IMPLEMENTING IMRT IN CLINICAL PRACTICE: A JOINT DOCUMENT OF THE AMERICAN SOCIETY FOR THERAPEUTIC RADIOLOGY AND ONCOLOGY AND THE AMERICAN ASSOCIATION OF PHYSICISTS IN MEDICINE

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INTRODUCTION

Traditional radiation treatment techniques, including three-dimensional conformal radiation therapy (3DCRT), do not provide a method for sparing critical structures that push into and are partially or fully surrounded by a target or combination of targets. Intensity-modulated radiation therapy (IMRT) does provide the ability to spare normal tissues that are surrounded by targets with concave surfaces, and this advantage is currently being exploited to escalate tumor dose. Such truly three-dimensionally conformal dose distributions are now possible as a result of developments in the area of treatment planning with the addition of inverse algorithms and as a result of the introduction of the multi-leaf collimator (MLC) equipped treatment machines capable of delivering intensity-modulated beams. These new developments involve concepts that are not simple, and it is vital that those who intend to implement IMRT in a clinical program clearly understand the process, so that this new modality is safely applied. IMRT represents a new and exciting paradigm in the treatment of solid tumors, and it is expected that the development of such a clinical program will be encouraged not only from within the radiation oncology community but also from medical colleagues and hospital administrators. This overwhelming enthusiasm needs to be tempered by a humbling understanding of the complexities of IMRT implementation and delivery. It is with this background that the current document is written. However, although it is important to point out that the major goal of this undertaking is to promote the safe use of this important new technology, this document serves only for the purpose of educating our community about IMRT and should not be interpreted otherwise. In taking the reader through the steps of the IMRT process, it will become apparent that this new technology is both complex and time-consuming, and many suggestions are presented to help guard against potential errors.

This document should be viewed as a primer for the suggested procedures that can be used to form an overall plan for implementing IMRT. It is important for readers to understand that these procedures are in fact suggestions only and that strict adherence to the various IMRT techniques described here is not in any way mandated by the American Society for Therapeutic Radiology and Oncology (ASTRO) or the American Association of Physicists in Medicine (AAPM). The overall approach described here is not the only safe and effective way of introducing IMRT into clinical practice, and other safe and effective approaches are being used at a number of institutions. It is also important to point out that this document is not a statement of a standard of care and that practitioners are solely responsible for the safe and effective implementation of IMRT. There is no warranty, expressed or implied, of the suitability of this document for a particular purpose.

There are many examples of how the IMRT process can be misunderstood, leading to either undesired or even potentially dangerous results. Only one example will be given in this introductory section to illustrate the type of information provided by this document. The point is made in a number of sections that using inverse planning for IMRT will not guarantee an optimum treatment plan. One reason is...
that approximations are always introduced when moving from calculated intensity patterns to dose delivery, and mathematically optimum solutions are inevitably changed and therefore lost during this step. In addition, the results of inverse planning are strongly dependent on the specification of dose constraints and other parameters that guide the optimization process, and finding an optimum solution will depend on an operator’s ability to set dose constraints and state objective functions. If the operator does not specify the problem in a way that demands a good solution, it is unlikely that the best possible plan or a near equivalent will be obtained. A common outcome of these limitations is excessive underdosing of the target or targets. Although critical structure sparing is possible with inverse treatment planning, to an extent often not obtainable with traditional 3DCRT, such planning does not tell the operator whether a better plan exists, and it is possible to abbreviate or even entirely skip the important manual iterative step in the process that should be used to guide the optimization. Training and experience are essential elements in the pursuit of an acceptable plan in such situations. This document provides information that will help expedite implementation of a safe and effective IMRT program.

By way of introducing IMRT, one must consider the differences relative to older planning and treatment techniques. A partial list of examples is given here.

- IMRT dose distributions are often more heterogeneous within the target, which makes prescribing a dose to a single point generally unsatisfactory.
- IMRT intensity maps can contain many extrema and are often nonintuitive and unfamiliar to most radiation oncologists, physicists, and dosimetrists. Thus, incorrect application of modulated fields, in terms of their placement and orientation, may not be obvious to the user, forcing additional burdensome quality assurance (QA) steps.
- Radiation leakage through and between the MLC leaves, as well as through other shielding in the accelerator head, can result in a higher whole-body dose during IMRT, because the accelerator will usually be giving substantially more monitor units to deliver the desired tumor dose.
- IMRT allows for the simultaneous treatment of the primary tumor and regions of subclinical disease. This feature can make it difficult or even impossible to use “standard” dose fractionation for both volumes.
- Conformal radiation techniques, especially IMRT, often require an acute understanding of radiographic anatomy for both tumor and critical structure definitions.
- The highly conformal nature of IMRT is leading to significant improvements in such areas as target and organ motion detection and control and patient immobilization.
- IMRT requires a much-expanded emphasis on QA procedures to guarantee its proper implementation.

Given the substantial differences between IMRT and conventional radiation planning and delivery methodologies, this document, written by the combined ASTRO and AAPM committee, is intended to provide education for clinicians that are considering using this new modality. An additional important aim of this document is to suggest a program of training and clinical experience for all members of the treatment team, which will encourage the safe and effective use of IMRT. Suggestions for the division of roles and responsibilities of the various individuals involved in the process will also be given as part of this effort.

Furthermore, it is the intention of ASTRO and AAPM to provide complementary information to the definitions of IMRT that have been accepted by the American Medical Association and the Centers for Medicare and Medicaid Systems (formerly HCFA). ASTRO and AAPM clearly understand that IMRT is a technology that is rapidly evolving and that represents an exciting avenue for additional research and development. Nonetheless, it is vital that the radiation community appreciate that new techniques and technology require not only technical research but also clinical outcomes before becoming an accepted modality for the community radiation oncology practice. Although ASTRO and the AAPM encourage such research, it is important to understand that current reimbursement for IMRT is predicated on a process of care that has been subjected to peer review and that has been reviewed and approved by the American Medical Association and Centers for Medicare and Medicaid Systems.

**Planning a new IMRT program**

Starting a new IMRT program requires considerable planning and forethought. The following list is provided to emphasize this point. It is suggested that all of the items listed be considered essential parts of the process of establishing a program that is safe for patients.

Steps in starting a new IMRT program are as follows:

1. Define program scope for institution.
2. Develop staffing for this program.
3. Identify necessary space and equipment.
4. Develop a program budget.
5. Purchase equipment and prepare space.
6. Hire additional staff as needed.
7. Develop written policies and procedures.
8. Acceptance test new equipment.
10. Provide training for all personnel.
11. Develop and implement a comprehensive QA program.

**Patient selection for IMRT**

It is vital that radiation oncologists develop IMRT treatment protocols that either are currently accepted based on outcome data in peer-reviewed journals or follow existing multi-institutional IMRT protocols. Although it is not the intention of ASTRO and AAPM to dictate clinical conditions for IMRT to the physician, there is, nonetheless, an inherent danger in using this technology for what may seem like a worthwhile endeavor without understanding the con-
IMRT may improve target volume dose or reduce critical organ dose for a number of tumor sites treated with either curative or palliative intent. The decision process for using IMRT in clinical practice requires an understanding of the accepted peer-review practices that take into account the risks and benefits of such therapy compared with conventional treatment techniques. At this time in the development of IMRT, all clinical data are presented with short follow-up and are generally limited to prostate cancer and head-and-neck cancer. All other clinical sites should go through considerable deliberations before IMRT is used.

Examples in which IMRT can be helpful for head-and-neck treatment are parotid sparing for treatment involving either the nasopharynx or the oropharynx. IMRT is also a benefit for planning situations in which the combined tasks of using noncoplanar fields, applying wedges with varying collimator orientation, and assigning field weights become overwhelmingly complex. However, care should be taken to guarantee that considerations such as monitor unit efficiency are not compromised to the point that potential disadvantages outweigh the advantages of IMRT.

Intensity-modulated radiation therapy is often associated with very compressed isodose lines that can be placed between a target and a nearby dose-critical structure. However, it should be understood that this is not a unique characteristic of IMRT, and similar dose distributions might be achievable with other highly conformal, multifield plans. Again, in these cases, the advantages of IMRT must be carefully weighed against the complexity of this new technology and the potential for dose delivery errors or increased whole-body dose for the patient.

The advantages of IMRT are most obvious when a critical structure (e.g. the optic nerve) invaginates a target by creating a concavity in its surface (taken here as the planning target volume, or PTV) or when the critical structure is completely surrounded by that target. In this type of geometric situation, IMRT can be used to shape the isodose lines around the critical structure in a way that is not achievable with 3DCRT. A target that has regions of its surface that are concave should be a common condition for using IMRT instead of simpler treatment approaches.

The IMRT process

Once the determination is made that a particular case is indeed suited for IMRT, the process can be organized into the following list of patient-specific steps. The individuals responsible for the various tasks are indicated in this list (See Steps 1 and 2 for coding) in the order of their level of responsibility. This process is specific and particularly useful in inverse treatment planning; however, it should not be viewed as the only appropriate methodology.

