3D Treatment Planning and Intensity-Modulated Radiation Therapy

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Three-dimensional (3D) image-based treatment planning and new delivery technologies have spurred the implementation of external beam radiation therapy techniques, in which the high-dose region is conformed much more closely to the cancer patient's target volume than was previously possible, thus reducing the volume of normal tissues receiving a high dose. This form of external beam irradiation is referred to as three-dimensional conformal radiation therapy (3DCRT), and its development and clinical use are discussed in considerable detail elsewhere.[1,2] Several groups have already reported on their early clinical experience with 3DCRT for the treatment of prostate cancer, and the results are encouraging.[3-5]

Three-dimensional planning is not just an addition to the current radiation oncology planning process, but rather represents a radical change in practice, particularly for the radiation oncologist. The two-dimensional (2D) treatment planning approach emphasizes the use of a conventional simulator for designing beam portals, based on standardized beam arrangement techniques applied to whole classes of comparable patients. Three-dimensional treatment planning emphasizes a virtual simulation, image-based approach for objectively defining tumor and critical structure volumes for the individual patient.

The use of the terms 2D and 3D as descriptors for the planning process has caused some confusion in the radiation oncology community. One should recognize that planning the cancer patient's treatment is, and always has been, a 3D problem, and 2D planning refers to the process and tools used. Three-dimensional treatment planning does not require the use of noncoplanar beams, a common misconception. Noncoplanar beams have been used for years in selected sites such as breast cancer, even though 2D treatment planning systems could not accurately account for the geometry. Clearly, noncoplanar breast tangential fields represented on a 2DRTTP system by a single, or at most a few, slices cannot be considered a 3D treatment plan. Radiation oncologists will be able to transition to 3D planning much more easily if they approach 3DRTTP as a new treatment planning process, emphasizing image-based target volume design rather than as a reflection of a particular beam configuration.

One of the important factors contributing to the current 3D process is the standardization of nomenclature, published in the International Commission on Radiation Units and Measurements (ICRU) Report 50.[6] This report has provided a language and a way of thinking about the problem for defining the volume of known tumor, suspected microscopic spread, and marginal volumes necessary to account for set-up variations and organ and patient motion. Figure 1 illustrates the ICRU 50 formal definitions for the gross tumor volume, clinical target volume, planning target volume, and organs at risk. Some brief discussion on the use of the ICRU 50 methodology is presented in a later section. Also, the reader is referred to the literature for more details regarding the use of ICRU 50 nomenclature.[7,8]

Table 1 lists the various tasks that make up the 3D planning dose and delivery process in its current technology state. 3DCRT treatment plans generally use an increased number of radiation beams that are angled and shaped to conform to the planning target volume using the 3DRTTP system's beam's-eye view and room's-eye view displays (Figures 2A and 2B). To improve the conformity of the dose distribution, conventional beam modifiers (eg, wedges or compensating filters) are sometimes used. This form of 3DCRT must now be referred to as traditional or conventional...
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3D CRT, because a more advanced form of 3DCRT, called intensity-modulated radiation therapy, is already emerging. Intensity-modulated radiation therapy can achieve even greater conformity by optimally modulating the radiation beam intensity (fluence) throughout each treatment field.[9]

These advances in radiation oncology technology are truly exciting and are occurring at a very rapid pace. However, as the implementation of 3D planning and dose delivery systems becomes more widespread, the radiation oncology team must understand that ensuring the safety and accuracy of this new modality is more difficult (in its current development state) than with the standard 2D process. Therefore, it is essential that the radiation oncology team stay well informed on the new technologies and maintain a strong commitment to a rigorous quality assurance program when this new treatment modality is implemented in the clinic. This article will update a previous review of advances in 3DRTTP and dose delivery.[10]

Advances in 3D Treatment Planning

Three-dimensional RTTP systems are currently going through a rapid transition period, having emerged from university-developed systems to Food and Drug Administration-approved commercially available systems in the early 1990s. These first-generation commercial systems provide specific functionality, such as virtual simulation or 3D external beam dose planning. Such limited functionality has resulted in clinics needing multiple treatment planning systems to provide for various high-tech treatment modalities, like virtual simulation, 3D external beam dose planning, high-dose-rate brachytherapy, prostate seed implant, and stereotactic radiosurgery. This is clearly not very satisfactory, resulting in increased costs and inefficiencies.

