Guidance document on Delivery, Treatment Planning, and Clinical Implementation of IMRT

IMRT subcommittee of the Radiation Therapy Committee

Contents

1.0 Introduction

1.1 Relation of IMRT, 3Dconformal, and traditional practice

Intensity modulated radiation therapy (IMRT) is an extension of 3D conformal radiation therapy (3DCRT). 3DCRT is a change from traditional practice in that it uses targets and normal structures identified on multiple transverse images, field design based on beam's eye view (BEV) projections, volumetric dose calculations, and volumetric plan evaluation tools such as dose volume histograms (DVHs). IMRT uses all the tools of 3DCRT and adds other novel features. IMRT seeks to further shape dose distributions by modulating the intensity of each field. Thus, there are new capabilities of linear accelerators and collimators that need to be installed, commissioned, and maintained. Also, computing the needed intensity patterns and machine instructions to create them complicates the treatment planning process significantly. The computer algorithms associated with the planning need to be commissioned for dosimetric accuracy. Users must learn how to use inverse planning systems to produce high quality plans. These are new tasks that physicists and other radiation oncology staff need to accomplish. Many physicists are now struggling with the question of "what do I need to know and do to implement IMRT safely and effectively."

1.2 Objectives for this document

The objectives for this document are

A. to describe in general terms how IMRT differs from 3DCRT, thus explaining where the main issues lie,
B. to provide the key facts about these differences and give references so readers can get more details if desired,
C. to describe how the differences impact commissioning, and provide guidance on the commissioning process, citing references where possible,
D. to describe the impact on ongoing quality assurance (QA) and provide guidance on QA practice, citing references where possible, and
E. to describe how these processes fit together with others and provide guidance on clinical implementation.

Because of the emerging and rapidly changing nature of IMRT, this document cannot be definitive or prescriptive. Task group reports and a code of practice will eventually emerge as the field matures, but the intention here is to provide such guidance as possible during this introductory period. We have tried to avoid being overly repetitive of other documents, such

as the recent report of the IMRT Collaborative Working Group (CWG) [Nov 15 RJ], special issues of Medical Dosimetry (Vol 26, num1,2) or ASTRO Scope of practice [substitute proper name and reference, if available], with which readers should also be familiar.

1.3 Organization

After this introductory section, this presentation follows with a description in section 2 of delivery methods used for IMRT and associated commissioning and QA. An understanding of delivery mechanisms is necessary to appreciate some of the factors that impact IMRT treatment planning. Section 3 on planning follows. That section covers commissioning a planning system for dosimetric accuracy, which is inherently related to the delivery mechanism. It also covers learning how to effectively use an inverse planning system. The organization of these two sections addresses objectives A – D, that is, explain the differences from 3DCRT and provide guidance on commissioning and quality assurance. Finally, section 4 on clinical implementation outlines the issues that need to be addressed by the physicist and others in order to bring IMRT online, and so addresses objective E.

2.0 Delivery techniques for IMRT

The difference between 3DCRT and IMRT with respect to treatment delivery is implied in the phrase: “intensity modulation.” 3D conformal therapy uses blocks or MLCs to define fixed field boundaries. Modulators such as wedges or tissue compensators are often employed to improve dose homogeneity within the target. IMRT extends the complexity of the modulation to achieve more complex dosimetric aims, such as creating dose distributions with concavities. Many methods of achieving this modulation have been proposed and applied to clinical practice. One class of techniques holds the beam direction constant and indexes the collimator shape to the delivered dose, thus subjecting any given point in the patient to a desired proportion of “open” and “blocked” beam. Another technique uses fixed gantry angles and physical attenuators to achieve the modulation. Yet another class of techniques moves the gantry during the irradiation, indexing the collimator shape and gantry angle to the delivered dose. Each delivery technique has its own unique features that give rise to different commissioning and quality assurance considerations.

This section will emphasize those techniques that have been commercially implemented and therefore of most interest to practicing physicists. Techniques that are under development but not yet commercially available are described more briefly. This section concentrates on those aspects of treatment delivery that are specific to IMRT and suggests commissioning and quality assurance tests for the various techniques.

Although IMRT planning and delivery are intimately related, this section suggests tests of the IMRT delivery system that can be manually created, independent of the IMRT planning system. In this fashion, the causes of any dose deviations can be more easily isolated to the delivery or planning system.

Sections 2.1 and 2.2 describe IMRT delivery systems that use fixed gantry angles and multileaf collimators (MLCs). Section 2.3 describes IMRT delivery systems that make use of fixed gantry angles and physical attenuators. Sections 2.4 and 2.5 describe IMRT delivery systems that make use of gantry rotations. Section 2.6 provides background information on the leaf sequencing algorithms that are used in the segmental and dynamic IMRT techniques described in 2.1 and 2.2.

2.1 Segmental IMRT with MLC

The CWG recommends the term “segmental IMRT” (SMLC-IMRT) when the collimator shape is constant during irradiation and changes between irradiations. Synonymous terms are “step-and-shoot” and “stop-and-shoot”.. The gantry does not move during irradiation.

2.1.1 MLC positional accuracy

In conventional 3DCRT, the MLC defines the outer aperture of the beam shape. An uncertainty of 1-2 mm in leaf location may be inconsequential. Segmental IMRT builds up a fluence pattern by adding together many segments, some of which may be quite narrow. For a segment nominally only 10 mm wide, a 1-2 mm uncertainty in position may correspond to a 10-20% uncertainty in dose. [Can we quantify this using small field dosimetry publications?] Furthermore, the beam edges move to many locations within the treated area, so their locations must be known to high precision so that the summation is accurate. For these reasons, the accuracy of relative MLC leaf motions must be maintained to a precision of

tenths of a millimeter. Conventional quality assurance tests for static MLCs are not sufficiently sensitive for this purpose.

A key point for IMRT is that the location of the radiation field edge be well established with respect to the nominal location of the MLC leaf. For MLCs with rounded leaf ends, there is always an offset between the beam edge as defined by the light field and that defined by the 50% decrement line of the radiation field. This is typically 0.4 to 1.1 mm depending on the MLC type, beam energy, and location with respect to the central axis. This offset can also exist with double-focussed MLCs if the MLC motion deviates from the desired spherical arc. Users may have the choice of calibrating their MLC so that the nominal position corresponds to the light field or radiation field edge. (In practice, calibrating the MLC nominal position to the light field edge has certain advantages, especially if it is the standard method used and supported by the vendor.)

In either case, the physicist should:

a. a. measure the offset between the radiation field edge and the nominal leaf position as a function of distance from the central axis, both positive and negative. (Often, the offset can be treated as a constant value to sufficient accuracy.
b. create a test sequence that abuts irradiated strips at different locations across the field, adjusted to account for any offset so that the 50% decrement lines superimpose, and
c. irradiate a film and scan across the match lines to check the uniformity of the dose (figure 2.1).

The offset can of course be measured using the test sequence described in b-c with different values of the offset applied. Alternatively, the full width at half maximum can be measured for strips of known nominal width to obtain the offset. Films should be obtained at different gantry and collimator angles to check the effect of gravity on the matchlines. For MLC systems that employ carriage motion, sequences should be created that test the matchlines over the full range of travel.

Tests of matchline uniformity can detect MLC variation to a precision of about 0.1-0.2 mm. More precise control is likely unattainable. This positional variation will produce a dose variation of about ±5% in the matchline and is unlikely to cause significant dose error when many beam segments from many angles superimpose.

Another useful test to semi-quantitatively check the MLC positional accuracy is to film a test sequence that creates 1 mm strips at regular intervals. Visual inspection can detect improper positioning to a precision of 0.3-0.5 mm (figure 2.2). Again, such films should be at different gantry and collimator angles and over the full range of carriage motion.

Physicists need to comprehensively check the MLC positional accuracy during IMRT commissioning and develop a subset of checks as part of routine quality assurance. It is clearly prudent to test frequently at first and reduce the frequency as experience builds. In IMRT, unlike conventional treatment, MLC calibration and performance affects dose delivery to the central target region. For that reason, the QA program should include tests at least weekly. This program might include tests that focus on machine performance, such as a daily output check using multiple narrow segments and/or films as described above, and might also include overall planning and delivery tests for specific patients, as described in section 3.6.2 below. If a facility moves toward using independent calculation techniques to check individual patient plans (section 3.6.1), then tests of machine performance will need to be performed on at least a weekly basis.

2.1.2 Linear accelerator performance at low MU

Depending on the planning system used for IMRT, segments may be delivered with few or fractional MU. The dose/MU constancy should be checked throughout the range of use for IMRT. Similarly, the flatness and symmetry of the beam should be checked. Fast film such as Kodak TL can test for flatness and symmetry stability for few MU, especially if placed on the blocking tray. Summing several irradiations of small or fractional MU may also be reasonable, since variations at low doses are unlikely to be clinically important unless they are systematic.

It has been noted that some delivery systems can display some dosimetric anomalies when using very few MU because of the communication lag between the MLC control system and the linear accelerator console (refs Xia, Ezzell, Low) These anomalies occur outside the normal range of use for clinical treatments, but could affect film QA tests if the number of MU is reduced to avoid saturating the film.

2.1.3 MLC control issues

Some linac manufacturers (e.g. Siemens) have implemented segmental IMRT as an extension of conventional treatments: each IMRT segment is considered a separate field. In order to be efficient, a computer control system is needed to set up and verify the potentially large number of segments, but the process is qualitatively the same for modulated or unmodulated fields. This simplifies the control system but the record/verify overhead limits the number of fields that can be treated in a given time. Others (e.g.Varian) have developed a dedicated linac/MLC control system that directly controls and monitors the indexing of the MLC shape to the delivered MU. This permits more segments to be delivered in a given time at the cost of less opportunity for external verification. It is not clear that either system conveys any advantage in the dose distribution obtained in practice. Whatever the delivery system, the clinical physicist needs to understand:

a. how the MLC is calibrated,
b. how the MLC position is indexed to MU,
c. how and to what precision the MLC position is measured,
d. what tolerance applies to the MLC position, and if it can be controlled,
e. what interlocks check that the MLC position is correct,
f. what verification records or logs are created by the control system, and
g. how to respond if the QA checks show that the calibration has drifted.
h. how to recover from delivery interruptions

2.1.3 MLC physical characteristics

The transmission characteristics of the MLC are more important for IMRT than for 3DCRT because the leaves shadow the treatment area for a large fraction of the delivered MU. Transmission through the body of the leaf is important, as are the amount and consistency of transmission between the leaves. Most planning systems require an average transmission value, so the measurement device (film or chamber) should span a large enough area to adequately sample inter- and intraleaf leakage.

