since the late 1970's, other imaging modalities are now being incorporated into the planning process including magnetic resonance (MR), ultrasound (US), positron emission tomography (PET),

and single photon emission computed tomography (SPECT). In addition, the advent of the CT simulator (virtual simulation) has extended the image handling capabilities of treatment planning systems to include digitally reconstructed radiographs (DRRs) and multiplanar patient representation. Current focus in image-assisted treatment planning includes fusion of images from various sources with those from CT.

While the evolution of treatment planning technology has moved toward 3-D conformal capability, there is also an evolution toward a fully integrated electronic patient record. In this regard, software is being developed to export planning data to the treatment units directly from the planning system and also to store dose distributions superimposed on patient images as part of the patient's electronic record. Because of possible equipment combinations and permutations, third party software development will likely be an important part of the evolution of an integrated electronic patient record.

8.6 System Specifications

Treatment planning systems consist of multiple components both in terms of hardware as well as software. The software usually has a vast number of options. In addition, the user interface can vary dramatically from one system to another. Thus, writing detailed specifications for a treatment planning system is a non-trivial undertaking. However, the specifications are an essential requirement for a number of reasons. First, specifications are required if one plans to use a formal tendering process for equipment purchase. Second, specifications provide the standards that determine whether the installed system can perform according to the manufacturer's promise (e.g., acceptance testing). Third, the specifications provide a standard by which quality assurance measurements can be assessed in terms of long-term compliance, especially following software updates.

The system specifications can be divided according to (1) hardware, (2) system administration software, (3) network and interface software, and (4) treatment planning software. Appendix 8.I gives the contents of a tender document, which includes a summary of what should be considered under specifications. The AAPM Task Group 53 [46] has given some general comments on specifications. For example, specifications should be reasonable constraints that are readily quantifiable, testable, and measurable. It is not very useful to describe a global specification as "2% accuracy in dose calculations" since this is too broadly based and not realistic. Under what specific conditions is this specification to be enforced?

Specifications can take various forms. These include:

(1) System capabilities such as performing particular functions or not (i.e., "yes" or "no" answers).

(2) Quantitative assessments such as calculation speed, numbers of images it can store.

(3) Statements of accuracy such as would be applied to dose calculations and beam geometry displays.

8.6.1 Sources of uncertainties

In order to understand system tolerances and to define criteria of acceptability, one needs to have a clear understanding of all the sources of uncertainties associated with radiation treatment planning programs. Furthermore, there is no point in specifying an accuracy of 0.1% in dose and 0.1 mm in geometry if the actual treatment of the patient cannot be done any more accurately that 5% in dose delivery and 5 mm in spatial accuracy. In general, the tolerances lie somewhere between these two extremes. Sources of uncertainties in the treatment process include:

- *Mechanical treatment machine related uncertainties*. These include gantry rotation, collimator rotation, shielding block repositioning, and field size settings.
- *Dosimetric treatment machine related uncertainties.* These include accuracy and reproducibility of the monitor ionization chamber, reproducibility of field flatness and symmetry with a change in machine mechanical settings such as gantry rotation, collimator rotation, and collimator opening.
- *Imaging related uncertainties.* These include issues related to imaging accuracy such as geometrical distortion in MR or beam hardening in CT, issues related to data transfer and conversion from CT numbers to electron densities, inaccuracies in image registration, and resolution limitations especially with radionuclide studies.
- *Patient-related uncertainties.* These include patient repositioning and organ motion during any one of the steps of the planning and treatment process such as CT scanning, simulation, and treatment. Patient changes of weight and tumor shrinkage also generate treatment uncertainties.
- *Uncertainties in the definition of target volumes and normal tissue localization.* It has been shown that target volume determination is one of the larger uncertainties in the entire treatment process [70,72,115].
- *Beam measurement uncertainties.* These include uncertainties related to the detectors, the size of the detectors, the precision and accuracy of the

measurements, and the composition of plastic phantoms if these are used instead of water for certain regions such as the buildup region.

- *Dose calculation uncertainties.* These are related to beam measurement uncertainties as well as limitations in the calculation algorithms.
- *Dose display.* Decisions are often made at a computer display terminal about beam placement and dosimetric assessment. If the dose distribution display is offset from the true anatomy then inappropriate decisions might be made about beam placement.
- *Dose evaluation uncertainties.* Dose volume histograms (DVHs) provide a means of optimizing treatment plans. Inaccuracies in volume determination and dose binning procedures could impact the accuracy of DVHs.
- *Biological modeling uncertainties.* While biological modeling is in a very embryonic stage of clinical usage, the models are being used more frequently for fractionation and volume effects comparisons. Because of the complexity of biological response and the simplicity of most existing models as well as the scarcity of controlled clinical data, these models have major limitations in their capability of predicting tumor control probabilities (TCPs) and normal tissue control probabilities (NTCPs).

The uncertainties described above do not include any issues related to treatment errors that can occur as a result of incorrect implementation of the proposed treatment plan.

8.6.2 Suggested tolerances

Definition of criteria of acceptability for treatment planning systems is very difficult due to the uncertainties listed above and due to the variation in calculation algorithms used by different commercial treatment planning systems. Various authors have given their opinions on criteria of acceptability or suggested tolerances [19,38,61,81,125]. The AAPM Task Group 53 [46] does not give a table of recommended values but does indicate the range of accuracies that are probably achievable and have divided these estimates into what might be possible on conventional 2-D and modern 3-D treatment planning systems. These possible criteria of acceptability were generally based on personal and anecdotal experience with very little being based on a thorough quantitative analysis.

A statement of uncertainty must also include a clearly defined associated probability of compliance. Thus, stating that a calculation should be accurate to 2% is meaningless unless there is an indication of whether this value represents one standard deviation, two standard deviations or a specific confidence interval. Van Dyk et al. [125] give tolerances in the form of one standard deviation. In general, we feel that these criteria are still relevant although perhaps, with improvements in dose calculation algorithms, these criteria could be tightened to some degree. Like Van Dyk et al. [125], the TG53 Report [46] also indicates that different regions within the radiation beam and anatomy will have different levels of accuracy, with the build-up region and regions of tissue density variation having the largest inaccuracies (Figure 8.17).

Levels of accuracy practically achievable are clearly dependent on the capabilities of specific dose calculation algorithms. Thus a statement of a suggested tolerance is literally that, i.e., a *suggested* tolerance. Such numbers can be used as goals but need to be considered in the context of the specific treatment planning system's capabilities and departmental needs. Table 8.4 is adapted from TG53 and gives the possible achievable tolerances while Table 8.5 provides more specific criteria of acceptability for external beam dose calculations. While not indicated in the Task Group report, we recommend applying these suggested criteria of acceptability to the 67% confidence level, i.e., one standard deviation. The goal of researchers who are developing new dose algorithms for external beams should continue to be 2% accuracy everywhere except in high dose gradient regions where the accuracy should be 2 mm in geometric displacement of isodose curves [61].

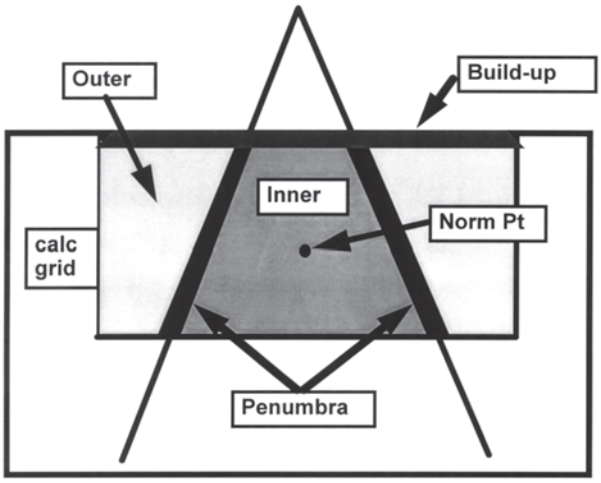


Figure 8.17
Different regions of dose calculation accuracy. [Reprinted with permission from reference [46].]

For brachytherapy, uncertainty estimates are more difficult to determine because of the very short treatment distances and the resulting very large dose gradients. Measurements are very difficult to perform, and one often has to be satisfied with published data. Also, brachytherapy calculations include absolute outputs in Gy or Gy/hr, thus requiring a clear understanding of the absolute source output specifications in terms of radioactivity or source strength (see chapter 18). The recommendations by Van Dyk et al. [125,126] continue to be relevant (Table 8.6).

The goal of researchers who are developing new brachytherapy algorithms should continue to be 3% accuracy in dose everywhere at distances of 0.5 cm or more [125,126].

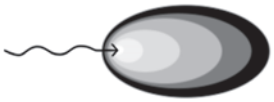


Table 8.4
Generally Achievable Tolerances for 3-D Treatment Planning Systems [Adapted with permission from reference [46].] Percentages are quoted as a percentage of central ray normalization dose.

FREQUENCY (MHz)	ACHIEVABLE TOLERANCE	COMMENT
Entry of axial contours	0.1 cm	Based on CT data entry
Outlining of PTV given a CTV	0.3 cm	Depends on contour expansion routine
Use of MR for target delineation	0.2 – 0.5 cm	Depends on image registration and geometric distortions
Beam location resolution	<0.1 cm	
Collimator setting	0.1 cm	
Aperture definition	0.1 cm	
Collimation and aperture display	0.1 cm	
Gantry angle	<1 deg	Resolution typically 0.1 degree
Table/collimator angle	<1 deg	Resolution typically 0.1 degree
Dose, central 80% of beam width, central axis slice, no beam modifiers, no inhomogeneities	1%	
Dose, central 80% of beam width, non axial slice, no beam modifiers, no inhomogeneities	1%	
Dose in penumbra (80–20%), open field, no inhomogeneities	1–5 mm	Depends on model and grid effects
Dose to normalization point in blocked field	2%	
Dose under block, no inhomogeneities	2%	
Dose in block penumbra, no inhomogeneities	1 mm	
DVH accuracy	Difficult to define	Depends on dose grid, region of interest grid, accuracy of volume determination, size of histogram, plan normalization.
Predicted NTCP	Difficult to define	Depends on model, organ, fractionation, and volume.

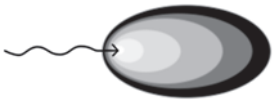


Table 8.5
Sample Criteria of Acceptability for External Dose Calculations. [Adapted with permission from reference [46].] Percentages are quoted as percent of the central ray normalization dose.

SITUATION	ABSOLUTE DOSE AT NORMILIZATION POINT (%)	CENTRAL RAY (%)	INNER BEAM (%)	PENUMBRA (MM)	OUTER BEAM (%)	BUILDUP REGION (%)
HOMOGENEOUS PHANTOMS						
Square fields	0.5	1	1.5	2	2	20
Rectangular fields	0.5	1.5	2	2	2	20
Asymmetric fields	1	2	3	2	3	20
Blocked fields	1	2	3	2	5	50
MLC-shaped fields	1	2	3	3	5	20
Wedged fields	2	2	5	3	5	50
External surface variations	0.5	1	3	2	5	20
SSD variations	1	1	1.5	2	2	40
INHOMOGENEOUS PHANTOMS**						
Slab inhomogeneities	3	3	5	5	5	–
3-D inhomogeneities	5	5	7	7	7	–

* Absolute dose values at the normalization point are relative to a standard beam calibration point.
** Excluding regions of electronic disequilibrium.

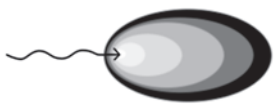


Table 8.6
Sample Criteria of Acceptability for Brachytherapy Calculations. Percentage is a percent of local dose.

SITUATION	CRITERION (%)
Single point source Distances of 0.5 to 5 cm	5
Single line source Points along normal to the central 80% of the active length and distances of 0.5 to 5 cm	5
Source end effects Difficult to quantify; therefore no specification is given	

8.7 Practical Considerations

Perhaps, the greatest variability in the amount of effort spent by different institutions on the purchase, commissioning, and quality assurance process of any technology is related to computerized treatment planning systems. There are various reasons for this including:

(1) Variations in design and complexity of computerized treatment planning systems from simple 2-D systems running on a single personal computer with a popular operating system to very sophisticated 3-D treatment planning systems running on higher level hardware possibly with a central server and multiple stations combined with a more specialized software platform.

