Guidance document on delivery, treatment planning, and clinical implementation of IMRT: Report of the IMRT subcommittee of the AAPM radiation therapy committee

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Intensity-modulated radiation therapy (IMRT) represents one of the most significant technical advances in radiation therapy since the advent of the medical linear accelerator. It allows the clinical implementation of highly conformal nonconvex dose distributions. This complex but promising treatment modality is rapidly proliferating in both academic and community practice settings. However, these advances do not come without a risk. IMRT is not just an add-on to the current radiation therapy process; it represents a new paradigm that requires the knowledge of multimodality imaging, setup uncertainties and internal organ motion, tumor control probabilities, normal tissue complication probabilities, three-dimensional (3-D) dose calculation and optimization, and dynamic beam delivery of nonuniform beam intensities. Therefore, the purpose of this report is to guide and assist the clinical medical physicist in developing and implementing a viable and safe IMRT program. The scope of the IMRT program is quite broad, encompassing multileaf-collimator-based IMRT delivery systems, goal-based inverse treatment planning, and clinical implementation of IMRT with patient-specific quality assurance. This report, while not prescribing specific procedures, provides the framework and guidance to allow clinical radiation oncology physicists to make judicious decisions in implementing a safe and efficient IMRT program in their clinics. © *2003 American Association of Physicists in Medicine.* [DOI: 10.1118/1.1591194]

Key words: 3-D conformal radiotherapy, intensity-modulated radiation therapy, inverse planning, plan optimization, quality assurance

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I. INTRODUCTION

A. Relation of intensity-modulated radiation therapy (IMRT), three-dimensional conformal radiation therapy (3DCRT), and traditional practice

IMRT is an extension of 3DCRT that uses nonuniform radiation beam intensities that have been determined by various computer-based optimization techniques. Three-dimensional conformal therapy 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 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, new capabilities of linear accelerators (linacs) and collimators must 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 IMRT planning must be commissioned for dosimetric accuracy. Users must learn how to use inverse planning systems to produce and evaluate high quality plans. These are new tasks that physicists and other radiation oncology staff must accomplish. Many physicists and their colleagues are now struggling with the question of ''what do I need to know and do to implement IMRT safely and effectively?''

B. Objectives for this document

The objectives for this document are

(a) to describe in general terms how IMRT differs from 3DCRT with respect to treatment delivery, treatment planning, and clinical implementation and give references so readers can get more details if desired;

(b) to describe how these differences impact commissioning of the treatment planning and delivery systems, and provide guidance on the commissioning process;

(c) to describe the impact on ongoing quality assurance (QA) and provide guidance on QA practice; and

(d) to describe how these processes fit together with each other and provide guidance on the clinical implementation of IMRT.

Because of the emerging and rapidly changing nature of IMRT, this document cannot be definitive or prescriptive. Task group reports and Codes of Practice will eventually emerge as the field matures. Our intention in this document is to provide guidance 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)[1] and special issues of *Medical Dosimetry*,[2,3] with which readers should also be familiar. We have also consulted with ASTRO representatives who are developing recommendations for the clinical use of IMRT. It should be recognized that the development of IMRT is still in its infancy and is rapidly evolving. Therefore, many specific statements made within this document are likely to be outdated as the new generation of planning and delivery systems become available.

C. Organization of this document

After this introductory section, this presentation follows with a description in Sec. II 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 III on treatment 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. These two sections address objectives (a)-(c); that is, they explain the differences from 3DCRT and provide guidance on commissioning and QA of treatment planning and delivery systems. Finally, in Sec. IV on clinical implementation we outline the issues that have to be addressed by the physicist and other team members in order to bring IMRT online, and so we address objective (d).

II. DELIVERY SYSTEMS FOR IMRT

The difference between 3DCRT and IMRT with respect to treatment delivery is implied in the phrase *intensity modulation*. Three-dimensional conformal therapy uses blocks or multileaf collimators (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 intensity 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 during irradiation and indexes the collimator shape to a fraction of the total prescribed MU for that direction, 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 QA considerations.

In this section we will emphasize those techniques that have been implemented commercially using MLCs since they are the most common and of widest interest to practicing medical physicists. It provides guidance for commissioning and QA for these. Other techniques are described briefly.

Although IMRT planning and delivery are intimately related, in this section we suggest tests of the IMRT delivery system using MLC control files that have been developed independently from the IMRT planning system. In this fashion, the causes of dose deviations can be isolated to the delivery or planning system.

In Secs. II A and II B we describe IMRT delivery systems that use fixed gantry angles and MLCs. In Sec. II C we describe IMRT delivery systems that make use of fixed gantry angles and physical attenuators. In Secs. II D and II E we describe IMRT delivery systems that make use of gantry rotations and MLC. In Sec. II F we provide background information on the leaf sequencing algorithms that are used in the segmental and dynamic IMRT techniques described in Secs. II A and II B.

A. General issues of IMRT delivered 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. Each collimator shape thus is a subfield (or a segment). The desired intensity pattern is obtained by the fractional weighted summation of the intensity pattern from all subfields.

1. MLC leaf positional accuracy

In conventional 3DCRT, the MLC defines the outer aperture of the beam shape. An uncertainty of 1 to 2 mm in leaf location may be inconsequential to the output and, in general, to clinical outcome, since the uncertainty is small compared with the aperture size. Segmental IMRT builds up a fluence pattern by adding together many segments, some of which may be quite narrow. Several investigators have shown that, for beam widths of 1 cm, uncertainties of a few tenths of a millimeter in leaf position can cause dose uncertainties of several percent.[4,5] Furthermore, the beam edges move to many locations within the treated area, so their locations must be known to high precision so that their contributions sum accurately. For these reasons, the accuracy of relative MLC leaf position must be maintained to a precision of better than a millimeter. Conventional QA 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 must be well established with respect to the nominal location of the MLC leaf end. For MLCs with rounded leaf ends, there is an offset between the beam edge as defined by the light field and that defined by the 50% decrement line of the radiation field.[6] This is typically 0.4 to 1.1 mm de-

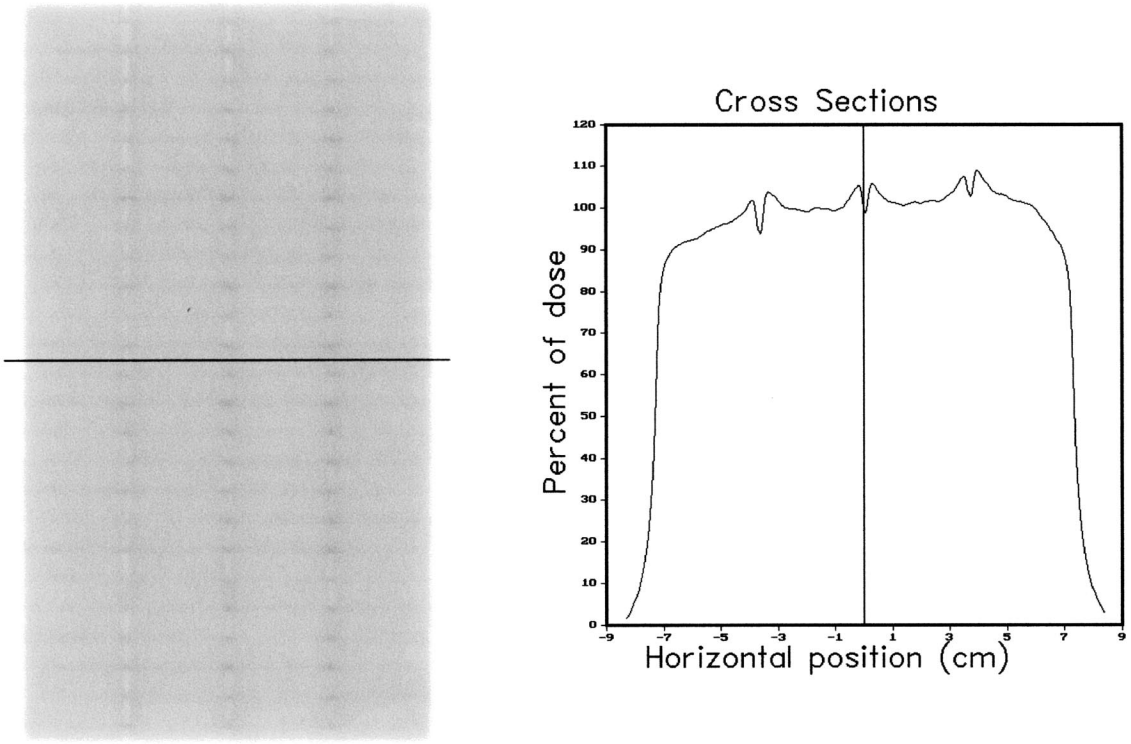

FIG. II.1. (a) MLC test pattern with a 2 cm wide strip. (b) QA film produced by moving the pattern in 2 cm intervals and irradiating in a step-and-shoot fashion. The strips should abut at the 50% decrement lines as described in Sec. II A 1. The line on the film shows the location of the scan (c), which is used to assess the quality of the matching. This MLC has a rounded leaf end design.

pending on the MLC type, beam energy, and location with respect to the central axis. An offset can also exist with double-focused 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.[7] (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.)