The penumbra of the leaf ends should be measured with a high resolution detector such as a film scanner or a diode to permit accurate modeling of the penumbra by the planning system.

The available treatment area is less for IMRT than for conventional treatments because IMRT requires that an MLC leaf traverse the entire field, not simply define an outer border. Each manufacturer has different specifications for leaf extension, travel across central axis, etc., that affect the available treatment area. The physicist needs to know the specifications in order to acceptance test the delivery system and to test that the planning system correctly handles the limitations.

2.2 Dynamic IMRT with MLC

The CWG recommends the term "dynamic IMRT" (DMLC-IMRT) when the collimator shape changes during irradiation. "Sliding window" is a synonym (although that term has also been used in the context of segmental MLC to describe some leaf sequencing strategies.) The gantry does not move during irradiation. Here, the leaf positions, leaf speed, delivered MU, and dose rate all interact.

2.2.1 MLC positional and leaf speed accuracy

The requirements for MLC positional accuracy are the same for segmental and dynamic IMRT with MLCs. The films suggested in section 2.1.1 and depicted in figures 2.1 and 2.2 are relevant, and indeed were first suggested in the context of DMLC. In addition, the accuracy of DMLC delivery depends on the accuracy with which the speed of each leaf is controlled. The dose rate of the linac also affects the delivered intensity, and the control system may vary the leaf speed, dose rate, or both to achieve the desired result. Test patterns should be constructed that check conditions that are leaf speed and dose rate limited.

For example, a test pattern could move a gap that is 1 cm wide by several cm long across the central axis. The reading of an ion chamber at the central axis should be directly proportional to the programmed MU.

Of course, such a test only checks leaves that cover the ion chamber position. Film can be used to test leaf speed stability for several leaves simultaneously. A specific leaf pair can be programmed to move a gap of fixed width across the field. A fixed gap moving at a uniform rate should produce a uniform fluence and hence a uniform density across a film. (Actually, the fluence and density will also depend on the shape of the extended source, as shown in figure 2.4, in which a 5 mm gap has been panned across a 14 cm field width for three positions of the carriage for a Varian MLC. This very narrow gap permits the film to "see" only a portion of the extended source at any point, leading to the rounded density profiles.) By combining several leaf motion patterns on a single film, the stability of the leaves moving at different rates can be tested.

The ion chamber and film measurements can be combined into an efficient quality assurance test. The central leaves can scan a gap across the ion chamber for a fixed number of MU, producing a constancy check. Simultaneously, a film placed upstream of the chamber can image that gap as well as others off axis that are moving at different rates. The density strips, normalized to that of the central point, provide additional constancy information.

As mentioned before, during commissioning the performance needs to be checked at different gantry and collimator angles. Routine quality assurance will employ a subset of those measurements done during commissioning.

2.2.2 Other DMLC issues

Most of the considerations listed in sections 2.1.2 – 2.1.4 for segmental IMRT also apply to dynamic IMRT. In addition, the DMLC control system may have a minimum distance between opposing leaves to prevent collisions during motion. This minimum gap affects the minimum dose that can be delivered during a treatment and limits the amount of tissue sparing that can be achieved with dynamic IMRT. The physicist should check what that gap is and incorporate a test of its stability into the routine QA of the machine, especially if the IMRT planning system used uses that information. [Need to get input from DMLC user: Chen, Ting?]

2.3 IMRT with physical attenuators

A number of workers have described the use of physical attenuators to accomplish the modulation required for IMRT. In these systems, an attenuator must be constructed for each gantry position employed and then placed in the beam for each treatment. The problems of commissioning and maintaining an MLC are replaced by issues related to material choice, machining accuracy, and placement accuracy.

2.4 IMRT with rotating fan beams (tomotherapy)

The first IMRT system to achieve wide commercial application was the Peacock developed by Nomos Corporation. A slit collimator (“MIMiC”) is added to a convention linac and defines a fan beam approximately 20 cm wide and 2 cm long. The fan beam irradiates a narrow slice of the patient as the gantry rotates. During the rotation, collimator leaves move in and out of the beam under computer control, modulating the fraction of time that each segment of the fan is open or blocked. The temporal modulation of the collimator is indexed to the gantry angle. Several slices are irradiated sequentially in order to treat the entire area of interest. Accurate motion of the couch is necessary to prevent significant dosimetric errors at the junction between slices and is accomplished using a couch indexing device from the manufacturer (“Crane®”).

As an add-on device, the MIMiC® requires special considerations. One is the additional weight to the gantry head, requiring preliminary testing of gantry balance and isocentricity. Second, the rotational performance of the accelerator should be tested. The MIMiC® is not interfaced to the accelerator and assumes a constant monitor unit delivered per degree of arc motion. It is also not integrated with record-and-verify systems so preparations for recovery from treatment interruptions are necessary.

2.4.1 Peacock positional accuracy

References ??? describe the two key elements in commissioning and quality assurance of the Peacock® system. One is the physical alignment of MIMiC® collimator on the linear accelerator to ensure that the device is accurately centered and perpendicular to the axis of gantry rotation. Commissioning the collimator alignment employs superimposed film images at gantry angles of 90^{o} and 270^{o} (see figures 1 and 5 of Saw, et al).

The second element is the determination of the precise couch increment to achieve the best dose uniformity across the slice junctions. This latter point is especially crucial since the dose can change by 25% per mm of misalignment. The couch is moved between slices a distance equal to the MIMiC® radiation field width projected to isocenter. The accurate measurement of this width is the responsibility of the physicist and the method for measuring it is provided

by the manufacturer. However, it is the patient that must move this amount, not only the couch, so good patient immobilization is required as well. If the couch bearings are not operating properly (for example due to rust or contaminants) the couch may bind imperceptibly causing the Crane® to twist slightly such that the couch does not arrive in the proper location. Only a very small position error is required to cause a measurable dosimetric error in the field abutments. A measurement of the abutment can be straightforwardly conducted by placing a sheet of radiographic film at the plane of isocenter and irradiating successive open MIMiC® fields. Uneven couch motion by the Crane® will appear as varying over- and underlaps between the fields. Periodic checks of the couch motion are necessary. Low et al describe daily and weekly quality assurance tests on this delivery system.

2.4.2 Peacock dosimetric measurements

As with the MLC systems described earlier, key elements are to measure the transmission through the collimator and the penumbra of the leaves. The penumbra needs to be measured with high spatial resolution (0.2 mm or better)

2.4.3 Helical tomotherapy

A prototype device that delivers the treatment in a helical fashion with simultaneous gantry and couch motion is under development at the University of Wisconsin. The helical delivery reduces the dosimetric consequence of errors in couch motion. That device is not yet commercially available.

2.5 IMRT with rotating cone beams (Intensity modulated arc therapy)

Intensity modulated arc therapy (IMAT) is a delivery technique developed at the University of Maryland that may soon be available commercially. This method combines dynamic motion of the collimator with gantry motion. The MLC shape and gantry position are indexed to the delivered MU. One arc is used to produce each intensity level used in the modulation.

2.5.1 Commissioning and quality assurance issues for IMAT

[need input from Cedric]

2.6 Leaf sequencing for segmental and dynamic IMRT with MLCs

For IMRT delivered with MLCs, leaf sequencing algorithms are needed to translate the intensity patterns produced by the planning system into instructions about how to move the leaves. In general, there are many possible sequences of leaf motions that could produce a desired intensity pattern. The search for efficient sequences is an area of ongoing research. Algorithms have been devised that minimize the number of segments or that minimize the number of monitor units Algorithms also need to account for mechanical limitations of the collimator and the need to minimize dosimetric problems such as the tongue and groove effect.

In practice, the leaf sequencing is part of the planning process, and so the algorithm employed is determined by the planning system. For the clinical physicist, commissioning the leaf sequencing algorithm is not a separate exercise; it is part of commissioning the planning

system (see section 3.5). Nevertheless, it is useful for the physicist to understand the concepts involved, in part to aid in comparing IMRT approaches and choosing between them.

2.6.1 Sliding window algorithms

In the sliding window approach to leaf sequencing, a leaf pair moves from one side to the other across the treatment area. A point in the patient "sees" the source if it is not blocked by either the leading or trailing leaf. Adjusting the relative motion of the leading and trailing leaves controls the fluence pattern. The basic concept applies whether the motion is continuous during irradiation (dynamic IMRT) or alternates with irradiation (segmental IMRT). Unfortunately, the term "sliding window" has been used in two ways: as a synonym for dynamic motion and to signify unidirectional leaf trajectories. Figures 4 and 5 of Xia and Verhey (MedDos), figures 5 and 6 of the CWG report (RJ), and figure 2 of Chui et al (MedPhys Dec 2001) illustrate the idea of a sliding window leaf sequence and its realization in dynamic and segmental modes.

Conceptually, each leaf pair is considered separately when constructing the pattern of motions. However, practical MLC limitations require modifications to account for interactions between neighboring leaves. Sliding window approaches can be constructed to accommodate leaf extension, interdigitation (collision), and tongue-and-groove constraints. Interdigitation refers to the end of a trailing leaf extending past the end of an adjacent leading leaf. Such a pattern is more likely to cause a collision and is forbidden for some MLCs (fig 2 of Xia and Verhey, MedDos). The tongue-and-groove effect refers to an underdose that occurs in a junction region between neighboring leaves if the tongue on one leaf extends beyond its neighbor's groove and later the situation is reversed with the groove extending beyond the tongue (fig 1 of Xia and Verhey, MedDos). Incorporating such constraints complicates the motion; however, in general, sliding window algorithms effectively minimize the total number of MU required for treatment at the cost of increased number of segments. In practice, these algorithms may be more efficient for delivery systems that can quickly move from segment to segment and in which treatment time is limited by physical leaf motion.

2.6.2 Areal or reducing algorithms

Other algorithms (refs) allow bidirectional motion and consider the entire intensity pattern instead of each row independently. The areal and reducing algorithms reduce the number of segments required at the cost of increased total monitor units. Adding interleaf motion constraints to deal with interdigitation and tongue-and-groove effects increases the number of segments by about 20%-35% (Xia and Verhey, MedPhys 98). In practice, these algorithms may be more efficient for delivery systems in which treatment time is limited by the overhead in moving from segment to segment.