(2) Variations in staffing skills of radiation therapy departments and the corresponding ability to deal with sophisticated technology. Thus, a large academic institution, in all likelihood, will spend much more time and effort on the purchase and commissioning of a new system compared to a relatively small private practice clinic which has fewer staff.

(3) Variations amongst physicists and radiation oncologists in their perception of acceptable tolerance levels and the time and effort required to commission a new system.

(4) Variations of technologies available in a given department such as:
- Multimodality linear accelerators with multileaf collimation and electronic portal imaging
- Stereotactic radiosurgery
- CT-simulation
- Multiple imaging sources including CT and MR imaging
- Intensity modulated radiation therapy (IMRT) with stationary segmented treatments or with dynamic treatments
- Simulation with digital image capture capabilities
- Radiation oncology information management systems that allow image and treatment plan data transfer throughout the radiation oncology department
- Participation in clinical trials requiring patient treatment and QA data to be transmitted through the Internet to the study site (e.g., RTOG)
- Multiple satellite facilities networked to provide centralized treatment planning capabilities

8.7.1 Staffing considerations

The above variations in technologies are a clear indication of the impact on the organizational considerations of the treatment planning process. One fact is clear. The increased complexity of treatment planning technologies requires more, rather than less, staff to ensure that the technologies are used safely and that appropriate QA procedures can be implemented and carried out routinely. Furthermore, the rapid changes in software involve software upgrades almost on an annual basis, which, in turn, require a (partial) recommissioning of the treatment planning system. This is in sharp contrast to older treatment planning systems that one purchased with relatively few changes until a major new release was issued every 3 to 5 years.

As indicated in AAPM TG53 [46], the treatment planning QA process is largely the responsibility of the radiation oncology physicist although it is recognized that other members of the team such as dosimetrists, radiation therapists, radiation oncologists, and systems managers also have important roles. As such, it is very much a team effort with clinical, physical, and administrative components. A breakdown in communication or in effort by any one member of the team could result in misadministrations of dose to the patient with major consequences.

8.7.2 3-D versus 2-D

The discussion of what comprises 2-D versus 3-D treatment planning has been significant in the last ten years. Today, 3-D is given such a special connotation that it implies that in the past, the third dimension was never considered. In reality, the third dimension has always been considered overtly, indirectly, or intuitively. The modern imaging devices and image display technologies have made 3-D viewing of patient anatomy much easier and the image manipulation tools provide radiation oncologists with target volume delineation capabilities that can easily be carried out on multiple 2-D slices to give comprehensive 3-D display capabilities. The following are some of the capabilities that have made 3-D treatment planning a major advance:

- Multislice imaging with thin slice thicknesses and small interslice spacing.
- User friendly target volume and normal tissue delineation tools.
- Use of different imaging modalities with image registration techniques to aid in target volume and normal tissue delineation.
- 3-D reconstructions of targets and normal tissues including transparent surfaces and volume rendering displays including beam surface entry on the external patient contour.
- Easy manipulation and display of 3-D reconstructions from planar image data.
- Beam geometry display incident on the patient at any angle with the possibility of non-coplanar beams.
- Irregularly shaped fields using shaped shielding or multileaf collimation.
- Beam's eye view displays to aid the assessment of adequate target coverage and minimal normal tissue coverage.
- Digitally reconstructed radiographs for comparison with digitized simulator films or electronic portal images.
- Room's eye view of treatment geometry with a view from any angle in the treatment room.
- Dose volume histograms assessing all the dose data in 3-D for both the target and normal tissues.
- Dose calculation capabilities that allow for scatter integration in all three dimensions while accounting for patient surface contours and tissue densities also in 3-D. This remains a confusing issue even in "3-D" treatment planning systems where the scatter dimensionality is often not 3-D and quite frequently it is only 1-D or 2-D.

8.7.3 CT simulation versus 3-D RTPS

Virtual simulation is that process whereby the patient's treatment can be simulated using a patient that is represented by the image information acquired through some imaging modality, most commonly CT or MR. CT scanner vendors now provide CT simulators that are primarily CT scanners with beam geometry display software (see chapter 5). The virtual simulation process can be performed *without* the patient present. Furthermore, most functions carried out on a CT simulator can also be accomplished with a 3-D treatment planning computer. The primary difference between CT simulators and 3-D treatment planning systems is that historically the treatment planning computer vendors have emphasized dose calculation capabilities first and image manipulation capabilities second. CT simulator manufacturers, however, with their depth of experience in diagnostic image handling routines, have produced 3-D virtual simulation software that tends to be more sophisticated in comparison to treatment planning computers. These differences, however, are decreasing, and in the future it is highly likely that CT simulators will provide dose calculation capabilities and treatment planning computer vendors will enhance their image manipulation routines.

8.8 Purchase Process

The purchase process for treatment planning computers can follow the generic approach of any of the modern technologies used in radiation oncology (see chapter 2). The details will vary from one institution to another dependent on institutional size, the available staff, computer expertise, other technologies in the department, and financial resources. The following summarizes some of the steps to consider in the purchase and clinical implementation process.

8.8.1 Assessment of need

At the very beginning of purchase considerations, it is important for the purchasing organization to define its exact interest, needs, and desires of the treatment planning system. Factors to consider in setting the direction for purchasing a system are summarized in Table 8.7.

The needs are best defined by an equipment selection committee with the involvement of physicist, oncologist, dosimetrist, and computer staff. Based on this information, decisions need to be made regarding the general capabilities of the treatment planning system as well as the number of treatment planning stations required, the interfacing and/or networking with appropriate diagnostic scanners or CT simulators.

8.8.2 Request for information

Fairly early in the purchase process, it is very useful and educational to send out a request for information to all vendors of treatment planning systems. This request should describe the process that will be used for the purchase and solicit technical specifications and a budgetary quote for the general system type that the purchaser aims to place in the department. There are several reasons for this. First, it provides the purchaser with enough baseline information to decide early which systems rank highly for satisfying the departmental needs and allows for a short listing of preferred manufacturers who will be contacted for further detailed information. The information received will also be used in developing a detailed tender document. It also provides a rough estimate of the funding level needed for the new system. This will allow the purchaser to down scale the system if it is out of budgetary range or to budget properly for the system in an upcoming budget year.

8.8.3 Vendor demonstrations/presentations/site visits

With the requests for information in hand, it is possible to invite the top ranked three or four vendors to provide more detailed information. This is best done by asking the vendors to bring in a treatment planning system to the purchaser's institution and to let staff of the purchaser's institution have some direct hands-on experience. If this is not possible, then site visits to clinics using the system is the next best alternative. At this stage it is important that the future clinical users of the system, such as dosimetrists or treatment planners, participate in this process. They are able to make the best comments about the user interface and the system's capabilities and limitations. However, other aspects of the system should also be evaluated, especially the aspects that relate to data entry and system commissioning. A great deal of frustration can occur in a system that has a wonderful treatment planning interface but a very poor data entry process. The amount of data required for actual dose calculation commissioning needs to be clearly understood since there is tremendous variation from one vendor to another. Some vendors require that the measured data are sent to the factory for data entry and the vendor then returns the appropriate commissioning data to the user. This is a good process from the perspective that it reduces the amount of time and effort required by the user for commissioning. However, it is a poorer process from the educational perspective since the data entry and manipulation usually provide the user with a clear understanding of the capabilities and limitations over the usual range of treatment conditions. Furthermore, it

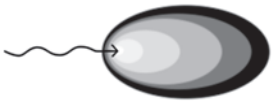


Table 8.7
Factors to Consider at the Early Phase of the Purchase Process for an RTPS

ISSUES	QUESTIONS/COMMENTS
Status of existing treatment planning system	Can it be upgraded? Hardware? Software?
Projected number of cases to be planned over the next 2 to 5 years	Include types and complexity, e.g., number of 2-D plans without image data, number of 3-D plans with image data, complex plans, etc.
Special techniques	Stereotactic radiosurgery? Mantle? TBI? Electron arcs? HDR brachytherapy? Other?
Number of work stations required	Depends on caseload, average time per case, research and development time, number of special procedures, number of treatment planners, whether system is also used for monitor unit calculations.
Level of sophistication of treatment planning	3-D conformal radiation therapy? Participation in clinical trials? Networking capabilities?
Imaging availability	CT? MR? SPECT? PET? Ultrasound?
CT-simulation availability	Network considerations.
Multileaf collimation available now or in the future	Transfer of MLC data to therapy machines?
3-D conformal radiation therapy capabilities on the treatment machines	Can the treatment planning system handle the therapy machine capabilities?
The need for special brachytherapy considerations	e.g., Ultrasound guided brachytherapy. Can ultrasound images be entered into the treatment planning system?
Intensity modulated radiation therapy capabilities	Available now or in the near future?
Treatment trends over the next 3 to 5 years	Will there be more need for IMRT, electrons, or increased brachytherapy
Case load and throughput	Will treatment planning become the bottleneck?

places the purchaser at risk if for any reason the vendor offers limited technical support or, worse, goes out of business. The user would then be unable to commission any new treatment beams.

The vendor visits to the purchasing institution also provide an opportunity for a presentation by the vendor on the system's dose algorithms. It needs to be clearly understood from these presentations what algorithm is actually implemented currently and what new or modified algorithms remain to be implemented in the system with corresponding timelines. Usually, the vendors' time lines tend to be overly optimistic. Thus, if particular software requirements are essential for the purchaser's clinical operation but not yet available, then the vendor's projected timelines should be considered judiciously.

With these vendor demonstrations, it is very useful to perform a number of typical treatment plans for common situations encountered in the clinic. These examples often bring to light issues that could become problematic in the transition from present practice. One especially important aspect of this is the time/monitor unit calculation process. Some treatment planning systems may force substantial changes to existing practice.

Another and related aspect is the treatment plan normalization process. It is very important to understand both of these issues since they could have a major impact on existing operational procedures. Certainly, one wants to make educated decisions in advance and not be required to make treatment procedure changes because of a poor understanding of the system's capabilities.

As part of this evaluation process it is also very important to communicate with institutions that are already users of the top-ranked systems of interest. Those who have practical experience can best give direct and personal feedback especially on issues of importance to the purchaser.

8.8.4 Tender process

With the technical specifications in hand from various vendors, the purchaser is in a position to develop a detailed tender document. The rationale for a tendering process has been outlined in chapter 2. Briefly, the tender process provides the user with three benefits:

(1) The user is educated by writing the technical specifications in a tender document.

(2) The user has better chance at obtaining the best price since the vendors recognize that they are being placed in direct competition with other vendors.

(3) The tender response is a legal document that can be used by the user if the vendor does not meet the specifications outlined in the tender document.

A sample of a Table of Contents of a tender document for a treatment planning system is summarized in Appendix 8.I.

8.8.5 Selection criteria

Generally, the user already has developed a set of selection criteria before the tender is submitted to the vendors. Based on the needs assessment, it is useful to make a list of those items that are *"essential," "important but not essential," "useful,"* and *"not needed."* Included in this list should be optional items that are not always part of the standard package. Optional items can be very costly if they are not recognized early before the purchase process is complete. Table 8.8 gives an example of a limited list of items and how they might be ranked by a particular institution.

Note that this table is not comprehensive but is intended to give a sampling of the kind of items that might be considered in ranking treatment planning systems. No system will provide *all* the options the user desires. Furthermore, this is a listing of desired capabilities of a treatment planning system but gives no indication of how well these functions have been coded, how good the user interface is, how easy it is to enter the radiation data, nor how stable the system operates. These are additional factors that the purchaser will have to rank when comparing different systems, using input data from the vendor demonstrations and visits.