Therefore, the physicist should perform the following.

(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.)
(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.
(c) Irradiate a film and scan across the match lines to check the uniformity of the dose (Fig. II.1).

The offset can 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 leaf position variation to a precision of about 0.2 mm.[8,9] More precise control is likely unattainable. This positional variation will produce a dose variation of about $\pm 5\%$ 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 leaf positional accuracy is to film a test sequence that creates 1 mm strips at regular intervals.[8] A visual inspection can detect improper positioning to a precision of about 0.5 mm (Fig. II.2). Again, such films should be at different gantry and collimator angles and over the full range of leaf bank motion.

Physicists must comprehensively check the MLC leaf positional accuracy during IMRT commissioning and develop a subset of checks as part of routine QA. It is prudent to test frequently at first and reduce the frequency as experience builds. In IMRT, unlike conventional treatment, MLC calibration and performance affect dose delivery to the central target region. This program might include tests that focus on machine performance, such as a daily output check using multiple narrow-segment tests, films as described above, and might also include overall planning and delivery measurements for specific patients, as described in Sec. III F 2. If a facility moves toward using independent calculation techniques to check individual patient plans (Sec. III F 1), then

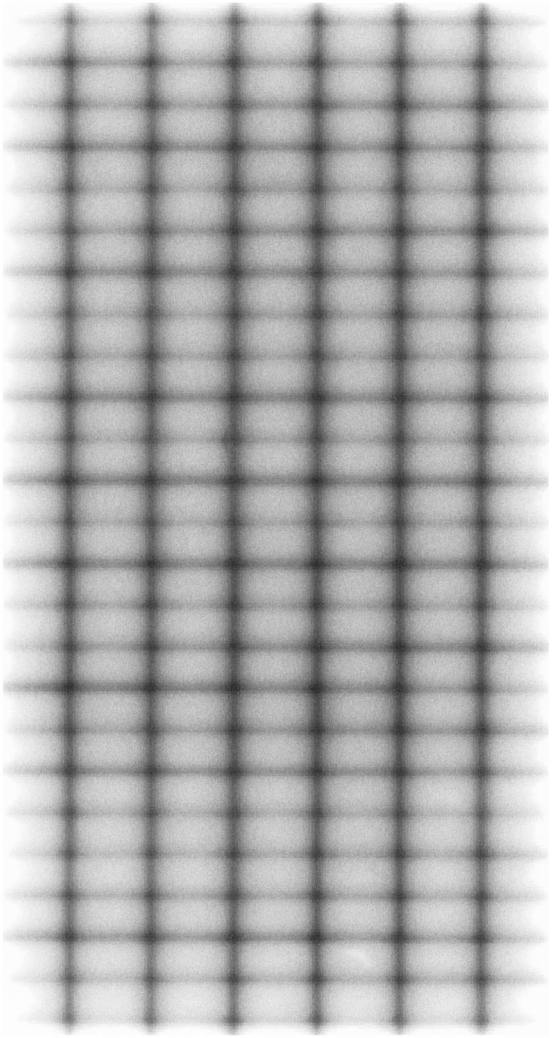

FIG. II.2. (a) MLC test pattern with a 1 mm wide strip. (b) QA film produced by moving the pattern in 2 cm intervals and irradiating in a step-and-shoot fashion. This MLC has a rounded leaf end design.

tests of machine performance will need to be performed on at least a weekly basis.

2. Linac performance for small MU delivery

Depending on the planning and delivery system used for IMRT, segments may be delivered with few or fractional MU. The dose-per-MU constancy should be checked throughout the range of use for IMRT. Similarly, the flatness and symmetry of the beam should be checked.[5,10] Fast film such as Kodak TL can test for flatness and symmetry stability for a 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 dosimetric discrepancies when using very few MU because of the communication lag between the MLC control system and the linac console.[9,11,12] These discrepancies can occur within the normal range of use for clinical treatments. They can affect film QA tests if the number of MU is reduced to avoid saturating the film, but this may be mitigated by reducing the MU delivery rate proportionally. The clinical impact of this observation needs further investigation.

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. 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 period. Others (e.g., Elekta and Varian) have developed a dedicated linac and 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 of individual segments. Regardless of the delivery system, the clinical physicist needs to understand the following: (a) how the MLC is calibrated, (b) how the MLC leaf position is indexed to MU and whether fractional MU are permitted, (c) how and to what precision the MLC leaf position is measured, (d) what tolerance applies to the MLC leaf position and whether it can be controlled, (e) what interlocks check that the MLC leaf position is correct, (f) what verification records or logs are created by the control system, (g) how to respond if the QA checks show that the calibration has drifted, and (h) how to recover from delivery interruptions.

4. 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 leaf is important, as are the amount and consistency of interleaf leakage.[13,14] (This document applies the term ''leakage'' for radiation that includes transmission through materials plus transport through gaps.). Most planning systems require an average transmission value, so the measurement device (film or chamber) should span a large enough area to adequately sample interleaf leakage and intraleaf transmission.

The penumbra of the leaf ends in the direction of leaf travel should be measured with a high-resolution detector such as a film or a diode to permit accurate modeling of the penumbra by the planning system. Measurement of the leaf penumbra in the direction perpendicular to leaf travel is presently less of an issue, since most current treatment planning systems do not model MLC leaf sides and therefore ignore the effect of interdigitations of leaves and tongue-and-groove in the dose calculation. However, many reduce or eliminate interdigitations in the leaf sequencing step and so mitigate this deficiency.

The available treatment area is less for IMRT than for conventional treatments because IMRT requires that an MLC

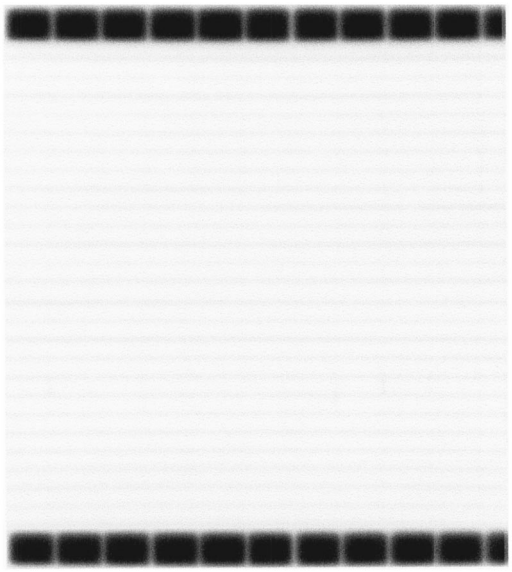

FIG. II.3. (a) MLC test pattern with all the leaves closed together except for the first and last pair, which have a 2 cm opening to force the upper jaws to remain open. (b) QA film produced by moving the pattern in 2 cm intervals and irradiating in a step-and-shoot fashion. Incomplete abutments will show as strips of increased density. This MLC has a focused leaf end design and abutting leaves should close completely.