Figures for section 2

Figure 2.1 MLC QA film with 2 cm strips programmed to abut and associated density scan

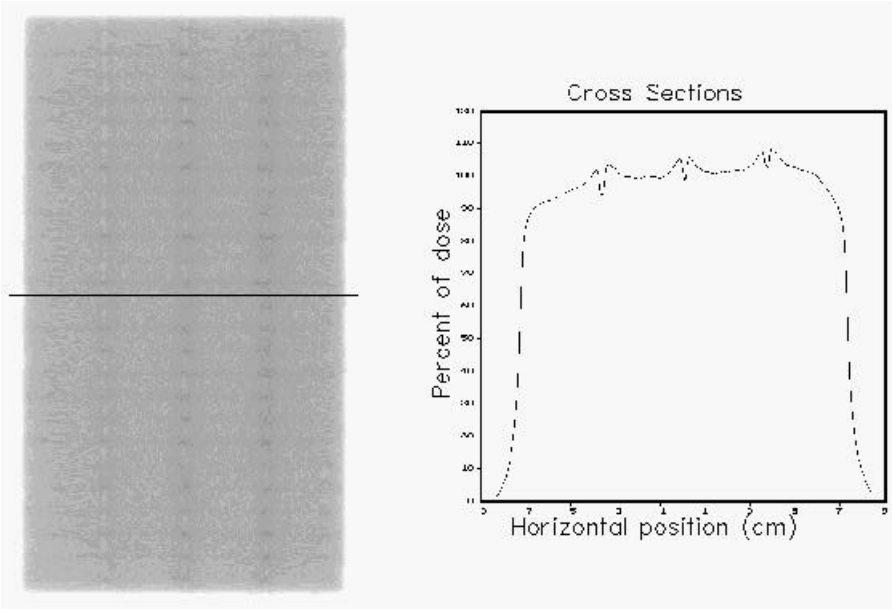
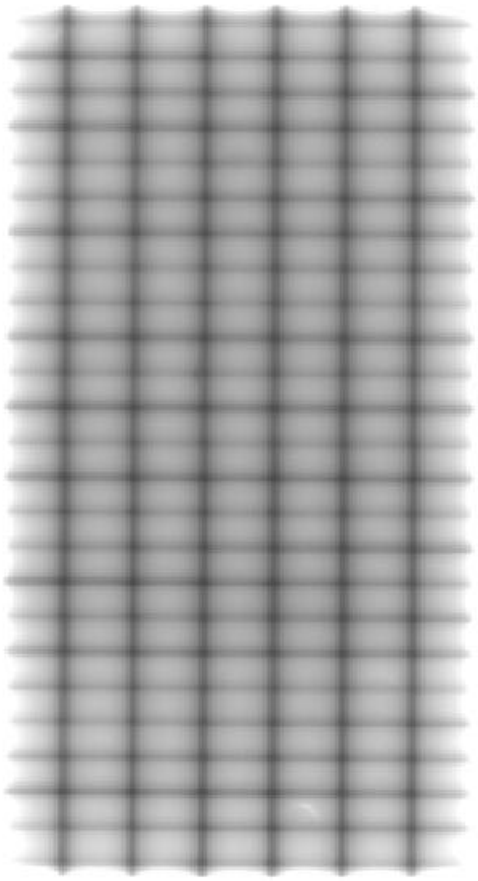


Figure 2.2 MLC QA film with 1 mm strips programmed to occur at 1.5 cm intervals



3.0 IMRT treatment planning

This section provides guidance related to treatment planning issues to clinical physicists who anticipate setting up an IMRT program. The specific purposes of this section are:

to describe the IMRT treatment planning process, highlighting areas that differ from "conventional" treatment planning (sections 3.1-3.3),
to describe a process for learning how to apply inverse planning to particular clinical cases (section 3.4),
to describe an approach to commissioning an IMRT planning system for dosimetry accuracy (section 3.5), and
to describe approaches to quality assurance for individual patients' treatment plans (section 3.6).

3.1 Differences between IMRT and conventional treatment planning: dose calculations and beam modeling

3.1.1 Modeling head scatter, penumbra and transmission

IMRT doses are calculated by dividing beams into smaller sections, called beamlets, that have varying intensities. The dimensions of the beamlets may be too small to establish electronic equilibrium within them, so calculations based on corrections to broad beam data will not suffice. Some method of integrating dose kernels must be used or Monte Carlo techniques applied. The small collimator openings also make head scatter modeling important.

For conventional fields, aspects such as transmission through collimators and penumbra affect the results at the edges of and outside beams and so have reduced clinical importance. For IMRT delivered with MLCs, the beamlets are created by moving the MLC leaves through the irradiated field, and so accurately modeling penumbra around and transmission through the MLC leaves is critical.

For this reason, special care must be taken during commissioning when measuring these parameters. For example, a five field prostate treatment planned for IMRT on a commonly used system blocks a point within the prostate for over 60% of the MU, and leaf transmission typically contributes 4% of the total dose.

The dosimetric accuracy of the plan is even more dependent on the fidelity of the penumbra representation. Having multiple small beamlets means having multiple beam edges throughout the target volume, so getting the penumbra right is crucial. Experience has shown that the penumbra should be measured with film, diode, or very small chamber. A beam model based on scans obtained with a chamber having an inner diameter of 0.6 cm may not produce accurate IMRT calculations.

3.1.2 Leaf sequencing and deliverability

Inverse planning systems need to determine a pattern of beamlet intensities for each field and translate those to delivery instructions for the system being used. For MLC systems, a leaf sequencing algorithm determines the MLC movements to best replicate the desired patterns (see section 2.6). Parameters such as collimator transmission, leaf shape at the end and sides (rounded-end and tongue-and-groove effects), and physical limitations to motion all affect the

doses actually delivered. Some idealized intensity patterns may not, in fact, be deliverable. For example, leaf transmission sets a lower bound on the minimum deliverable intensity.

Different systems handle the interplay between inverse planning, leaf sequencing, and dose calculation differently.

(a) Some systems first determine a set of beamlet intensities that, if delivered, would give the desired dose. Dose calculations during the inverse planning iterations are for idealized beamlets. Subsequently, a leaf sequencing algorithm is used to create the delivery instructions. This algorithm incorporates corrections for transmission, penumbra, etc., so that the delivered dose closely resembles that which had been previously calculated, but no calculation is done based on the final delivery sequence.
(b) Some systems append a final dose calculation based on the actual delivery sequence, in order to reduce any difference between what is planned and delivered, but possibly obscuring the connection between the planning parameters and the final result.
(c) Some systems incorporate full dose calculations for the proposed leaf sequences into each iteration of the inverse planner, thus ensuring that what has been planned can be delivered, at the cost of increased calculation time.

The manner in which this interplay is handled affects the accuracy of dose calculation and the speed of planning.

Note that some IMRT systems may use different algorithms during optimization than for a final dose calculation, in order to accelerate the process. The accuracy of the final calculation is most important, but the accuracy of the intermediate method may influence the quality of the optimization results. For example, if the optimization dose calculation over- or underestimates penumbra or scatter dose, then the dose distribution returned by the optimizer may change after the final calculation, producing suboptimal results. It may not be clear to the user what to change to improve the plan. The physicist needs to know the approach used and its limitations. There is usually a tradeoff between speed and accuracy, and the commissioning process (section 3.5) needs to identify any weaknesses.

3.1.3 Heterogeneity corrections

Heterogeneity corrections may be more important for IMRT than for conventional treatments, for several reasons.

(a) IMRT treatments often incorporate more and different beam directions than used conventionally, so previous clinical experience with uncorrected doses may not translate well. Heterogeneities that affect some beamlets more than others may give rise to localized dose differences that are different than previously experienced.
(b) IMRT is used to escalate doses to targets and/or reduce doses to critical organs. DVHs are used to evaluate and (frequently) prescribe treatments. The reliability of clinical experience with DVH prescriptions and results will be significantly compromised if heterogeneity corrections are not used, at least for body sites such as lung in which the corrections are clearly needed for accurate results.

Facilities that presently do not correct for heterogeneities will face certain new tasks and difficulties.

(a) Determine the conversion from CT number to relative electron density for the imagers used.

(b) Check the planning system results using heterogeneous phantoms. Simple slab geometry using solid phantoms with air cavities or cork inclusions have been used traditionally to check low density effects. Anthropomorphic phantoms are another possibility, typically using TLD. Some simple testing by each clinic is needed to validate the local implementation of the heterogeneity correction.
(c) Plan how to handle contrast agents or streaking artifacts that may assign undesired CT numbers to voxels and inappropriately influence the dose calculations. For example, many planning systems allow bulk densities to be assigned to specified regions, replacing the troublesome areas. Also, plans could be run with and without the corrections to determine the magnitude of any effects.
(d) Decide which types of plans need corrections. The CWG report recommends that heterogeneity corrections be used, however, it may well be that heterogeneity corrections are necessary for lung treatments but are less necessary for prostate treatments and even undesirable if contrast or rectal gas cause dosimetric artifacts.

3.2 Differences between IMRT and conventional treatment planning: planning algorithms

Simple IMRT planning can be accomplished by manually adding subfields with various weights and evaluating the dose distribution. In each iteration of the process, the human decides what changes to make to revise the design. The planning process is not automated and is sometimes called “forward planning”. This method typically produces a limited number of subfields and is a natural evolution of 3D conformal planning. A number of publications have described successful methods (e.g. UCSF, U of M, Ghent, U of Maryland). The method lends itself to “step-and-shoot” delivery techniques and has also been used for intensity modulated arc therapy (IMAT).

More complex IMRT planning breaks each beam into many small beamlets and determines the intensity of each. This highly complex problem requires more automated methods for solution. This process has come to be called “inverse planning.” The human specifies beam directions (or arc angles), target dose goals, and dose constraints or goals for sensitive structures, and then an automated optimization algorithm calculates intensity patterns that create a dose distribution that best meets the prescription. (In optimization terms, “constraints” are limits that cannot be violated, and “goals” are desired objectives. In these paragraphs, we use the term objectives to indicate both goals and constraints.) If the planner wishes to change the result, he or she alters the objectives and reoptimizes. Some systems have limited ability to modify the intensity patterns by deleting segments.