Over the next few years, the treatment planning system manufacturers will begin to combine these planning programs into a single integrated image-based 3DRTTP system that provides planning capability for multiple treatment modalities, resulting in considerable cost savings. In addition, we should soon see improved efficiencies based on the use of intranets. An intranet is a special type of internet-related technology with the potential to dramatically improve a radiation oncology clinic’s ability to use 3DRTTP. A radiation oncology clinic’s intranet will make use of client server (and browser) technology that will provide easy-to-use Windows-like displays, permitting users to easily navigate through multiple treatment planning and other clinical applications, data, and graphical displays using point-and-click technology. However, prior to further discussion on information technology, it is important to describe some of the improved features now readily available on 3DRTTP systems.

Imaging for 3D Planning

The development of powerful but relatively inexpensive computer systems has allowed the integration of computed tomography (CT)-based target volume and normal tissue definition with the process of radiation therapy treatment planning, creating an entirely new device, the CT simulator. The CT simulator differs in both purpose and function from the conventional simulator.[11,12] A typical CT simulation uses a helical CT scanner with localization software, a patient registration and laser marking system, and a dedicated computer workstation for virtual simulation and generation of digitally reconstructed radiographs.

Although the current generation of CT simulators provides powerful new 3D capabilities, several improvements in the hardware are still needed for treatment planning purposes because the CT scanner currently used was designed for diagnostic radiology use. Specifically, a larger CT gantry aperture is needed. Current scanners have a 70-cm diameter, which limits some treatment set-ups. Also, the CT reconstruction size needs to be larger (currently only a 52-cm diameter is provided). CT simulator couch tops that mimic the geometry of a medical linear accelerator are also needed, as are improved registration systems for going from the real patient to the virtual patient and then back to the real patient for treatment. Other issues that continue to be of concern are data storage and data transfer. Also, a satisfactory process for quantitating the effects of respiratory organ motion or other organ movements has not yet been developed for CT simulation.

For effective use of CT simulation, the radiation oncologist must become familiar with CT cross-sectional anatomy and with the appropriate use of CT contrast materials that aid in the identification of the gross tumor volume and organs at risk. When CT simulation/3DRTTP is first introduced in the clinic, assistance from a diagnostic radiologist in contouring the organs at risk and gross tumor volume/clinical target volumes can be invaluable. However, identifying normal tissues and tumor on a treatment-planning CT can be difficult even for an experienced diagnostic radiologist, as the planning CT images are typically acquired in a nonstandard diagnostic patient.
position. Since 3D planning requires the definition of target volumes and normal tissue on a CT scan, strong consideration should be given to incorporating image-based, cross-sectional anatomy training into radiation oncology residency training programs. In the interim, short courses on image-based anatomy are needed for practicing radiation oncologists.

While CT is the principal source of image data for 3DRTTP, there is a growing demand to incorporate the complementary information available from magnetic resonance imaging (MRI). The sharply demonstrated tumor-soft-tissue interface often seen on an MRI scan in tumors such as in the brain can be used to better define the gross tumor volume.[13] Several groups have also demonstrated the value of MRI in distinguishing the prostate gland from surrounding normal structures.[14,15] In addition, functional imaging modalities such as single photon emission computed tomography (SPECT) and positron emission tomography (PET) will likely prove to be important in both the target definition phase of treatment planning and also in the follow-up studies needed to assess efficacy. For example, Marks et al have reported on the use of SPECT lung perfusion scans to determine functioning regions of the lung.[16,17] The functional lung volume data are used in calculating dose-volume histograms rather than the CT-defined anatomy and are referred to as functional dose-volume histograms. Radiation beams are planned that minimize irradiation of these functioning areas. Similarly, PET imaging is used to aid in defining the patient's lung cancer gross tumor volume/clinical target volumes. However, use of multimodality imaging in the treatment planning process brings with it the need for better image registration tools.