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.[15]

The problem of leaf-end transmission is an example of how MLC design decisions can interact in a way that can be very significant for IMRT. For example, Varian systems have rounded leaf ends and the leakage for abutting ends can be 20%.[58] Furthermore, the control system forces a minimum separation of 0.5 mm while leaves are moving. Interdigital leaf motion is allowed, however, on some MLC systems. For SMLC-IMRT, this means that the leaves need not abut in the treated area, but can be moved under a jaw. The planning system should take advantage of that capability. For Siemens units, on the other hand, the leaf ends are straight and interdigital leaf motion is not allowed, so abutments occur in the treated area. Whether or not problematic leakage occurs depends on the accuracy of the leaf positioning. Figure II.3 shows a QA film designed to test the effects of abutments for a Siemens machine. A test pattern was designed to let closing positions of all 27 pairs of MLC leaves move across the IMRT field width while two small openings in the top and the bottom of the field are used to force the upper jaws to remain open. Incomplete abutments will show up as locations of increased leakage.

B. Additional issues with 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. However, each pair of leaves in the MLC, defining a gap, moves unidirectionally, each with an independent velocity as a function of time. Here, the leaf positions, leaf speed, delivered MU, and dose rates all interact.

1. MLC leaf positional and leaf speed accuracy

In the DMLC method of IMRT delivery, because of the relatively small gaps between opposed leaves and because most regions are shielded by leaves most of the time, the delivered dose is very sensitive to the transmission through the leaves and the rounded leaf ends, the leakage between the leaves, and the magnitude of the extrafocal radiation (head scatter); these may be of lesser importance in the SMLC method of IMRT delivery. Therefore, the requirements for MLC leaf positional accuracy are even more stringent for dynamic IMRT with MLCs.[8,13,16]

A key point is that the sensitivity of output to leaf position depends on the programmed gap between them, and this may frequently be smaller for DMLC treatments than for alternative SMLC treatments. The films suggested in Sec. II A 1 and depicted in Figs. 2.1 and 2.2 could be used for periodic QA, and indeed were first suggested in the context of DMLC.[8] A variation of ± 0.2 mm in the gap width can result in a dose variation of $\pm 3\%$ for each clinical DMLC field.[13] 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 is also a related variable, and the control system may vary the leaf speed, dose rate, or both to achieve the desired result. Test patterns should be constructed to check conditions that are limited by leaf speed and dose rate.[9,17–19] For example, a test pattern could move a gap that is 1 cm wide by several centimeters long across the central axis. The gap should travel a fixed distance, perhaps spanning the maximum field width. Varying the programmed MU will cause the dose rate and/or leaf speed to be regulated. The reading of an ion chamber at the central axis should be directly proportional to the programmed MU, and deviations from that proportionality would be indicators for concern.

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. (The fluence and density will also depend on the shape of the extended source if a very narrow gap is used.) 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 QA 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 QA will employ a subset of those measurements done during commissioning. The accuracy of the gap is the critical parameter for accuracy of dose delivery with DMLC. This is impacted by the long-term gradual performance degradation of individual drive motors for the leaves and stability of the MLC leaf carriage with gravity causing sag and backlash in the MLC carriage and support assemblies. A comprehensive QA program for DMLC delivery has been recently described.[16]

2. Other dynamic MLC issues

Most of the considerations listed in Secs. II A 2–II A 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.[20,21] 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 uses that information. For example, a test field could incorporate leaf pairs with that minimum gap moving across the field at different speeds.

C. IMRT with physical attenuators

A number of workers have described the use of physical attenuators to accomplish the modulation required for IMRT.[22–25] 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 a MLC are replaced by issues related to material choice, machining accuracy, and placement accuracy. IMRT delivery with physical attenuators is a viable alternative to IMRT delivery with MLC. In some ways, the physical attenuators are much simpler and devoid of problems such as leaf positioning accuracy, interleaf leakage and intraleaf transmission, rounded leaf, and tongue-and-groove effect that are intrinsic to MLC systems. However, there are other issues associated with calculating the dose in the presence of a complex metallic filter, such as beam hardening and scatter from the filter, that need to be addressed adequately.

D. 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 conventional linac and defines a fan beam approximately 20 cm wide and 1 to 4 cm long. The fan beam irradiates a narrow axial 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 (Crane®) from the manufacturer.

As an add-on device, the MIMiC® requires special considerations. One is the weight added to the gantry head, requiring preliminary testing of gantry balance and isocentricity. Second, the stability of radiation output with rotation of the accelerator should be tested. The alignment of the MIMiC® collimator with the rotational axis of the accelerator should also be checked every time that it is attached to the machine. The MIMiC® is not interfaced to the accelerator and assumes a constant MU delivered per degree of arc motion. The intensity modulated radiation delivery from this device is also not integrated with record-and-verify (R/V) systems, so preparations for recovery from treatment interruptions are necessary.

1. Peacock positional accuracy

Several references[26–29] describe the key elements in commissioning and QA of the Peacock® system. One is the physical alignment of MIMiC® collimator on the linac 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° and 270° (Fig. II.4[27]).

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 millimeter of misalignment.[30,31] The couch is moved between slices a distance equal to the MIMiC® radiation field width projected to the 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 conducted by placing a sheet of radiographic film at the plane of the 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.*[29] describe daily and weekly QA tests on this delivery system. Also, a method of mitigating the problem by varying the location of the abutment regions has been reported.[32,33]

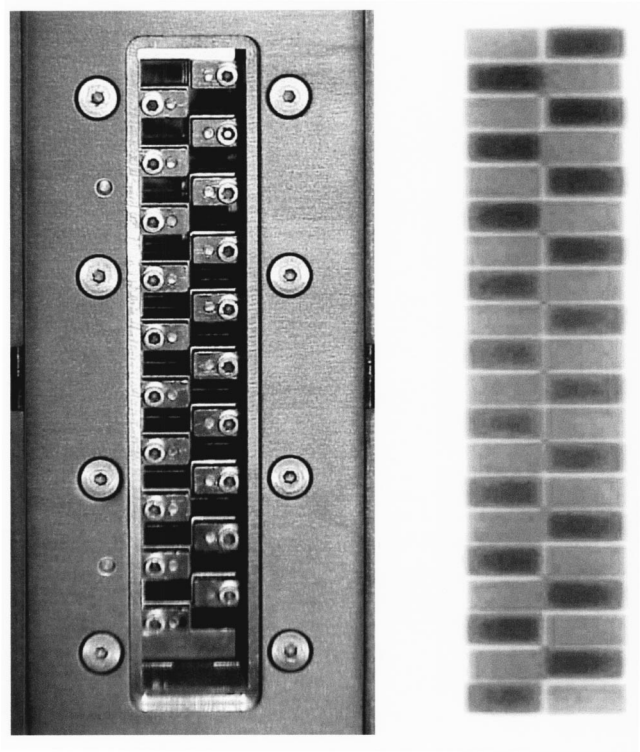

FIG. II.4. Checkerboard pattern design using MIMiC® leaves and the resulting exposed film from laterals. Reprinted with permission from Saw *et al.* (Ref. 27).

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 must be measured with high spatial resolution (0.2 mm or better). In addition, the rate at which the binary collimators open and close can affect the effective output and the physicist should determine this.[34]

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.[35,36] The helical delivery has the potential to reduce the dosimetric consequence of errors in couch motion. Because that device is just becoming commercially available, commissioning and QA information is limited at this time.

E. IMRT with rotating cone beams (intensity-modulated arc therapy)

Intensity-modulated arc therapy (IMAT) is a delivery technique developed originally at the William Beaumont Hospital that may soon be available commercially.[37,38] 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. This is a new technique for which there as yet are few references regarding commissioning and QA issues.[39]

F. 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.[40] The search for efficient sequences is an area of ongoing research. For example, algorithms have been devised that minimize the number of segments,[41–43] the number of MU,[44] the leaf travel,[45] or the delivery time.[46–48] Additional considerations include the smoothness of intensity distributions,[49] the increments of intensity levels, and the spatial resolution of the intensity map.[50–53] In general, the number of subfields (segments) calculated by the leaf sequencing algorithm increases with complexity of intensity pattern, which in turn strongly influences the overall accuracy of IMRT delivery. Therefore, it is important that the leaf sequencing algorithms minimize the number of subfields (segments) without compromising the dose conformity. Moreover, algorithms also need to account for mechanical limitations of the collimator and the need to reduce dosimetric problems such as the tongue-and-groove effect and the leaf transmission.[54–57]

In practice, because the leaf sequencing is part of the planning process, 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* Sec. III E). Nevertheless, it is important for the physicist to understand the concepts involved, in part to aid in comparing IMRT approaches and choosing between them.