8.8.6 Purchase

Once all of the details of the system evaluations have been accumulated from the tender document, from other users of the systems, and from all the staff members participating in the decision-making process, it is still possible to return to the vendor for additional information and for a final negotiation on the purchase price. At this stage it is important to have a very clear understanding of what is included in the quoted price and what components are considered options at an additional price. This is the final opportunity for assessing and indicating the departmental needs. It may be possible to negotiate some of the options, extra peripherals or extra workstations for a multistation system as part of the quoted system price. Attention must also be paid to items such as software or hardware upgrade contracts and costs. Software upgrade contracts are very useful in that all new software upgrades will be provided at the cost of the contract. This makes it easier from a budgeting perspective since an annual fee will be automatically forecast in the budget, rather than having to negotiate with administration annually. Similar arguments can be made for hardware although vendors tend to be somewhat cautious about hardware upgrade contracts since hardware is changing so rapidly. It is understandably very difficult for vendors to define a long-term contract without a clear knowledge of what the specifications or the cost of the hardware are likely to be over a period of 3 to 5 years.

8.9 Acceptance Testing

Acceptance testing of a new device usually is an assessment that the device behaves according to the specifications defined by the manufacturer. If the tendering process is used, then the details of these specifications will already be found in the tender document. It is good practice to define the acceptance testing procedures in advance as part of the tender response. For treatment planning systems, the measurement of performance for all the parameters, especially the dose calculation component of the system, is difficult to perform in a brief time period. This is due to the nature of assessing a treatment planning dose calculation process. The steps include: (1) the measurement of "input" radiation data, (2) the entry of the data into the treatment planning system, (3) the calculation of dose for a series of beam configurations for which measurements have also been performed, and (4) the comparison of the calculations with the measurements. These steps effectively com-

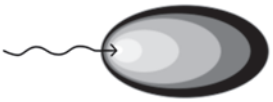


Table 8.8
Sample Selection Criteria and Possible Rankings (Concept adapted from a similar table produced at the Princess Margaret Hospital, Toronto, Canada)

ITEM	ESSENTIAL	IMPORTANT BUT NOT ESSENTIAL	USEFUL	NOT NEEDED
Hardware				
Computer system				
Computer platform		PC		
Operating system	Windows			
Windowing platform	NT			
Network capabilities	*			
Storage devices				
Hard drive	*			
Floppy drive	*			
Zip/Jaz drive		*		
Streamer tape	*			
Optical disk				*
Input/Output				
Patient data				
Digitizer	*			
Film scanner	*			
Laser camera		*		
Plotter (Vector)				*
Printer (Black & white laser)			*	
Printer (Color)	*			
Network	*			
Keyboard	*			
Image transfer				
Floppy				*
Magnetic tape			*	
Cartridge			*	
Network		*		
Optical disk			*	
CT scanner data (specify manufacturer)	*			
MR scanner data (specify manufacturer)	*			
Simulator images (specify manufacturer)		*		
Portal images (specify manufacturer)		*		
User interface				
Mouse	*			
Keyboard	*			
Interface customizable		*		
Photon dose calculations				
Homogeneous calculations				
Table lookup				*
TAR/SAR/DSAR		*		
Convolution/superposition	*			
Monte Carlo			*	
Inhomogeneity corrections				
Ratio TAR (Equiv. path length)				*
Power law				*
Equivalent TAR				
Convolution/superposition	*			
Monte Carlo		*		

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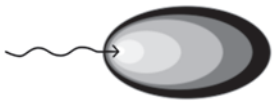

Table 8.8
Continued

ITEM	ESSENTIAL	IMPORTANT BUT NOT ESSENTIAL	USEFUL	NOT NEEDED
Data entry				
From water phantom	*			
Other				
Asymmetric jaw calculations	*			
Dynamic wedge calculations	*			
Electron dose calculations				
Table lookup*				*
Pencil beam (Hogstrom) – 2-D			*	
Pencil beam (Hogstrom) – 3-D	*	* (or)		
Pencil beam (Cunningham/Dutreix)	* (or)	*		
Diffusion equation			*	
Monte Carlo		*		
Data entry				
From water phantom	*			
Brachytherapy				
Calculations				
Inverse square for point source	*			
Sievert integral	*			
Tissue correction factor	*			
Polynomial		*		
Table look up			*	
Dwell time for PDR, HDR	*			
Anisotropy corrections		*		
Data entry				
Orthogonal films	*			
Stereo entry		*		
CT data entry	*			
Ultrasound data entry	*			
Time/MU calculations	*			
Special features				
Anatomy				
Enter target volumes on CT images	*			
Enter target volumes on MR images	*			
Image fusion	*			
Auto external contour	*			
Auto add bolus	*			
Surface rendering	*			
Wire frame rendering		*		
Multiplanar reconstruction	*			
Movie loop		*		
Real time image rotation		*		

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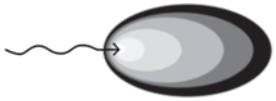

Table 8.8
Continued

ITEM	ESSENTIAL	IMPORTANT BUT NOT ESSENTIAL	USEFUL	NOT NEEDED
Beam features				
Beam's eye view	*			
Room's eye view	*			
Observer's eye view	*			
Digitally reconstructed radiographs	*			
Virtual simulation	*			
Asymmetric jaws	*			
Non coplanar calculations	*			
Compensator/Attenuator calculations	*			
Dose features				
Dose volume histograms	*			
Simultaneous display of alternate plans	*			
Multileaf collimations (MLC)				
Input of field shape configuration	*			
Automated entry from target volume + margin	*			
Display of leaf positions	*			
Manual move of individual leaves	*			
Automated "shape" transfer to machine	*			
Ability to overlay leaves on simulator film		*		
MLC specific calculations	*			
Other				
Security				
Password protection	*			
Basic data entry change protection	*			
Write protection of basic data & files	*			
Documentation				
Program documentation	*			
On-line help		*		
Service support	*			
Source code available		*		
Programmers developers kit		*		
Ancillary programs				
Display of original beam data	*			
Output of all parameters for individual units	*			
Editing of parameters to improve data fits	*			
Direct comparison of calculated vs. measured	*			
Multiple block distances/transmission		*		
Interface with water phantom system	*			
Manipulations of wedge data	*			

prise the commissioning component of the treatment planning system and will take several weeks or months to perform for all the photon and electron energies and all the brachytherapy sources available in the department. It is not fair for the manufacturer to have to wait for the completion of all the commissioning tests before the acceptance document is signed and payment is issued.

A practical set of acceptance tests comprises a series of tests that assess the basic hardware and software functionality. The user should have, as part of the pre-purchase evaluation process, requested the vendor to demonstrate the system capabilities and accuracy of calculation. For dose calculations, this could be demonstrated by asking the vendor for the results of benchmark data. The data from AAPM Report Number 55 [86] could be used for photons and, for electrons, the data of the Electron Collaborative Work Group (ECWG) could be used [111]. Thus, with the knowledge that the system can meet the standards of these benchmark data, the acceptance testing process will consist of convincing the purchaser that these standards can still be met for the system that has just been installed via a series of spot checks.

A practical approach to acceptance testing is first to test the system's hardware including the central processing (CPU) unit(s) as well as the peripherals. Commercial diagnostic programs can test the basic CPU as well as some system components such as disk drives. Running some simple input/output procedures can test input/output devices. Simply entering a known contour shape and assessing its accuracy on a printer or plotter will provide some basic assessment of the proper functioning of the system. AAPM TG53 has suggested a more comprehensive approach and some examples taken from this report are summarized in Table 8.9.

All the results from the acceptance testing should be carefully recorded along with a clear description of the procedure used to perform the tests. Since the user can only test basic functionality but cannot conduct a thorough beam commissioning in reasonable time, the user should sign the acceptance document indicating that basic functionality testing is accepted but the final acceptance testing will be completed as part of the commissioning process. While the legal/financial aspects of this are open to some procedural ambiguity, at least there is an indication to the vendor that more detailed testing remains to be performed in a longer time frame.

8.10 Commissioning

Commissioning involves getting the system ready for clinical use. This means entering the appropriate basic data, including radiation data, machine data, imaging-related data so that the system is capable of representing the beam geometries and the dose that will be delivered to the patient. The following summarizes the various components of commissioning a radiation therapy planning system.

8.10.1 Non dose-related components

Treatment planning involves developing an optimized beam arrangement: (1) to cover the target volume and to avoid critical tissues, (2) to determine an accurate dose distribution both in the target and critical tissues, (3) to evaluate the dose distribution using tools such as DVHs to aid in the determination of an optimized treatment plan, and (4) to develop information, such as DRRs, for assessing the actual implementation of the treatment plan on the therapy unit. This section will address issues related to the non dose-related components of the treatment planning system as well as describe a test phantom that can aid this commissioning process.

We will describe an approach analogous to AAPM TG53 [46] in evaluating the nondosimetric components. This approach involves the usual sequential steps in the treatment planning process.

Anatomical Description

Conventionally, the patient's anatomy was described by one or more external patient contours and possibly some contours of internal structures. Today, we are more likely to derive detailed 3-D patient anatomical information including both external contours and internal structures from multislice CT or MR scanning. For cancer of the prostate patients treated with brachytherapy, prostate anatomical data can also be derived from transrectal ultrasound imaging. Since the CT, MR, or ultrasound data are used for tumor and normal tissue localization, it is crucial that these data accurately represent the patient and that the optimized beam geometries are properly localized on this information. Errors in beam geometry locations with respect to tumor or normal tissues could result in geographic misses or normal tissue complications.

Table 8.10 gives a summary of various issues that need to be addressed in commissioning the image procedures.

Once the image data have been entered into the system, the anatomical structures need to be carefully assessed for geometric accuracy and shape. If contours are entered via a digitizer, then their accuracy can be assessed by entering known shapes, printing them out, and checking for a direct correlation between input and output. In the modern 3-D systems, however, the anatomical representation of the patient can be much more complex, therefore, requiring more comprehensive test procedures. A patient can be represented by various

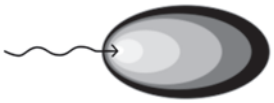

Table 8.9
Examples of Acceptance Test Features [Adapted with permission from reference [46].]

ISSUE	SAMPLE TESTS
CT input	Create an anatomical description based on a standard set of CT scans provided by the vendor, in the format, which will be employed by the user.
Anatomical description	Create a patient model based on the standard CT data discussed above. Contour the external surface, internal anatomy, etc., Create 3-D objects and display.
Beam description	Verify that all beam technique functions work, using a standard beam description provided by the vendor.
Photon beam dose calculations	Perform dose calculations for a standard photon beam data set. Tests should include various open fields, different SSDs, blocked fields, MLC-shaped fields, inhomogeneity test cases, multi-beam plans, asymmetric jaw fields, wedged fields, and others.
Electron beam dose calculations	Perform dose calculations for a standard electron beam data set. Tests should include various open fields, different SSDs, blocked fields, inhomogeneity test cases, surface irregularities, and others.
Brachytherapy dose calculations	Perform dose calculations for single sources of each type, as well as several multi-source implant calculations, e.g., standard gynecological insertions, two plane implants, seed implants, and others.
Dose display, dose volume histograms	Display dose calculations results. Use a standard dose distribution provided by the vendor to verify that the DVH code works as described. User-created dose distributions may also be used for additional tests.
Hardcopy output	Print-out all hardcopy documentation for a given series of plans and confirm that all the textual and graphical information is output correctly.

objects including points, contours, slices, 3-D structures, 3-D surface descriptions, and multiple data sets of self-consistent volumetric descriptions [46]. The latter might well require image registration techniques allowing the translation of a volume described in one data set to a volume in another data set (e.g., from MR to CT images). Table 8.11 describes anatomical structure considerations for 3-D treatment planning systems.

The actual verification of the issues listed in Tables 8.10 and 8.11 is not trivial and can be aided by the use of specialized phantoms. Craig et al. [27] have described such a phantom. Because of the importance of assessing non dose-related QA issues, its design will be described here to provide a guide to those embarking on new 3-D treatment planning systems. It is expected that this design will be enhanced or other analogous phantoms will be produced to aid the testing and commissioning of modern treatment planning systems.

The phantom design is shown schematically in Figure 8.18A. It consists of two components: (1) a *rotatable component* to assess the display of the radiation beam graphics and CT data set manipulations, and (2) a *body component* to assess the treatment of anatomical volumes and the conversion of CT numbers to relative electron densities. Figures 8.18B and 8.18C show pictures of the rotatable and body components, respectively. The rotatable component is constructed of different materials with divergent edges to represent square beam edges incident on a patient at a standard 100 cm source-axis distance (SAD). This component is rotatable so that it can represent both couch and gantry rotations. The body component is made of a 20 cm by 30 cm Lucite oval with an 8 cm diameter hollow cylin-

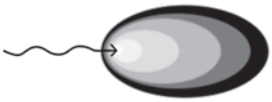

Table 8.10
Image Input Considerations [Adapted with permission from reference [46].]