Patient-specific steps

1. Based on available preplanning information, determine optimum treatment position and immobilize the patient (radiation oncologist, RO; dosimetrist, D; medical physicist, MP).
2. Establish reference points (e.g. using radiopaque markers) on the patient or the immobilization device in preparation for computed tomography (CT) scanning (radiation therapist, RT; D, MP).
3. Obtain CT images in the treatment position (RT, D).
4. Fuse CT data set with any other available imaging studies (D, MP).
5. Contour and develop all targets (e.g. gross tumor volume, clinical tumor volume, planning target volume), normal critical structures, skin surface, and other relevant regions of interest (RO, D).
6. Consider expanding critical structures with a margin to form a planning risk volume (PRV) (See 1993 ICRU Report #50) that allows for movement and setup errors (D, RO).
7. Write treatment planning goals as the total dose to each target, dose per fraction, and number of fractions, and state the normal structure dose constraints (RO).
8. Assign importance values or develop objective (sometimes called “cost”) functions or other methodology for developing the treatment plan as appropriate for the planning system (RO, D, MP).
9. Select gantry positions and table angles for standard MLC dose delivery or start/stop gantry angles for tomotherapy (D, MP).
10. Select beam energy (D, RO, MP).
11. Perform dose planning to meet or approximate treatment planning goals (D, MP).
12. Evaluate plan using dose statistics, dose–volume histogram (DVH) review, and visual examination of dose distribution (RO, D, MP).
13. As necessary, adjust dose constraints and cost functions, and repeat optimization process (RO, D, MP).
14. Approve final plan and write dose prescription (RO).
15. Determine monitor unit settings (D, MP).
17. Estimate (using a measurement, calculation, or some more generic approach) stray or leakage radiation dose reaching patient’s entire body or body site of interest outside the field of radiation, and inform radiation oncologist (MP).
18. Electronically transfer all treatment parameters into a verify-and-record system. Double-check all delivery information (D, MP).
19. Validate plan with film and/or chamber measurements (MP).
20. Verify intensity patterns when delivery approach allows this to be done (MP, RT).
21. Port film to verify isocenter placement before start of treatment (RT).
22. Evaluate and correct, if necessary, port film and other appropriate images (RO).
23. Deliver treatment (RT).
24. Document all treatment parameters, and record daily treatment in patient’s chart (RT).

25. Obtain and review weekly port films to document iso-center placement (RT, RO).

Planning strategies

Research is currently lacking on whether highly detailed intensity maps are a requirement for producing complex dose distributions. However, it is prudent to match the treatment planning and delivery processes to obtain an efficient overall IMRT technique. For example, if a particular planning algorithm produces a highly detailed intensity map, a delivery method capable of faithfully reproducing the distribution should be used. Alternatively, using complex delivery techniques when a particular inverse planning algorithm produces simple intensity distributions could lead to unnecessary errors.

There are many different combinations of the planning and delivery parts of IMRT, and it is important to understand that the exact configuration of the total system can have an important impact on a number of aspects of the IMRT process. Examples of the things that might be modified as the combination of planning and delivery change are leakage radiation, treatment verification, QA procedures, treatment time, and MLC wear and tear.

Forward treatment planning

Distinguishing between forward and inverse treatment planning is not easy, because the two methodologies are interconnected. One way of separating these two planning techniques is to think of forward planning as focusing on the beams used for treatment, whereas inverse planning starts with a description of a desired dose distribution and derives the beam shapes as a second step. The distinction is blurred, because during forward planning, the operator must consider the final dose distribution when selecting either beam apertures or beam modifiers (e.g., wedges). However, even with this overlap, inverse treatment planning is a distinctly new approach that can produce dose distributions not previously obtainable. Forward planning, which includes also the use of class solutions, is an approach that uses treatment settings that have worked in the past for a specific site, but inverse algorithms are not employed (See “Aperture-based inverse planning” for the weight-optimized version of this approach). Starting with a set of conformal fields, some internal apertures, wedges, or possibly even additional beam directions are added to modify the shape of isodoses lines so that they bend around critical structures or to boost certain regions of the target (1).

Inverse treatment planning

Inverse treatment planning defines the desired dose to target and critical structures as a starting point, and intensity-modulated beam arrangements are derived to “acceptably” approach or meet these desired dose limits. At least single-point dose constraints, but more commonly a multipoint description of dose–volume limits, drive the process. Objective functions or importance values can also be used to steer or guide the optimization.

Beamlet-based inverse planning. Traditional treatment plans, including 3DCRT, typically use fewer than 10 fields. This number includes the fields used for boosting certain regions of the target and the addition of electron fields over the spinal cord for some head-and-neck treatments. IMRT is different in that the number of fields used in the final plan can be more than 50 and, for a delivery technique called tomotherapy, can easily go above 1000. Inverse treatment planning uses modern computer technology to help solve the difficult problem of assigning weights to this large number of fields, so that dose constraints for both normal tissues and targets may be met and objective functions satisfied. Inverse treatment planning is the most common treatment strategy currently used for IMRT and is an essential step for complex planning situations such as head-and-neck cases with multiple targets carried to different total doses and numerous critical structures.

In working with such a large number of fields, inverse planning algorithms must test millions of combinations to satisfy numerous dose constraints that are based on the contoured tissue of CT, magnetic resonance imaging, and/or positive emission therapy images. Early work by Brahme et al. (2) expressed the relationship between a desired dose distribution and the required radiation intensity function as an integral equation. Later work by Censor et al. (3) led directly to the planning techniques that are now used to solve the inverse radiation therapy problem. These authors were the first to describe the fully discretized optimization model that was driven by a clear statement based on planning goals. This technique, called beamlet-based inverse planning, considers small-beam elements (typically 1 × 1 cm or 0.5 × 0.5 cm) in the optimization. This method can result in a very large number of beamlets with corresponding weights. However, in some cases, the beam elements are grouped using sequencer (also called translator or interpreter) software that allows a more efficient delivery with a standard MLC. This translation leads to the 50 or more fields mentioned above. It is also possible to use special binary collimators (The NOMOS MIMic collimator is an example) to handle the large number of beam elements without taking the approach of combining beamlets. Binary collimators can deliver an extremely large number of individual beamlets.

Aperture-based inverse planning. Beamlet-based inverse planning works from a large number of small beamlets to a more manageable number of larger apertures. Another method, called aperture-based inverse planning, is closely related to the class solution method discussed above. In this case, the apertures are set from the beginning of the process using a set of rules that tend to follow anatomic contours as they are seen in the beam’s-eye view for each beam direction (4). These apertures may be the same as, or at least similar to, those used for the class solution approach. The difference is that the same inverse planning algorithms used for beamlet-based planning and driven by dose constraints
and objective functions are used to find the weights of these apertures. The idea of aperture-based planning is that the field openings used in the optimization can be controlled to simplify the delivery step, with a reduction in the total number of monitor units needed to solve a particular planning problem.

**Direct aperture optimization.** There are new techniques that optimize the shapes and weights of the apertures during the optimization process (5). The constraints imposed by the MLC are directly incorporated in the optimization process, and the plan is ready for delivery at the end of the optimization. Research aimed at the clinical demonstration of this approach for simplifying delivery without sacrificing plan quality is ongoing.

**Delivery techniques**

The mechanical parameters that can be continuously varied during IMRT dose delivery are gantry position, MLC configuration, and couch position. If the MLC leaves or the MLC plus the gantry move when the beam is turned on, the delivery is referred to as dynamic. In some cases, treatment unit output is also adjusted as these mechanical components are moved. When the gantry rotates and a binary collimator is used for delivery, the technique is called tomotherapy (See Fig. 1). If the gantry rotates while a standard MLC changes shape, and the intensity pattern is built in layers, the treatment is referred to as intensity-modulated arc therapy (6) delivery. There are 2 types of tomotherapy. Serial tomotherapy moves the patient support system by a set amount after each arc is completed, and the beam is shut off. Spiral tomotherapy duplicates the helical pattern used for CT scanning by moving the couch in a smooth motion as the radiation source rotates continuously. Of these three rotating gantry techniques, only serial tomotherapy with a binary collimator is in routine use treating a significant number of patients at this time. The binary collimator was described by Carol et al. (7) and Mackie et al. (8) and is manufactured by the NOMOS Corporation (Cranberry Township, Pennsylvania). This is an add-on collimator that can be positioned below the standard jaws of any linear accelerator.

There are two distinct methods of dose delivery that are employed when a standard MLC system is used together with fixed gantry positions. Each was developed at about the same time as the work cited above for the binary collimator. These are the superimposed field technique, first suggested by Galvin et al. (9), and the so-called sliding window technique, proposed by Convery and Rosenbloom (10). The superimposed field segment technique is simply a way of taking the matrix of beamlet weights for a fixed gantry angle and organizing them into an efficient delivery of overlapping subfields. The sliding window technique uses an open field strip defined by a standard MLC that moves across the total field width. The window opening for each multileaf collimator element pair varies as the leaves move across the patient, so that the intensity pattern determined for opposed leaves can be different according to the different leaf trajectories used. As described by Convery and Rosenbloom (10), this mode of delivery has the radiation beam on during the entire delivery and is called “dynamic multileaf collimation,” or DMLC.

The delivery can also be accomplished in a stepwise fashion with the beam paused as the leaves move between control points and is called a “step-and-shoot” technique. Implementation of the superimposed field technique uses a step-and-shoot delivery and is sometimes referred to as “segmental multileaf collimation.”