**Image Registration**

Spatial registration (fusion) of 3D images from different modalities, most commonly CT, MRI, or PET/SPECT, is a major area of research for radiology and radiation oncology.[18-20] The approaches used to register two or more data sets can be divided into manual and automatic, or some combination. Frequently, approximate alignment is achieved through the use of manually interactive software followed by final alignment by an automatic algorithm. Currently, only a few 3DRTTP systems provide an image fusion capability in their software. Of the many automatic methods, those using statistical criteria to optimize the correlation of anatomic features of the images are especially promising. They do not require edge detection and need minimal or no data preconditioning. The approach maximizing the measure of mutual information[21,22] and the popular and related Woods method[23] are examples of promising research in this area. In addition to automated image registration methods such as these, a general method for formally testing the accuracy of image registration is also needed.

**Image Segmentation**

The process of segmenting the cancer patient's planning CT image data set (ie, contouring the gross tumor volume, clinical target volume, planning target volume, specified organs at risk, and skin) is one of the most important but, unfortunately, most time-consuming elements of the 3D treatment planning process. In our clinic, a prostate cancer patient's CT data set (typically about 80 slices) can be segmented in about 30 minutes; the bladder, rectum, and femoral heads are contoured by the dosimetrist, and the prostate gland is contoured by the radiation oncologist. For other sites, the time requirement is even greater, and thus, there is still a need to develop software that will automate (or at least nearly automate) the contouring task.

When contouring the gross tumor volume, it is important to use the appropriate CT window and level settings to determine the maximum dimension of what is considered to be potential gross disease. At this time, defining the clinical target volume is more of an art than a science, since current imaging techniques are not capable of detecting subclinical tumor involvement directly. Thus, the boundary of the clinical target volume must be defined by the radiation oncologist based on clinical experience. The planning target volume margin must also be specified by the radiation oncologist, in consultation with the radiation oncology physicist, based on clinical experience. Unfortunately, there are limited data for internal organ motion and set-up error for most sites other than prostate.[24]

When defining the planning target volume, the radiation oncologist should recognize that the margin around the clinical target volume need not be uniform but should account for the asymmetrical nature of positional uncertainties.

Many 3DRTTP systems still do not possess accurate methods for providing a true 3D margin around the gross tumor volume (Figure 3). Typically, the margin expansion is drawn or specified in 2D around the gross tumor volume contour to get the planning target volume. For large contour differences in neighboring slices, this will yield margins that are too small in the cranial-caudal direction. Bedford and Shentall describe methods to compute target margins.[25] When defining the beam aperture, additional margin beyond the planning target volume is needed to obtain dose coverage because of beam penumbra. Some physicians (and physicists) have
confused this margin in the past by thinking of the planning target volume boundary as the required beam edge, which is incorrect. For coaxial beam arrangements, the additional margin is typically 7 to 8 mm, except for the inferior and superior borders. In those directions, 12 to 15 mm margins are required because of the beam divergence effects to have planning target volume coverage by the prescription minimum isodose treatment volume.

3D Treatment Planning Displays

Three-dimensional RTTP systems typically display the delineated tumor/target volume and organs at risk cross-sectional contours as surface-rendered objects using a variety of styles that include transparency, texturing, and lighting (Figure 2). Some planning systems are beginning to use volume-rendered objects (Figure 4).[26] Volume rendering provides more soft-tissue structure and should aid the physician in defining the patient's clinical target volume(s). However, the volume-rendered displays will not alleviate the need for contours, as they will still be needed for calculation of dose-volume histograms.