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. We are using it here with the second meaning. Figures II.5 and II.6 illustrate the idea of a sliding-window leaf sequence and its realization in dynamic and segmental modes. (*See also* Figs. 5 and 6 in the CWG report[1] and Fig. 2 in Chui *et al.*[58])

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, and tongue-and-groove constraints. Interdigitation re-

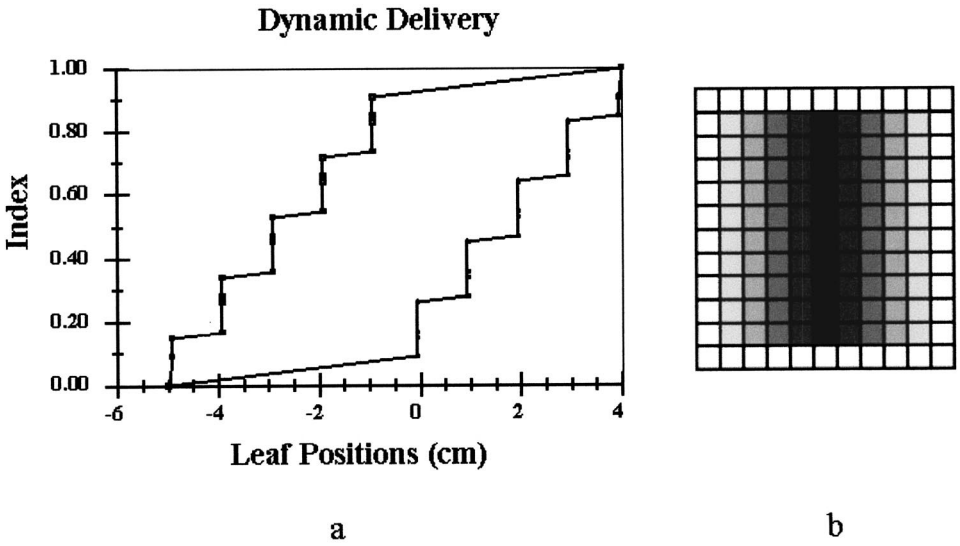

FIG. II.5. The leaf trajectory of opposing leaves as a function of dose index for dynamic MLC delivery (DMLC-IMRT). A nonzero slope indicates leaf motion during irradiation; (b) is the intensity map. Reprinted with permission from Xia and Verhey (Ref. 59).

fers 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 (*see* Fig. 2 of Xia and Verhey[59]). 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 (*see* Fig. 1 of Xia and Verhey[59]). This is attributed to the design of the MLC in which the sides of each leaf have steps or some kind of a tongue-and-groove arrangement to reduce the transmission between leaves. The width of the step is small, usually of the order of 1 mm, and as a result is ignored when planning fixed fields. However, this can cause a problem when MLC is used for IMRT or to provide internal blocking. 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 an increased number of segments (i.e., subfields for SMLC or control points for DMLC).[42] 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. Areal or reducing algorithms

Areal and reducing algorithms allow bi-directional motion and consider the entire intensity pattern instead of each row independently. These algorithms reduce the number of segments required at the cost of increased total MU. Adding interleaf motion constraints to deal with interdigitation and tongue-and-groove effects increases the number of segments by about 20% to 35%.[41,45] In practice, these leaf sequences may be more efficient for delivery systems in which treatment time is limited by the overhead in moving from segment to segment.

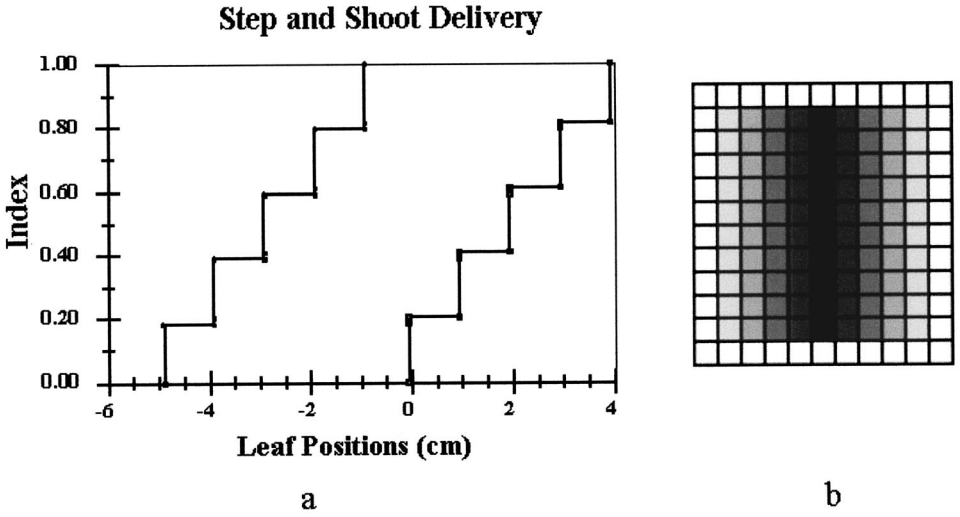

FIG. II.6. The leaf trajectory as a function of dose index for step-and-shoot MLC delivery (SMLC-IMRT); (b) is the intensity map. Reprinted with permission from Xia and Verhey (Ref. 59).

III. TREATMENT PLANNING FOR IMRT

In this section we provide guidance related to treatment planning issues to clinical physicists who anticipate setting up an IMRT program. The specific purposes of this section are the following:

(a) to describe the IMRT treatment planning process, highlighting areas that differ from ''conventional'' treatment planning (Secs. III A–III C);
(b) to describe a process for learning how to apply inverse planning to particular clinical cases (Sec. III D);
(c) to describe an approach to commissioning an IMRT planning system for dosimetric accuracy (Sec. III E); and
(d) to describe approaches to QA for individual patients' treatment plans and treatment delivery (Sec. III F).

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

1. Modeling head scatter, penumbra, and transmission

IMRT doses are calculated by dividing beams into smaller sections, called *beamlets*, that have varying intensities. Because the dimensions of the beamlets may be too small to establish electronic equilibrium within them, calculations based on corrections to broad-beam data will not suffice. Some method of integrating pencil beams or dose kernels must be used,[60–64] or Monte Carlo techniques must be applied.[65–68] The small collimator openings also make accurate head-scatter modeling important.[69,70]

For conventional fields, issues 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, beamlet intensities are varied by moving the MLC leaves through the irradiated field; therefore, accurately modeling penumbra and transmission for the MLC leaves is critical.[71–73] For example, a typical five-field prostate treatment planned for IMRT blocks a point within the prostate for more than 60% of the MU, and leaf transmission typically contributes 4% of the total dose. Since IMRT fields have multiple beam edges throughout the target volume, the dosimetric accuracy of the plan is dependent on the fidelity of the penumbra representation. Special care must be taken during commissioning when measuring these characteristics. Experience has shown that the penumbra should be measured with film, diode, or a very small chamber. A beam model based on scans obtained with a chamber having an inner diameter larger than 0.3 cm may not produce accurate IMRT calculations. For this reason, special care must be taken during commissioning when measuring these parameters.

2. Leaf sequencing and deliverability

Inverse planning systems must determine a pattern of beamlet intensities for each field and translate it 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* Sec. II F). 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 delivered doses. Some idealized intensity patterns may not, in fact, be deliverable.[74] 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 all or some of the iterations of the inverse planner, thus ensuring that what has been planned can be delivered, at the cost of increased calculation time.
(d) Some systems permit weight optimization of the segments of actual delivery sequence to further improve the dose conformation and its adherence to treatment planning objectives.

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 (Sec. III E) should identify any weaknesses.

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 are used conventionally, so previ-

ous 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 from those 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, in particular, for body sites such as lung in which the corrections are clearly needed for accurate results.

To summarize, practitioners need to understand that IMRT often uses higher prescribed doses, larger fraction sizes, different beam arrangements, and/or different dose distributions than conventional treatments. Clinical experience with a heterogeneous/homogeneous conversion factor derived from conventional treatment planning may be irrelevant to IMRT, especially in the lung.