IMAGE	TESTS	RATIONALE
Image geometry	Document and verify parameters used to determine geometric description of each image (e.g., number of pixels, pixel size, slice thickness).	Vendor and scanner-specific file formats and conventions can cause specific geometrical errors when converted for RTP system.
Geometric location and orientation of the scan	Document and verify parameters used to determine geometric locations of each image, particularly left-right and head-foot orientations.	Vendor and scanner-specific file formats and conventions can cause specific geometrical errors when converted for RTP system.
Text information	Verify that all text information is correctly transferred.	Incorrect name or scan sequence identification could cause misuse or misrepresentation of the scans.
Imaging data	Verify accuracy of grayscale values, particularly conversion of CT numbers to electron density.	Wrong grayscale data may cause incorrect identification of anatomy or incorrect density corrections.
Image unwarping (removing distortions)	Test all features, including documentation tools, which assure that the original and modified images are correctly identified within the system.	Methodologies, which modify imaging information, may leave incorrect data in place.

der at its center into which cylinders containing different shapes can be inserted. At the superior end of the body component is a 10 cm diameter cylinder containing four 2.5 cm diameter rods of materials with different known electron densities. The rotatable component of the phantom contains, in its base, a fiducial marker system consisting of three wires forming a "Z" pattern, which allows for the accurate registration of the phantom's coordinate system. The procedure for assessing a treatment planning system consists of: (1) setting the desired rotations on the rotatable component, (2) CT scanning the phantom, (3) transferring the image data set to the treatment planning system, (4) analyzing the beam geometry display and evaluating the anatomy display/data with known values for the phantom (e.g., geometry, volumes, expanded volumes, electron densities). These authors used this phantom to assess three different 3-D treatment planning systems and one CT simulator since the virtual simulation capabilities on CT simulators are very similar to those on treatment planning systems. Figure 8.19 shows an image through the phantom, which has rotations equivalent to a gantry angle of 30º and a couch angle of 60º. The beam geometry is for a 5×5 cm^2.

The use of this phantom discovered some specific concerns related to contours generated from multiplanar CT image reconstructions, contour expansion algorithms, volume determinations, and CT number to electron density conversions. The latter related more to user data entry whereas the former issues related to the commercial software produced by the treatment planning system vendors. Problems found in the software evaluated clearly indicate the need for QA of the nondosimetric components of treatment planning systems.

An analogous but more specialized version of a QA phantom was described by Paliwal et al. [97]. Their phantom was designed specifically for the QA of cancer of the prostate patients entered into a 3-D RTOG, dose escalation clinical trial. The need for such assessments is clearly relevant to clinical trials but also has to be considered for non-trial patients as well.

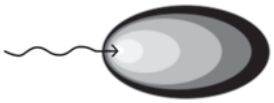

Table 8.11
Anatomical Structure Considerations [Adapted with permission from reference [46].]

ISSUE	TESTS	RATIONALE
Structure attributes	Verify type (e.g., external surface, internal structure, inhomogeneity) and capabilities that are dependent on that type.	Incorrect attributes may cause incorrect usage of the structure.
Relative electron density definition	Verify correct definition of relative electron density.	Relative electron densities used in dose calculations depend on the method of definition.
Display characteristics	Check color, type of rendering, and type of contours to be drawn when displaying the structure.	Display errors can cause planning errors due to misinterpretations.
Auto-segmentation parameters	Check parameters for autocontouring and other types of autostructure definition for each structure.	Incorrect parameters can lead to incorrect structure definition.
Structure created from contours	Address issues such as: • Can non-axial contours be used? • Is the number of contour points limited? • What is the impact of sharp corners in contours? • What happens with missing contours? • Is regular spacing required between contours? • Does the algorithm handle bifurcated structures?	Errors in functionality, use, or interpretation could lead to systematic errors in treatment planning for a large number of patients.
Structure derived by expansion or contraction from another structure	Address issues such as: • What are the limits of the expansion algorithm? • 2-D vs. 3-D expansion. If 3-D, verification must be done in 3-D. If 2-D, 3-D implications must be understood. • Verify algorithm with complex surfaces (e.g., sharp point, square corners, convexities, etc.)	Planning target volumes (PTVs) are often defined by expansion from the clinical target volume (CTV). Errors in the expansion could cause errors in target definition and the corresponding optimized treatment plan.

Continued

8.10.2 External beam photon dose calculations

The commissioning of a photon beam for dose calculation purposes begins with an entry of machine-related beam parameters for each photon beam to be commissioned. Many of these parameters are summarized in Table 8.12.

The next step of commissioning is the entry of the basic radiation data that will be used by the dose calculation algorithms. A large component of these data are generated by measurements in a 3-D water phantom system [118] (see chapter 19) and are entered into the treatment planning computer through a network connection or via some magnetic media. Because the software of these systems can come in various versions, it is important to ensure compatibility and that the data have been transferred accurately.

Central ray data are required by all systems and can be entered in a variety of forms dependent on the requirements of the treatment planning system including tissue-air ratios (TARs), tissue-phantom ratios (TPRs), tissue-maximum ratios (TMRs), or percentage depth doses (PDDs). All systems also require a number of crossbeam profiles, always for open square fields but also for shielding blocks, MLCs, and wedges either physical or dynamic. Of course, dynamic wedge data are more difficult to obtain using an automated 3-D water phantom system. For this, integrated measurements will have to be obtained using point measure-

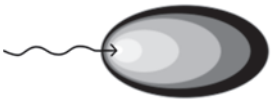

Table 8.11
Continued

ISSUE	TESTS	RATIONALE
Structure derived from non-axial contours	• Tests should be similar to tests for creation of structures from axial contours but should be performed separately for all contour orientations. • Verify bookkeeping for source of structure definition.	Various difficulties can arise dependent on the underlying dimensionality of the data structures and design of the code.
"Capping" (How end of structure is based on contours)	• Verify methods of capping and evaluate 3-D implications. • Document default capping for various structures. • Establish clinical protocols for each 3-D anatomical structure. • Ensure sufficient coverage by imaging procedure to avoid extrapolation problems.	Capping can affect issues such as dose calculation results, target volume shapes, BEV display, DRR generation, and effects of lung densities on dose calculations.
Structure definition	• Verify basic surface generation functionality. • Run test cases for which the exact formulation of surface mesh has been calculated by hand. • Verify surface generation functionality for extreme cases (e.g., sharply pointed contours, unclosed contours.) Tests will depend on the algorithm.	These tests should convince the user that the algorithm generally works well.

ments with an ionization chamber or diode in a water phantom, using a linear detector array, or using appropriately corrected optical density measurements from a film densitometer.

Various authors [13,45,46,110,125,126] have defined the types of tests that should be performed to assess the quality of the dose calculation algorithms. Table 8.13 summarizes the relevant parameters and variables that should be considered in the testing process. In each case it is appropriate to do the test for a "common" situation and for the practical limiting conditions. Thus if an accelerator has normal field size limits of 5×5 cm^2 to 40×40 cm^2, then it would be appropriate to do tests for 10×10 cm^2, 5×5 cm^2, and 40×40 cm^2. Table 8.13 contains both the suggested parameter for evaluation and the possible range that might be considered. Clearly, these ranges need to be adapted to each specific treatment machine, each treatment planning system, as well as the specific clinical applications in a given department.

For inhomogeneity corrections, some measurements can be performed in slab phantom geometries although it may also be practical and expedient to use the benchmark data of various authors [32,66,73,74,86, 103,112,114]. Clearly, the benchmark data are good for assessing trends but will not necessarily agree at the 2–3% level since these data were measured on different treatment machines.

Especially important in the context of lung inhomogeneities is the assessment of the effects of electron transport in high energy (>10 MV) photon beams both for small fields and for large fields near the beam edges. A major weakness for many conventional calculation algorithms is the ability to adequately model the influence of the long range of secondary electrons set into motion by the high energy photons [73,74,85,140].

Some sample commissioning test data for photon dose calculations are shown in Figures 8.II.1 through 8.II.9 in Appendix 8.II. Many of these tests were based on the input and measured data provided by AAPM Report 55 [86].

8.10.3 Electron dose calculations

The processes by which electrons interact differ substantially from that of photons as manifested by the rapid dose fall-off for electron beams. Thus, the calculation algorithms are based on different models of radiation interactions. However, the process for electron

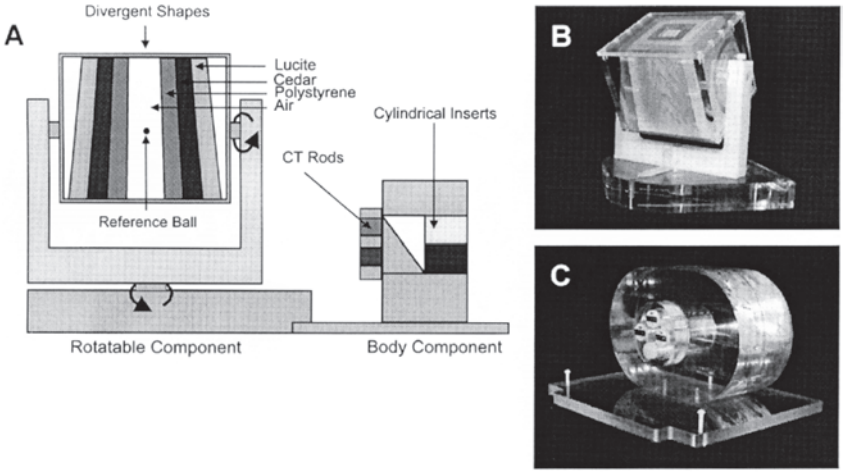

Figure 8.18
A. Schematic of QA phantom showing the rotatable and the body components. B. Picture of rotatable component. C. Picture of body component. [Reprinted from International Journal of Radiation: Oncology-Biology-and Physics. Vol. 44, T. D. Craig, D. Brochu, and J. Van Dyk, "A Quality Assurance Phantom for Three-Dimensional Radiation Treatment Planning," pp. 955–966, copyright 1999, with permission from Elsevier Science.]

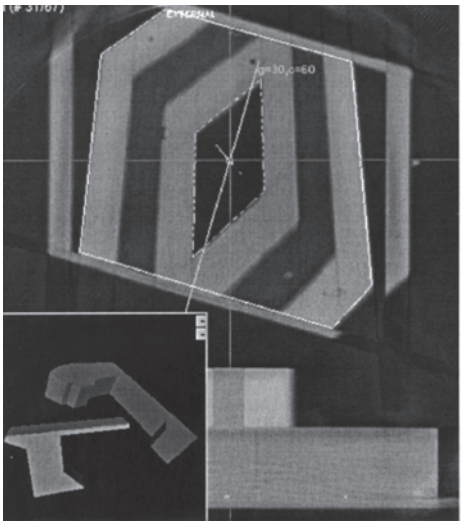

Figure 8.19
CT image through rotatable component of the phantom. The phantom is rotated such that it represents a gantry rotation of 30° and a couch rotation of 60°. The inset shows the machine orientation on the treatment planning system generating the dashed line on the cross sectional image representing a 5 x 5 cm^2. The matching of the dashed line with the edges of the different phantom materials indicates that the treatment planning system is capable of handling this geometry. [Reprinted from International Journal of Radiation: Oncology-Biology-and Physics. Vol. 44, T. D. Craig, D. Brochu, and J. Van Dyk, "A Quality Assurance Phantom for Three-Dimensional Radiation Treatment Planning," pp. 955–966, copyright 1999, with permission from Elsevier Science.]

beam commissioning is similar, in principle, to that of photon beams with the variation that different depths and field sizes will be chosen for the in-water measurements and different geometries will be used for the inhomogeneity corrections. The experimental aspects of electron dosimetry are somewhat more challenging compared to photons, primarily due to the rapid dose gradient in both the depth and lateral directions. Thus, often more than one dosimetric procedure is required to obtain data measured in two or three dimensions. The basic data are usually central axis PDD and beam profiles chosen at depths near the surface, near the depth of maximum dose, and several in the dose fall-off region. Additional consideration needs to be given to the bremsstrahlung tail both along the central axis as well as crossbeam profiles at larger depths. Special consideration also needs to be given to the depth dose variation with small field sizes since this behavior can result in rapid changes with dose while making relatively small changes in field size. An important consideration is the prediction of output for irregularly shaped fields as produced by different field cutouts. A recent two-source model has been developed by Chen et al. [21], which is capable of accounting for output factors for a wide range of energies, distances, and field sizes. This alleviates the need for multiple measurements of output factors for individual field shapes although the model remains to be implemented as part of a commercial treatment planning system.

