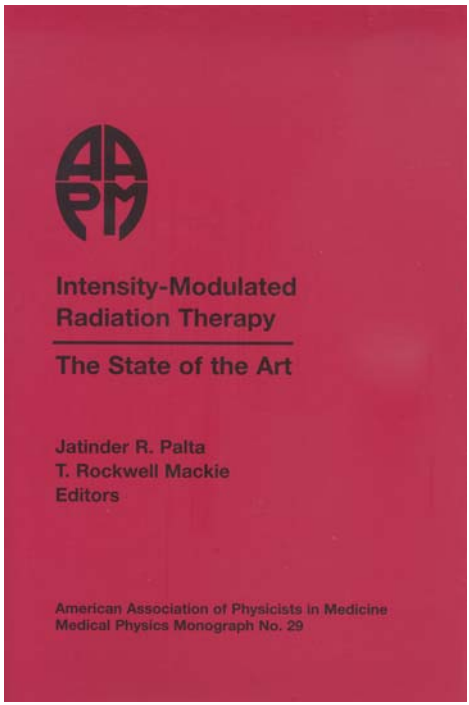

Here is a sample chapter from this book.

IMRT Delivery System QA

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Introduction

Multileaf collimator (MLC) use is increasingly common in radiation therapy clinics throughout the world. These devices are well established as a replacement for conventional blocks in the majority of treatment sites where static field techniques are used for conventional 3-D conformal radiation therapy (3DCRT). At the present time only a small percentage of MLC-equipped centers are using the MLC for intensity-modulated radiation therapy (IMRT), even though the technology has been commercially available for almost 10 years. The hesitance is in large part due to the complexity of the technical aspects of planning and delivery. Before this new technology can be safely implemented, each component of the process must be understood by the users, and a comprehensive quality assurance (QA) program should be in place. A QA program will need to address treatment-planning systems, delivery issues involving

MLC mechanics, electronics, and software, and patient treatment verification. Only delivery issues will be presented here.

In the broad sense, QA for IMRT delivery encompasses acceptance testing, commissioning, routine MLC QA, and patient-specific QA. It begins at the time of installation of new equipment or at the time an existing MLC is upgraded for use with IMRT in order to affirm the capability for accurate IMRT with the specific MLC. Commissioning implies the accurate acquisition of the treatment planning parameters specific to IMRT, rigorous testing of the dose calculation algorithm under the increased demands of intensity modulation, and ancillary techniques such as respiration gating and the splitting of large fields. Periodic MLC-specific QA checks of the stability of the mechanical aspects of the MLC, i.e., leaf positioning, and the dosimetric aspects of the linac for small numbers of monitor units (MU), i.e., linearity and symmetry, ensure that when the treatment parameters are correctly set, the correct dose is delivered. Verification of the integrity of the treatment plan from the planning through the delivery stages (patient-specific QA) is the last component. These procedures complement each other, and together they ensure accurate dose delivery.

The QA for MLC used in static mode, conventional 3DCRT, is relatively simple. Similar to the procedures required for jaws and blocks, the QA checks involve mechanical alignment of the MLC to the accelerator and leaf position reproducibility (Mubata, Childs, and Bidmead 1997; Hounsell and Jordan 1997). The QA procedures specific to the use of IMRT present special issues for dose delivery compared to 3DCRT. Hardware and software for MLC are still relatively new to the end users in the clinic, and the potential for dosimetric errors is still not well understood, while the consequences of such errors may be clinically significant. Individual treatment centers should expect a learning curve for understanding novel treatment planning and QA issues. The urge to implement IMRT at individual therapy centers should be tempered while these issues come into focus and are addressed at each center.

In general, when MLCs are used to perform intensity-modulated treatments, they require more stringent tolerances and, in turn, a more involved QA program. Tests used for static QA of the MLC need to be redesigned to achieve the required accuracy. This emphasis is justified if one considers that for static treatments these parameters only define the dose near the borders of the field; depending upon the proximity of abutting critical tissues, 1 to 2 mm uncertainty of the leaf positions is acceptable. Periodic checks of the projected leaf positions with graph paper at isocenter are sufficient for this purpose. However, for IMRT, the leaves modulate the dose delivered throughout the target volume; more specifically, the dose delivered with IMRT is sensitive to the width of the gap defined by each leaf pair. Then, it is only a matter of assuring that the leaves are in the correct position at each moment during treatment. Regardless of MLC designs, or whether the delivery mode is segmental (SMLC) or dynamic (DMLC), these tests should stress the precise execution of the gap width defined by opposing leaf positions; and for DMLC, the ability of the leaves to maintain their specified leaf speed is also important.