Another approach currently in the research stage of development places a physical attenuator in the path of the beam at fixed gantry angles instead of using the MLC. Physical attenuators can produce arbitrary intensity patterns by introducing different amounts of attenuating material in the path of the beam at different positions within the
beam’s-eye view projection of the target. There are three potential limitations to this approach: First, the maximum amount of attenuation that can be achieved with such a device is limited by the attenuating properties of the material used for the compensators. Second, the limited attenuation of most of the materials used for compensators requires the combined use of either cerrobend blocks or an MLC to limit the transmitted radiation that occurs outside the beam’s-eye view of the target to the typical 3% to 4% value. If cerrobend blocks are used to define the field in which the compensator is used, an additional fabrication step is added. Third, there is no readily available automatic equivalent to MLC-based IMRT, and the physical devices must be changed during treatment. However, this technique has a major potential advantage of requiring far fewer monitor units, thus resulting in less patient whole-body dose compared with multileaf IMRT. Additionally, physical attenuators may allow for steeper dose gradients, because the technique is not limited by the size of a collimator leaf or its orientation. Although there is intense research interest in this methodology for IMRT delivery, it is not currently an accepted delivery method as defined by the current procedural terminology nomenclature, and the existing current procedural terminology codes for IMRT planning and delivery (77301 and 77418) should not be reported for billing purposes when facilities use this methodology (As new methodologies for IMRT are developed, and after their processes of care are subjected to peer review, ASTRO will consider submission of these methodologies to the American Medical Association for its evaluation for possible addition to the current procedural terminology nomenclature).

**IMRT is a new paradigm**

Intensity-modulated radiation therapy represents a new paradigm within the field of radiation oncology, because it allows for true conformal dose distributions to be planned for and implemented. The best example is the creation of an invagination or concavity in a dose cloud having an otherwise convex surface. If a concavity in a target is the result of a critical structure pushing against its surface or overlapping its PTV, protection of this tissue not previously achievable can be produced using IMRT. Often the improvements in the dose distribution with IMRT are accomplished at the expense of dose homogeneity within the target, and high-dose regions sometimes spill over to surrounding critical structures. Dose homogeneity is not the only compromise related to the use of IMRT. Often monitor unit efficiency is degraded, and beam-on times increase with the introduction of IMRT. Furthermore, making changes in the position of isodose lines is not as easy with IMRT as it is with conventional 3D conformal planning. In the past, isodose lines were to a great degree controlled with simple changes of aperture sizes and/or field directions. For IMRT, this control is indirect and involves adjusting the dose constraints and other parameters used in the optimization process, and sometimes it is not possible to obtain an exact fit of the dose cloud to some highly irregular target.

Each IMRT dose delivery system coupled with a particular inverse optimization approach has its own set of advantages and disadvantages. While recognizing that no system is perfect, it is important for each institution preparing for or currently using IMRT to understand the features of the particular system chosen for IMRT. For example, it would not be hard to make choices that drive segment numbers so high that treatment times would become too protracted for the patient to remain in a stable position; or to make choices resulting in monitor units so high that leakage radiation reaching the patient total body was excessive. Therefore, although true optimization can be planned, its implementation may require compromise by both the physicist and the physician. A clear understanding of such is vital for the implementation of IMRT for any given patient.

One simple way of handling the problem of balancing the trade-offs inherent in the IMRT process is to set limits. Doing so may involve using the following list of items, and separate lists could be made for different disease sites.

**Competing factors for IMRT:**

- Amount of leakage radiation reaching the patient’s total body
- Overall treatment time
- Dose heterogeneity for the target
- Level of undertreatment for the target

Calculating leakage radiation reaching the patient is a simple matter when the ratio of the required IMRT monitor units to the monitor units used traditionally to treat a particular site is compared as a crude measure. Tomotherapy approaches can increase this ratio by more than a factor of 10, but it is important to point out that the ratio of monitor units does not tell the entire story. If extra shielding is placed in the collimator system and the accelerator head near the collimator, its attenuation should be taken into account. However, measurements similar to those made to verify leakage radiation at the time any linear accelerator is commissioned can be used to make sure that the extra shielding is positioned to decrease leakage radiation for all parts of the patient’s body. If it is decided that leakage radiation reaching the patient is higher than the desired value, the user has 3 options: (1) The number of sweeps of the gantry can be limited when tomotherapy is used (e.g., using a separate, more monitor-unit efficient standard supraventricular field when treating head-and-neck lesions); (2) A larger tomotherapy aperture can be used, so that more anatomy is treated for each pass of the gantry; and (3) An IMRT dose delivery technique that is more monitor unit efficient can be substituted. The major point here is that taking any of these measures to decrease leakage radiation will affect one or more of the items listed above. That is, it is likely that dose heterogeneity will increase and/or it will be harder to avoid some increase in the amount of underdosage of the target.

Similar arguments can be made for the number of seg-
ments used for step-and-shoot dose delivery. Various optimization parameters can be changed to decrease the number of segments as a technique of speeding dose delivery. For example, the number of intensity levels used in the translation of the intensity pattern derived from the inverse optimization can be decreased as a means of decreasing the final number of segments. However, this modification will again negatively change target coverage and target dose homogeneity.

Some of the changes mentioned in this section are easily accomplished, and the user is encouraged to experiment with different settings for the optimization software. It may also be possible to easily change the dose delivery method. This is because the same inverse planning software package may offer more than one option. For example, a system might have the ability to use either the dynamic sliding window or the step-and-shoot sliding window. The expected difference for these two approaches will be the delivery time. The reason for listing the 4 items of leakage radiation, treatment time, target dose heterogeneity, and target coverage is to use these factors as an aid in making decisions for the selections of options and parameters for both the planning and the delivery aspects of the IMRT process. When performing inverse planning, multiple iterations are required to better understand the subtleties of the above-noted examples. At least during the early phase of implementing a new IMRT program, performing only 1 or 2 iterations will substantially limit one’s understanding of the advantages or disadvantages of inverse planning.

TRAINING REQUIREMENTS FOR IMRT

Steering dose optimization to produce a plan with dose homogeneity and target coverage that is not severely compromised relative to that obtained with conformal techniques while taking advantage of IMRT’s ability to spare invaginating critical structures is not a simple task. Obtaining good plans for complex cases is often difficult and requires hands-on experience and/or extensive training for members of the radiation oncology care team. A number of training courses are available for IMRT. Some academic institutions and IMRT vendors offer such training, and private companies have started courses on IMRT as well. In addition, the various professional societies have developed symposia and workshops on the topic. With the rapid proliferation of IMRT programs within academic/research institutions, many resident trainees by now have had exposure to this new technology.

Training for the other members of the radiation oncology team is also important. A medical physicist responsible for an IMRT program must be aware of the large number of associated technical details and clinical considerations associated with IMRT planning and treatment. As more and more community departments with limited physics and dosimetry support start using IMRT, the possibility that patient safety will be compromised is of great concern. For this reason, training of physicists and dosimetrists in the use of IMRT is important. Through the accrediting and educational processes, organizations such as ASTRO, AAPM, and the Commission on Accreditation of Medical Physics Education Programs are working hard to make sure that proper training and education for IMRT are made available in the future.

Intensity-modulated radiation therapy treatment planning is not yet fully automated. The medical physicist and dosimetrist cannot sit down at the planning workstation, request a certain dose distribution, and receive a result that exactly matches this request. Instead, the entire procedure remains an iterative process. Because of the numerous technical and clinical variables associated with IMRT methodology, experience and rigorous consideration of the complexities are key to helping the novice negotiate the steep learning curve. ASTRO and AAPM believe that one should not rely solely on the companies selling treatment planning equipment for IMRT to provide training, but should develop the fund of knowledge required to safely master the complexities of IMRT from multiple sources, including peer-reviewed literature, textbooks, formal course work, and hands-on training. IMRT is evolving, and dynamic and continuing education will be crucial for maintaining skills.

EQUIPMENT COMMISSIONING FOR IMRT (RESPONSIBILITY OF MEDICAL PHYSICIST)

In general, the commissioning of a complete (planning plus delivery) IMRT system is quite complex. The discussion in this section will separate the commissioning aspect into the planning and delivery components and will end with a presentation of the issues that relate to the combined process.

Dose calculation algorithm issues

Different inverse planning systems can have very different approaches for handling IMRT. Some systems might use approximate (primary beam only) dose calculation schemes compared with the algorithms that are now standard for 3D conformal planning. Few systems, if any, rely strictly on these results for treating patients. It is common practice to complete the inverse planning process by recalculating the dose as a final step using a more precise algorithm to guarantee that the delivered dose is correct. This recalculation is accomplished using a more sophisticated algorithm and with beams directed through the initially derived apertures. It should be understood that this approach makes the optimization process hard to control. This is a fundamental problem that is best illustrated by discussing a complex planning case such as treatment of a head-and-neck tumor under a cooperative group protocol with a beamlet-based inverse planning approach. The obvious way to start the inverse optimization is to use the dose constraints stated in the protocol as input into the planning process. For most systems, doing so will produce some result that may or may not meet the dose constraints. If the constraints are not met, various parameters within the plan-
ning system can be adjusted to try to improve the result. If the dose constraints in the protocol have been properly stated and thus are generally achievable, this adjustment should not involve relaxing the dose values. However, this technique is not guaranteed to work, because some target geometries could prove more complex than anticipated by the drafters of the protocol. For a difficult case, and after what could be a number of iterative runs, an accepted plan is obtained, and a delivery method is selected. At this point, a more precise method of dose calculation is introduced. When it is possible to create a plan that is better than what is required by the protocol statement of dose constraints, some change of the dose distribution introduced by recalculation might not be a problem. On the other hand, if this calculation degrades the plan (in the sense that the overly optimistic result of the less accurate algorithm is corrected by the more accurate follow-up calculation) and puts it outside the stated dose constraints, it is not obvious how to proceed to achieve an acceptable result. The problem is that introducing a different calculation algorithm midstream in the iterative process of finding an acceptable plan complicates the procedure of working toward a solution that meets the demands of a complicated protocol.