Near real-time beam's-eye view and room's-eye view displays are now standard features for most commercially available 3DRTTP systems. The beam's-eye view display provides the planner with an effective means of choosing beam directions and designing beam apertures to maximize planning target volume coverage and minimize irradiation of any organs at risk. On most systems, customized beam apertures are shaped manually around the planning target volume using a computer mouse, analogous to the manual design of blocks using a wax pencil on a simulation radiograph. More advanced systems automatically shape treatment apertures to conform to the shape of the planning target volume projection based on a specified margin. The room's-eye view display, using transparent renderings of the planning target volume and organs at risk, allows quick graphical positioning of the treatment isocenter. The room's-eye view display is also helpful in evaluating the geometry of multiple beam arrangements. Particularly when noncoplanar beam arrangements are used, care must be taken to avoid the selection of a beam direction that is untreated because of table and gantry collisions or other treatment room restrictions. A needed feature, currently missing on 3DRTTP systems, would be an automatic collision avoidance feature to prevent lost time and effort in creating a treatment plan that is undeliverable.

High-quality digitally reconstructed radiographs and rapid computation speed are also essential features of a modern 3DRTTP system. The digitally reconstructed radiograph serves the same purpose as a conventional simulator radiograph. However, the target volume and organs-at-risk contours can be overlaid on the digitally reconstructed radiograph and thus provide a more quantitative tool to appreciate the geometric relationship of these volumes and the portal aperture. Advanced 3DRTTP systems provide a full range of digitally reconstructed radiograph image manipulation features controlling image display and geometric parameters. Particular aspects of the image presentation can be enhanced by changing the window and level settings, as well as the contrast and brightness of the pixel display. The CT numbers can be grouped into ranges corresponding to bone, fat, muscle, or tissues; the CT numbers in each category can be modified by a weighting factor and redisplayed to provide enhancement or suppression of a structure based on attenuation values.[27] An example of this type of digitally reconstructed radiograph, referred to as a digital composite radiograph, is shown in Figure 5.

Dose Calculations

Early generation 3DRTTP systems used dose calculation algorithms similar to those used in 2DRTTP systems and thus provided improved dose visualization, but not improved accuracy.[8,28] However, more advanced dose-calculation algorithms that compute the dose from more of a first-principles approach and thus provide a more accurate means of predicting dose have now become the standard for 3DRTTP systems. These algorithms use convolution energy deposition kernels that describe the distribution of dose about a single primary photon interaction site.[29] The convolution kernels are obtained by using the Monte Carlo technique to interact monoenergetic primary photons at the origin in a phantom, and to transport the charged particles and scattered and secondary photons that are set in motion. The energy that gets deposited about the primary photon interaction site is tabulated and stored for use in the convolution method. In addition to describing how scattered photons contribute to dose absorbed at some distance away from the interaction site of primary photons, the convolution kernels take into account charged particle transport.

In the future, the direct use of Monte Carlo simulation for 3D dose planning and evaluation should be feasible. Groups at the Lawrence Livermore National Laboratory, the National Research Council of Canada, and several universities are actively pursuing development of such capability.[30-32] This method is the only one capable of computing the dose distribution accurately for complex geometries that include interfaces of materials with very dissimilar atomic numbers, such as near...
metal prostheses used for femoral head replacement. The major obstacles preventing this technique from clinical implementation have been the lengthy computation times required and the need for a detailed quantitative description of the incident radiation beam. The first obstacle is rapidly being overcome as the computation power of microprocessors continues to increase dramatically (doubling about every 18 to 24 months). In addition, researchers are actively working on reducing the computation time by using clever variance reduction techniques and the macro Monte Carlo technique.[33,34] Rogers and coworkers are actively working on overcoming the second obstacle with the development of the Monte Carlo code called BEAM, which simulates the radiation beams from medical accelerators.[30] A practical point should be made here regarding dose calculation programs as they pertain to dose prescription and dose distribution evaluation. In the 3D era, because of better visualization tools, there has been a tendency to emphasize the minimum isodose line or isodose surface covering the planning target volume for prescription and reporting purposes. This is unfortunate, because dose at the periphery of the planning target volume can be associated with significant uncertainties due to the steep dose gradient close to the edge of the beam. Radiation oncologists should understand that the dose along the central axis of a beam is likely to be more accurate than at the periphery regardless of the dose calculation algorithm used. In fact, ICRU Report 50 points out that the dose at the central part of the planning target volume is the most representative single dose value for the planning target volume and recommends that it, along with the maximum and minimum dose to the planning target volume, be used for reporting.[6] **Interactive Treatment Plan Optimization**