In inverse planning, the user specifies objectives for the dose distribution using single dose values, a few dose-volume points, or fully flexible DVHs. Importance factors may be used to change the relative weight given to different structures. Internally, the planning system represents these objectives in a cost function, which must be maximized or minimized by an optimization algorithm. The cost function numerically represents the tradeoffs that are incorporated into clinical judgment. By changing the objectives, the user alters the cost function and so influences the result.

It is important to realize that “inverse planning” and “optimization” do not guarantee a good solution. The planner may set up dose objectives that are impossible to achieve or conversely that are so loose that the optimizer is not guided in a useful direction. In general, a treatment planner often needs several trials before finding an acceptable solution, and it may not be easy to know what to change in order to push the solution in a desired direction. A process for developing that knowledge is suggested in section 3.4. The success of an inverse planning

system depends to a large extent on offering a cost function that effectively represents clinical concerns and that a user can intuitively regulate.

Optimization algorithms used to minimize the cost functions can be classified into two broad categories: deterministic and stochastic. Deterministic methods move from one proposed solution to the next using computed first and/or second derivatives of the cost function. The direction and size of each step (i.e. which beamlet intensities change and by how much) depend on the computed gradients. Minimization can be relatively fast but cannot escape from a local minimum.

Stochastic methods move from one proposed solution to the next by randomly changing beamlet intensities according to some scheme. Disadvantageous changes are sometimes allowed, and so escape from local minima is possible. Such methods are slower than gradient descent methods, since the optimizer spends a lot of time evaluating and rejecting random moves. Simulated annealing is one stochastic technique that has been adapted to IMRT. In practice, stochastic and gradient descent methods can be combined.

The possible existence of local minima depends on the form of the cost function and constraints. If the cost function depends only on simple linear or quadratic functions with one goal dose per structure, then local minima do not exist. Dose/volume constraints can cause local minima, and local minima can exist if the cost function depends on biological models in which different dose distributions can result in the same complication or control possibilities. Similarly, they can exist if the number and orientation of treatment fields is a parameter to be optimized.

Since most inverse planning systems permit (or require) dose volume constraints, then it appears that the solution space for many clinical problems will have local minima. If they are clinically equivalent, then there is no difficulty, but in general it is not at all clear how a planner might know that a given solution is a local or global minimum. Planners have the challenge of discovering ways to force the inverse planning systems into different parts of solution space by changing initial conditions, such as by rearranging beam order, changing initial beam weights, or initial fluence patterns.

There are other approaches to inverse planning that may avoid issues of local minima. For example, the planning constraints can also be modeled by a system of linear inequalities that can be solved by projection algorithms.

3.3 Differences between IMRT and conventional treatment planning: specific planning issues

3.3.1 Dose uniformity vs. dose shaping

Target dose inhomogeneity has been claimed to be an unavoidable consequence of IMRT. This is not necessarily true and is a consequence of the characteristics of some early IMRT planning systems and their applications. If IMRT is directed to produce a uniform dose to the target as its prime goal, then it should be able to accomplish that, effectively replacing wedges and tissue compensators. In principle, IMRT should always do no worse than conventional treatment techniques, for the former has more flexibility or degrees of freedom. On the other hand, if IMRT is used to produce dose distributions with concave shapes and/or steep gradients near critical organs, then target dose uniformity will suffer. To create a complex dose distribution, IMRT casts shadows with some beamlets and balances them with higher intensities from other beamlets. The balancing is not perfect, so localized variations within the

target and elsewhere can be expected. In general, one should expect the dose inhomogeneity in the target to increase as:
(a) the required dose difference between target and critical structure increases,
(b) the distance between target and critical structure decreases,
(c) the concavity of the required dose distribution increases, and
(c) the number of available beam directions decreases.

As part of the commissioning process, a user can evaluate the performance of the optimization with respect to these expectations. As noted above, a successful inverse planning algorithm should allow a user intuitive means to control the balance between the competing goals of target dose uniformity and low dose outside the target.

3.3.2 Target and structure delineation

There are issues in target and structure delineation that are specific to inverse planning for IMRT.

Inverse planning puts more responsibility on the clinician to carefully delineate what is to be treated. For example, in conventional radiotherapy, regional treatments can be designed by drawing ports on simulation films that encompass the gross target and the draining lymph nodes. To treat the same region with IMRT, the clinician must contour the nodal regions explicitly as well as the gross disease and assign desired the doses. With inverse planning, the physician designates targets instead of designing fields, so careful and accurate contouring is essential.

Conversely, volumes that should be kept below certain doses also need to be explicitly constrained. Treating with novel beam arrangements may put new tissues at risk. For example, many head and neck patients are conventionally treated with parallel-opposed lateral fields that are reduced to deliver boost doses to gross disease. The spinal cord is blocked after approximately 40 Gy, and electron fields then boost the posterior neck nodes. Some parts of the oral cavity may be blocked throughout the treatment. Applying IMRT with five to nine axial beams may make it possible to spare much of the parotids and reduce subsequent xerostomia. But parts of the anterior mucosa that previously were totally spared would now be within several fields, as would tissue posterior to the spine. Unless the user establishes dose constraints there, the inverse planner may give undesired dose to these regions (Figure 3.1).

In general, all areas of potential interest should be contoured so that DVHs can be evaluated and constraints applied if needed.

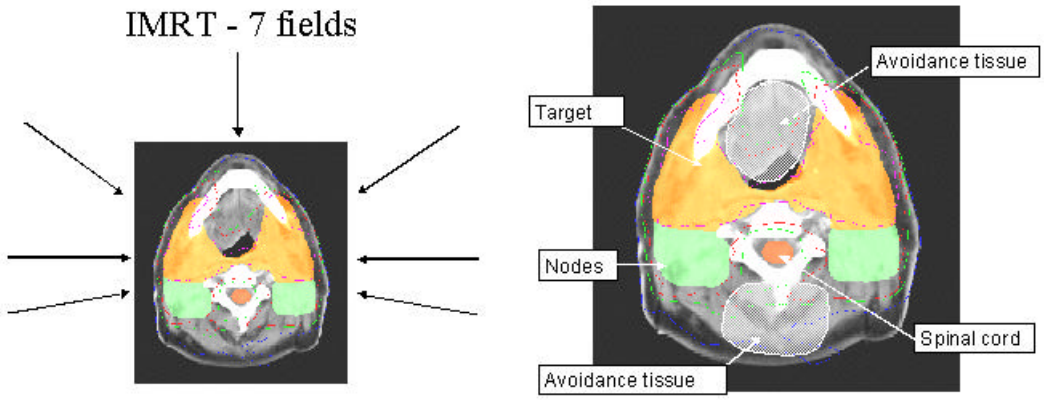


Figure 3.1 Use of avoidance structures to limit doses in inverse plans

3.3.3 Buildup region

Care must be taken when target volumes are drawn within the buildup region. Firstly, calculated doses are often inaccurate and lower than delivered dose. Secondly, the inverse planner will see the low doses in the buildup region as underdosing the target and will increase the intensities of the corresponding beamlets. Those high intensities may well degrade the overall plan quality, likely causing hot spots in the target or elsewhere. It may not be obvious to the user that the hot spots are a consequence of the inverse planner fighting with the buildup effect instead of being "unavoidable with IMRT". This issue is especially important for planning systems that expand the CTV by defined margins in three dimensions and then plan to the expanded PTV. Even if the CTV is well within the buildup region, the PTV may not be. Unless the user inspects the PTV on each slice, this anomaly may not be detected.

Of course, if the target really is in the buildup region, then the dosimetric problem is also real and is better solved by adding bolus than by relying on the accuracy of dose calculations in the buildup region. It is better to put the bolus on for scanning so that is accurately represented in the plan.

3.3.4 Flash and mobile targets

Inverse planning for targets such as the breast is problematic. Conventional plans add beam margins in air ("flash") to account for daily changes in shape, but inverse planning algorithms only treat defined targets. At present, commercial planning systems do not offer reliable heuristics to expand the beams to accommodate these needs.

For breast IMRT, both the flash and buildup problems present significant difficulties and so that site should be considered with caution. To date, published studies have used manually-created segments or university-based inverse planning systems where additional control by the human planner is possible.

Respiratory motion can also cause more problems for IMRT treatments than for conventional treatments. Any plan evaluation needs to consider how the plan shown on paper for a static image might be different in the living patient. Some IMRT planning systems produce relatively "noisy" intensity maps, that is, adjacent beamlets may have significantly different intensities. The summation of all these beamlets on a static image may produce an acceptable

distribution. But if respiratory motion moves tissues during the treatment over distances comparable to the beamlet size, then deviations in delivered dose may be substantial. Similarly, tomotherapy with slit collimators presumes that the patient is a rigid body that can be indexed longitudinally with high accuracy. Studies have shown that positioning errors can produce dose gradients of 25% for each millimeter of misalignment. Physicians and physicists must realistically assess these potential errors when selecting patients for IMRT, especially for sites in the abdomen and thorax.

3.3.5 Margins

Deciding what margins to apply is a question for all types of conformal radiotherapy, but IMRT and inverse planning create additional issues.

Planning systems often offer means for expanding target contours in three dimensions, often with six independent values (anterior, posterior, medial, lateral, superior, inferior). However, it may be difficult to encode a more complicated instruction, such as "expand this brain tumor by 1.5 cm in all directions except where it is limited by the skull." A conventional planner can handle this deficiency by designing the beams appropriately. If the DVH for the PTV shows low doses, and those low doses are seen to be outside the skull, then the planner can decide not to worry about them. An inverse planning algorithm cannot decide to ignore certain parts of a PTV. In such cases, the PTV must be explicitly drawn instead of using the expansion tools.

More generally, the ability of IMRT to produce rapid dose falloff outside a target makes the assessment of margins even more important. Where gradients are high, the consequence of localization errors is large, as for retreatment of a paraspinal tumor. Hence the need to combine the ability to perform IMRT with excellent localization tools if high precision radiotherapy is the goal. Less obviously, IMRT may be used to design gradients to fit a clinical need, for example, "treat the brain tumor GTV to 60 Gy, a 10 mm margin to 50 Gy, and have the dose drop off rapidly after that."

Planning systems differ in how they expand targets and normal structures and how the expansion regions are treated in the inverse planning. Users need to understand if targets can expand into structures (and vice versa), if regions can overlap, if priorities can be assigned for optimization, how doses are reported in expansion regions, etc.