The solution to this problem is to perform the optimization using a dose calculation algorithm that is as sophisticated as possible. Unfortunately, as already stated, the accuracy of the dose calculation used during the initial optimization may not be under the control of the user. This difficulty has led some treatment planning system manufacturers to take the approach of going one step further than simply performing a recalculation with a more accurate algorithm when the optimization is complete. Instead, at the end of a beamlet-based inverse optimization, the derived apertures are used for an additional inverse “weight” optimization that uses the more precise dose calculation algorithm. This method can potentially avoid a dramatic modification of the dose distribution as the change from a crude to a more precise calculation algorithm is made. However, especially when desired dose constraints were never achieved, using this approach could miss better plans that use a different set of apertures.

Although the example used here is for treating under a cooperative group protocol, this same conflict will arise during the process of finding a final plan for nonprotocol cases as long as the user adopts the philosophy of starting with fairly strict dose constraints for any IMRT case and relaxing them with caution until a solution is found. Thus, users should be aware of the limitations of the particular IMRT treatment planning system they are using so that the best possible dose distribution is found for a particular planning problem.

During the phase of purchasing a new IMRT treatment planning system, it is recommended that manufacturers be asked about the differences that might be expected when comparing dose-volume histograms obtained after the optimization step with those obtained after dose delivery has been brought into the process and a final calculation of the dose distribution performed. Also, during the phase of taking commissioning measurements for a new IMRT system, it is helpful to allocate some time to understanding the relationship between the dose distribution that results from the initial optimization and that obtained after reoptimization with a more accurate algorithm or after a final inverse weight optimization of the apertures.

**Commissioning of the multileaf collimator**

The important issue for MLC commissioning relative to IMRT is the calibration of leaf position. This is not to say that careful calibration of an MLC system is less important for other modes of radiation therapy. However, implementing IMRT with a standard MLC introduces an additional consideration in that positioning of the MLC leaves for IMRT can be slightly different from when this device is used for simple block replacement. This difference is an issue for MLCs that have rounded ends. Confusion about how the leaves can or should be calibrated might lead to important dose errors that can easily be avoided. For step-and-shot delivery techniques, this problem can best be visualized as a lack of proper abutment of the different field segments that make up the intensity pattern. For DMLC, this problem can be visualized as a scanning window that has an incorrect width, for example, one that should have the leaves separated by exactly 10 mm being reduced to 9 mm as a result of calibration error, so that some point under the moving slit receives a dose that is 10% low.

A number of investigators (11, 12) have demonstrated that the rounded-leaf end geometry makes the edge projected by the light diverge slightly from the position where the beam intensity for an MLC-defined field falls to 50% of its central value. These studies have shown that the X-ray field will be larger than the light field by about 0.5 mm on each side of a field. There are two ways of handling this problem: (1) The leaves can be calibrated to agree with the actual X-ray field, and (2) A correction can be made within the treatment planning to adjust for this difference. In either case, it is up to the user to understand this problem and to make the adjustments necessary to guarantee accurate dose delivery. The references cited above plus one more recent paper (11–13) present detailed descriptions of the procedure that could be used to calibrate an MLC for DMLC dose delivery.

**Commissioning of the combined system**

A major problem in describing exactly what is needed for the step of commissioning a system for IMRT is the multitude of combinations of inverse planning approaches and dose delivery methods used by the companies selling IMRT planning packages. This difficulty is compounded as a result of the very different hardware provided by the various linear accelerator manufacturers. An additional problem results from the fact that a single treatment planning company can offer, in the same planning package, a number of different combinations of optimization algorithms and delivery techniques. For example, the user might be able to select be-
tween a sliding window step-and-shoot approach and DMLC. Alternatively, a selection between sliding window and superimposed fields might be available. In cases in which different combinations are possible, it is important to consider each combination as a separate capability and to guarantee that options that have not been commissioned are blocked from use until their commissioning is complete.

It must be recognized that there is no perfect delivery system. All of the approaches mentioned in Fig. 1 have advantages and disadvantages when measures like QA overhead, faithfulness of intensity pattern modeling, and monitor unit and segment number efficiency are considered. In addition, implementation of any one of the delivery techniques presented in Fig. 1 may differ from one treatment planning company to another. For this reason, when various delivery options are offered for the particular accelerator available for IMRT, for the verify-and-record system used for IMRT control and for the planning system used, it is best to start with a single technique and to add other approaches only when those methods are fully understood and commissioned.

In the case of simple forward planning, it is possible to use extremely straightforward techniques to verify that a treatment planning system is performing within acceptable limits. Single fields can be computer generated and checked to demonstrate that they agree, within well-established limits available in the literature, with measured data. This is not true with IMRT, for which each field can be unique, and commissioning for IMRT must include the extra step of checking results at the level of the final combined fields.

This subsection will limit the discussion of the commissioning of the combined systems to checks that are performed at the final stages of the process and are aimed at identifying problems in the overall procedure. The method described here is generic in the sense that it can be used for any combined system, and it is easily implemented for each. However, promoting this approach to verifying equipment performance should not be interpreted as indicating that more extensive testing is unnecessary. Detailed commissioning tests are essential when attempting to analyze problems that are detected during the verification procedures used to test final output of the combined system, and the user is encouraged to perform tests that are tailored to address the specifics of individual systems.

The procedure described here requires a small amount of equipment that should be available for any center considering starting an IMRT program. It is modeled on the procedure first used by NOMOS to check the commissioning of their IMRT system. This company provides a rectangular solid phantom that accommodates film, and a minor modification to this device allows a small ionization chamber to be used, as well. The first step is to obtain CT scans of the phantom. The planning tools that should exist as a part of the contouring package on any treatment planning system can be used to draw shapes to represent targets and critical structures. Dose constraints are established, and the contours are used to optimize the dose for some field arrangement established by the user for testing. The film must be cut to a size that guarantees accurate positioning, so that a printout of the dose distribution can be properly registered with the measured dose distribution. The phantom with film is irradiated, and the calculated and measured dose distributions are compared.

It is suggested here that in addition to tests adopted by the manufacturer of a treatment planning system, relevant AAPM Task Group reports should be consulted to identify checks that should be carried out to verify the performance of the entire system (planning plus delivery).

Handling routine software upgrades for inverse treatment planning systems is different relative to 3DCRT in that these new systems integrate the treatment planning process with dose delivery. Inverse planning systems derive the intensity patterns needed to produce a prescribed dose distribution and provide software to translate the patterns into the MLC movement or positions needed to model the intensity maps. This integration changes the way software upgrades for treatment planning systems have been handled in the past. The major difference is that, at least for some types of changes in the software, performance checks must also include the delivery part of the process.

**Tissue heterogeneity corrections**

The Radiation Therapy Oncology Group (RTOG) has made tissue heterogeneity corrections a requirement for their IMRT head-and-neck protocols. As an increasing number of other cooperative group protocols are launched to study IMRT, it is critical that the dose calculation used for inverse planning be as sophisticated as possible to eliminate this factor as a possible criticism of the final outcome of a particular study. This means that it is critical to carefully and fully commission all aspects of the dose calculation algorithm, including the part that carries out the corrections for tissue heterogeneities, when this is handled as a selectable option.

The problem with heterogeneity corrections for IMRT is that few systems provide easy ways to directly check the accuracy of the algorithm used for optimization. However, for the systems that follow the optimization with a more accurate dose calculation method, it should be possible to perform certain simple verification tests. For example, if a Monte Carlo calculation is used for recalculation of the dose distribution using the apertures derived during optimization, the accuracy of this algorithm can be checked against measurements for simple beam geometries. Of course, such tests are outside of the optimization process, so that the result may be accurate, whereas, as is pointed out in “Dose calculation algorithm issues,” the plan is not truly optimal.

At least for the majority of cases that do not have a metal prosthesis in the path of any beam, tissue heterogeneity corrections will not substantially change the dose distribution for prostate treatment. When there is a metal prosthesis, it is sometimes possible to select the beam directions so that the high-density regions are avoided. For treatment of tumors in the head-and-neck region, air cavities can change
the dose distribution, and heterogeneity corrections are recom-
mended for the final dose calculation. The technique of compar-
ing corrected and uncorrected plans can always be used to give some level of comfort that the obtainable target coverage and critical structure sparing are not substantially changed.

The change in the dose distribution when beams pass through a large amount of lung tissue can be significant. Currently, considerable research is going into investigating how IMRT might be applied to this disease site. Until these data are available in the peer-reviewed literature, treating lung lesions with IMRT should be considered research only.