The optimization (more accurately termed plan improvement) of a conventional 3DCRT plan relies on an iterative, interactive plan optimization approach. Typically, the initial beam arrangement is selected based primarily on clinical experience using beam’s-eye view and room’s-eye view displays. The arrangement is then modified based on the evaluation of the dose distribution using dose-volume histograms, 2D isodose sections, and room’s-eye view 3D isodose volume displays until the resulting dose distribution is approved by the radiation oncologist. The planned dose distribution is most often a uniform dose to the target volume (eg, ≤ 7% variation from maximum to minimum dose at a specified dose level), with doses to critical organs at risk held below some tolerance level that has been specified by the radiation oncologist.

**Automated Computer Optimization**

Interest in treatment planning computer optimization and automation has been renewed with the development of 3DCRT and the corresponding increase in image and graphic data available to the planner. Investigation of computer optimization has also intensified because of intensity-modulated radiation therapy’s requirement that optimal nonuniform beam fluences be determined.[35-37] The task of automated computer optimization can be better understood by considering it as two components: (1) specification of an optimization criteria, and (2) the optimization (search) algorithm used. The optimization criteria is expressed mathematically as an objective function whose value (sometimes referred to as score or cost) denotes the goodness of the treatment plan. The search algorithm then attempts to determine the plan parameters, which minimizes the objective function (Figure 6).

Objective functions and associated constraints are typically based on dose and dose-volume parameters for the target volume and critical normal structures. More recently, objective functions have been expressed in terms of biological indices, such as some weighted combination of tumor control probabilities and normal tissue complication probabilities. The development of robust tumor control probabilities and normal tissue complication probabilities models that accurately predict clinical outcome will emerge from the ongoing 3DCRT clinical trials as dose-volume outcome data are gathered and analyzed; but to date, these models should be viewed with some caution. One of the most promising search algorithms for intensity-modulated radiation therapy is simulated annealing.[38] This algorithm is derived from statistical mechanics, and attempts to mimic the behavior of a system of interacting particles that are progressively cooled and allowed to maintain thermal equilibrium while reaching the ground state. With this approach, there is no restriction on the order (eg, quadratic) of the objective functions or on the number of constraints. In addition, it has the potential to escape from the local minimum of the objective function, and thus find the global minimum (ie, the best plan) (Figure 6). However, simulated annealing is generally slower than the deterministic optimization algorithms that have been used in the past for computer optimization and thus, from a practical standpoint, may limit the search parameters (eg, table and gantry positions). More details of the various computer optimization methods being investigated for intensity-modulated radiation therapy can be found in the literature.[39,40]
Plan objective function and optimization search algorithms are an important research area for intensity-modulated radiation therapy with no clear winner established as yet. As computer power increases, the optimization search algorithm is unlikely to pose the real problem. Rather, the more difficult problem will probably be the development of a robust means to specify the optimization criteria that will be applicable to the diverse population of cancer patients and also satisfy individual physician preferences. Until such an optimization criteria specification is developed, inverse planning will continue to resemble the iterative, forward plan-improvement approach, in which a physician still must evaluate dose distributions (dose-volume histograms and room's-eye view 3D isodose volumes) and make iterative changes to the objective function input parameters in order to obtain an acceptable plan.