3.3.6 Radiobiological issues

IMRT plans can have radiobiological consequences that differ from conventional plans. Conventionally, patients are treated with a consistent dose/fraction. In order to give more dose to gross disease, field sizes are reduced and boosts are given at the same dose/fraction. Clinical experience with this system has established the prescription doses. When one IMRT plan is used from the beginning of treatment, targets to get different total doses also receive different doses/fraction. For example, a head and neck patient to receive 66 Gy to the base of tongue and 50 Gy to the posterior neck nodes would receive 2 Gy/fraction to the GTV and 1.5 Gy/fraction to the nodes. The 50 Gy would be given over 33 fractions instead of the typical 25. The target dose to the nodes might need to be increased in order to have the same radiobiological effect as 50 Gy in 25 fractions. Conversely, the lower doses per fraction may improve the sparing of normal tissues. One could also use multiple IMRT plans in a regional treatment plus boost fashion, thereby using a consistent dose/fraction, but this requires the ability to sum distributions and apportion dose goals between plans.

These effects are reduced if IMRT is only used for the boost portion of the treatment, but the ability of IMRT to produce unconventional dose distributions is compromised if only used for a part of the treatment.

Target doses are often less uniform with IMRT than with the conventional treatment. The clinical consequences may depend on whether the "target" is bulky disease or microscopic inclusions in normal mucosa. Initial reports comparing IMRT to conventional treatments indicate that acute reactions are less for prostate treatments but more for head and neck treatments. Physician training needs to include these anticipated changes from conventional practice.

3.3.7 Plan evaluation

IMRT treatment plans need to be evaluated carefully and somewhat differently than other plans.

Inspecting and comparing DVHs are useful, but not sufficient, since DVHs have no spatial information. IMRT may create hot spots or cold spots in unexpected locations. For example, in 3D conformal treatments in which beams are defined using BEVs, the user typically knows that the CTV is well within every field, and so a low dose tail on a DVH for the PTV reflects penumbra at the periphery. With IMRT, those low doses may occur in the center of the CTV, with a radically different effect on tumor control (Figure 3.2). Conversely, localized high doses may occur well outside the target. Planners need to inspect the isodoses on each image slice. At a minimum, it is very important that the planning system reports the global hot spot, and it is better if the DVH for all non-target or non-segmented tissue is available for inspection.

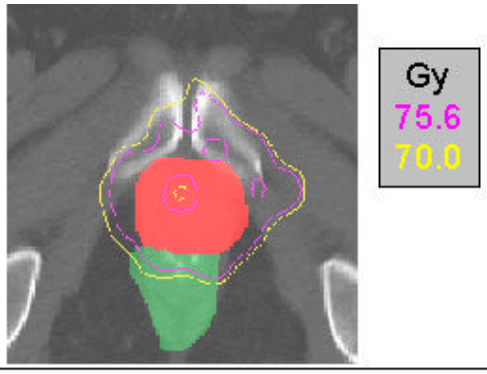


Figure 3.2 Unwanted appearance of a localized cold spot from an inverse-planning system

Plan evaluation for IMRT should include an assessment of the potential problems and pitfalls outlined in this section:

a. Is the dose uniformity in the target acceptable? Are the stated plan goals for hot spots and target coverage satisfied?
b. Are the stated plan goals for normal tissue sparing satisfied?
c. Are the margins and dose gradients safe given realistic expectations for setup reproducibility? Might geometric miss of the target or overdose to a structure result?
d. Will patient or organ intrafraction motion during the treatment compromise the accuracy?
e. Are there high doses in the buildup region that may be inaccurate or an indication that the inverse planner has struggled to "fix" low doses there?
f. Have inhomogeneity corrections been applied appropriately?
g. How does this plan compare to a conventional alternative? What regions are being treated or spared differently compared to traditional methods?
h. Are there low intensity segments that could be removed without compromising plan quality?

This list is not exhaustive but serves to illustrate the caution and skepticism that should be brought to bear.

3.4 Learning how to use the inverse planning system

Learning how to use a particular system's inverse planning tools to best advantage can be a significant undertaking. The previous sections have outlined some of the issues that may be challenging for a new user. More fundamentally, inverse planning requires learning a new set of skills. One challenge is getting a feel for how to adjust the plan parameters (prescription, goals, constraints, priorities, beam geometry, ...) in order to shift a dose distribution in the desired direction. The user needs to learn how much the results of optimization change with changes in available control parameters. A second challenge is developing realistic expectations for what can be accomplished with IMRT. A common problem is asking for an impossible distribution and therefore getting poor results. In such a situation, relaxing the objectives may produce a better plan. These issues interact; the user needs to learn how to express the clinical objectives using the tools available in the planning system and then to adjust those parameters to steer the plan.

New users should expect to spend considerable time learning how to apply IMRT to the body sites of interest in their institution. Each new site should be regarded as a new commissioning effort, with implications for imaging, immobilization, setup verification, etc., as well as planning (see section 4). Setting aside overall clinical implementation and concentrating on planning issues, developing an IMRT planning procedure for a clinical site (e.g. prostate or head-and-neck with parotid sparing) consists of several steps.

(a) Determine conventions for contouring targets and normal tissues. For example, will the rectum or rectal wall be contoured, and over what length?
(b) Decide what margins should apply and what dose gradients are appropriate.
(c) Decide what dose-volume limits define the minimum characteristics of an acceptable plan, both for targets and normal tissues. RTOG protocol H-0022 for orophayngeal cancer (http://www.rtog.org/members/protocols/h0022/h0022.doc) provides a good example. This is a non-trivial exercise but absolutely necessary. Evaluating hot spots may be especially challenging since the DVHs of these plans often have long high dose tails. Is the maximum reported dose a concern, given that it may be a single voxel? Is reviewing the dose to a minimum volume, perhaps 1 cm^3, more realistic?
(d) Once the criteria for acceptability are set, decide what aspects are to be optimized. For example, the goal might be to minimize the dose to the hottest 30% of the rectum while maintaining the prostate CTV doses within certain ranges. Conversely, the goal might be

to maximize the dose in the prostate CTV while maintaining the dose to the hottest 10% of the rectum to 75 Gy. It is useful to decide on one parameter to hold constant for all the subsequent comparisons.

(e) Having determined how to evaluate the plans, then begin to try different combinations of the planning parameters to find those that produce good results. The range of possibilities is huge, and so some systematic approach is needed. One might fix the number and orientation of beams to some relatively large number, so the beam selection is not likely to be limiting plan quality (e.g. nine coaxial beams at 40^{o} increments). Then, for fixed target doses, gradually tighten the normal tissue constraints. After the constraints are finalized, try different beam combinations.

(f) Compare the results to a manually-planned, 3D conformal alternative. Carefully assess what volumes are being treated that were not before. What is being spared that was not before? Does improved tissue sparing justify non-uniform target doses? Is the increased cost and complexity justified by real dosimetric improvement? When comparing IMRT to 3D conformal plans, it is crucial to make sure that the problem definition is consistent, e.g. same contours, margins, and criteria for acceptability.

(g) Repeat the process for a number of patients to establish a robust methodology.

Some studies have reported specific protocols that have proved useful for particular body sites and particular planning systems.

3.5 Commissioning an IMRT planning system for dosimetric accuracy

Dosimetric commissioning of an IMRT planning system should follow a systematic sequence. Many of these tests require that the system allow the user to specify a desired intensity pattern and apply it to a phantom so that the resulting doses can be measured and confirmed. The basic scheme is to start with single beams on a simple, flat (i.e. geometric) phantom with controlled intensity patterns, then controlled intensity patterns for multiple beams, then multiple beams treating hypothetical targets in the flat phantom, then (if possible) multiple beams treating hypothetical targets in anthropomorphic phantoms. The goals are to determine first if the beam parameters are accurate using simple situations that are easy to evaluate, and second to determine the level of accuracy to expect in clinical situations.

The primary dosimetry tools are water-equivalent or other plastic phantom(s), ionization chamber, film, and a film scanning system. Note that if the phantom is CT scanned with the ionization chamber in place, the sensitive volume can be outlined as a region of interest in the plan. The mean dose to this region as reported by the plan can then be directly compared to the measured dose.

Cylindrically symmetric chambers are preferable to plane-parallel chambers for multiple beam irradiation because of their axial symmetry. Small volume chambers are best unless the dose gradients can be kept low over the size of the chamber. Film that can be irradiated to a typical daily dose is also preferred in order to remove uncertainties caused by monitor unit scaling.

(a) For a series of open fields on the flat phantom, confirm that the central axis depth dose and off axis profiles match expected values.

(b) For a series of simple intensity patterns, e.g. wedge, pyramid, well, …(Figure 3.3a-c), measure the dose/MU at multiple points with an ion chamber. Test profiles at multiple locations and directions with film. Create patterns that have systematic changes in intensity levels. As noted above, careful attention to agreement along high gradient edges

at this point can uncover penumbra representation problems that would cascade in full patient plans. A random distribution (figure 3.3d) helps to determine the level of accuracy one might see in a patient treatment.

(c) Apply a simple modulated shape to plans using gantry, collimator, and couch angles and translational shifts and confirm that these geometric motions are properly implemented and understood.

(d) Apply a simple intensity pattern to multiple beams irradiating the flat phantom at different angles. For example, create 10x10 cm array of 100% beamlets with a central 4x4 section and apply it to 5-7 axial beams at equal angular increments. Vary the central section intensities from 100% to 0% (Figure 3.3e). Measure the dose in low gradient regions with the chamber and the dose distribution in multiple planes with film (Figure 3.4).

(e) Design a series of tests of idealized targets in the flat phantom to be treated with multiple fields. Start with simple targets requiring little modulation (sphere) and progress to more complicated target/critical organ combinations that require more (C-shape surrounding a critical organ, cylindrical shell surrounding a critical organ, with progressively tighter constraints on the organ.) As before, measure the dose in a low gradient region with the chamber and the dose distribution in multiple planes with film.

(f) Evaluate dose calculation accuracy in the presence of heterogeneities using a simple geometry.

(g) As need and resources permit, test simple and complex targets in heterogeneous and anthropomorphic phantoms.