THE IMPORTANCE OF PATIENT IMMobilIZATION (RESPONSIBILITY OF RADIATION ONCOLOGIST, RADIATION THERAPIST, DOSIMETRIST, AND PHYSICIST)

Intensity-modulated radiation therapy provides a method for handling many treatment planning problems that were previously unmanageable or that required complex solutions that were not very elegant and were hard to implement. With this new technology, it is now possible to treat lesions that partially or fully surround critical healthy tissues, but the demands on the immobilization system used to control the patient’s daily setup may be noticeably increased. This section discusses this problem.

Institution-specific effectiveness of immobilization

To take full advantage of the ability of IMRT to tightly conform dose distributions to targets that abut or even partially or fully surround critical structures and to use this important feature to decrease margins, it is important to pay close attention to patient immobilization. The safe dissemination of IMRT will, to some degree, depend on the use of immobilization techniques that achieve a setup reproducibility that is consistent with the reduction in margins that automatically occurs when isodose lines have to be threaded between a target and a critical structure that lie in close proximity.

It is important to analyze each different disease site at which this new treatment modality will be used to determine the level of setup reproducibility that is required and to adopt the degree of immobilization that is appropriate to meet that need. It is also important to realize that immobilization accuracy will be patient specific. Elderly or obese patients, for example, may present much more challenging immobilization problems than young, thin patients.

The RTOG has adopted an interesting approach relative to immobilization for its head-and-neck IMRT protocols. All institutions might consider this approach when starting to use IMRT for the first time for each new disease site. Using the RTOG oropharyngeal cancer protocol as an example, growth margins of 5 mm are required for all targets when forming PTVs and for the spinal cord when forming a PRV. However, participating institutions can apply smaller margins if they perform studies documenting the reliability of their immobilization for head-and-neck treatments; they must forward this information to the RTOG QA Center for review and approval. It is possible for any institution to apply this approach to each new disease site. Information available in the literature (14, 15) can be used to establish a recommended margin size, or the numbers found in the literature might be reduced based on an institution’s demonstration to itself that such a change is justified. This can be accomplished by copying the techniques reported in the literature.

Consequences of organ and tissue motion and deformation

Intensity-modulated radiation therapy tends to accentuate the problem of structures moving in and out of high- and low-dose regions, because the dose distribution is built using any one of the delivery methods described above. Using tomotherapy as an example, the dose is delivered in narrow cross-sectional strips, and the possibility exists for a portion of the target volume to move in a way that allows it to receive a dose that is substantially less or substantially greater than the prescribed dose for a particular fraction of the dose delivery. The same situation can occur for a narrow sliding window delivery approach at fixed gantry positions, but the underdose or overdose should not be as severe as it might be for tomotherapy, because the dose delivered during 1 fraction is divided over a number of different gantry angles. As new gantry angles are added, underdosage and/or overdosage will tend to be averaged. For tomotherapy, averaging from fraction to fraction can occur, and this problem may yet prove to be unimportant. Although this problem has not been shown to be clinically relevant for either step-and-shoot IMRT or tomotherapy, it is a theoretical problem for regions of the body such as the lung, where respiration can constantly move a target. However, there continues to be considerable interest in this problem, and research is being conducted by a number of institutions (See, for example, Refs. 16 and 17) to try to control the motion of structures during IMRT.

Treating during suspended breathing is one solution to the problems created by respiration movement when using IMRT. The effectiveness of voluntary breath holding techniques is not easily confirmed, and the use of gating technology is still in its infancy. Given the complexities of using either of these techniques and the lack of clinical supporting data at this time, AAPM and ASTRO do not consider IMRT appropriate for lung cancer in a nonresearch setting. This statement supports the conclusion drawn in “Tissue heterogeneity corrections,” which was based on uncertainties about the accuracy of inhomogeneity corrections for IMRT treatment planning.

In addition to the movement caused by breathing, other physiologic changes in the body can result in either intrafraction or interfraction changes in the position of internal structures. In the first case, organ filling can change during treatment, whereas in the second, the changes occur between treatments. Such changes can shift the location of not only the structure that is filled but also the position of any surrounding structures. Examples of this situation are
changes of bladder filling and changes in rectum and bowel filling as the amount of fecal matter and gas changes. The between-fraction changes are potentially addressed with the adaptive therapy techniques described in the next section.

Adaptive therapy

Adaptive therapy is the use of certain types of imaging information acquired during the course of radiation therapy to change a patient’s setup or treatment plan to improve dose conformality. There are adaptive therapy techniques that adjust the isocenter of the treatment beams at the time each fraction is delivered, so that different positions of the patient on the treatment couch can be accommodated, and margins can be reduced. These adaptive therapy techniques substantially lessen the requirements on the immobilization system. One popular adaptive therapy technique uses ultrasound to localize the prostate for each treatment fraction (18). The idea is to use the ultrasound information to simply reposition the treatment isocenter to follow structure movement. Such systems are fast, and it is common to have the radiation therapist perform the ultrasound procedure and make the isocenter adjustment.

A second popular technique implants gold marker seeds (on the order of 5-mm \( \times \) 1-mm diameter) at 3 positions in the prostate and uses them to adjust field apertures each day (19). This approach usually employs an electronic portal imaging device to visualize the seeds and requires some software to achieve fast correction.

Another approach to adaptive therapy uses frequent or daily CT imaging to determine a patient’s current position relative to initial planning. This information can be gathered each day before the patient’s treatment or as 2 or 3 separate studies performed before the start of the first treatment. Obtaining the CT scans before each treatment could allow a correction to be made on a daily basis and is referred to as an “online” approach. The technique of scanning a number of times before the start of treatment provides a method for establishing patient-specific margins (20). It is referred to as an “offline” approach; the information gathered before treatment starts determines the size of the margins used for treatment. Also, accumulating CT data for a number of patients can be used to provide important data for establishing site-specific margins.

The use of ultrasound to obtain daily localization information for prostate treatment is now considered state-of-the-art, whereas obtaining daily CT information is considered still experimental.

DOSE PRESCRIPTIONS FOR IMRT
(RESPONSIBILITY OF RADIATION ONCOLOGIST)

This section argues that the complexity of inverse treatment planning necessitates the use of clear treatment planning goals to transfer information from the radiation oncologist to the dosimetrist. The treatment planning goals can take the exact form as the final written prescription, but they serve a different purpose in that they can be modified a number of times as the iterative inverse planning proceeds. The final version of the treatment planning goals can be used to write the prescription for the patient’s treatment. In addition, it is important to understand that the numbers entered into the treatment planning system may differ somewhat from the dose constraints specified by the radiation oncologist. This deviation between input data and the final results is system dependent and can go beyond the inability of the software to achieve what is requested. In some situations, it is possible that artificial numbers must be used to move dose distributions and their DVH representations in one direction or another. To summarize, there are 3 separate concepts that should be clearly understood: (1) the original statement of the physician’s goals, (2) the values entered into the treatment planning system to drive the optimizer (planning parameters), and (3) the statement of the final planning results as a prescription for treatment.

Treatment planning goals

There are two major reasons for encouraging the use of clear, detailed goals for inverse planning. First, this procedure helps avoid the possibility of unknowingly leaving important information out of the optimization. Developing treatment planning goals as separate templates for different disease sites can serve as a reminder of relevant critical structures. Second, when initial goals cannot be satisfied, it is important that these goals be revised in a careful and organized way by the radiation oncologist until an acceptable solution is found. It is also important that the treatment planner, having understood the physician’s goals, modify the planning parameters in a careful and organized way to have the best chance of finding a plan that satisfies the physician’s goals.

The first point can be made with the example of contouring the spinal cord but forgetting the brainstem where it intrudes slightly into the top of the target region for a head-and-neck treatment. If dose constraints for the brainstem are not included as part of the optimization, the possibility of developing an IMRT planning solution that overdoses this structure exists. Only an examination of the dose distribution for the cross-sectional slices passing through the upper part of the target will detect the problem. That is, the DVH for this structure will not exist if it is not contoured, and no equivalent of a forward-planning port film is available for IMRT treatments. Thus, the possibility of this problem’s going undetected is substantial.

Examples of the second point are the following: (1) dose constraints and objectives are set at the start of planning, so that they are easy to meet, and (2) the planning parameters are relaxed during the iterative process with large increments when a solution is not reached. In both cases, it is impossible to know whether solutions that are better than the one obtained exist and have been missed. One solution to this problem is to set the initial dose constraints and objectives so that a solution is not found and then to relax these limits in small increments by entering new planning
parameters. The task of defining obtainable planning goals is greatly simplified if there exists an IMRT treatment procedure for a particular disease site that is written by a multi-institutional protocol group. Alternatively, it might be possible to find the information needed to write the treatment planning goals by referring to the peer-reviewed literature. Another, less desirable, possibility is to base dose constraints on past experiences of similar cases treated using 3DCRT techniques.

For the purpose of this document, the treatment planning goals and the final written prescription have the same form. The specifics are included in the following section, where an oropharyngeal cancer IMRT protocol (#H-0022) developed by the RTOG is discussed in some detail. As an example of an IMRT prescription, the information given in this protocol is very specific. This prescription information can be easily modified to become the treatment planning goals for an oropharyngeal cancer case. This modification from the RTOG prescription to the treatment planning goals is accomplished by replacing actual dose values with blanks so that the results of each planning run can be inserted as the planning progresses.