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

(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 has been used traditionally to check low-density effects. Anthropomorphic phantoms are another possibility, typically using TLD for point dose measurement. Some simple testing by each clinic is needed to validate the institution's 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 should 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 material or rectal gas causes dosimetric artifacts.

B. 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 planner 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 3-D conformal planning. A number of publications have described successful methods.[75–79] The method lends itself to ''step-and-shoot'' delivery techniques. This approach can be automated to various degrees, both for designing the segments based on beam's-eye-view projections of targets and structures and determining the relative weight to give each segment.[80,81]

Another approach to IMRT planning breaks each beam into many small beamlets and determines the intensity of each.[82–86] Having a large number of segments or beamlets makes the problem of determining individual intensities very complex and requires computerized methods for solution. This process has come to be called *inverse planning*. The planner 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 the general literature of optimization, the term *constraints* refers to limits that cannot be violated, and the term *goals* denotes 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 value, a few dose–volume points, or fully flexible DVHs. Importance factors may be used to change the relative weight given to different objectives.[87] 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 attempts to represent the tradeoffs that are incorporated into clinical judgment. By changing the objectives, the user alters the cost function and so influences the result.

Many investigators have worked on the problem of developing clinically successful inverse planning algorithms, and the literature is rapidly expanding, as are the commercial implementations. It is important to realize, however, 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. Optimization algorithms are mostly heuristic local minima search schemes that do not always guarantee that a globally optimal solution to the problem as stated will be identified, and certainly cannot guarantee clinical optimality. 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 Sec. III D. 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: determinis-

tic and stochastic.[1] *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. Because disadvantageous changes are sometimes allowed, escape from local minima is possible. Such methods are slower than the gradient descent methods mentioned previously because 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 objectives. 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 objectives can cause local minima,[88] 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 objectives, then it appears that the solution space for many clinical problems will have local minima. There is no difficulty if they are clinically equivalent, but, in general, it is not at all clear how a planner might know that a given solution is the best solution. 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 changing initial fluence patterns.

C. Differences between IMRT and conventional treatment planning: Specific planning issues

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 never do worse than conventional treatment techniques, for the former has more flexibility or degrees of freedom.[89] 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 may suffer. To create a complex dose distribution, IMRT casts shadows with some beamlets and balances them with higher intensities from other beamlets. Because the balancing is not perfect, localized dose 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 adjacent critical structure increases; (b) the distance between target and critical structure decreases; (c) the concavity of the required dose distribution increases, and (d) 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.

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 and what is to be avoided. 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 the desired doses. With inverse planning, the physician designates targets instead of designing fields, so careful and accurate contouring is essential. The delineated structures should be consistent from slice to slice so that structures are smooth in three dimensions. It is important to review the outlined structures prior to beginning optimization.

In addition to designating targets, the clinician must explicitly define all volumes that should be kept below certain doses. If an important structure is not identified and objectives set for it, then unacceptably high doses may be placed there by the inverse planning system.

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. However, 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 objectives for these regions, the inverse planner may give undesired dose there (Fig. III.1).

In general, all areas of potential interest should be contoured so that DVHs can be evaluated and objectives applied if needed. It is very important to recognize that in an IMRT plan extremely, high-dose areas can show up in unconstrained normal tissue. Therefore, it may become necessary to define ''normal tissue'' objectives to avoid such problems. When assigning dose–volume objectives to normal tissues

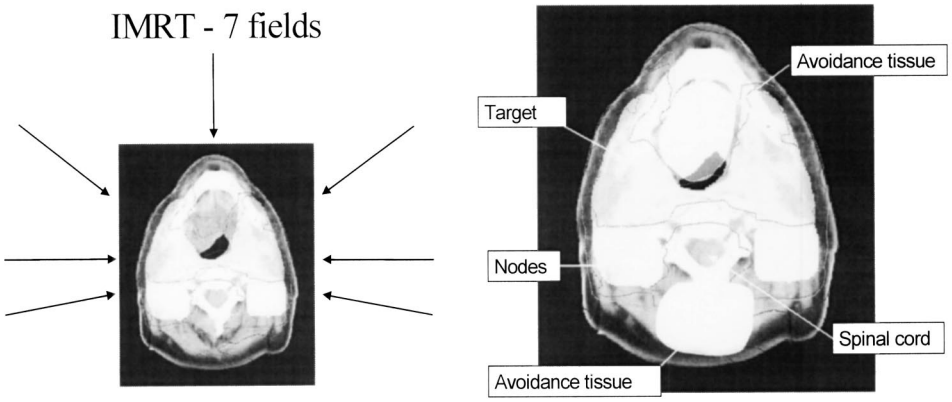

FIG. III.1. The use of avoidance structures to limit doses in inverse plans. The left panel shows the beam directions used, and the right shows the structures, including avoidance areas that would not be contoured in conventional planning.

and when evaluating DVHs for the plan, it is important that the entire organ is contoured and included in the dose calculation volume. If not, the planner and physician must be aware of the fact and adjust their plan evaluation process accordingly.

3. Dose grid

As is generally the case with 3DCRT, the size of the critical organs and the expected dose gradients near them impact the choice of the resolution of the dose grid used. Often, IMRT is used in situations in which high gradients are needed, and the dose grid may have to be finer than usual.

The dose grid also should be finer than the size of the beamlets or incident fluence map so that the effects of modulation are adequately sampled.

4. Buildup region

Care must be taken when target volumes are drawn within the buildup region. First, calculated doses are often inaccurate and lower than delivered doses. Second, the inverse planning algorithm 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 planning engine fighting with the buildup effect instead of being ''unavoidable with IMRT.'' This issue is especially important for planning systems that expand the clinical target volume (CTV) by defined margins in three dimensions and then plan to the expanded planning target volume (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 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 it is accurately represented in the plan.

5. 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; therefore, that site should be considered with caution. Most published studies have used manually created segments or university-based inverse planning systems where additional control by the human planner is possible.[90–93]

Respiratory motion can also cause more problems for IMRT treatments than for conventional treatments.[94,95] Any plan evaluation must 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.[31] Physicians and physicists must realistically assess these potential errors when selecting patients for IMRT, especially for sites in the abdomen and thorax.

6. 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 more complicated instructions, such as avoiding intersections with other re-

gions or boundaries. An experienced planner can handle this deficiency by designing the beams appropriately. If the DVH for a brain tumor PTV shows low doses, and those low doses are seen to be outside the skull, 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 produced by 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.[96–99] 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.

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 whether targets can expand into structures (and vice versa), whether regions can overlap, whether priorities can be assigned for optimization, how doses are reported in expansion regions, etc.

7. Radiobiologic issues

IMRT plans can have radiobiologic consequences that differ from conventional plans.[100–102] Conventionally, patients are treated with a consistent dose per fraction. To give more dose to gross disease, field sizes are reduced and boosts are given at the same dose per fraction. Clinical experience with this system has established the prescription doses. When one IMRT plan is used from the beginning of treatment, targets that are to get different total doses also receive different doses per fraction.[77,103] 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 in 33 fractions instead of the typical 25. The target dose to the nodes might have to be increased in order to have the same radiobiologic effect as 50 Gy in 25 fractions. Conversely, the lower doses per fraction may improve the sparing of normal tissues.[104] One could also use multiple IMRT plans in a regional-treatment-plus-boost fashion, thereby using a consistent dose per fraction, but this requires the ability to sum distributions and the user to 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.[103,105,106] Physician training needs to include these anticipated changes from conventional practice.

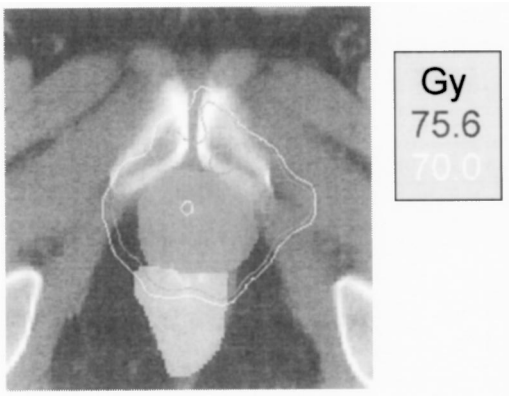

FIG. III.2. The unwanted appearance of a localized cold spot from an inverse-planning system.