Electronic Data Exchange
The amount of information that must be processed in this new 3D era is orders of magnitude greater than in the previous 2D era, and thus requires significant changes in the radiation oncology department's computer and communications infrastructure. The planning and delivery of intensity-modulated radiation therapy can only be made practical, safe, and affordable through the increased use of computer automation and open architecture, common standards-based medical information systems. The reader is referred to a previous issue of *Seminars in Radiation Oncology*, in which a review of the use of information technology in radiation oncology was presented.[41] An electronic patient chart and image file is an essential component of the integrated planning-delivery-verification system that will eventually replace the stand-alone systems used today. The new system will depend on the development of robust intranets and extranets to access data and applications that are stored on the radiation oncology department's servers, and perhaps those of other clinics, healthcare organizations, and radiation oncology vendors in various locations. The electronic records will be shared among the different groups within the department (eg, radiation oncologists, physicists, dosimetrists, radiation therapists, treatment machine maintenance technicians, administrators) and also with the other hospital departments as needed. Thus, the importance of computer networks, servers, distributed databases, and browser technology for radiation oncology must be stressed.

The Radiation Therapy Oncology Group's (RTOG) 3D Quality Assurance Center (3DQA) ([http://rtog3dqa.wustl.edu/](http://rtog3dqa.wustl.edu/)) is an example of how the World Wide Web can be effectively used in radiation oncology. The 3D planning and verification digital data for patients entered on the National Cancer Institute-sponsored 3D dose-escalation trials in prostate cancer, lung cancer, and supratentorial glioblastoma multiforme that are now in progress are submitted to the 3DQA Center via the internet.[42] The target volume and designated organs-at-risk contours superimposed on CT display, verification images, and the 3D dose distribution are reviewed for protocol compliance. Once reviewed, the data are stored in an open architecture, common standards database that is linked with the RTOG clinical outcome database in Philadelphia.[43] We believe this new way of submitting protocol data and performing QA review, as well as the new type of linked databases, will revolutionize the conduct and analysis of clinical trial outcome data, allowing researchers to better understand the relationship between doses, volumes, and patient outcomes. This effort, in turn, will lead to the development of improved tumor control probabilities and normal tissue complication probabilities models that will make the planning of intensity-modulated radiation therapy more effective and efficient.

For an institution to participate in RTOG 3DCRT clinical trials, the 3DRTTP system to be used must have the RTOG Data Exchange Specification implemented.[44] This feature allows the treatment planning data listed in Table 2 to be submitted to the 3DQA Center for review and inclusion in the new database. To date, over 700 protocol patient data sets have been submitted to the 3DQA Center using this exchange format. The RTOG Data Exchange Specification will ultimately be replaced by the radiation therapy information objects of Digital Imaging and Communication in Medicine 3.0,[45] which themselves were motivated in part by the RTOG standard. However, this replacement must await the implementation of the radiation therapy information objects and their support by both commercial 3DRTTP companies and the RTOG 3DQA Center. The uncertainty of a time frame for broad acceptance and implementation of the Digital Imaging and Communication in Medicine radiation therapy objects, coupled with the wider commercial implementation of the RTOG Data Exchange Specification, suggests that the RTOG data exchange will continue to play an important role in support of 3DCRT multi-institutional trials for several more years.

The broad experience with 3DRTTP data exchange gained thus far by the 3DQA Center has created keen awareness of the need for continued work in the area of data exchange by the 3DRTTP
manufacturers. Users should encourage the manufacturers of their 3DRTTP systems to implement new features on their systems that will simplify the data submission process. For instance, a utility could be provided that would allow the user to preselect the data required for submission specific to the 3DRTTP protocol. This utility would in turn create a button on a user interface for submitting data. When clicked, the protocol data would automatically be selected and sent to the 3DQA Center. All additional edit features shown in our prototype interface would be used only for exceptional submissions, such as those correcting contour or planning problems in earlier submissions for the same patient in order to reduce the amount of data requiring resubmission.

Advances in Treatment Delivery

In the 2D paradigm, radiation therapy is delivered with radiation beams of uniform intensity across the field. Simple beam modifiers such as wedges and compensators are often used to account for missing tissue and, in some instances, to shape dose distribution. While this approach works well for simple, regularly shaped target volumes, it is severely limited for complex target shapes or for geometries in which the planning target volume is in close proximity to several critical organs at risk. In the 3D paradigm (intensity-modulated radiation therapy), these limitations are overcome by employing nonuniform beam fluence distributions for a selected number of beams or via arc therapy. The dose distribution is produced by dividing each beam into tiny subdivisions called "beamlets," with each beamlet's intensity determined by a computer optimization algorithm. The concomitant development of the multileaf collimator and the medical accelerator computer control systems, which made possible the use of the multileaf collimator in a dynamic mode, have spurred the development of intensity-modulated radiation therapy.[9,46,47] Now, several different methods for intensity-modulated radiation therapy delivery are being used clinically (or are in the process of being clinically implemented) and are briefly discussed below.