The same general format used for the oropharyngeal protocol can be applied to other anatomic sites by making appropriate modifications. An example of how this general idea might be transferred to a different site is the nasopharyngeal cancer protocol #0225 (See the RTOG web page www.rtog.org), for which the same template has been used to state the treatment planning goals and the prescribed dose.

The dose prescription

Creating the dose prescription for an IMRT treatment is complex for two major reasons. First, some inverse planning algorithms are currently designed to allow parts of the target to receive a higher dose simultaneously, whereas other parts purposely receive a lower dose. This simultaneous boost technique requires some compromise in the overall fractionation scheme used for IMRT, compared with traditional sequential boost approaches. For this reason, it is suggested that a clear statement of the dose per fraction and number of fractions be explicitly stated in the planning goals/prescription for each target region. This technique encourages the radiation oncologist to carefully consider the adjustment that must be made in the total dose for a particular region of the target when it is necessary to use an unconventional number of fractions or total dose, that is, when forcing all targets to receive a particular prescribed dose in the same number of fractions. Taking the RTOG oropharynx protocol as an example, the dose prescription for the targets is written as follows:

The gross tumor will receive a total dose of 66 Gy delivered at 2.2 Gy per fraction in 30 fractions of 95% of its volume. Regions of subclinical disease considered to be at high risk will receive up to 95% of their volume, a total dose of 60 Gy delivered at 2.0 Gy per fraction in 30 fractions, and subclinical disease at low risk will receive up to 95% of its volume a total dose of 54 Gy delivered at 1.8 Gy per fraction in 30 fractions.

The second problem with writing prescriptions for IMRT relates to the reason that this new treatment modality is so appealing. IMRT allows the sculpting of dose distributions to follow the irregular surfaces of complex targets and to accommodate critical structures that invaginate these targets or their PTVs. However, control over the dose distributions is not perfect, and some compromise in target coverage and dose homogeneity is expected. This compromise often forces a situation in which incomplete target coverage and increased dose heterogeneity must be accommodated as part of the prescription. One way of handling this problem is to state the allowed underdose and overdose as part of the prescription. For many inverse planning systems, a series of points describing a crude dose–volume histogram can be used to guide the optimization. Again, the RTOG oropharynx protocol is an example of how 3 points are used for constraining and prescribing doses for the gross tumor volume:

The prescribed dose must cover 95% of the volume of the PTV of the gross tumor. Not more than 1% of the PTV of the gross tumor can receive a dose that is less than 93% of the prescribed dose, and not more than 20% of this PTV can receive a dose that is greater than 110% of the prescribed dose.

Two different techniques have traditionally been used for dose prescriptions for radiation therapy. The first technique prescribes to a single point within the target volume, and the second prescribes to an isodose surface that covers the target. The complexity of IMRT treatment plans has led to the introduction of a third method, as described in the examples just given. This is a dose prescription technique that is a modification of prescribing to a dose surface in that it allows some amount of the target to receive a dose that is less than the prescribed dose.

Because IMRT is best suited for situations in which critical structures are in proximity to a target, this modification to standard prescription techniques should be adopted to provide a method for resolving conflicting planning goals. It is important to realize that accepting some level of underdose of a PTV is a new concept that could compromise treatment outcome.

The examples given above use a three-point dose–volume description for target dose prescription. This approach is consistent with the way the treatment planning goals are provided for many inverse planning systems. In most cases, it is also possible to state critical structure dose limits using a similar level of detail. It is important to remember that there are two types of critical structures, and the IMRT dose constraints for each are handled differently. Structures such as the spinal cord do not exhibit a significant volume effect when treated with photons; thus, a single number dose limit is commonly used. The spinal cord is an example of a “serial” structure. There are also “parallel” structures, such as the bladder and rectum, which have some ability to repair damage caused by radiation. Tissues such as the salivary

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glands are referred to as “paired” structures in that there is more than one gland providing saliva flow. Additionally, maintaining adequate salivary function requires only partial sparing of one gland. Thus, for the parotids, a much more complex statement of the dose constraints should be included in the planning goals supplied to the dosimetrist. An example for the parotids can be found in the RTOG protocol for treating oropharyngeal cancer with IMRT; it is restated below:

1. Mean dose to either parotid <26 Gy, or
2. At least 50% of either parotid gland will receive <30 Gy, or
3. At least 20 cc of the combined volume of both parotid glands will receive <20 Gy.

The treatment record

It is important to link dose reporting to the dose prescription. Thus, by using the prescription technique described in the last section, one way of reporting the results of the treatment is to use the same format as the prescription. Again following the RTOG oropharynx protocol, the reported dose for each target then becomes the following: the dose covering 95% of each PTV, the percentage of each PTV receiving less than 93% of the prescribed dose, and the percentage of the PTV receiving more than 110% of the prescribed dose.

This type of summary description of the dose distribution can be accompanied by the now standard reporting of dose–volume histograms, 3D dose distributions, and dose/volume statistics.

**IMRT TREATMENT PLANNING (RESPONSIBILITY OF THE DOSIMETRIST, MEDICAL PHYSICIST, AND RADIATION ONCOLOGIST)**

As a result of the extremely large number of competing parameters that must be defined before the start of the inverse optimization and reconciled within the planning process, it takes considerable experience to know whether a dose distribution is as good as is reasonably achievable. IMRT treatment planning systems do not guarantee an optimum solution. Therefore, it is important to guard against the possibility of accepting plans that could easily be improved upon. This caution is particularly important now as this technology moves from a few pioneering institutions to a growing number of smaller community clinics.

The subsections that follow are aimed at providing details about the inverse planning process that should be understood as a first step in guaranteeing safe use of this new technology.

**Utility of dose–volume constraints**

No uniform approach to configuring inverse planning systems exists, and differences can exist at every level of the process. For example, one implementation might use a single point description of the target dose limits, whereas another system might use the more popular multipoint prescription method described above. Multiple point constraints allow the user to specify an acceptable variation in the dose homogeneity for a target, thus giving added control over the optimization. Such constraints are usually linked directly to a desired dose–volume histogram in that they are specified as the percentage of the volume of a particular structure (target or normal critical) that receives a certain dose. As previously stated, it is also helpful to have multiple point constraints for critical structures, so that partial volume irradiation for these tissues is also controlled within the optimization process.

The sections that follow will explain why systems might be limited in their capabilities and will make the argument that IMRT should be used in a carefully controlled way. That is, planning and dose delivery systems should be benchmarked (See “System benchmarking”) against each other, patients should be treated under well-defined protocols (See “Plan evaluation”) whenever possible, and proper training of all personnel involved in the process should be undertaken (See “Training requirements”).

**Approximate, feasible, and optimum solutions**

The user of any inverse planning system must understand that such systems take many different approaches to seeking an optimum plan. Furthermore, “optimum” is a mathematical concept that cannot be realized in practice, owing to the approximations that are necessary when moving from a derived intensity map to a deliverable sequence of MLC shapes or to DMLC trajectories. Most planning systems will return a result even if the dose constraints are not met. To avoid excessive planning times, it is common practice to limit the length of time used to try to find an optimum solution. When a solution is not found, such systems will stop at some point and highlight the dose limits that are not met.

Providing even an elaborate set of dose constraints, for which each target has 3 or more dose–volume values to describe these limits and for which specific limits are given for critical structures, will not give a single solution or plan. Instead, except when the dose constraints are so restrictive as to be physically impossible, there will exist different combinations of the dose–volume histogram curves and critical structure dose limits that meet the constraints. Each is referred to as a feasible solution. To separate the feasible solutions, cost or objective functions are typically added to the optimization process to find a single optimum solution. These cost functions help sort through the feasible solutions to find the one that best fits the user’s statement of the desired solution. For example, the cost function might steer the optimization so that the feasible solution that also gives the lowest average dose to the rectum is found when treating the prostate. Cost functions can be more complex than the simple example given here and represent a powerful means of guiding the optimization process to finding a desired solution. However, the operator often does not know where
the optimization process may lead. This uncertainty complicates the task of constructing the cost functions when, again using the prostate example, there are numerous competing goals, such as sparing both the bladder and the rectum while guaranteeing a relatively homogeneous dose to the target.

The user should also be aware that there could be more than one optimum solution. This is because valleys exist in the solution space, so that the optimization stops at a point that is not necessarily the global minimum. This means that a better solution does exist, but the optimization does not find it.

The discussion above refers to finding a mathematically optimum solution. The situation is further complicated by the fact that implementing the so-called optimum solution inevitably changes the result, so that it is no longer the same plan and most likely is not the optimum deliverable plan.

The fact that the inverse planning process does not necessarily return the best treatment plan makes the IMRT process somewhat unpredictable. The absence of any guarantee that an optimum plan is reached is the major reason for arguing that a clinical component should be included in all IMRT training programs, so that users of the various available planning systems can better recognize the difference between acceptable and inferior plans. Current inverse planning systems cannot make this decision for the operator.