For inhomogeneity corrections, single beam tests are adequate since most electron beam treatments are

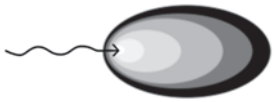

Table 8.12
Basic Beam Parameters [Adapted with permission from reference [46]

DESCRIPTOR	COMPONENTS
Beam description	Machine Modality Energy
Beam geometry	Isocenter location and table position Gantry angle Table angle Collimator angle
Field definition	Source-collimator distance Source-tray distance Source-MLC distance Collimator settings (symmetric or asymmetric) Aperture definition, block shape, MLC settings Electron applicators Skin collimation
Wedges	Name Type (physical, dynamic, auto) Angle Field size limitations Orientations Accessory limitations (blocks, MLC, etc.)
Beam modifiers	Photon compensators Photon and/or electron bolus Intensity modulation (various types)
Normalization	Beam weight or dose at beam normalization point Plan normalization Isodoses in absolute dose

used in a single beam mode other than when they are used as adjacent beams. Again, the use of previously published benchmark data will greatly facilitate the commissioning process [18,36,37,79,111].

Some sample commissioning test data for electron dose calculations are shown in Figures 8.II.10 through 8.II.13 in Appendix 8.II. These tests were based on the input and measured data provided by the ECWG report [111].

8.10.4 Brachytherapy

Commissioning of brachytherapy calculations is approached using similar principles as used for external beam, although in this case it is much more difficult to perform measurements for comparison with calculations. Dose gradients are more severe compared to both external photon and electron dosimetry. Furthermore, these gradients vary rapidly in three dimensions. To date, there is no simple dosimetry system that can easily handle these rapid dose variations. As a result, the user is much more reliant on previously published data, which was either determined through sophisticated analytical or Monte Carlo calculations or by very precise measurements under well-controlled conditions. As AAPM Task Group 53 [46] indicates, the commissioning of the brachytherapy component of a treatment planning system is often more straightforward compared to external beam calculations for a number of reasons:

- Standard sources are used which have general characteristics.
- Most dosimetric data are derived from the literature rather than individual measurements.
- Calculation algorithms are relatively simple.
- Some treatment-related complexities, such as tissue inhomogeneities and shields within applicators, tend to be ignored. While this makes the commissioning and calculation process easier, it clearly results in inaccurate predictions of dose under these circumstances. More research in this area is still required.

The commissioning process consists of entering the right source information and performing a series of checks to ensure that the resultant calculations agree with published benchmark data. Relevant benchmark data can be found in the NCI funded Interstitial Collaborative Work Group report [5], AAPM Task Group 43 report on brachytherapy sources [91], AAPM Task Group 56 report on the AAPM Brachytherapy Code of Practice [93], and in various other reports [43,128,133-135].

AAPM Task Group 53 [46] divides the brachytherapy commissioning process into six components: (1) source entry methods, (2) source library contents, (3) source strength and decay, (4) single source dose calculation tests, (5) multiple source calculation tests, and (6) miscellaneous tests.

Source Entry Methods

- *Orthogonal films* can be tested by generating sample source distributions, and projecting them onto two orthogonal films (simulated), the data entry capabilities can be tested. By purposely misidentifying sources, or entering an incorrect

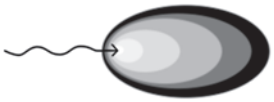

Table 8.13
Initial Photon Dose Calculation Tests Including the Variables to Consider and the Possible Range of Parameters

TEST	RANGE
Point doses	
TAR, TPR, PDD, PSF: Square fields	5×5, 10×10, Max. $\times$ Max.
TAR, TPR, PDD, PSF: Rectangular fields	5×10, 5×20, 5×30, 30×5
TAR, TPR, PDD, PSF: Irregularly shaped fields	Defined by Cerrobend or MLC
Inverse square law	80, 100, 120
Attenuation factors	
Wedges	Wedge factor, 5×5, 10×10, 5×20
Compensators	Compensator factors for clinically relevant geometries
Tray factors	Clinically relevant field range
Output factors	For square and rectangular fields
Dose distributions or dose profiles	
Homogeneous water phantom	
Square fields, normal incidence: Profiles	5×5, 10×10, Max. $\times$ Max. Depths=$d_{max'}$, 5, 10
Rectangular fields, normal incidence	5×10, 5×20, 5×30, 30×5. Depths=$d_{max'}$, 5, 10
Effect of SAD/SSD	10×10/SSD=80, 100, 120
Wedged fields (Physical & Dynamic)	Square/rectangular fields. Sizes depend on wedges.
Contour correction	10×10 at 40° on flat phantom
Bars, blocks, or MLC	10×20 field with 10×2 block
Irregular "L"-shaped field	Profiles through central ray and open/off-axis portion
Multiple beams	Parallel pair, 3-field, 4-field
Arcs/Rotations	360° rotation, 2 adjacent 180° arcs
Off axis calculations	Profiles at 10 cm off axis for 15×30 at d_{max}, 5, 10
With wedges	Relevant field size at $d_{max'}$, 5, 10
Collimator/couch rotations	Between 30–60°
Asymmetric jaws	(0, 10) $\times$ 20 at $d_{max'}$, 5, 10; (–5, 10) $\times$ 20 at $d_{max'}$, 5, 10
Inhomogeneous phantoms	
Square fields/slab geometry	5×5, 10×10, 5×20
Various geometries	Published benchmark data/evaluate trends
Anthropomorphic phantom	Composite of typical treatment for lung/pelvis/head, With wedge, compensator, shield, MLC, asymmetric jaws, or tray
Machine settings	
Square fields	5×5, 10×10, Max. $\times$ Max.
Rectangular fields	5×10, 5×20, 5×30, 30×5
Irregular fields	As per irregular fields above
Anthropomorphic phantom	As per anthropomorphic tests indicated above

source location or magnification, the system functionality and integrity can be tested. *Stereo shift* films can be tested the same way as orthogonal films.
- *Keyboard entry* can simply be tested by reviewing the data entered.
- *CT-based* source localization can be tested by obtaining CT scans of a phantom implanted with dummy seeds in well-defined locations. This will assess artifacts in the images due to the high density seeds and will also provide a check of the accuracy of the seed localization techniques.
- Catheter trajectory geometry can be tested by entering known geometries of catheters and observing the details of the brachytherapy software in reproducing the known geometry. If source locations are determined by the software, then this also should be tested using known configurations.
- *Stereotactic implants* are performed by some institutions and require highly precise tests of the CT imaging process and the accuracy by which the catheter can be positioned usually within the brain. This can be done by performing a total stereotactic process on a phantom with special localizers that can be seen on CT. The test implant can then be assessed for accuracy of the placement of the radioactive sources with respect to the markers in the phantom.

Source Library

- Each property of each source should be verified at the time of commissioning and also on subsequent QA tests.
- Distributions should be calculated with each source to ensure consistency and accuracy.
- Source strength quantities and units should be assessed for accuracy and consistency with the source vendor's specifications.

Source Strength and Decay

- For each source, check specification of source strength, e.g., reference air kerma rate, air kerma strength, apparent activity (mCi), apparent activity (MBq), equivalent mass of radium (mgm Ra).
- Ensure that all source strength conversions from the manufacturer's specifications to the treatment planning system are correct.
- Check the specifications associated with the source description, e.g., decay constant, half life, average life, dose constants, and other relevant constants.
- The source decay calculation should be checked for accuracy.
- The absolute dose and/or dose rate should be calculated at a series of reference point and checked for accuracy.

Single Source Dose Calculations

- Each dose calculation algorithm should be checked against known published data, manually calculated data, or an independent and well-established computer algorithm. This check should be performed for a number of points in 3-D space.
- Line source calculations should be checked for accuracy of anisotropy using well-tested reference/published data.
- Corrections for tissue attenuation and scatter should be checked for known geometries at a series of reference points in 3-D.

Multiple Source Dose Calculations and Optimization Algorithms

- The doses from multiple sources should be added and compared to expected values. Tests should be performed for all source types and typical/simplified configurations such as three caesium-137 tubes for gynecological applications, iridium-192 strings, iodine-125 volume implants.
- For high dose rate brachytherapy, optimization algorithms should be tested for the robustness of the optimization process. Furthermore, the user needs to have a clear understanding of the appropriateness of the optimization features.

Global System Tests

- Typical clinical examples can be tested for overall integrity and accuracy. Examples here could include: a typical Fletcher-Suit intracavitary treatment, an iridium-192 breast boost, an iodine-125 volume implant, and if mixed sources are ever used, the combination of different sources for a typical case should also be tested.

Other Tests

These could include tests for specific procedures in a given institution. For example:

- Iodine-125 eye plaque treatments for ocular melanomas. Tests include seed localization on the eye, inclusion of backscatter of the plaque and other factors affecting the dose distribution.
- The use of a neutron emitter such as californium-252 will require a unique approach that accounts for the increased radiobiological effect of the emitted neutrons.

8.10.5 Data transfer

There are at least three major sources of input data. The first includes measured data from a 3-D water phantom system. The second includes image data usually from a CT scanner but also from MR or ultrasound or, less frequently, from SPECT or PET. The third includes data from keyboard and mouse and involves details of the plan input such as field size, gantry angle, collimator rotation, beam energy, brachytherapy source information, etc. The latter is standard practice for any treatment planning system. The first two usually require network connections or magnetic media such as discs (floppies, Zip, Jaz, or other disk cartridges) or tape and must have file formats that are compatible with the treatment planning system. As part of the commissioning process, it is important to check for hardware compatibility, especially when the data sources are from different manufacturers. For image data DICOM version 3 or DICOM RT (for radiation therapy) formats have been adopted by the ACR and NEMA in the United States. While file compatibility should be defined in the specifications, compatibility of file formats can only be assessed by going through a file transfer process. It is important that the data from the water phantom system and the patient image sources are checked for accuracy and that they have been properly transferred into the radiation therapy planning system. This can be simply done by performing analysis of the input data for well-known configurations, i.e., are the geometries correct with no magnification errors, or no spatial coordinate errors. Do the dose data make sense? Have the CT numbers been properly transferred to electron densities and to scattering powers? Errors in image data transfer could show up as one of the following [110]:

- Incorrect pixel values, e.g., areas of black in white or gray background or vice versa. These types of errors are usually easy to spot.
- Missing lines or sections of lines within the image.
- Incorrect patient information, e.g., scan size, matrix size. Such errors can cause serious errors later in the planning process.
- In terms of image shape, problems can occur when a change in pixel matrix size occurs between the scanner and the planning system. This could show as a magnification error.

The conversion to electron density and scattering power is often performed with a user-defined look-up table. The data within the table are then used with a linear interpolation to determine the relative electron density for any CT number. Usually such tables are generated using a water equivalent circular phantom with a number of different materials inserted into the phantom of known electron densities representative of normal tissues within the patient, especially lung and bone equivalent materials. Various papers have described the CT number to electron density conversion [9,11,47,89,99]. The electron densities determined with such a phantom should agree to within 4% of the known values [126]. In-house phantoms can be used for this although commercial phantoms (e.g., Radiation Measurements Inc. (RMI) Model 465) are also available. The RMI phantom is a 33 cm diameter circular slab of solid water with 20 interchangeable inserts of materials of known electron density [26]. Twenty inserts are really more than necessary. The phantom described by Craig et al. [27] provides four interchangeable inserts and is entirely adequate for providing the data for a bilinear conversion curve. If more points are really felt to be necessary, then some or all of the four rods can be interchanged and a second calibration scan taken.