Tomotherapy Intensity-Modulated Radiation Therapy

Mackie et al first proposed an approach called "tomotherapy," which literally means "slice therapy," by which intensity-modulated radiation therapy is delivered using a narrow slit beam.[48] A slit mini-multileaf collimator system (called MIMiC) of the type proposed by Mackie et al is now commercially available (Peacock, Nomos Corporation, Sewickley, Pa) and is implemented in a large number of clinics worldwide. The Peacock system's MIMiC is mounted to a conventional low-energy megavoltage medical linear accelerator, and treatment is delivered to a narrow slice of the patient using arc rotation (Figure 7).[49] The beam is collimated to a narrow slit (approximately 2 cm × 20 cm), and beamlets of varying intensity are created by driving the MIMiC's leaves in and out of the radiation beam's path as the gantry rotates around the patient. A complete treatment is accomplished by sequential delivery to adjoining axial slices. This system was first implemented clinically at the Baylor College of Medicine (Houston, Tex).[50] Since then, several institutions have reported their experience with the Peacock intensity-modulated radiation therapy system.[51-53] Examples of a conformal dose distribution for a complex geometry that is achievable with this form of intensity-modulated radiation therapy are shown in Figure 8.

With this approach, a significantly increased number of monitor units is required compared to conventional 3DCRT without delivery of dose to the patient's target volume. This results in an increased workload for radiation shielding requirements, as well as an increased whole-body dose to the patient, primarily due to leakage radiation. Matic and Low, using this intensity-modulated radiation therapy system, reported that the dose 10 cm from the target volume, due to scatter and leakage radiation, is approximately 2.5% of the total target dose, and is still as great as 0.5% at 30 cm from the target volume.[54] Followill et al concluded that the increased whole-body dose from intensity-modulated radiation therapy compared to conventional dose delivery poses a slightly increased risk of secondary fatal malignancies.[55]

Treatment plan verification still depends strongly on dosimetry measurements performed using ionization chambers, radiographic film, and/or thermoluminescent dosimeters in special intensity-modulated radiation therapy phantoms.[52,56] At our institution, these measurements are performed in the evening or on the weekend before each patient's initial intensity-modulated radiation therapy treatment session. Intensity-modulated radiation therapy delivery places significant constraints on the design and operational characteristics of dosimetry equipment due to the dynamic dose delivery. The dosimetry instrumentation and the entire QA process used for intensity-modulated radiation therapy are early in their development and will continue to undergo reevaluation.

A new type of treatment unit designed to deliver tomotherapy is under development at the
University of Wisconsin (Madison).[57] Figure 9 shows the treatment unit as originally proposed by Mackie et al, in which intensity-modulated radiation therapy would be delivered as the patient is moved through a ring-gantry in much the same way as a spiral CT study is performed.[48] Specifically, the beamlets are created using a mini-multileaf collimator similar to MIMiC and a low-energy linear accelerator mounted in a modified CT scanner gantry. The original proposal also included a conventional diagnostic CT system mounted on the same gantry to allow the simultaneous acquisition of a CT verification scan study.

More recent thinking suggests that megavoltage CT imaging may be all that is needed.[57] This approach eliminates the field abutment problem inherent in the axial tomotherapy approach and provides for on-line treatment verification.