It is necessary to identify sources of leaf positioning error for the specific MLC design, and to develop QA tests and frequencies to detect these mechanical problems

before dose errors become significant. Analysis of QA data to track the long-term stability of MLC performance can reveal patterns of MLC failure. These areas then need to be monitored closely to ensure that the planned dose is delivered accurately and reproducibly. Manufacturer's modifications to MLC hardware and software often follow from an analysis of the frequency and severity of malfunctions during clinical use.

This chapter will focus on dose delivery related QA procedures applicable to acceptance testing and routine MLC QA specific to IMRT. Some of these methods use static fields; they are applicable to all three MLC designs, Siemens, Elekta, and Varian. However, many of the tests rely on dosimetric measurements using the dynamic mode, and so are only applicable to the Varian MLC.

MLC Alignment

As for the movable jaws and conventional metal-alloy blocks, the alignment of the MLC leaves affects the spatial uncertainty between the peripheral extent of the radiation beams and the perimeter of the target volume. For IMRT, MLC alignment in the direction of leaf travel affects the registration of the intensity-modulation (IM) patterns between fields altering the composite dose distribution for the plan and also shifts the IM dose distribution for each individual field relative to the patient's anatomy. In some regions, such as when the spinal cord is to receive a low dose, dose gradients may be very large within an IMRT field, as much as 10% per millimeter, similar to using a metal conventional block to shield the cord. Fortunately, the effect from one field is, in general, diluted by the dose from the other IM beams; on the other hand, IMRT fields have more frequent gradients than conventional fields. Misalignment of the MLC in the direction perpendicular to leaf motion typically shifts the dose distributions for all the fields in the same direction with respect to the patient anatomy, comparable to a systematic patient setup error.

Alignment in the direction of leaf motion, including leaf bank skewness and centerline offset can be readjusted via leaf calibration using the alignment of the jaws as a guide. Alignment in the direction perpendicular to leaf motion is fixed at the factory. Even optimal alignment of the MLC does not ensure perfect registration between fields. Gantry sag, the displacement of the field in the radial direction, is maximal at gantry angles of 0° and 180°, while gantry roll is maximal at 90° and 270° and shifts these fields vertically downward. Similar problems exist for IM fields delivered with fixed compensators.

Misalignment of the MLC relative to the isocenter can be evaluated with the following procedure. A film is irradiated with two complementary leaf patterns, which nominally suggest a uniform field. For MLC with an interleaf space coincident with the central axis (Varian and Elekta), the patterns are similar to those illustrated in figure 1. For this leaf configuration, the fields match at the central axes. When the center leaf overlies the central axis (Siemens), the match line perpendicular to leaf motion is shifted off the axis by 0.5 cm. Ideally, the image would appear as in figure 2a, a uniform field with a low-density strip from Top to Bottom, corresponding to tongue-and-groove

underdosage. MLC leaves with rounded edges (Varian and Elekta) will yield a high-density strip from Left to Right if their digital readouts are calibrated to the light field edge, corresponding to added leakage through the rounded edges of the opposed leaves. If the leaves are calibrated using the radiation field edge, then the high-density region will appear relatively uniform. Doubly focussed MLC leaves (Siemens), in theory, should also be uniform from Left to Right. A second image is produced with the same leaf patterns (center leaf reversed for the Siemens MLC), but with the collimator rotated exactly 180° between fields. The density change of the strips in this image is proportional to the misalignment of the MLC and can be calibrated with a third image, figure 2b, using the same two fields as for figure 1, but introducing a 1 mm shift in each directions, simulating an 0.5 mm misalignment (0.5 mm is a reasonable tolerance limit), in both the radial and transverse directions. These images may be visually evaluated or scanned. These images may be obtained at other gantry angles as well.