An additional consideration for data transfer relates to institutions that participate in clinical trials. Some clinical trials groups such as the RTOG request that the QA data be submitted through the Internet. The data requested include CT image data, target volumes and normal tissues volumes as outlined on the images, dose distributions and related information, DVHs, DRRs, digitized simulator films, and digital portal images. These data need to be transferred in a well-defined format according to the clinical study requirements. The RTOG website (http://rtog3dqa.wustl.edu/) has the detailed requirements for the formats of this information, specifically for 3-D conformal therapy studies. Prior to participating in such multi-institutional trials, the participating clinics need to qualify by submitting some test cases to validate their capabilities of transferring the proper data in an appropriate format.

8.10.6 Other

As part of the commissioning process, it is important that the quality of input data from the imaging sources is appropriately evaluated. Chapter 7 discusses the use of imaging for radiation therapy planning. Ten Haken et al. [116] have given a good review of issues related to evaluating the quality of the image input data to the treatment planning computer.

In addition, special and individualized techniques require their own special commissioning. Examples of special techniques that require additional work-up and commissioning are illustrated in Table 8.14. Some of these are described in other chapters of this book.

8.11 Quality Assurance

In general, quality assurance involves three steps: (1) the measurement of performance, (2) the comparison of the performance with a given standard, and (3) the

actions necessary to maintain or regain the standard. For treatment planning systems, the commissioning process provides the standard by which the system must be maintained. Thus, once the treatment planning system is commissioned for clinical use, on-going QA must be performed to ensure the integrity of the data files and the reproducibility of the calculations. The number repeatability tests chosen must be reasonable such that there are no major human resource costs and so that the tests will actually be performed. It is too easy to request too many tests for evaluating every detailed software routine; however, an impractical number of tests increases the likelihood that these tests will not be performed at all. Issues related to QA of treatment planning systems have been described in a number of reports [13,25,35,45,46,62,81,86,110,117,125,126, 131].

8.11.1 Training

It cannot be overemphasized that user training is probably the most important QA aspect of the use of treatment planning computers. Well-trained and inquisitive users can spot inaccuracies or errors in individual treatment plans. Such errors are often related to the user rather than changes in the system's files or in the system's operations. Innocuous errors can be generated as a result of a user's misunderstanding of the system's algorithms or the system's input requirements. Thus, while a system could be functioning perfectly, an error in user input can generate major errors in output. Training is part of the system commissioning process before being placed into clinical service, but it is also a very important part of on-going QA. The training should include the following [125]:

Manufacturer's Training Course

Most commercial treatment planning vendors provide an applications training course with the purchase contract. These courses should include: (a) a review of the system architecture both in terms of hardware and software; (b) a description of the algorithms used and the program capabilities and limitations; (c) hands-on use of the system to gain experience with radiation and patient-related data entry and the running of the programs; and (d) hardware maintenance for simple local hardware servicing.

Staff Training

All staff performing clinical treatment planning must be appropriately trained prior to clinical usage. Furthermore, on-going training is required to ensure that changes are not creeping into the planning process. Training considerations include the following: (a) a special time set aside to operate the system and use the programs; (b) a set of predefined treatment planning projects, which give the staff member an initial understanding of the use of the programs. These projects should move from simple, single beam calculations to multiple beams, to the use of ancillary devices such as blocks and wedges, to actual clinical examples; (c) on-the-job training of clinical cases with all calculations being checked closely by a qualified user for a specified period of time (e.g., 3 months). This could be done on a technique basis such that the actual length of training to gain experience with all standard techniques in the institution could well last one or two years; (d) the development of a document outlining limitations of calculation algorithms including sample comparisons to measurements; (e) a document outlining special procedures developed in the clinic.

As the technology of radiation oncology evolves, new procedures will be implemented into clinical practice. Further training will be required for new techniques that are developed. It is also useful to provide periodic in-service review sessions to ensure that shortcuts and efficiency measures that often evolve in treatment procedures are not at a detriment to the accuracy of the resulting treatment plan.

8.11.2 Reproducibility tests

The following outlines the factors that should be considered in assessing system reproducibility with time. The tests and the frequencies are only provided as a consideration and cannot be defined in unique and absolute terms. Each department has a different type of computer system and different levels of staff expertise,

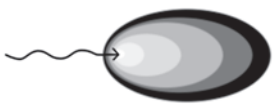

Table 8.14
Techniques Requiring Special Work-up

Beam junctions
Electron Arcs
Stereotactic radiation therapy (chapter 16)
Small field eye techniques
Automated optimization routines (chapter 15)
Intensity modulated radiation therapy (chapters 12 and 15)
Total body irradiation (chapter 17, Part A)
Total skin irradiation (chapter 17, Part B)
Intraoperative radiation therapy (chapter 17, Part C)
High dose rate brachytherapy (chapter 18)
Intraoperative high dose rate brachytherapy (chapter 17, Part C)
Stereotactic brachytherapy

in addition to different organizational structures. In some institutions, dosimetrists perform most of the treatment planning. In others, this is performed by radiation therapists. Physicists have a varying degree of involvement with a very major involvement in routine treatment planning in some places and only a leadership role in others. Thus, QA tests and their frequency need to be developed on the basis of institutional requirements. Table 8.15 provides a summary of the kinds of things to consider and the possible frequency by which these things could be done [110,125].

The following expands on some of the points listed in Table 8.15 with the numbers referring to the test number listed in the table.

1(a). Most modern systems check the memory automatically when the system is turned on. However, some systems are never turned off. In such cases, it is useful to do a separate memory check at a monthly interval.

1(b) and 1(c). Digitizer and plotters can be checked by entering a known contour through the digitizer and plotting it out. A direct comparison will indicate the functionality. Each patient should also be checked for accuracy of contour since some systems require a digitizer scaling entry every time a new patient is planned.

1(d). Since the video display unit is used for generating beams on targets and normal tissues, its accuracy should be checked at least quarterly. A standard color or gray scale representation should be checked for consistency.

2. The assessment of CT data transfer should be performed quarterly or whenever any software or hardware is changed on the CT scanner or in the treatment planning system. Scanning a test phantom with known geometry and various materials of known electron density provides a suitable test. Such phantoms have been described in this chapter (section 8.10.1) and elsewhere [26,27].

3. The external beam tests need to be performed for both photons and electrons.

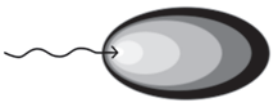

Table 8.15
A Sampling of Possible Quality Control Checks and Corresponding Frequencies

TEST	EACH OCCASION	WEEKLY	MONTHLY	QUARTERLY	SEMI-ANNUALLY
1. Hardware					
(a) Memory	System turn on		*		
(b) Digitizer		*			
(c) Plotter		*			
(d) Video display				*	
2. CT (or other) scan transfer	*			*	
3. External beam software (done for photons and electrons)					
(a) Data set					*
(b) Reference field size plan					*
(c) Non-reference field size plan					*
(d) Variation in beam parameters					*
(e) Interactive beam options					*
(f) Monitor units	Each patient				*
4. Brachytherapy					
(a) Data set					*
(b) Source reconstruction					*
(c) Dose reconstruction					*
(d) Interactive options					*
(e) Independent check	Each patient				

3(a). The testing of consistency of the input data set can be done by performing a check sum of the data files. Failing a check sum process, a hard copy of the data should be assessed for consistency. Any changes in the data files will need to be reviewed by further investigation.

3(b). Reference field size plan refers to calculating a plan for a beam perpendicularly incident onto a rectangular homogeneous phantom. Thus, the conditions are similar to the conditions for which the data had been entered.

3(c). Non-reference field size plan refers to using a field size that was not originally entered in the data set. This then checks for the interpolation and calculation of different rectangular fields. Preferably a different field size would be chosen for this calculation each time this check is performed. The results are compared against the original data obtained as part of the commissioning process.

3(d). The following parameters should be assessed on a rotating basis: variation in SSD, oblique incidence, physical wedge, dynamic wedge, collimator rotation, inhomogeneity correction, off axis calculation, shaped fields with blocks or MLCs. Agreement with reference plans should be exact. Discrepancies should be assessed especially if details such as grid spacing have not been maintained constant.

3(e). By using the 3(d) tests as comparators, the following tests can be performed to assess consistency: change in beam position, change in beam weight, change of field size, point dose calculations including hot spots.

3(f). An independent check should be performed of the monitor unit or time calculation for every beam that is to be treated. This check could be done by a manual procedure or by an independent computer program. This independent algorithm should neither use the same database as the treatment planning system nor any of its subroutines.

4(a). Again a check sum assessment can be used. Failing a check sum process, a hard copy of the data should be assessed for consistency. Any changes in the data files will need to be reviewed by further investigation.

4(b). This can be done by using a set of reference films of sources in a phantom to reconstruct the source positions. A test of the entire imaging process can be performed by taking a new set of films of the same phantom.

4(c). These should be done for a single reference seed and a single reference line source for the sources used in the department.

4(d). These can be checked by the removal of a source or by changing the source activity.

4(e). For each patient, it is recommended that a relatively simple independent check be performed using a system of dose calculations such as the Manchester system [65,83], the Paris system [80,102], the Quimby system [48], or others [108]. If the implant follows the distribution rules, then the agreement should be within 10%. If there is a variation from the distribution rules, then an assessment needs to be made as to whether the trend makes sense.

8.11.3 *In vitro*/*in vivo* dosimetry

Various checks can be performed to assess the entire planning process from computer data input to dose delivery. Perhaps the most common and the most controlled method is to use a special purpose anthropomorphic phantom (*in vitro dosimetry*) such as the Rando phantom. This phantom can be processed through the CT scanner, simulation, and entire planning process. It can be loaded with thermoluminescent dosimeters (TLDs) (see chapter 19) and irradiated like a patient. The TLD measurements will give a direct comparison with expected dose accounting for all aspects of the planning and dose calculation process including ancillary devices and contour and tissue inhomogeneity corrections. This process is useful for assessing a new treatment planning system, for assessing major changes in treatment planning software, or for assessing a new treatment technique, e.g., IMRT. The level of accuracy achievable should be better than 3% to 4% since the dose delivered to the patient should be better than 5%. A recent report by Dunscombe et al. [40] gives a good overview of the use of anthropomorphic phantom measurements to evaluate the quality of a treatment planning system. While this process gives a good check in the high dose and low dose regions, differences near the beam edges are difficult to interpret as to whether the calculations are off, the measurements were off, or the beam placement was inaccurate. In vitro dosimetry must be developed in such a manner that differences between measurements and calculations can be readily interpreted.

Another check of the entire treatment planning and dose delivery process is to place dosimeters on or in the patient (*in vivo dosimetry*). There is a similar concern about interpretation of the results if there are differences between measurements and calculations. Radiation oncologists often wish to know the actual dose delivered to critical structures such as the eyes, gonads,

or a fetus. Sometimes these regions are very close to the edge of the radiation beams and, therefore, small changes in beam alignment or patient positioning can result in major changes in measured dose with corresponding ambiguity in the interpretation of the results. These interpretation difficulties should be discussed in advance with the radiation oncologist requesting the measurements to minimize unnecessary work. Better results can be obtained in regions of less rapid dose variation, either on the patient's skin surface or in body cavities such as the mouth, trachea, esophagus, vagina, uterus, or rectum. Diodes and MOS-FET dosimeters can be used as alternatives to TLDs (see chapter 19).

Another form of in vivo assessment of planning accuracy is to use treatment verification imaging (see chapter 13). Generally, this is better for assessing field placement on the patient although electronic portal imaging devices are also used as exit dosimeter systems. A direct comparison of the portal image with a DRR generated by the treatment planning computer will give a good assessment of patient alignment.

8.11.4 Quality assurance administration

Responsible Qualified Medical Physicist

A very important component of any QA program is the organization and administration of the program so that it is implemented and executed according to a well-defined schedule. Furthermore, accurate records of the testing process are essential. If no records are kept, then it is almost equivalent to not carrying out the tests. Proper administration requires that one person, a qualified medical physicist, be responsible for the QA program of a treatment planning system [46]. While this individual does not have to carry out all the tests and their evaluations, he/she must ensure that the tests are being done according to the specified frequency, that proper records are maintained, and that appropriate corrective actions are taken as needed. With increased sophistication of treatment planning computers, a systems manager can be given the responsibility of the hardware and software maintenance. This individual needs to work under the guidance of the responsible physicist.