**Conventional Multileaf Collimator Intensity-Modulated Radiation Therapy**

A conventional multileaf collimator, used in a dynamic mode, provides a full-field approach to intensity-modulated radiation therapy, compared to the slit-field approach of tomotherapy. For a fixed gantry position, the gap formed by each pair of opposing multileaf collimator leaves is swept across the target volume under computer control with the radiation beam on to produce the desired fluence profiles (Figure 10). The setting of the gap opening and its speed for each multileaf collimator leaf pair are determined by a technique first introduced by Convery and Rosenbloom[58] and extended by Bortfeld et al[59] and Spirou and Chui.[60] This intensity-modulated radiation therapy approach, referred to as dynamic multileaf collimator or “sliding window,” was first implemented for clinical use at the Memorial Sloan-Kettering Cancer Center in New York.[61] The various steps of treatment planning and delivery for this form of intensity-modulated radiation therapy and the associated QA programs are discussed in the article by Burman et al.[37]

Another multileaf collimator approach uses a sequence of static multileaf collimator fields (typically called “segments” or “subfields”) that are set up and delivered at each orientation of the gantry under computer control (Figure 11). This method is sometimes referred to as “step-and-shoot,” and the leaf sequences can be determined by the method suggested by Bortfeld et al.[62] In this approach, the linear accelerator is switched on and off for a predefined number of monitor units for each subfield automatically without human intervention. This allows a completely automatic treatment delivery of all subfields of all beams of a treatment plan, including gantry rotation. Most medical linear accelerator manufacturers now offer this type of computer control feature. Thus, widespread implementation of this form of intensity-modulated radiation therapy is anticipated over the next several years.

A third multileaf collimator approach, called intensity-modulated arc therapy, has been suggested by Yu and coworkers.[63-65] In this case, multiple superimposing arcs are used with the beam aperture changing shape during gantry rotation under computer control, with the radiation beam on to produce the desired fluence profiles. The cumulative fluence distribution of all arcs generates the desired dose distribution.

**X-ray-Compensating Filter Intensity-Modulated Radiation Therapy**

A physical compensation filter approach can also be used to deliver intensity-modulated radiation therapy. Filters designed using 3DRTTP are capable of compensation for not only the missing tissue deficit, but also for internal tissue heterogeneities. Filters can be designed by calculating a thickness along a ray line, using an effective attenuation coefficient for the filter material and dose-ratio parameters for effective depths that generate the desired intensity-modulated radiation therapy fluence profile when the filter is placed in the radiation beam. Stein et al are investigating the use of physical modulators fabricated using low-melting-point alloy poured into foam molds, which are cut using a computer controlled cutter.[66] In addition, Dubal et al recently described a compensating filter approach for intensity-modulated radiation therapy for the treatment of breast cancer.[67] The compensator method for intensity-modulated radiation therapy suffers from the cumbersome and time-consuming manufacturing process and from the need to enter the treatment room to change the filters, thus increasing the time allocated for patient treatment. It is likely that this approach will serve only as an intermediate step to large-scale implementation of multileaf collimator intensity-modulated radiation therapy treatments.

**Conclusion**

The use of 3DRTTP and 3DCRT/intensity-modulated radiation therapy dose delivery is advancing radiation oncology by providing the opportunity for both more conformal dose distributions and more complete and thorough safety systems. Although much of the current 3DCRT process requires interactive tasks (some still very laborious), the path is clear toward overcoming the technological
obstacles so that a nearly automated planning, delivery, and verification system will become a reality over the next decade. This system will allow radiation oncologists to significantly increase dose to many tumor sites while concomitantly lowering doses to organs at risk. Most of the tasks will be automated, thus lowering the overall costs currently needed to provide high-quality external beam radiation therapy.

These new technologies present a new set of QA challenges. The introduction of 3D conformal radiation therapy/Intensity-modulated radiation therapy techniques must be supported by strong QA programs. As many of these new technologies are not fully developed, there may be increased potential for patient treatment error. However, as long as there are rigorous QA procedures in place, a commitment to adequate staffing and continuing education, and the implementation of complementary safety and QA devices, such as a record-and-verify system, there should be no increase in errors. In fact, minimizing the human steps needed to treat a cancer patient with radiation will likely lead to a reduction in errors.

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