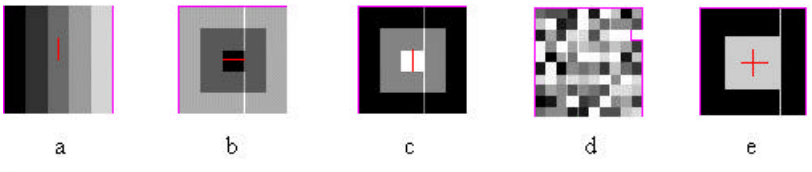


Figure 3.3 Examples of user-controlled intensity shapes used for commissioning tests.

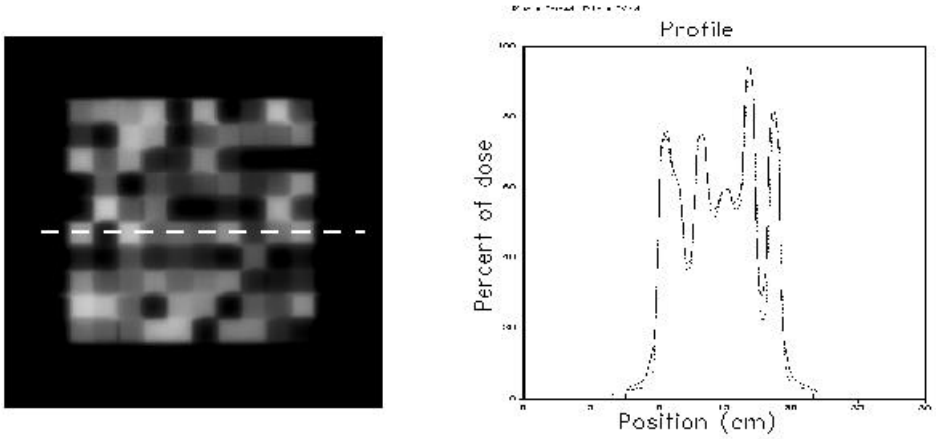


Figure 3.4 Dose profile measured with film across one line of a random intensity pattern (plan = dotted, film = solid)

There are at present no specific recommendations for dosimetric accuracy of IMRT plans Attention needs to be paid to high dose regions representative of targets and low dose regions representative of critical structures. A goal of commissioning is to develop an understanding of the dosimetric uncertainties so that clinical plans can be meaningfully evaluated, especially with respect to critical structures. It is true that IMRT plans may have localized dose gradients that make measurement more difficult, but these may be more problematic for individual

beams than for the combination of all. It may also be difficult to determine if differences between measurement and calculation are caused by planning, delivery, or measurement technique. For this reason, the delivery system should be commissioned separately from and before the planning system. The construction of good commissioning tests is a challenge and a subject for ongoing research and development.

3.6 Quality assurance of individual treatment plans

A primary difficulty with designing quality assurance tests for individual patient plans is not knowing all the likely failure modes for this new modality. Skepticism and caution are clearly indicated. Monitor unit checks for IMRT treatments cannot be accomplished by simple manual calculations, although some computerized independent calculation methods have been reported. Direct measurements are more commonly used and serve to test many aspects of planning and delivery.

3.6.1 Independent calculation methods

Independent calculation methods to verify monitor units and absolute doses are becoming available for IMRT plans. There have been some algorithms reported that take MLC delivery files and calculate doses that can be compared to the IMRT planning system's prediction. Some methods calculate delivered intensities from the delivery files and then apply sector integration or other techniques to approximate the dose. Some facilities have eliminated most point dose measurements after developing and commissioning such independent systems, but that commissioning task is a large one.

"Independent" dose calculation methods that derive their input information from the planning system files will not catch errors in that input information (plan done on wrong patient, with wrong treatment unit…) or errors in transferring data from the planning system to the treatment system, i.e. record/verify system. To give the most confidence, one should use to use output from the R/V system as input to the independent calculator, along with SSDs obtained directly on the patient or measured on an image.

As mentioned in section 2.1.1, independent dose calculation methods will not catch errors caused by the treatment delivery system.

3.6.2 Verification measurements

Verification measurements are commonly made of a "phantom plan" or "hybrid plan". The patient's plan is applied to a CT study of a phantom, in which dose measurements can be made using ion chambers and/or film.

It is important to realize that some errors in input data or calculations will not be caught in this way, since the assumptions and calculation methodology for the patient are transferred to the phantom. For example, the planning system might "see" the CT couch as part of the patient, adding several centimeters of radiological depth to the posterior fields and inappropriately increasing those intensities. Measurements of the subsequent phantom plan would confirm the dose calculation, not uncover the error. Phantom measurements test the dose calculation and delivery mechanism, but do not check some assumptions used in the planning process.

It is useful to have phantoms that reasonably approximate the body site in question. Examples could be a 30x30x15 cm rectangular phantom for the trunk and 15x15x15 cm rectangular phantom for the head. The routine use of a phantom that is not equivalent in size needs to be validated by testing at least once against a more appropriate phantom. More anthropomorphic phantoms are also commercially available.

3.6.3 Other plan checks

TG-40 and TG-53 both have recommendations for checks of individual plans that certainly apply to IMRT plans, but again there are additional concerns. Since inverse planning systems, not humans, design the beams, it is important to check that the anatomical areas covered make sense.

Similarly, inverse planning systems may have the option of shifting the isocenter from an original setup point before treatment. Clearly, recognizing such a shift is crucial.

A helpful method to check for these situations is to compare digitally reconstructed radiographs (DRRs) from the plan, with target volumes superimposed, to simulator films and/or port films of the treatment. Since the DRR is generated from the plan data, correspondence to the actual patient as seen on the film confirms that the virtual model aligns with the real world. Clearly, high quality DRRs are needed for such a comparison to be trustworthy.

The plan evaluation issues discussed in section 3.3.7 should also be considered during plan checks.

3.7 Conclusion

Commissioning an IMRT planning system is a challenging project that must be undertaken with an understanding of the dosimetric and clinical concerns. The goal of this section has been to provide a framework on which the physician and clinical physicist can build a plan for that undertaking.

4.0 Clinical implementation of IMRT

4.1 Overview

Work needed to implement IMRT includes all that is needed to implement 3DCRT and more. This section will concentrate on the additions and provide guidance related to issues of clinical implementation of IMRT.

Each facility should designate an implementation team to think through the implications in advance and periodically update procedures as lessons are learned. In order to truly benefit from IMRT, various resources must be in place and all persons involved in IMRT, not only physicists but also physicians, dosimetrists, therapists and administrators, must be properly trained before the actual treatment. Consideration should be given not only to bring the modality to the clinic, but also to keep it running smoothly and keep pace with upgrades and future enhancement in IMRT technology. Furthermore, IMRT is an integrated system and careful thought should be given to every single technical/physical component and treatment step. The overall integration should also consider human involvement in the procedure and address the issues related to staff education and training.

The clinical implementation of IMRT includes the following aspects:

1. Equipment and space requirements (section 4.2)
2. Time and personnel requirements (section 4.3)
3. Changes in treatment planning practice (sections 4.4.1 – 4.4.5)
4. Changes in treatment delivery practice (sections 4.4.6 – 4.4.9)
5. Quality assurance of equipment and individual patient treatments (section 4.5)
6. Staff training and patient education (section 4.6)
7. Changes in scheduling, billing and charting practice (section 4.7)
8. Overall integration (section 4.8)

In the following we will offer guidance on these aspects of IMRT, suggesting questions that the clinical implementation team will need to ask and provide potential answers where possible. The goal is to provide a framework to organize the task of bringing IMRT into the clinic.

4.2 Equipment and space requirements

4.2.1 Shielding

IMRT treatments require more about a factor of 2-10 more monitor units (MUs) than conventional treatments, so room shielding should be re-evaluated. This factor is about 2-4 for the MLC based IMRT treatments. For sequential tomotherapy delivery, this factor can be up to a factor of 10, depending on number of rotations involved. Primary barriers are not usually affected, although use factors should be assessed because IMRT treatments typically use arcs or many more gantry angles than conventional treatments. Workload for secondary barriers will definitely increase and shielding design needs to be evaluated.

4.2.2 Space planning

Extra space may be needed for additional computer workstations, especially if IMRT planning is to be done on a dedicated system. Space may also be needed for additional equipment, such

as add-on collimators, dosimetry phantoms and instrumentation, as well as patient immobilization devices. Space for additional personnel may be required.

4.2.3 Equipment

It may be necessary to upgrade existing accelerators to provide IMRT functionality, such as adding an MLC, upgrading an existing MLC to dynamic capability, or purchasing special add-on collimators. Similarly, existing record and verify systems may need to be upgraded to accommodate IMRT treatments. Computer networks may need to be enlarged or improved in order to permit the needed file transfers.

Additional dosimetry equipment may be needed for the commissioning and ongoing quality assurance of IMRT. It is important to have an efficient film scanning system to accomplish these tasks. Additional phantoms may also be needed.

4.3 Time and personnel requirements

It is essential to anticipate the number of additional staff that will be needed to implement and maintain an IMRT program.

Sufficient time and resources must be allocated to complete all the tasks involved in clinical implementation. The physics staff will need to complete comprehensive and quantitative measurements to assure that the treatment planning and treatment delivery systems are accurate. Physicians and treatment planners will need to learn a very different approach to planning. The implementation team will need set up and test the processes used for individual patient treatments. Quality assurance procedures will need to be modified. Many of the staff: physicians, physicists, dosimetrists, therapists, and engineers, will need special training. It is important to stress that these tasks will likely require an initial investment of several person-months of work on the part of the physics staff and other members of the implementation team.

After the initial implementation effort, there will also be an increase in the ongoing quality assurance activities for both the IMRT systems and individual patient treatments. Other sections describe these activities in detail.

4.4 Changes in treatment planning and treatment delivery

4.4.1 General considerations

The details of IMRT treatment will differ from institution to institution, but the general IMRT treatment process shown in figure 4.1 will serve to frame the discussion.