Communication

An important ingredient of any QA program is communication. This is especially true for treatment planning since often there are many people involved in the process. Furthermore, data sources are also varied. It is important to know, for example, if the CT scanner software or hardware is being upgraded so that proper QA tests can be performed at the treatment planning system. Often such scanners exist in other departments and can work under the jurisdiction of a different administration leaving the channels of accountability independent of the treatment planning process. Thus, clear channels of communication need to be defined.

System Management and Security

As treatment planning systems become networked into clusters with various planning and target volume delineation stations, system management becomes an integral component of the entire QA process. This also entails maintaining an adequate check on system security and limiting user access not only to the system but also to specific software and data file modifications.

Regular backups are an essential component to ensuring no loss of important and confidential patient information [46]. This could include daily backups of the most recent patient information, weekly backups of all patient information, and monthly backups of the entire treatment planning system. This could also include the archiving of patient data for clinical trial purposes.

Personnel Requirements

The implementation of an extensive QA program for treatment planning systems is a time-consuming process and could involve medical physicists, dosimetrists, radiation therapists, physics technicians, and computer personnel. A sampling of the time required was published by Van Dyk et al. [125] and has been updated in Table 8.16.

Added to these numbers should be the time required for purchasing the system, for additional radiation measurements required for commissioning, as well as issues related to system administration and quality assurance management. These numbers have not accounted for the additional commissioning and QA of special techniques.

8.12 Summary

Treatment planning is the "hub" of the radiation therapy process. While a variety of tools (e.g., simulation, CT simulation, simulation-CT, virtual simulation) have become important components of the treatment planning process, these sources of data all come together in the treatment planning system. Because of the multifaceted nature of treatment planning, it has been difficult to define a simple series of tests that define the QA program. This is in contrast to simulators and radiation treatment machines for which such programs have existed for many years. While redundant checks for monitor unit and time calculations have been standard practice for many years, it is only very recently that task groups have developed QA programs for treatment planning systems [13,46,110,125]. This is partly due to the tremendous variation in treatment planning systems and algorithm capabilities and partly due to the very

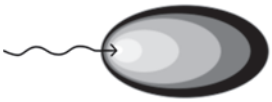

Table 8.16
Estimated Personnel Requirements for Commissioning and QA of Treatment Planning Computers

PROCEDURE	FULL TIME EQUIVALENT
1. Commissioning	
• Photons	4–7 days/beam energy
• Electrons	3–5 days per beam energy
• Brachytherapy	0.5–1 day/source type
• MU/time calculation program	0.2–0.5 day/beam energy
2. Quality assurance	
• Reproducibility tests (dependent on number of beam qualities and brachytherapy sources)	1–3 days/6 months
• Manual calculations	
– Treatment plan	0.1–0.3 hours/plan
– Monitor units/time	0.1–0.2 hours/plan
• *In vivo* dosimetry	0.3–2 hours/patient

complex nature of the entire treatment planning process, since it involves multiple facets ranging from contour measurements, patient image entry, to radiation data measurements, data entry, target volume tools, dose calculation evaluation procedures and hardcopy outputs. Because of these multiple steps and the corresponding complexities, a simple and unique QA program cannot be defined for all institutions. However, each institution will have to develop and implement its own QA program. This provides users with confidence that the treatment planning activities are being executed accurately. Furthermore, a thorough QA program will provide the user with a clear understanding of the treatment planning system's capabilities and limitations.

In the future, we can expect to see treatment planning as well as treatment delivery become more accurate and more automated as computer memories and speeds increase. Indeed, the ability to use Monte Carlo dose calculations for routine treatment planning is fast approaching. Furthermore, inverse planning algorithms will enhance the dose optimization capabilities such that IMRT and dose escalation will be possible routinely. We are living in an age with extremely rapid improvements in the modern technology of radiation oncology. It is our hope and expectation that as the technologies improve, patient cure and quality of life will also improve.

Acknowledgments

We would like to thank Graham Garvey for his help with the figures on dose calculation algorithms and Eugene Wong for his contribution to the electron beam summaries.

Appendix 8.1 Tender Document

The following is a sample table of contents of a treatment planning computer specifications document used for tendering for a multi-station treatment planning system. This has been adapted from the treatment planning computer system tender document produced at the Ontario Cancer Institute/Princess Margaret Hospital in 1994.

1. DOCUMENT OBJECTIVES
2. DEFINITIONS
   - 2.1 Base 3-D unit
   - 2.2 Standalone server node
   - 2.3 Remote 3-D node
   - 2.4 Remote 2-D node
   - 2.5 Remote MU calculation node
   - 2.6 Remote 3-D Volume-Delineation node
3. SUMMARY OF ESSENTIAL REQUIREMENTS
4. REGULATIONS, CODES AND STANDARDS
5. VENDOR GUARANTEES
   - 5.1 Specification Guarantee
   - 5.2 Service Guarantees
     - 5.2.1 Response time
     - 5.2.2 Hardware support
     - 5.2.3 Software support
   - 5.3 Third Party Products
     - 5.3.1 Embedded software
     - 5.3.2 Hardware
   - 5.4 Performance Guarantee
   - 5.5 Computer Protection
   - 5.6 Upgradeability
   - 5.7 Indemnity
   - 5.8 Price Guarantee
6. VENDOR INFORMATION
   - 6.1 Vendor Statistics
   - 6.2 Model Statistics
   - 6.3 Future Capabilities
7. PURCHASE PROCEDURE
   - 7.1 Site Preparation
   - 7.2 Delivery
   - 7.3 Installation
   - 7.4 Acceptance Testing
8. PAYMENT TERMS
9. SPECIFICATIONS
   - 9.1 Hardware
     - 9.1.1 Host CPUs
     - 9.1.2 Terminals
     - 9.1.3 Interactive input devices
     - 9.1.4 Storage disks
     - 9.1.5 Networking
     - 9.1.6 Digitizing tablet
     - 9.1.7 Backup tape device
     - 9.1.8 Printer
     - 9.1.9 Plotter
     - 9.1.10 Screen dump printer
     - 9.1.11 Film digitizer
     - 9.1.12 Nine track tape drive
     - 9.1.13 Other peripherals
   - 9.2 System Administration Software
     - 9.2.1 Security
     - 9.2.2 Backup
     - 9.2.3 Batch queue support
     - 9.2.4 Work load
     - 9.2.5 Other
   - 9.3 Network and Interface Software
     - 9.3.1 Image exchange formats
     - 9.3.2 X-ray CT images
     - 9.3.3 Magnetic resonance images
     - 9.3.4 Simulator digital radiographs
     - 9.3.5 Film digitizer
     - 9.3.6 Scanning dosimetry systems
     - 9.3.7 Portal imagers
     - 9.3.8 Other peripherals
   - 9.4 Planning Software
     - 9.4.1 Administration
     - 9.4.2 General
     - 9.4.3 Program features
     - 9.4.4 Installation data requirements
     - 9.4.5 Calculations
     - 9.4.6 Calculation speed performance
     - 9.4.7 Calculated dose accuracy
     - 9.4.8 Specific phantom tests
   - 9.5 Documentation and Training
     - 9.5.1 On-line help
     - 9.5.2 Manuals
     - 9.5.3 Training
   - 9.6 Service and Parts
     - 9.6.1 Diagnostics
     - 9.6.2 Preventive maintenance
     - 9.6.3 Warranty
     - 9.6.4 Consultant services
     - 9.6.5 Service contracts
     - 9.6.6 Parts inventories
   - 9.7 Environmental Requirements
     - 9.7.1 Power
     - 9.7.2 Operating conditions
10. OTHER INFORMATION

APPENDIX A. CALCULATION TESTS

Appendix 8.II Dose Calculation Tests

Figures 8.II.1 through 8.II.13 demonstrate a number of sample commissioning tests that can be performed to assess the quality of dose calculations in a treatment planning system. More examples have been published by Van Dyk [126]. Representative test data for photon dose calculations are shown in Figures 8.II.1 through 8.II.9. Many of these tests were based on the input and measured data provided by AAPM Report 55 [86]. Some sample commissioning test data for electron dose calculations are shown in Figures 8.II.10 through 8.II.13. These tests were based on the input and measured data provided by the ECWG report [111].

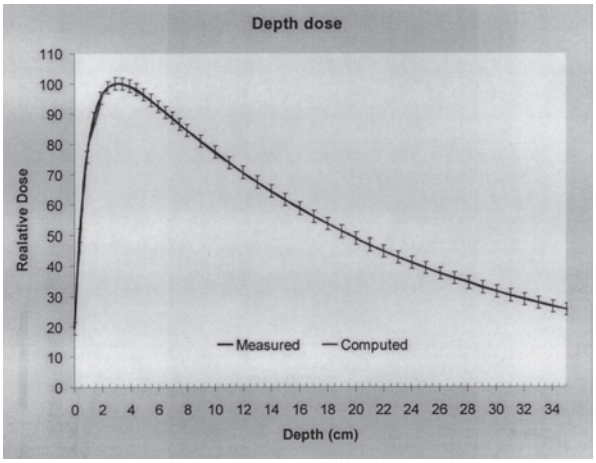

Figure 8.II.1
AAPM Report 55 test. Square field test for 5 x 5 cm^2 field of 18 MV x-rays. Measured versus calculations. Error bars refer to the criterion of acceptability of ±2%. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

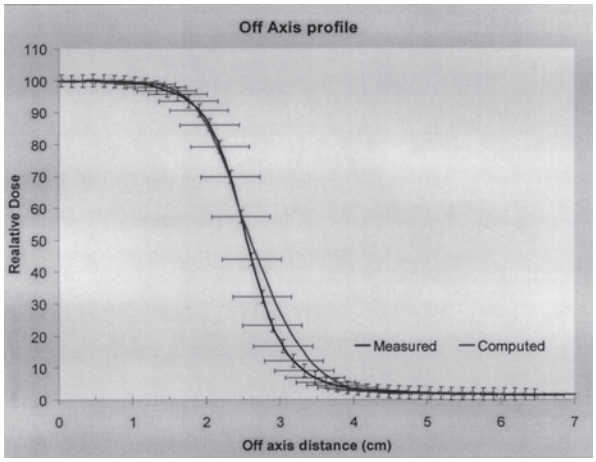

Figure 8.II.2
AAPM Report 55 test. Square field test for 5 x 5 cm^2 field of 18 MV x-rays. Dose profile at depth of 3 cm. Measured versus calculations. Error bars refer to the criterion of acceptability of ±2% in dose for the high dose, low dose gradient and ±4 mm in the high dose gradient. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

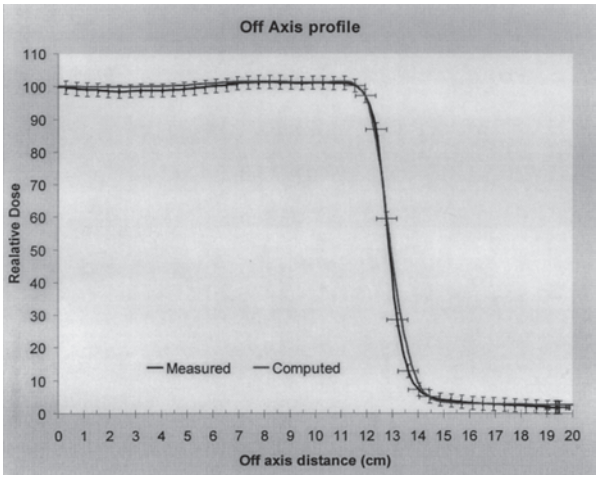

Figure 8.II.3
AAPM Report 55 test. Square field test for 25 x 25 cm^2 field of 18 MV x-rays. Dose profile at depth of 3 cm. Measured versus calculations. Error bars refer to the criterion of acceptability of ±2% in dose for the high dose, low dose gradient and ±4 mm in the high dose gradient. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