**System benchmarking**

Techniques for IMRT system benchmarking have not been fully developed at this time. The need for benchmarking is related to the fact that treatment planning system manufacturers have used extremely divergent approaches for optimizing plans and for actual dose delivery. This situation is different from that with 3D treatment planning, for which new treatment planning algorithms are discussed in the literature and slowly replace the older approaches as their advantages are documented and their implementations on different systems tend to be similar. Inverse planning for IMRT is different in that the phenomenal pressure among manufacturers (both linear accelerator and treatment planning companies) to bring new and innovative products to market as quickly as possible stands in the way of careful investigation of the products’ utility. At least some of the uncertainty that is created by this highly competitive situation can be removed with benchmarking of the different planning systems by choosing a difficult planning case and producing plans and delivery output for comparison. When possible, the user is encouraged to ask manufacturers to perform such benchmarking experiments before the user’s purchase of a treatment planning system for IMRT. The purpose of this benchmarking is to guarantee that a particular system can produce plans without having to compromise on target coverage any more than necessary.

A number of benchmark cases were distributed to the major treatment planning system vendors attending the ASTRO practicum conducted in San Diego in February 2003. These data sets were precontoured, and a detailed set of dose constraints was also distributed. (One nasopharynx case was named ASTRO2, and a cancer of the tonsil case was named ASTRO4.) Treatment planning companies should be able to show interested parties that they are able to meet the specified dose constraints for these difficult planning problems.

**Establishing margins**

All aspects of the IMRT process should be consistent. For example, if the goal of treatment is to create extremely compact isodose lines that are positioned at the interface of a critical structure that abuts a target region, attempts must be made to minimize obvious limitations that work against achieving this goal. If patient immobilization is not adequate, and adaptive therapy techniques are not available, the precise threading of isodose lines between adjacent structures will not be possible. A similar argument can be made for the process of target and critical structure identification. That is, if the position of these structures is not properly defined, isodose lines cannot be accurately placed relative to them. Handling the situation where dose-critical normal structures abut a target requires extremely careful contouring, which implies that the imaging studies used for structure identification must contain the information needed to successfully complete this task. Also, given that the imaging studies do provide the detail necessary to properly separate structures in 3D space, the radiation oncologist must have the training needed to recognize the boundaries.

The process of adding margins to contoured target volumes to create a PTV or to critical structures to obtain a PRV is not well defined for IMRT. The problem of growing structures to planning volumes is not new for IMRT, but the general complexity of these cases makes understanding this process more important. It is essential for a user of an inverse planning system to understand how contoured volumes are managed within a particular manufacturer’s software. This understanding includes the issue of how optimization is driven when growing 2 abutting structures creates a situation in which 2 volumes share voxels or when structures overlap because of imprecise contouring and the additional issue of how dose–volume histograms account for this condition.

A good example here is an oropharynx tumor for which the region of subclinical disease overlaps the mandible, because that structure is involved. Contouring the complete mandible and overlapping the clinical target volume for the subclinical disease will cause a conflict in the inverse planning. The solution, when contouring this structure, is to exclude the portions of the mandible believed to be involved. However, the DVH for the mandible will not include the entire volume. Some systems do allow for structure overlap for presentation of DVHs and dose statistics. It is incumbent upon the user to understand how volumes and their expansion to PTVs are handled for both optimization and dose reporting.
The problem of dose dumping

Incomplete contouring of critical structures can lead to a problem evident in many IMRT plans. This problem occurs when some regions in the path of one or more of the radiation beams are not identified through the contouring process and, as a result, are not assigned appropriate dose constraints. The problem manifests as dose streaking or dumping that is not detectable when reviewing dose–volume histograms. Although dose streaking is often obvious, excess dose deposited in obscure regions that do not require irradiation can be missed in some situations. One example is when noncoplanar fields that move outside the transverse plane are used. In such cases, it is important to remember the limitations of contouring only on transverse planes that do not extend beyond the cranial and caudal limits of the target. This practice might not be adequate in that important critical structures can fall in the path of noncoplanar beams while lying outside of the planes used for contouring, and dose streaking through them will not be identified and monitored as DVHs.

The use of noncoplanar beams is not the only cause of dose dumping in inverse planned cases. Another example is when the target or targets for a head-and-neck case surround the spinal cord anteriorly and laterally, and coplanar beams are used for the plan. If no dose constraint is assigned for the region of the neck posterior to the spinal cord, the inverse planning algorithm can find a solution that gives at or near the target dose to this nontarget tissue. For this reason, in addition to limiting the dose to all tissues that can be reasonably identified and assigned known dose constraints, some users use the technique of placing “phantom” structures with general dose constraints to serve the purpose of pushing the dose away from troublesome regions. However, a more reasonable practice is to take the time to expand the list of normal tissues that are usually considered to be important for planning particular cases. For example, it is now popular to include the oral cavity and lips in the list of contoured structures for head-and-neck IMRT. This is being done, because it has been recognized that inverse planning has a tendency to place unacceptably high doses in this region when targets are nearby. It is expected that as more critical structures are recognized as problematic, they will make their way onto the list of standard structures contoured for a particular disease site.

It should also be pointed out that accidentally skipping parts of essential normal critical structures in the contouring process can lead to dose dumping with potentially serious consequences. An example is when the spinal cord contours are not properly joined to the brainstem for head-and-neck treatment. If one or more of the transverse images are missed (or, as described previously, the brainstem is omitted, because it extends only slightly into the target region), the inverse algorithm can dump dose in the unspecified area. Because this region is not contoured, the DVH analysis will fail to detect the problem, and only a careful, detailed review of the dose distribution will avoid a potentially serious problem. However, detection can be difficult when many CT sections are included in the plan, and only a few demonstrate the problem.

PLANNING (RESPONSIBILITY OF RADIATION ONCOLOGIST, DOSIMETRIST, AND MEDICAL PHYSICIST)

Plan evaluation is a critical part of IMRT. This new technology greatly extends the ability to sculpt 3D dose distributions to fit the surface of highly irregular target volumes, but this new and important capability has a tendency to cause the user to view distributions that are inferior in other respects as being better than they really are. For this reason, for the initial treatment of a particular disease site, IMRT plans should not be accepted without careful deliberation and scrutiny.

How good is good enough?

It has already been mentioned that IMRT plans are different from 3DCRT plans in that the IMRT dose distributions can be shaped to follow the surface of critical structures that push within a target volume. 3DCRT plans can give conformal dose distributions with rapid dose falloff at the surface of a target, but this planning technique cannot handle concavities in the surface of a target. Although IMRT can cause dose distributions to bend around invaginating critical structures, it is difficult if not impossible to create a concavity in a dose distribution without degrading dose homogeneity. Although this dose inhomogeneity can be handled in a number of ways, the practice of allowing some underdosing of the PTV is gaining popularity as a measure used to avoid having excessively high-dose regions appear. Instead, this approach spreads the inhomogeneity so that some small percentage of the target volume receives a dose that is below the prescription dose, and some percentage receives a somewhat higher dose than that used traditionally. A problem arises when an inexperienced user of an IMRT planning system does not know exactly how much of the target volume can be safely underdosed to obtain the desired result of bending isodose lines. This is where multi-institution protocols are critically important.

Allowing underdosing of the target is not always handled in an explicit way with IMRT. However, it should be recognized that this practice could come into the process whenever margins are decreased to the point that they might be too small. An example is when the rectum pushes against the prostate gross tumor volume. In this case, there is no room to provide a growth for a PTV for the prostate at this interface. Using a zero or very small margin at this position around the prostate is equivalent to using a larger margin and allowing some underdosing of the PTV. The RTOG has chosen to state clearly both the accepted margin for a particular disease site and the amount of allowable underdose as part of their protocols. The statement of the prescription for PTV coverage for RTOG protocol H0022 was described in the previous section.
Importance of multi-institution protocols

Multi-institutional combined group studies have been extremely important for establishing the standard of care for treating various disease sites. Individuals or groups of individuals that have extensive experience with the treatment of a particular anatomic site typically write these protocols, and there is extensive internal review before a study is activated. A properly written protocol should include statements on patient selection, prescribed dose limits, acceptable dose homogeneity, fractionation schemes, and treatment verification. The differences inherent in the change from 3DCRT to IMRT make it extremely important to attempt to use multi-institutional group protocols whenever possible.

Examples of the differences that are problematic when making the shift from traditional treatment techniques to intensity-modulated dose delivery are as follows: (1) The fact that difficult radiobiology questions are introduced, because the inverse planning portion of IMRT encourages and sometimes mandates a simultaneous boost of regions at higher risk; (2) IMRT often produces tumor dose homogeneity compromises where critical normal tissues push against or intrude into a target; and (3) Inverse treatment planning does not necessarily lead the operator to an optimum solution and can generate a plan that is far from ideal. Other pitfalls exist and bolster the argument that well-designed treatment protocols should be used when treating patients with IMRT. The RTOG is actively generating IMRT protocols. At present, there are 2 open head-and-neck protocols. A Phase I/II protocol comparing conformal treatment with IMRT for oropharyngeal cancer (#H-0022) has been open for some time now, and a Phase II study for nasopharyngeal cancer (#0225) is now available. Also, an amendment is being prepared that will extend a Phase III randomized study to include IMRT comparing high-dose 3DCRT with standard-dose 3DCRT for treating patients with localized prostate cancer (#P-0126).