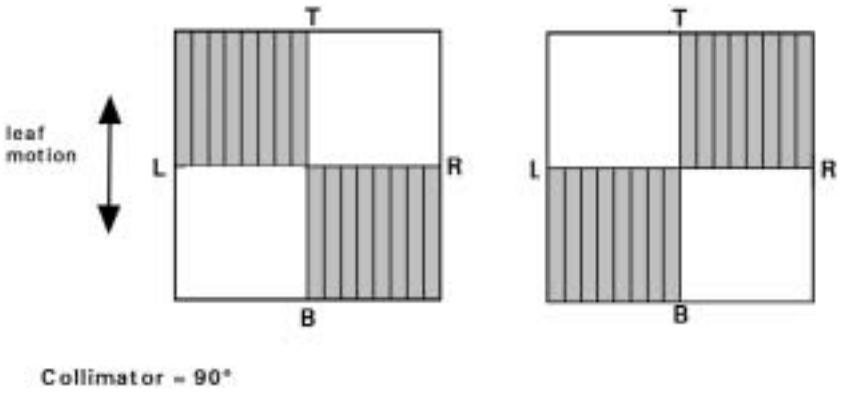

Figure 1. Complimentary leaf patterns to test the MLC alignment.

Leaf Positioning

For conventional 3DCRT, the accuracy of static field edges, whether defined by the MLC, blocks, or the jaws, only affects the high gradient regions near the borders of the target volume or critical structures. In these static treatments, 1 mm errors are usually tolerated. In contrast, the dose delivered with IMRT, whether SMLC or DMLC, can be very sensitive to errors in the calibration of leaf position (Budgell et al. 2000). Therefore, leaf movements must be executed much more precisely.

For DMLC, the impact of leaf calibration is illustrated in figure 3. Dose errors for fixed width gaps moving at constant speed are proportional to gap errors and inversely proportional to the gap width (ignoring leaf transmission). For example, if the nominal gap width is 2 cm, then a gap error of 1 mm, introduced by one or both leaves of a pair, will produce a 5% dose error. In clinical DMLC fields, neither the gap width

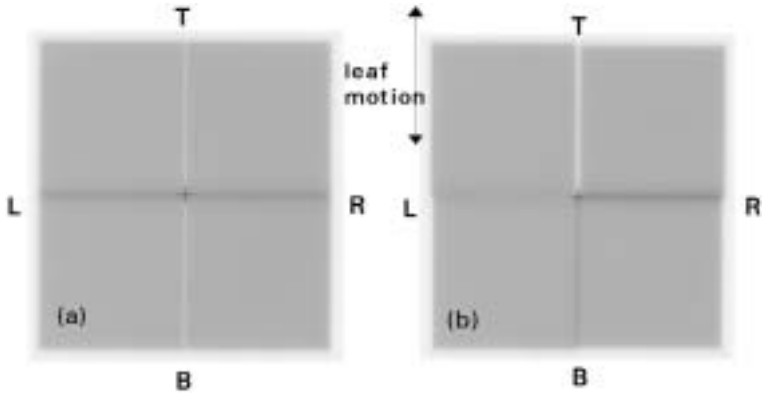

Figure 2. Composite images testing the alignment of the MLC using the leaf patterns from figure 1 for a Varian MLC. (a) Uniform field is interrupted by a tongue-and-groove underdose (vertical band) and leakage between leaf faces (horizontal band) when the leaves are calibrated using a feeler gauge or the light field. If the calibration is to the radiation field edge, the dark band should disappear. In either case, symmetry indicates perfect alignment. (b) The asymmetry shown here corresponds to 0.5 mm misalignments both perpendicular and parallel to leaf motion.

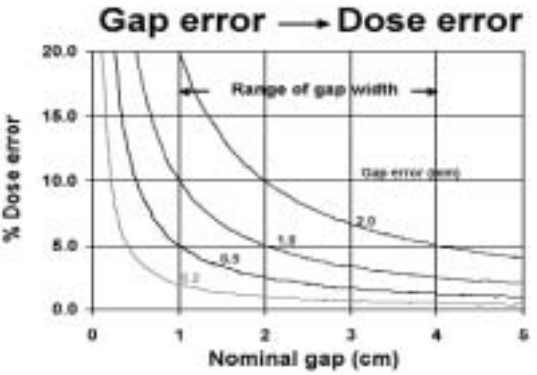

Figure 3. Relationship between dose error and gap error for DMLC fields. For the range of gap widths typical of DMLC fields, dose errors as a percent of dose delivered are shown as a function of the gap width error. Gap calibration error of ~0.2 mm translates to dose error of ~1% for typical DMLC fields. These numbers apply to SMLC as well, although the gap and dose errors are distributed differently. These curves do not account for transmission through the leaves, which will reduce the percent dose errors somewhat. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