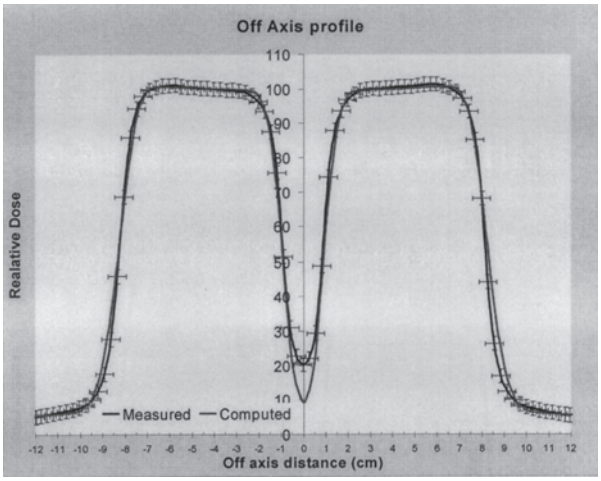

Figure 8.II.5
AAPM Report 55 test. Central axis block test for 16 x 16 cm^2 field of 18 MV x-rays. Dose profile at depth of 3 cm. Measured versus calculations. Error bars refer to the criterion of acceptability of ±2% in dose for the high dose, low dose gradient and ±4 mm in the high dose gradient. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

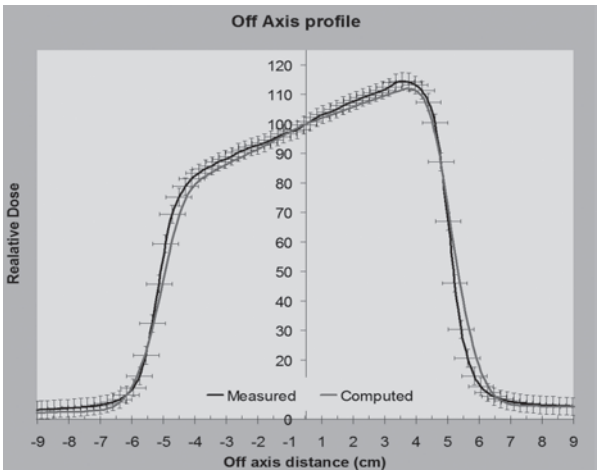

Figure 8.II.4
AAPM Report 55 test. Wedged square field test for 9 x 9 cm^2 field of 18 MV x-rays. Dose profile at depth of 3 cm. Measured versus calculations. Error bars refer to the criterion of acceptability of ±2% in dose for the high dose, low dose gradient and ±4 mm in the high dose gradient. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

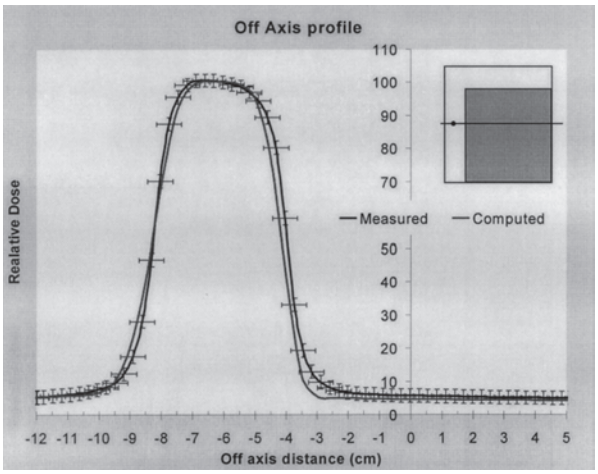

Figure 8.II.6
AAPM Report 55 test. Central axis block test for 16 x 16 cm2 field of 18 MV x-rays with a 12 x 12 cm^2 block. Dose profile at depth of 3 cm. Measured versus calculations. Error bars refer to the criterion of acceptability of ±2% in dose for the high dose, low dose gradient and ±4 mm in the high dose gradient. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

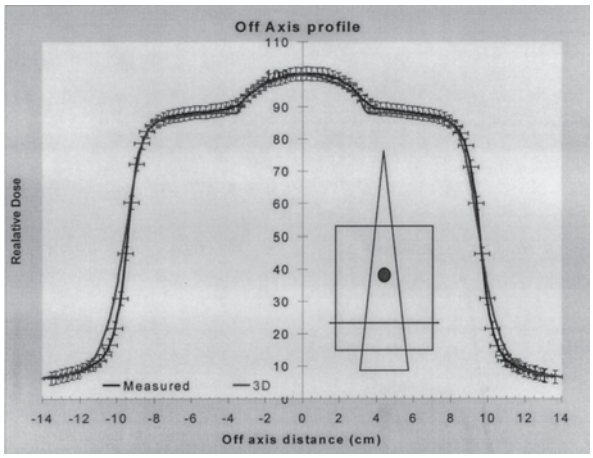

Figure 8.II.7
AAPM Report 55 test. Lung inhomogeneity test for 16 x 16 cm^2 field of 18 MV x-rays with 6 cm diameter x 12 cm long, lung cylinder of 0.29 g/cc at a depth of 8 cm. Dose profile at depth of 20 cm. Measured versus calculations. Error bars refer to the criterion of acceptability of ±2% in dose for the high dose, low dose gradient and ±4 mm in the high dose gradient. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

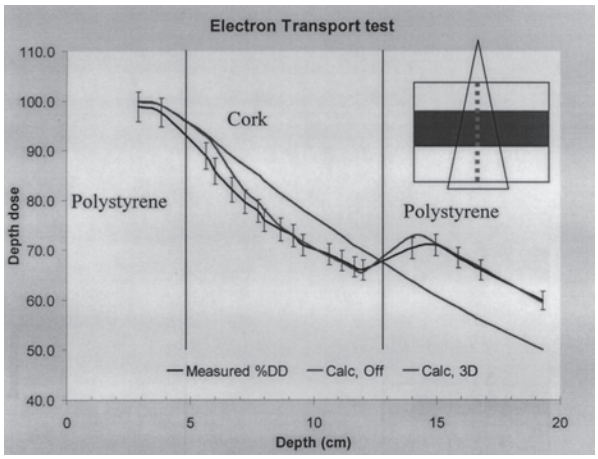

Figure 8.II.9
Electron transport test for 5 x 5 cm^2 field of 18 MV x-rays. Measured versus calculations. Error bars refer to the criterion of acceptability of ±3% for inhomogeneity correction. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

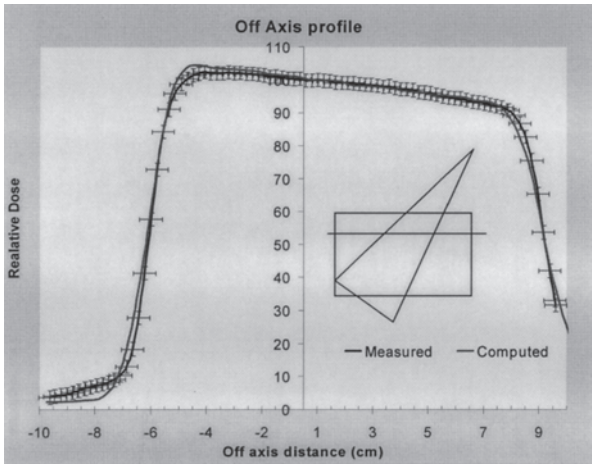

Figure 8.II.8
AAPM Report 55 test. Oblique incidence test for 10 x 10 cm^2 field of 18 MV x-rays at a 45° angle. Dose profile at depth of 3 cm. Measured versus calculations. Error bars refer to the criterion of acceptability of ±2% in dose for the high dose, low dose gradient, and ±4 mm in the high dose gradient. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

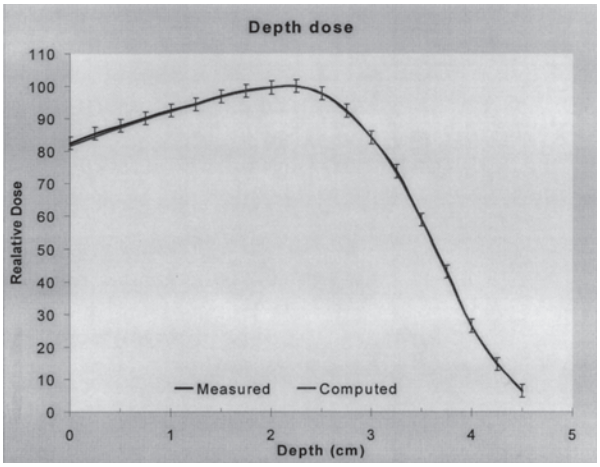

Figure 8.II.10
Electron Collaborative Work Group test for 15 x 15 cm^2 field of 9 MeV electrons. Measured versus calculations. Error bars refer to the criterion of acceptability of ±7% or ±4 mm. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

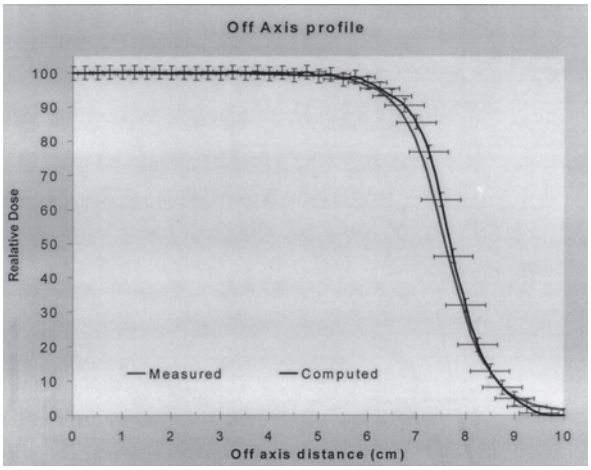

Figure 8.II.11
Electron Collaborative Work Group test. Dose profile test for a 15 x 15 cm^2 field of 9 MeV electrons at a depth of 2.25 cm. Measured versus calculations. Error bars refer to the criterion of acceptability of ±2% or ±4 mm. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

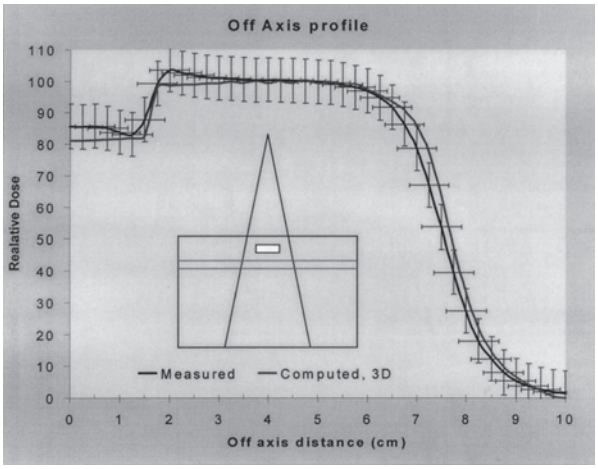

Figure 8.II.13
Electron Collaborative Work Group test for 2-D bone using 9 MeV electrons (experiment number 12). This is a 3 cm x 8 cm x 1 cm bone cavity. Measured versus calculations for a profile at a depth of 2.3 cm. Error bars refer to the criterion of acceptability of ±7% or ±4 mm in high dose gradient. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

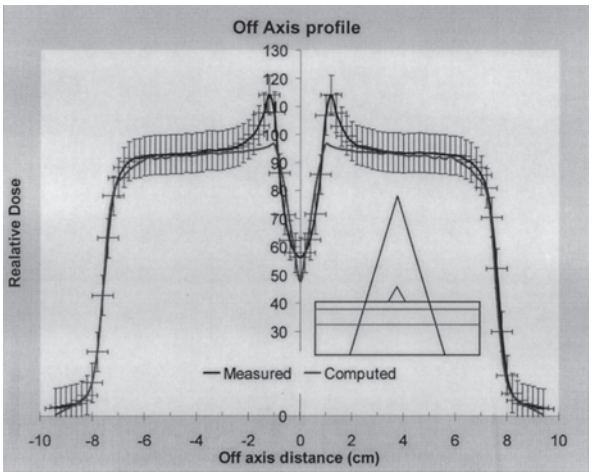

Figure 8.II.12
Electron Collaborative Work Group test for 15 x 15 cm^2 field of 9 MeV electrons. Measured versus calculations. Error bars refer to the criterion of acceptability of ±7% or ±4 mm in high dose gradient. [Figure courtesy MDS Nordion/Theratronics International Ltd.]

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