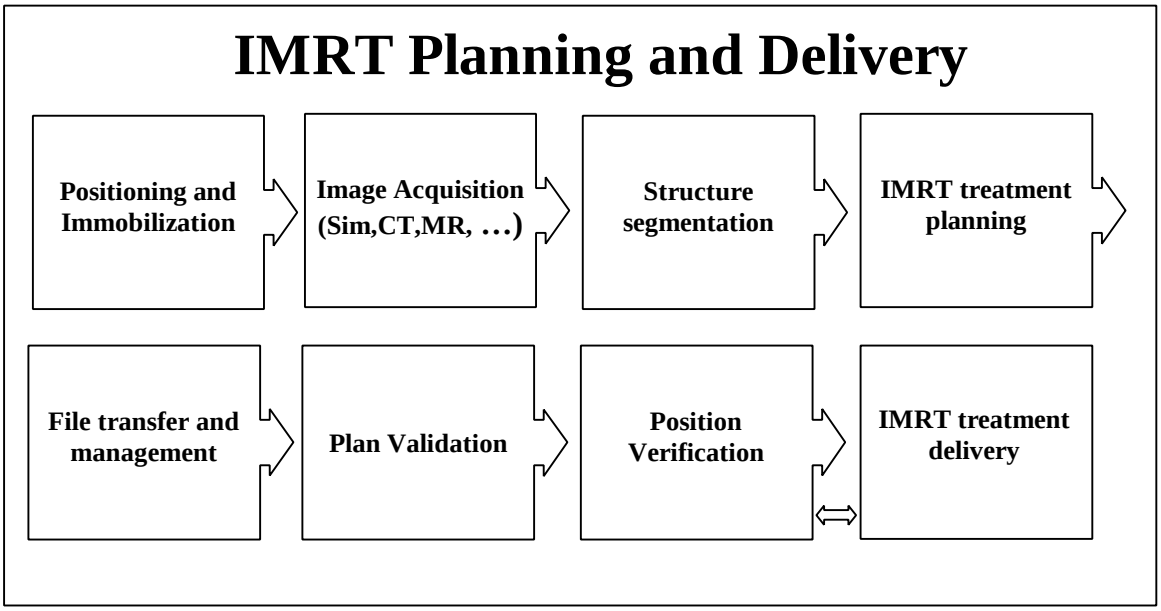


Figure 4.1 The overall process of IMRT planning and delivery

4.4.2 Immobilization

Because of the highly conformal nature of IMRT treatment, new immobilization techniques may be necessary to safely use the technology, such as supplementing thermoplastic masks with bite block fixation. Techniques to reduce or follow internal organ motion, such as by using ultrasound localization of the prostate or respiratory gating, may be desired. All these new procedures will impose their own burdens with respect to procedure design, training, and validation. If not already known, it may be necessary to study the reproducibility that can be achieved with the immobilization system in order to establish realistic margins for planning. Generally, the patients will be immobilized and marked as close as possible to the anticipated treatment isocenter.

4.4.3 Image acquisition

At an early stage in the process, the goals of treatment should be discussed carefully with the planner so that a clear understanding of the imaging and planning needs is established. As for 3D conformal treatments, a CT for treatment planning will be performed with the patient in treatment position with the immobilization device. Clinics may find that they need to obtain more slices at a finer spacing than had been the norm previously. For inverse planning systems driving a 1 cm MLC, slice spacing of no more than 0.5 cm should be used, and finer spacing may be needed to generate DRRs of sufficient quality. This is especially important when using an inverse planning system that may call for a shift from the original alignment point, and in any case one needs to verify that the isocenter in the plan corresponds to that used for treatment.

The range of slice acquisition may also be expanded in order to permit noncoplanar beams to be used. For example, for isocenters above the base of the sphenoid sinus, the protocol may be to acquire slices through the top of the head and inferiorly as indicated.

Highly conformal treatments, especially when designed with inverse planning, may require target and normal tissue structures to be identified with more care. Hence, the use of contrast agents for the CT and registration of images from other modalities, such as MRI or PET is often needed and may represent a change in typical practice.

4.4.4 Structure segmentation

As with all 3D planning, contouring targets and normal structures is labor-intensive for physicians and planners. With IMRT more demand is placed on the physicians to define structures in detail. For example, implementing a new parotid-sparing protocol for head and neck patients would require the parotids and at-risk nodal volumes to be defined on each axial slice, with due consideration for margins. This can be more difficult than defining conventional lateral fields on simulator films to treat the nodal volumes, hence requiring more of the physician's time.

4.4.5 IMRT treatment planning

The differences between planning for IMRT and for conventional treatments are discussed in section 2. In terms of clinical implementation, a key point is to allow time for the physicians and planners to develop their skills in using the system. Inverse planning in particular requires new modes of thinking: physicians need to quantitatively prescribe dose-volume limits that define an acceptable plan, and planners need to learn how to control the dose distribution by modifying unfamiliar input parameters. Clinics will need to develop tools to aid these tasks. Special forms should be implemented for recording the desired clinical objectives (section 3.4b-d), the planning parameters entered, and a comparison of the plan results with the clinical objectives.

Note that it is not certain that IMRT plans will be superior to alternative 3D-CRT plans. For a specific site, a comparison of 3D-CRT plans and IMRT plans may be obtained from published literature, showing the benefit of IMRT. In any event, practitioners should not utilize IMRT plans that are inferior to the treatments currently employed.

4.4.6 File transfer and management

When the IMRT plan has been satisfactorily computed and approved by the physician, one can generate the treatment control files. For MLC systems, these include leaf sequence files for each gantry angle. Since IMRT involves complex beam shapes and control files, digital capability for plan transfer is essential to avoid possible mistakes during manual transferring. Depending on the individual clinic's information system, the files can be transferred by floppy disk or, preferably, directly transferred to the record/verify server through data exchange software.

Since information transfer is a common source of treatment error, the clinical implementation team will need to answer many important questions. On a daily basis, the therapist will need to be able to verify that the appropriate file has been selected for each field or arc. If the files are on a floppy disk, how will the disks be stored and labeled so that choosing the wrong one is unlikely? Will patient and field identifiers be displayed so that they can be checked? Will a double check of that selection be required? Will it be documented? If the department has a record and verify system that fully supports the IMRT treatments, then many of these problems are reduced (and replaced by the need to verify the initial programming of the R/V

system). If the R/V system does not fully support the IMRT treatments, can it still verify some parameters, such as energy and monitor units? Does it have to be bypassed or turned off for the IMRT treatments? If so, how might that affect other processes, such as electronic record keeping or charge capture?

To expedite IMRT delivery, an auto-sequencing delivery system is sometimes used. Such delivery systems (in different forms) are currently available from all major accelerator vendors. "Dry runs" to test for collisions or other problems may need to be a part of routine plan validation.

4.4.7 Plan validation

The goal of IMRT plan validation is to verify that that the correct dose and dose distribution will be delivered to the patient. One needs to check that the plan has been properly computed and that the leaf sequence files and treatment parameters charted and/or stored in the R/V server are correct and will be executable. Items that need to be validated, preferably before the first treatment, include: monitor units (or absolute dose to a point), MLC leaf sequences or fluence maps, dose distribution, and collision avoidance.

Note that the details of what is to be measured or calculated for dosimetric validation will be tailored to each clinic's needs and may change with experience. However, it is important to emphasize that new users will need to spend much more time validating IMRT plans than is common with conventional treatments. Direct measurements will be necessary unless and until independent dose calculation methods are developed and validated.

4.4.8 Position Verification

Clearly, position verification is an important part of plan validation. The most critical point is to verify that the treatment isocenter matches the planned isocenter. This should be accomplished by comparing orthogonal films taken at simulation, DRRs from the planning system, and portal images from the treatment unit. As mentioned above, an inverse planning system may call for a shift from the original alignment point, so it is crucial to compare the isocenter on the DRRs with the setup films.

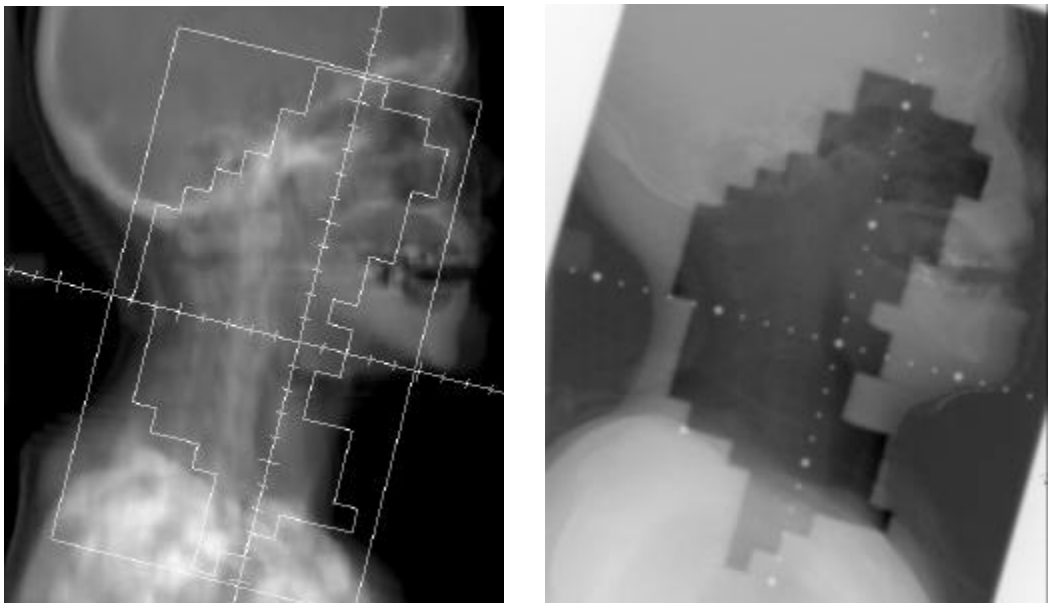


Figure 4.2 Example of DRR and portal image used for IMRT isocenter and field shape verification

Wherever possible, portal images should be obtained for the fields used for treatment, and it is useful to have the MLC field boundary as apertures for the ports and compare to corresponding DRRs from the planning system (figure 4.2). Depending on the imaging system available, it may be possible to obtain a portal image of the modulated field superimposed on the patient's regional anatomy, but such images are often hard to interpret.

If IMRT is to be applied to highly precise treatments near critical structures, then the frequency of on-treatment portal imaging may need to be evaluated.

In general, the implementation team will need to consider any changes in the portal imaging process, such as how to acquire the bounding MLC shape, how to verify the position of a slit collimator, or how to operate an electronic portal imaging system in the presence of dynamic fields.