8. 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 3-D conformal treatments in which beams are defined using beam's eye views, 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 different effect on tumor control (Fig. III.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 nontarget or nonsegmented tissue is available for inspection.

Plan evaluation for IMRT should include an assessment of the potential problems and pitfalls outlined below.

(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) Were organs contoured in their entirety? Are the plan goals appropriate for the fraction of organ contoured?
(d) 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?
(e) Will patient or organ intrafraction motion during the treatment compromise the accuracy?
(f) 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?
(g) Have inhomogeneity corrections been applied appropriately?
(h) How does this plan compare with a conventional alternative? What regions are being treated or spared differently compared with traditional methods?

(i) Is the increased whole body dose with IMRT a concern?[107]
(j) Are there unusual beam orientations that might involve collision with or shadowing by the treatment table?
(k) 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.

D. 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, and so forth) 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. 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* Sec. IV). 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 oropharyngeal cancer (http://www.rtog.org) provides a good example. This is a nontrivial 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. Because the range of possibilities is huge, some systematic approach is needed. One might fix the number and orientation of beams to some relatively large number so that the beam selection is not likely to be limiting plan quality (e.g., nine coaxial beams at 40° increments). Then, for fixed target doses, gradually tighten the normal-tissue objectives. After the objectives are finalized, try different beam combinations.
(f) Compare the results with a manually planned, 3-D 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 nonuniform target doses? Are the increased cost and complexity justified by real dosimetric improvement? When comparing IMRT with 3-D conformal plans, it is crucial to make sure that the problem definition is consistent, e.g., the 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.[108,109]

E. Commissioning an IMRT planning system for dosimetric accuracy

Dosimetric commissioning of an IMRT planning system should follow a systematic sequence.[17,110,111] 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 advance from simple to more complex tests. For example, start with single beams on a simple, flat (i.e., geometric) phantom with controlled intensity patterns. When those are validated, then progress to using controlled intensity patterns for multiple beams on the simple phantom. After that, apply multiple beams treating hypothetical targets in the flat phantom. Finally (if possible) progress to testing multiple beams treating hypothetical targets in anthropomorphic phantoms. The goals are, first, to determine 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.

In this discussion we assume that the required input information has been given for beam modeling and focus on how to test the resulting calculations. In Sec. II A 4 we discussed

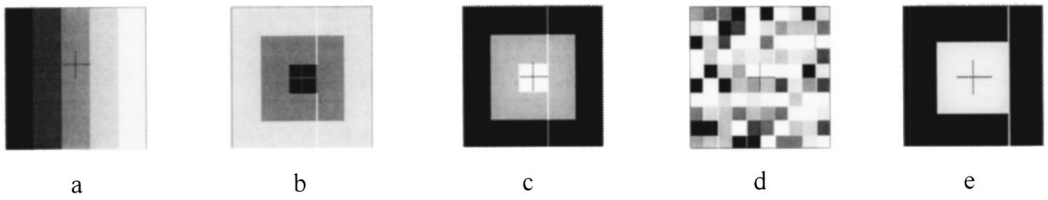

FIG. III.3. Examples of user-controlled intensity shapes used for commissioning tests.

particular concerns in obtaining the initial data for IMRT modeling.

The primary dosimetry tools are water-equivalent or other plastic phantom(s), ionization chamber, electrometer, 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 with 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.[112] Film that can be irradiated to a typical daily dose is preferred over faster films in order to remove uncertainties caused by MU 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, or well [Figs. III.3(a)–III.3(c)], measure the dose per MU at multiple points in low gradient regions with an ion chamber. Measure dose 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 might cascade in full patient plans. A random distribution [Figs. III.3(d) and III.4] 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 a 10×10 cm array of high intensity beamlets with a central 5×5 cm section with reduced intensity [Fig. III.3(e)]. Irradiate the flat phantom with five to seven axial beams at equal angular increments, each having that intensity pattern. This tests the planning and delivery for a summation of simple fields. Vary the central section intensities to test the planning and delivery over a range of conditions..

(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 (such as a sphere) and progress to more complicated target/critical organ combinations that require more (such as a

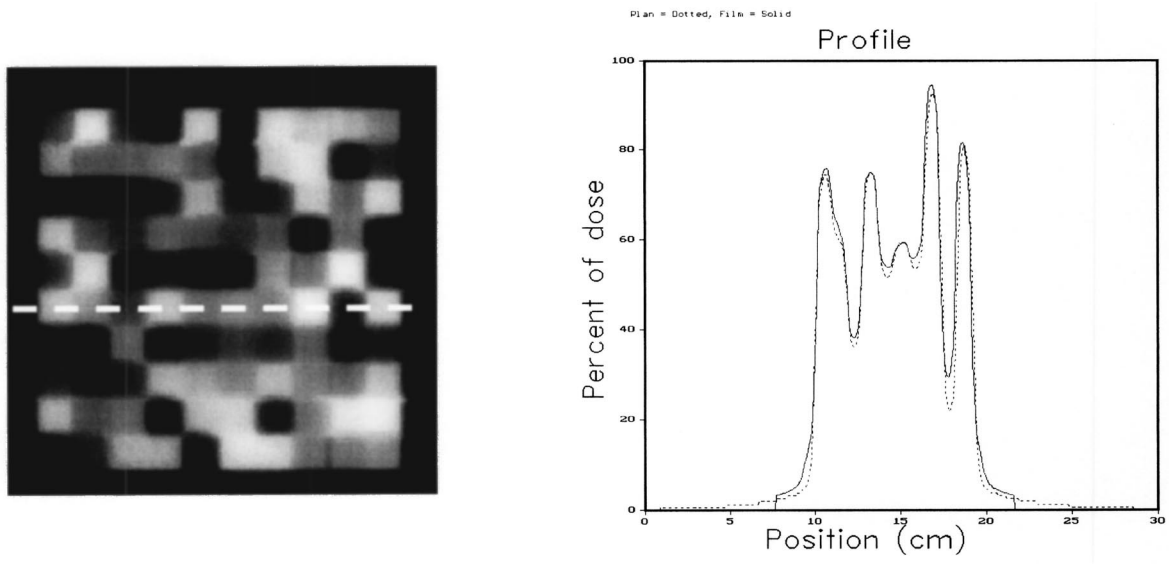

FIG. III.4. The dose profile measured with film across one line of a random intensity pattern (plan=dotted, film=solid), showing some systematic differences in low intensity regions.

C shape surrounding a critical organ or a cylindrical shell surrounding a critical organ, with progressively tighter objectives for 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.

It is difficult at this time to give specific recommendations for dosimetric accuracy of IMRT plans given the complexity of the plans and the measurement problems. A statement in the TG-53 report[113] deserves repeating:

> Here, we will not provide a table of recommended values, since it is clear that what is achievable with one kind of planning system may be quite unachievable with another. It is the responsibility of the radiation oncology physicist to determine
>
> 1. the accuracy of the institution's particular RTP system for a range of clinical situations; and
>
> 2. how that expectation of accuracy must be modified to account for any particular clinical situation, the kinds of treatment plans that are created, and other aspects of the local situation.

There is a developing consensus, however, that ion chamber measurements in low gradient areas of single beams [e.g., *see* Figs. III.3(a)–III.3(c) and III. 3(e)] should agree with the plans to the same accuracy as is achieved with conventional treatments, i.e., on the order of 2% to 3%. For more complex irradiations typical of patient treatments, there is a developing consensus that ion chamber measurements in high dose, low gradient regions should agree with the plan to within 3% to 4%.

Attention must 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 a 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.

F. QA of individual treatment plans

A primary difficulty with designing QA tests for individual patient plans is not knowing all the likely failure modes for this new modality. Concern and caution are clearly indicated. In developing a comprehensive QA system, it is useful to separate the complete treatment process into three sequential elements: (a) Dose and MU calculation; (b) information transfer from planning system to R/V system to delivery system; and (c) dose delivery.