nor the leaf speeds are fixed; nevertheless, the average dose error is inversely proportional to the average gap width, for which 1 to 4 cm is typical (LoSasso, Chui, and Ling 1998). For SMLC, overlapping or underlapping of abutting field segments lead to hot or cold spots in the abutment regions of approximately 13% mm^{-1} and 17% mm^{-1} of the average dose for the abutting segments, for 6 and 18 MV photon beams, respectively (Low et al. 2001). SMLC fields, which approach the resolution of DMLC fields, will experience the same average dose error throughout the field, although the errors will be concentrated in the abutment regions. For both SMLC and DMLC, if average gap calibration error is less than 0.2 mm, then the average dose error from this source in typical fields will be less than 1%.

A leaf calibration error, which shifts both leaves of a pair in the same direction by the same amount, will not produce a dose error in the usual sense; instead, the dose distribution for the individual leaf pair will be shifted. Potential problems may become apparent when the modulated fields are combined depending upon the magnitude of the shift, although such errors will be reduced more or less by the other fields. This scenario demonstrates the subtle, but important distinction between leaf position errors, which may be offsetting, and gap width errors. Precision QA test methods should focus on the stability of the gap width, rather than the leaf position, since gap width is a better indicator of dose delivery, and because it is easier to measure on a periodic schedule using mechanical and dosimetric procedures.

Calibration of MLC leaf positions should be performed with methods suggested by the manufacturer (Boyer et al. 2001). However, the manufacturer's specifications for leaf positioning accuracy, while adequate as a block replacement in static fields, may not be suitable for IMRT applications. Fine calibration and periodic checking of the leaf position and gap width calibration should be performed over the clinically used range of travel. There are many ways to carry out these checks; a few categorical examples will be described here.

Many of the following tests may be performed at different gantry and collimator angles to observe the effect of gravity and friction on leaf positioning and speed. It is important to establish baseline values for undesirable backlash as all mechanical systems have inherent tolerances, which allow their components to move without binding. It is wise for physicists and engineers to acknowledge and understand the effects that these tolerances introduce into treatments.

Light Field Projection

Prior to implementation of IMRT, periodic QA procedures for leaf position may have consisted of simply checking the field sizes using the field light projections of the leaf ends onto graph paper at the isocenter, similar to the calibration of the jaws. Unlike the jaws however, the light field and radiation field may not agree. The rounded leaves of the Varian and Elekta MLC allow significant transmission in the first millimeter; consequently, the radiation field edge defined by the 50% dose is shifted under the leaf by a fraction of a millimeter. The correct position of the leaves as measured by the light

field will obviously depend upon whether the calibration of the digital readout is based upon the light field or the radiation field. This procedure is consistent with the sole function of the MLC for static fields, that is, to shape the field edges. While this test is coarse by IMRT standards, it does provide a quick visual assessment of the MLC to a precision of about 0.5 mm, both on and off the axis and is useful when troubleshooting problems and machine down time is critical.

Mechanical Measurement Of The Gap (Feeler Gauge)

Since the delivered dose in IMRT fields is critically dependent upon the gap width, a direct independent measurement of the gap is worthwhile. The absolute calibration of the gap width defined by an opposed pair of leaves is obtained by setting a small gap, perhaps 1 mm (at isocenter distance). A feeler gauge having good precision (0.001 in. or 0.025 mm) is then inserted between the ends of opposing pairs of leaves. For rounded leaves (Varian and Elekta), the gap is measured at the center of the leaf; for focused leaves (Siemens), the measurement point is at the leaf edge closest to isocenter. The gauge should indicate the value of the gap demagnified to the aperture defining point at the MLC (e.g., 0.51 mm for a 1 mm gap for the Varian MLC, which is centered at 51 cm from the source). Each of the pairs of leaves can be measured in the same way (although by other methods), but observing the projections of the light field or the radiation field is more practical for determining the relative calibration of the remaining leaf pairs. The exception is the Varian MLC, where the leading edges of the leaves always form a straight line. Then by equalizing the gap between two pairs of leaves, the banks of leaves will be parallel to each other; the skewness and centerline offset can then be adjusted using the light field.