4.4.9 IMRT treatment delivery

IMRT treatments often take more time due to their increased complexity. They require more MUs, and often have more fields over more gantry angles than are used conventionally. For example, patients previously treated with laterals or four-field box fields may now have many fields, including obliques or arcs. Treatment field sizes are more limited for IMRT than for conventional treatments because of limitations of leaf over-travel and jaw over-travel. This may require what used to be one treatment field to be delivered using two or more IMRT fields. Studies have shown that, in head and neck treatment, the treatment time ratio between the IMRT plan and the conventional 3D-CRT plan is about 1.5-2.5. For prostate treatment, the time ratio is about 1-2, depending on the delivery system.

Foresight and training with respect to patient positioning will be needed to avoid problems with collisions or interference by patient support systems. "Dry run" tests may be useful.

4.5 Quality assurance of equipment and individual patient treatments

In general, the QA of IMRT has three natural aspects; commissioning and testing of the treatment planning and delivery systems, routine QA of the delivery system, and patient specific validation of treatment plans. The first task is mainly concerned with the integrity of the inverse planning and IMRT delivery system. The second one is concerned with the normal operation of the dynamic delivery system and will involve additions to the daily, monthly, and annual quality assurance protocols. The third task is to ensure an accurate and safe treatment of a patient. It is important to emphasize that IMRT is a rapidly evolving modality and the QA program must also evolve so that it handles new issues that arise.

4.6 Staff training and patient education

Like any other radiation therapy modality, IMRT is an integrated process and the staff training and education is a viable part of the clinical implementation of IMRT. It is much more complex and non intuitive than conventional 3-D conformal therapy. Experience gained by the staff in 3-D treatment planning and delivery is helpful but not sufficient for IMRT. There are significant differences between the two that necessitate additional specialized training. IMRT is often associated with sharp dose gradients, increased heterogeneity of dose within the target volume, low monitor unit efficiency (much larger number of MU compared to conventional radiation therapy for the same prescribed dose), and complex motion of multileaf collimators. It is imperative that each member of the IMRT team understands the

implications of each of these factors to use this technology safely and effectively. IMRT is so different from traditional radiation therapy that it can be easily considered as a special procedure necessitating didactic training for key members before they implement this new modality in their clinics. The training curriculum for each IMRT team member must include all of the critical steps in the IMRT process.

4.6.1 Radiation Oncologists

IMRT represents a significant departure from the current paradigm used in radiation oncology. Dose planning in conventional radiation therapy is accomplished in a very intuitive manner by optimizing the weights of strategically placed radiation portals that conform to the target volume. Planning solutions are often well understood and do not vary much from patient to patient for a particular disease site. On the other hand, IMRT planning process starts with the definition of treatment goal and constraints. The dose optimization is completely computer controlled and its success in achieving the clinical goals is very much dependent on the set of parameters used as input to the computer algorithm. Learning how to adjust the parameters to steer the results in the desired direction is complex and sometimes non-intuitive. Therefore, it is difficult to identify an optimal solution without having a complete understanding of the optimization process and its limitations. There is a significant potential of treating a patient with a sub-optimal IMRT treatment plan if the radiation oncologist lacks the training in this process.

One of the basic uses of IMRT is to treat tumors that are either in close proximity or surrounded by critical normal structures, and this presents two challenges. One is to segment the structures precisely and accurately, and the other is to choose appropriate planning margins judiciously. It is essential that the radiation oncologists are well-trained in image guided treatment planning and that they have a good understanding of treatment planning and delivery uncertainties.

Unlike conventional radiation therapy, the gross tumor and regions of sub clinical disease are often treated concomitantly to different dose per fraction in IMRT. Moreover, the dose distribution in the target volume is often much more inhomogeneous in an IMRT plan. It is important that the radiation oncologists critically evaluate differential dose fractionation schedules for IMRT in light of their clinical experience with conventional radiation therapy. This requires an understanding of the biologically effective equivalent dose concepts and tissue tolerance doses.

Radiation oncologists who did not have chance to get training in IMRT process during their residency training should consider getting such training through special workshops conducted by academic institutions that have active clinical IMRT programs. Some private companies have also started courses in IMRT.

4.6.2 Radiation Oncology Physicists

IMRT is much more challenging for radiation oncology physicists than the conventional radiation therapy. Radiation oncology physicists have much more significant and direct role in IMRT planning and delivery than in conventional radiation therapy. It requires an advanced understanding of mathematical principles of dose optimization, computer-controlled delivery systems and issues that relate to the dosimetry of small and complex shaped radiation fields. They also need to have a better understanding of treatment setup, planning and delivery uncertainties and its impact on patients treated with IMRT. Treatment planning optimization

for IMRT is based on dose-volume constraints and dose limits for critical structures and target tissues. Therefore, it is important that radiation oncology physicists understand these concepts and have a good familiarity with tomographic anatomy. They must understand the implications of a busy intensity patterns (with large peaks and valleys) on the treatment delivery accuracy and efficiency. The quality assurance testing for IMRT is much more complex than conventional radiation therapy. It is imperative that each physicist involved with IMRT should have special training in the whole process of IMRT.

4.6.3 Dosimetrists

The dosimetrists have a particularly difficult task of adjusting to IMRT planning. IMRT planning uses a paradigm that they are not used to in conventional radiation therapy planning. Compared to treatment planning for conventional radiation therapy, the emphasis in IMRT planning is more on selecting the most appropriate dose optimization parameters. They do not have to worry much about beam shaping, placement and weight optimization in IMRT. Like physicists, dosimetrists must understand the implications of dose-volume constraints on optimized dose distributions. They also need to understand, at least conceptually, the implications of treatment setup, planning and delivery uncertainties in IMRT. The best source of training for a dosimetrist is the facility radiation oncologist and physicist who have special training in the use of IMRT.

4.6.4 Radiation Therapists

Implementing IMRT requires the active involvement of the radiation treatment therapists. They should be involved in the design and testing of treatment procedures. It is important to set aside sufficient time for that participation and the related training.

If the IMRT delivery involves specialized equipment (e.g. add-on collimating device), then there will be the need to train the therapists in its use and storage. They may also have responsibilities for basic maintenance and quality assurance.

Therapists will need to be trained to use any new immobilization or localization systems.

However IMRT is delivered, be it with special collimators or existing MLCs, therapists will need to be trained in the new procedures. Carrying out mock procedures with phantoms needs to be part of the process of testing the new procedures. Delivery details that escape the physicist's notice may be important to the therapists. For example, the initial field shape for an IMRT treatment may obscure the light field or the crosshair, requiring that the patient be positioned before the MLC is programmed.

Therapists need to be provided with the means of knowing that the treatment they are about to deliver is correct. For conventional treatments with blocks or static MLC shapes, they can compare the field on the patient to the simulation film, DRR, or other plan data. For IMRT, the initial field shape may show only a narrow segment or be closed entirely. For IMRT treatments, the analog to the physical block or static MLC file is the dynamic IMRT file. The physicist may well have validated the intensity map produced by each file before treatment, but on a daily basis the therapist will need to be able to verify that the appropriate file has been selected for each field or arc. (These issues were discussed above in the section on file transfer and management.) Given the complexity of IMRT treatments, it is clearly best for the treatment delivery to be fully monitored by a R/V system. Even in that case, therapists will need to be trained so they can verify for themselves that the R/V programming is correct.

Therapists will need to be shown how to respond to unplanned events. They need to know how to interrupt and restart a treatment, how to recover from a partial treatment that requires the console to be reprogrammed, how to recognize and act on new error messages and interlocks.

Therapists will need to be trained on any new procedures related to portal imaging and to daily quality assurance tests. As with any QA procedure, clear instructions and action levels need to be provided.

4.6.5 Service engineers

Reliable performance of all aspects of the delivery equipment used for IMRT is essential. Compared to standard treatment techniques, it can be much more difficult to cleanly recover from an interruption in dose delivery after an intensity modulated treatment has started. Therefore, accelerators with a poor history of reliability are not suited for this type of treatment, and expanded preventive maintenance programs are extremely important. This is particularly important for the multileaf collimator component of the overall system. Intensity modulated dose delivery can place demands on the MLC that far exceed the criteria used for the design of these systems. When the standard MLC systems where designed in the late 1980s, IMRT was not anticipated as a routine treatment. It is now evident that some implementations can require several hundred field changes per patient, or many thousands of fields per treatment day. This situation can lead to component failure, and special QA procedures must be adopted to guarantee proper calibration of leaf position and to avoid treatment interruptions. With the cooperation of the medical physicist, preventive maintenance programs must be examined to determine that they are properly designed to address the special needs of IMRT. Additionally, service engineers must have a good working knowledge of the aspects of the treatment unit that are unique to IMRT. Service engineers need to understand that small changes or adjustments to an MLC can affect the machine output for IMRT delivery and should confer with the physicist whenever changes are made.

4.6.6 Patient education

Patients treated with IMRT should be informed of several issues. They need to be given realistic estimates of the time required for each treatment, description of the immobilization method used, and motions and sounds they will experience. Description of the goal of treatment and potential side effects may differ from conventional radiotherapy. These will be site- and protocol-specific. If IMRT is used to escalate doses, then the potential for acute or chronic sequelae may increase. Parotid sparing protocols may decrease the incidence of xerostomia but increase acute mucositis, especially if target doses are more inhomogeneous than with conventional treatments.

Another issue is the need to manage patients' expectations for IMRT. Patients may come with the desire to be treated with this new, highly advertised modality, whether or not it is advantageous or appropriate for their condition. Patients (and their families) also converse together, and some may question why their experience differs from others.

4.7 Patient scheduling, billing, and charting

IMRT treatments may take longer than conventional treatments. It may also be implemented on only some of the treatment machines. New immobilization techniques may also be introduced simultaneously and would impact simulation and treatment times. New imaging studies may be ordered. Staff responsible for scheduling will need to be advised of new scheduling requirements. They should be consulted early in the implementation process so that consequences of those changes can be anticipated and adjustments made.

Implementing IMRT offers new opportunities and requirements for billing and requires careful attention to compliance issues. Administrators and other staff will need to develop efficient tools for billing and documentation.

The implementation team will need to consider needed changes in charting procedures. This could relate to instructions for treatment delivery, documentation of daily treatment with many complex fields, documentation of QA procedures, and to dose summaries that adequately describe dose-volume goals and results.

4.8 Overall integration

This section has stressed the importance of using the combined expertise of an implementation team. Although the physics staff will carry much of the burden of installing and commissioning an IMRT system, ultimate success depends on the active support and involvement of physicians, dosimetrists, therapists, and administrators.