Each step in the process has its own potential sources of error, and the physicist should develop checks for each. These checks will involve some combination of inspection, calculation, and experiment. In the following sections we describe some of the possible techniques that have been used; each has its strengths and limitations. Each physicist and facility will need to balance patient-specific tests, such as described in this section, with standardized MLC and linac performance tests, such as described in Sec. II A. Patient-specific verification measurements test many (but not all) aspects of planning and delivery in a combined fashion. Patient-specific calculations combined with frequent machine QA represent another approach. The latter is the norm for conventional treatments and may become so for IMRT as the field evolves. In these early stages, physicists need to carefully assess the overall structure of their QA tests and frequencies.

1. Independent calculation methods

Independent calculation methods to verify MU and absolute doses are becoming available for IMRT plans. Algorithms have been reported that take MLC delivery files and calculate doses that can be compared with 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.[114–119] 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 (such as a plan done on the wrong patient or the with the wrong treatment unit) or errors in transferring data from the planning system to the R/V and treatment systems. To give the most confidence, one should use output from the R/V system as input to the independent calculator, along with necessary patient information such as source-to-skin distances.

As mentioned in Sec. II A 1, independent dose calculation methods based on pre-treatment information will not catch errors in the treatment delivery. Patient-specific calculations need to be part of a larger QA process that includes rigorous testing of the delivery system. In principle, independent dose calculations could include information derived from the delivery itself, such as from electronic portal imaging device (EPID) measurements or MLC log files, but such methods are still under development.

2. Verification measurements

Verification measurements are commonly made of a ''phantom plan'' or ''hybrid plan.'' This technique consists of

applying the MLC segments, leaf trajectories and MU for each field, derived from the final patient calculation, to a CT study of a standard phantom and then recalculating the final deliverable dose distribution in the phantom.[120,121] The phantom is then irradiated according to this plan and the doses measured using ion chambers, film,[122–124] or other detectors.[125–127] The results of the measurement are then compared to the predicted dose to the phantom. The logic of ''phantom plan'' methodology is that it verifies the correct transcription of IMRT delivery parameters, leaf sequence, and MU calculation. As mentioned above, there is a developing consensus that a reasonable action level for ion chamber measurements of such phantom plans in high dose, low gradient regions is 3% to 4%, with the understanding that small fields and localized gradients may cause additional uncertainties in some cases. Film is generally used to verify visually the dose distribution on at least one plane, at least qualitatively. Note that measurements on a single axial plane likely will be sensitive to the motions of a few leaf pairs, perhaps only one. It should also be noted that not all film scanning systems can track optical density accurately in the presence of high gradients. Therefore, the scanning system must be validated for accuracy for quantitative measurements.

It is important to realize that some errors in input data or calculations will not be caught by using phantom plans, since the dose distribution in the phantom is not expected to be the same as in the patient. 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. An independent calculation using the correct depths would show the error. However, a phantom plan would apply these inappropriate intensities to the phantom. Measurements in the phantom that confirmed this new dose calculation would not uncover the error. Phantom measurements test the dose calculation and delivery mechanism, but do not check some assumptions used in the planning process. Measurements that test the dose in the actual patient would be preferred; several groups are working on using electronic portal imaging devices to perform QA measurements using transmitted dose through the patient.[128–132]

It is useful to have phantoms that reasonably approximate the body site in question. Examples could be a $30\times30\times15$ cm rectangular phantom for the trunk and $15\times15\times15$ cm rectangular phantom for the head. The routine use of a phantom that is not equivalent in size must be validated by testing at least once against a more appropriate phantom. More anthropomorphic phantoms are also commercially available.

3. Other plan checks

TG-40[133] and TG-53[113] both have recommendations for checks of individual plans that certainly apply to IMRT plans, but again there are additional concerns. Because inverse planning systems, not planners, design the beam intensities, it is important to check that the target coverage is adequate in three dimensions and that the hot and cold spots are well understood.

Similarly, inverse-planning systems may have the option of shifting the isocenter from an original setup point before treatment. Clearly, recognizing and verifying 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 portal images of the treatment. Since the DRR is generated from the plan data, correspondence to the actual patient as seen on the portal image 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 Sec. III C 8 should also be considered during plan checks.

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

IV. CLINICAL IMPLEMENTATION OF IMRT

A. Overview

Work needed to implement IMRT includes all that is needed to implement 3DCRT and more. In this section we will concentrate on the additional aspects and provide guidance related to issues of clinical implementation of IMRT.

Each facility should designate an IMRT implementation team to think through the implications in advance and periodically update procedures as lessons are learned. For IMRT to truly produce a benefit, 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 bringing the modality to the clinic, but also to keeping it running smoothly and keeping pace with upgrades and future enhancement in IMRT technology. Furthermore, IMRT is an integrated system, and careful thought should be given to every technical and 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:

(a) Equipment and space requirements (Sec. IV B);
(b) time and personnel requirements including their responsibilities (Sec. IV C);
(c) changes in treatment planning practice (Secs. IV D 1–IV D 5);
(d) changes in treatment delivery practice (Secs. IV D 6–IV D 9);
(e) QA of equipment and individual patient treatments (Sec. IV E);
(f) staff training and patient education (Sec. IV F);

(g) changes in scheduling, billing, and charting practice (Sec. IV G);
(h) overall integration (Sec. IV H).

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

B. Equipment and space requirements

1. Shielding

IMRT treatments require about a factor of 2 to 10 more MU than conventional treatments, so room shielding should be reevaluated.[134,135] The MU are about 2 to 4 times more for the MLC-based IMRT treatments. For sequential tomotherapy delivery, up to 10-fold greater MU may be needed, depending on number of rotations involved.[134,135] 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. Because the enhanced workload affects the leakage component of radiation reaching secondary barriers, shielding design for these barriers must be evaluated.

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, film scanner, and instrumentation, as well as patient immobilization devices. Space for additional personnel may be required.

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 R/V systems may need to be upgraded to accommodate IMRT treatments. Computer networks may need to be enlarged or improved to permit the needed file transfers.

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

IMRT planning capabilities must be provided, either as a stand-alone IMRT planning system or as an add-on IMRT module to a conventional planning system. Many issues must be considered. For example, stand-alone systems may provide more resources for computation time and/or more expertise with regard to IMRT planning. Conventional planning systems may allow more easily the combination and/or comparison of non-IMRT and IMRT plans. However, if this capability is not provided, it certainly is useful to be able to contour on one system and have those contours available for both IMRT and non-IMRT planning.

C. 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 to set up and test the processes used for individual patient treatments. QA procedures will have 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, the ongoing QA activities will increase for both the IMRT systems and individual patient treatments. In other sections we describe these activities in detail.

D. Changes in treatment planning and treatment delivery process

1. General considerations

The details of IMRT treatment will differ from institution to institution, but the general IMRT treatment process shown in Fig. IV.1 will serve to frame the discussion.

2. Immobilization

Because of the highly conformal nature of IMRT treatment, new immobilization techniques may be necessary to safely use the technology,[96,136,137] 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.[138,139] 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.[140–142] Electronic Portal Imaging Devices (EPID) and implanted fiducial markers can provide a big help in this area. Generally, the patients will be immobilized and marked as close as possible to the anticipated treatment isocenter.

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 3-D conformal treatments, a CT for treatment

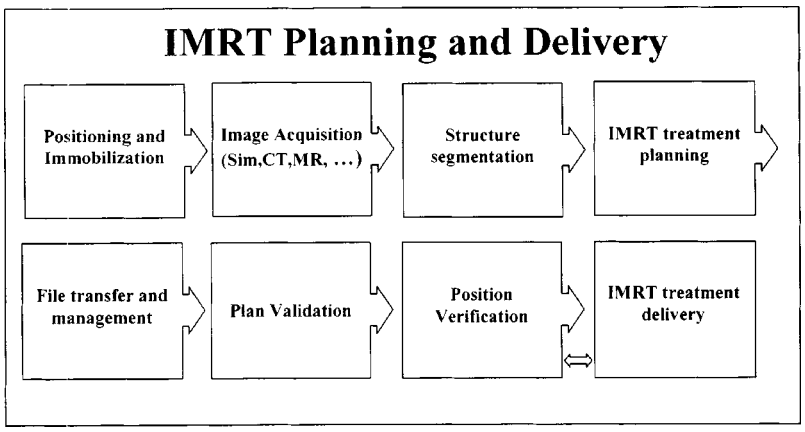

FIG. IV.1. The overall process of IMRT planning and delivery.