TREATMENT VERIFICATION (RESPONSIBILITY OF RADIATION ONCOLOGIST, RADIATION THERAPIST, DOSIMETRIST, AND MEDICAL PHYSICIST)

The QA step for 3DCRT planning systems typically relies on commissioning procedures that check the entire system rather than perform special checks for each patient. As part of the commissioning process for planning systems used for 3DCRT, the ability of a calculated dose distribution to faithfully model measured data is checked for a series of single fields. Simple additional tests that examine a number of combined-field plans are used to determine that the system can properly sum fields. The underlying assumption is that the planning system will perform within the limits determined at the time of commissioning, and periodic QA checks guarantee that this situation does not change with time.

Certain patient-specific checks are performed on a case-by-case basis for 3DCRT. It is accepted practice to follow procedures that ensure that the fields and other parameters that make up the approved treatment plan are correctly applied for each patient. There are basically two checks that are performed. First, at the start of each course of treatment, monitor unit calculations are independently checked for every field. Second, electronic or radiographic portal imaging is used to verify isocenter positioning (i.e., field placement relative to the patient’s bony anatomy) and to guarantee the correct shape and orientation of the apertures. Additional portal imaging is carried out periodically throughout the patient’s treatment to guarantee that changes such as tissue swelling and weight loss have not led to systematic setup errors that need to be corrected.

For IMRT, these traditional QA/verification procedures need significant modification. One reason is that portal imaging as it is used for 3DCRT is not usually applicable to IMRT. This is either because standard portals positioned relative to recognizable anatomy are not always generated when inverse planning assigns weights to individual beamlets and translates these weights to fewer deliverable field apertures, or because the individual beamlets are irradiated separately with a binary collimator that opens and closes as the gantry rotates. Thus, the concept of conformal fields is lost. However, checking of the isocenter used for the treatment is usually possible with IMRT, but the process can be complicated by limitations of some dose delivery systems, and it is also possible that the treatment isocenter is minimally related to the center of the mass of the targets being treated. Such can be the case for systems that have a limited field of view (for example, the MIMiC collimator mounted below the standard jaw system), and clearance issues rather than the target center of mass dictate treatment unit isocenter positioning.

Independent of the problem of verifying isocenter placement, there are the issues of checking monitor unit calculations and the dose distributions for IMRT. It has been mentioned in previous sections that a number of steps in the inverse planning process might not be adequately rigorous. Although important improvements have been made recently, early inverse planning systems did not fully account for scattered radiation, so that the 3D dose distribution did not have the accuracy achievable for 3DCRT planning systems, and the calculation techniques used to derive the monitor units for IMRT were not as precise as the methods used for more standard treatments. Additionally, at least for systems that do not use a follow-up dose calculation, the translation of beamlets to deliverable apertures introduces more approximations when a desired aperture shape can not be obtained because of physical limitations for the MLC. Taken together, all these factors increase the uncertainty for the derived dose distributions and have led to implementation of a radically new approach for individual patient QA procedures and treatment verification for IMRT. The
end result has been the use of patient-specific measurements to check the final dose distribution and the delivered dose for IMRT. These methods are described in guidelines for IMRT available from ASTRO and the American College of Radiology (ACR) (21, 22). To comply with the definitions of IMRT planning and treatment as set forth in guidelines from ASTRO and ACR, some of the procedures outlined below are required. Others have been added as suggestions for avoiding possible errors. The distinction between required and suggested procedures will be made in each subsection.

It is important to understand that IMRT technology is evolving, and new and different QA methods may be available shortly, but their implementation will require incorporation and editorial changes in existing guidelines before they are accepted for use in nonresearch settings or as a backup to currently required procedures.

Port film techniques and isocenter check methods

Intensity-modulated radiation therapy does not always use standard conformal fields as part of the treatment. Instead, for fixed-gantry delivery, the intensity patterns can be extremely complex, so that filming the field superimposed on the patient’s anatomy will not produce a particularly helpful image. This makes it difficult to follow standard methods for verifying treatment fields where portal conformity and isocenter positioning are often checked with the same image or set of images. For this reason, it is suggested that the two parts of the process be separated.

As a first step, for fixed-gantry treatment with either static or DMLC, the intensity variation can be verified offline with an appropriate imaging technique independent of the patient. This is a relatively simple procedure that can easily be added to the routine check done for this treatment modality. It should be pointed out that it is not always possible to perform this check. For dynamically moving gantry delivery with the MIMiC tomotherapy collimator, the problem is more complex, and no reasonable imaging methods have yet been proposed for directly verifying the intensity maps for this method. For static gantry delivery, the proper orientation of these patterns with respect to the patient also needs to be checked. One suggestion is to obtain portal images of each field using an MLC shape that follows the outline of the overall intensity pattern.

As a second step, the isocenter for the fields should be verified using images that show the patient’s anatomy for reference. The isocenter verification method discussed here can be used for any IMRT dose delivery method. For the fixed gantry methods or for intensity-modulated arc therapy delivery with a standard MLC, 2 orthogonal field films or digital images can be generated and compared with digitally reconstructed radiographs or with conventional simulator radiographs. Digitally reconstructed radiographs should always be consulted to check where the isocenter resides in the treatment plan, because this location may have been shifted from the original simulation. The orthogonal images produced with the treatment unit can use open fields that include a reasonable amount of the patient’s anatomy and should have some radiopaque markers that project from the head of the machine to clearly indicate the center of the X-ray beam. For tomotherapy using the NOMOS MIMiC collimator, a double exposure is not easily obtained. In this case, techniques for using the slit aperture for checking the isocenter have been developed. One method abuts 3 slit images to enlarge the amount of anatomy shown in a single image (23). With the general availability of digitally reconstructed radiographs, it is possible to produce images that correspond to the geometry of the 3 slit images produced with the MIMiC head. Doing so allows a comparison of the 2 images to guarantee isocenter placement.

Verification of intensity patterns

This section discusses simple ways of verifying that the intended intensity patterns are correctly delivered. It is sometimes possible to obtain a radiograph or electronic image of the intensity pattern for comparison to information supplied by the treatment planning system. When the radiographs or digital images are obtainable, they can be used quantitatively to verify the intensity patterns. However, it is suggested here that they at least be employed to visually check the intensity patterns to guarantee that they are correct for the patient being treated and that they are properly oriented relative to that patient’s position on the treatment couch.

Simple techniques exist for verifying the intensity patterns at each gantry angle for the fixed-gantry dose delivery techniques. One method places a film on the treatment couch without the patient in the room and delivers the intensity pattern, with the beam directed toward the floor, for one of the gantry directions used for the patient’s treatment. This process is repeated with a new film for every gantry angle used in the patient’s treatment plan. An electronic portal imaging device can also be used for this test.

The second method can only be done with film and saves time by creating the image of the intensity pattern as part of the patient’s treatment. This technique places the film between the X-ray source and the patient, so that the patient’s anatomy does not confuse the image. It is convenient to position the film at the level of the block tray, so that it is held perpendicular to the beam center axis. Because the monitor units are fixed by the actual treatment, the combination of film speed and amount of buildup material must be adjusted as a method of obtaining an acceptable film density. When considerable buildup material is used, it might be necessary to adjust the monitor units to account for the extra beam attenuation. However, because this test is performed once for each time a new treatment course is started, this correction can usually be ignored.

Using either technique for obtaining an image of the intensity pattern, the films or electronic images can be employed to visually check the character of the intensity patterns to guarantee that they are correct for the particular patient, that they are correct for the indicated gantry angle,
and that they are properly oriented (correct collimator rotation). Scanning the films with a microdensitometer to check the intensity level is a further enhancement of the technique that can also be used.

**Verification of monitor unit settings and dose distribution**

Applying the results of a patient’s IMRT treatment plan to a square phantom loaded with film or an ionization chamber is a technique popularized by NOMOS. This method for checking the complete plan (final field segments plus their weights) applies the plan derived for the patient’s anatomy to CT scans of standard phantoms, such as a solid cube or cylinder, and recalculates the dose distribution. This new plan can then be used to irradiate the actual phantom as a check of the dosimetry. Calibrated film scanned with a microdensitometer or an ionization chamber placed at a known position in the phantom can be used to check the accuracy of the monitor units calculated by the planning system. This is the QA method recommended by the ASTRO/ACR Joint Economics Committee (21, 22). When film is used for absolute dose determination, a clear understanding of how this dosimeter must be calibrated is essential. Factors such as differences in the chemical mix or temperature of the film processor must be accounted for if such measurements are to be meaningful.

The film method can also be used to verify the 3D dose distribution for IMRT. This verification can be accomplished by loading the phantom with a number of films or by repeating the measurement with the film placed in different positions relative to the plan isocenter. The calibrated output of a scanning densitometer is then compared with printed isodose information from the planning system.

It must be recognized that transferring the patient plan to a phantom could also transfer a number of possible errors in the planning process to this new calculation. Measurements that confirm this new calculation will not uncover such errors. Phantom measurements must also be accompanied by QA checks of the planning process. Eventually, this process should include independent calculations based on the data used for treatment, combined with careful tests of IMRT delivery systems.

**Independent monitor unit and fluence map calculations for IMRT plan validation**

A practical independent computational verification of monitor unit settings (24) can be carried out as an additional QA step. Such checks are independent of the delivery system in that they cannot detect problems such as calibration errors. However, they are a useful addition to the more commonly used procedures that do check delivery using measurement techniques.

**REFERENCES**