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 the use of nonaxial beams. For example, for isocenters above the base of the sphenoid sinus, the protocol may be to acquire slices through the top of the head. The acquisition of enough CT slices (fine slice thickness) may be necessary to produce DRRs of high quality and define anatomy adequately.

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

4. Structure segmentation

Structure segmentation is one of the most important and crucial steps of the IMRT procedure. The success of the IMRT procedure is closely tied to the accuracy of the target volume and critical structure delineation. As with all 3-D 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 and with rigor. 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.

5. IMRT treatment planning

The differences between planning for IMRT and for conventional treatments are discussed in Sec. III. 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 improve 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 [Sec. III D, (b)–(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 3DCRT plans. For a specific site, a comparison of 3DCRT plans and IMRT plans may be obtained from published literature, showing the benefit of IMRT. Even so, new users need to demonstrate to themselves that they can reproduce the essential characteristics of IMRT treatment techniques that the published literature has shown beneficial. In any event, practitioners should not utilize IMRT plans that are inferior to the treatments currently employed even if financially advantageous.

6. File transfer and management

When an 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, the digital capability for plan transfer is essential to avoid possible mistakes during manual transfer. Depending on the individual clinic's information system, the files can be transferred by floppy disk or directly transferred to the R/V 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. The therapist will need to be able to verify every day that the appropriate file has been selected for each field or arc. If the files are on a floppy disk,

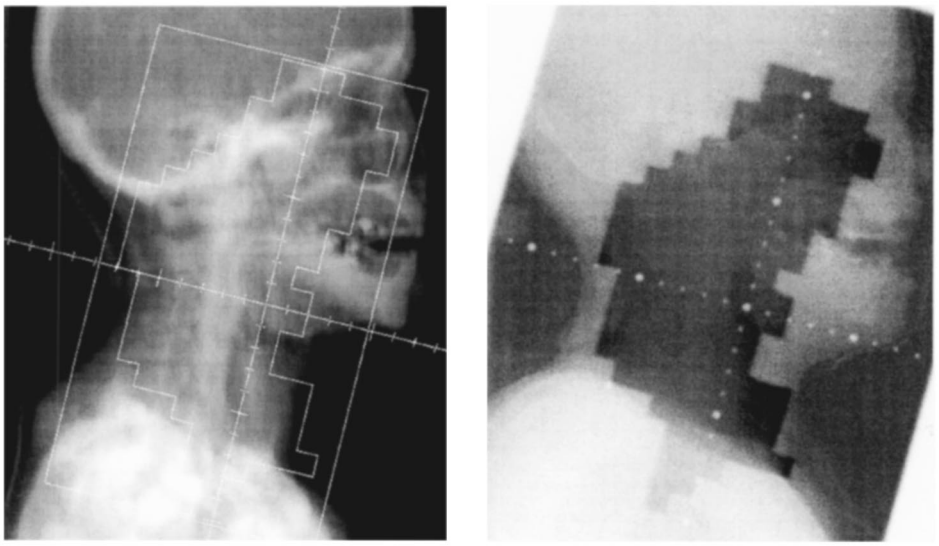

FIG. IV.2. An example of DRR and portal image used for the IMRT isocenter and field shape verification.

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 an R/V system that fully supports the IMRT treatments, then many of these problems are eliminated (and replaced by the need to verify the initial programming of the R/V system). If the R/V system does not fully support IMRT treatments, can it still verify some parameters, such as energy and MU? 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 autosequencing 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 should be a part of routine plan validation.

7. Plan validation

The goal of IMRT plan validation is to verify 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, before the first treatment, include MU (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 until independent dose calculation methods are developed and validated.

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.

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 (Fig. IV.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. As a minimum, weekly portal imaging is necessary.

In general, the implementation team must 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. In addition, use of daily target localization tools, such as ultrasound, will impact the need for and interpretation of portal images and may add the need to acquire, review, and archive other images.

9. IMRT treatment delivery

IMRT treatments often take more time to deliver than their conventional counterparts due to their increased complexity. They require larger numbers of MU and fields and

are more likely to use oblique gantry angles than are used conventionally. Because maximum field sizes maybe limited for IMRT because of limitations on leaf and/or jaw overtravel, IMRT treatments are more likely to require abutting two or more adjacent treatment fields for a single gantry angle. Experience has shown that, in head and neck treatment, the treatment time ratio between an IMRT plan and a conventional 3DCRT plan is about 1.5 to 2.5. For prostate treatment, the time ratio is about 1 to 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.

E. QA of equipment and individual patient treatments

In general, the QA of IMRT consists of three main tasks: 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 aspect is concerned with the normal operation of the delivery system and will involve additions to the daily, monthly, and annual QA 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 to handle new issues that arise.

F. Staff training and patient education

Like any other radiation therapy modality, IMRT is an integrated process, and staff training and education are an important part of the clinical implementation of IMRT. It is much more complex and less intuitive than conventional 3DCRT. 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 MU efficiency (much larger number of MU compared with conventional radiation therapy for the same prescribed dose), and complex motion of MLCs. 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. Patient education in the nuances of this new treatment modality is also essential.

1. Radiation oncologists

IMRT represents a significant departure from the current paradigm used in radiation oncology. Treatment 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, the IMRT planning process starts with the definition of treatment goal and objectives. 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 nonintuitive. 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 suboptimal 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 to 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 subclinical disease are often treated concomitantly to different doses per fraction in IMRT. Moreover, the dose distribution in the target volume is often much less homogeneous 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 the chance to get training in the IMRT process during their residency should consider attending special workshops conducted by academic institutions that have active clinical IMRT programs. Some private companies have also started courses in IMRT.

2. Radiation oncology physicists

IMRT is much more challenging for radiation oncology physicists than conventional radiation therapy. Radiation oncology physicists have a 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. Physicists also need to have a better understanding of treatment setup, planning and delivery uncertainties, and their impact on patients treated with IMRT. Treatment planning optimization for IMRT is based on dose–volume objectives 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 busy intensity patterns (with large peaks and valleys) on treatment delivery accuracy and efficiency. QA testing for IMRT is much more complex than it is for conventional radiation therapy. It is imperative that each physicist involved with IMRT should have special training in the whole process.

3. Dosimetrists

The dosimetrists have the 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 with treatment planning for conventional radiation therapy, the emphasis in IMRT planning is more on selecting the most appropriate dose optimization parameters. Less importance is assigned to beam shaping, placement and weight optimization in IMRT. Like physicists, dosimetrists must understand the implications of dose–volume objectives 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's radiation oncologist and physicist who have special training in the use of IMRT.

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., an 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 QA.

Therapists will have 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 must 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 every day the therapist must be able to verify that the appropriate file has been selected for each field or arc. (These issues were discussed previously 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 an 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, and 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 new daily QA tests. As with any QA procedure, clear instructions and action levels must be provided.

5. Service engineers

Reliable performance of all aspects of the delivery equipment used for IMRT is essential. Compared with 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 MLC component of the overall system. Intensity-modulated dose delivery places demands on the MLC that far exceed the criteria used for the design of these systems. When the standard MLC systems were 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 accelerated component failure, and special QA procedures must be adopted to guarantee proper calibration of leaf position and to avoid treatment interruptions. With the assistance 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 a MLC can affect the machine output[13] for IMRT delivery and should confer with the physicist whenever changes are made.

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, a description of the immobilization method used, and delivery system motions and sounds they will experience. A description of the goal of treatment and potential side effects may differ from that given for 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 in-

crease acute mucositis, especially if target doses are less homogeneous 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 that described by others.

G. Patient scheduling, billing, and charting

IMRT treatments may take longer than conventional treatments. They 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 dose summaries that adequately describe dose–volume goals and results.

H. Overall integration

In this section we have 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.

V. SUMMARY

This document provides guidance to the practicing radiation oncology physicists in treatment delivery, treatment planning, and clinical implementation of IMRT. Because of the emerging and rapidly changing nature of IMRT, this document cannot be definitive or prescriptive at this time. However, several task group reports and a code of practice will eventually emerge as the field matures. The IMRT Subcommittee of the AAPM Radiation Therapy Committee is currently working on a document that will provide specific recommendations on the tolerance limits and action levels for different IMRT tests that are described in this report. The intention here is to provide guidance during this introductory period.

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