Alternatively, the Millennium™ MLC series features a "Field Alignment Tool"[1], which when attached to the head of the machine between the banks of leaves, can be used with the feeler gauge to adjust the skewness and offset of the leaves as well as the gap. Using the feeler gauge at other gantry and collimator angles will assess the effects of gravity on the gap. Mechanical backlash due to gravity affects opposing leaves in the same direction and, therefore, the effect of backlash on the gap width should be less than its effect on the positions of the corresponding leaves individually.

The above procedure can also be used to verify the gaps at off-axis positions. Once again, this is quick to do for a single leaf pair. Narrow gaps at isocenter for the range of leaf travel can be defined as individual fields and consecutively set and measured at the MLC with the feeler gauge. The measured gaps should correspond to the set gaps demagnified to the MLC (with an additional off-axis correction provided for the Varian MLC from the MLCtable.txt file). Such a series of measurements is shown in figure 4 for a Varian Millennium 120 MLC. Upper and lower bounds correspond to the widths of the gauge, which are slightly larger and smaller than the gap, respectively.

[1] "MLC User Guide", (1999). Varian Associates, Inc., Oncology Systems, Palo Alto, CA

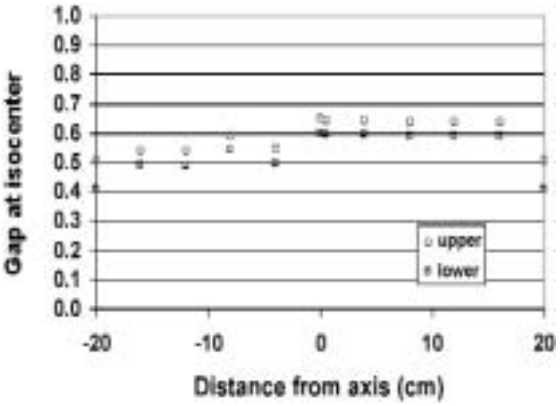

Figure 4. Verification of 0.5 mm (at isocenter) gap widths at off-axis positions using a feeler gauge. Measurements at the Varian MLC are magnified to the isocenter with an additional correction provided from the MLCtable.txt file. Values are plotted for widths of the gauge that are slightly larger (upper) and smaller (lower) than the gap.

Film Techniques

Radiographic film is a useful tool for verifying relative leaf position and gap width accuracy with the so-called "picket fence." There are many variations of this technique, but they all provide an assessment of the positioning of each MLC leaf individually relative to the alignment of the other leaves. Some methods irradiate abutting fields to generate uniform patterns at the junctions (Boyer et al. 2001; Low et al. 2001). Others irradiate narrow bands at specified intervals (Chui, Spirou, and LoSasso 1996). In either case, the technique is to irradiate a film-loaded cassette or Kodak Ready Pack film without additional buildup at isocenter using the lowest energy available, probably 6 MV X-rays, to obtain the sharpest image. After a brief series of irradiations using abutting fields or narrow bands using static, segmented fields or dynamic fields, the film can be processed and evaluated. The dose uniformity along the match lines and bands is sensitive to even small deviations of individual leaves. Discontinuities between adjacent leaves are easily detected with the naked eye as in figure 5 for a Varian Mark 2 MLC, where relative errors, ±0.5 and ±0.2 mm, in leaf positions are intentionally introduced for demonstration purposes in the image on the right. The reference image on the left does not contain errors. Figure 6 shows bands extending to ±14 cm laterally for a Varian Millennium MLC. An accurate scale can be superimposed upon the film image to observe the absolute accuracy of the leaves; a 4×4 cm grid is superimposed on the bands in this image. These films may be obtained at other gantry angles to observe the variations in leaf positions as when influenced by gravity. Commercial scanning and digital analysis routines[2] are available for those who prefer a more objective evaluation.

[2] Radiological Imaging Technology, Denver, CO.

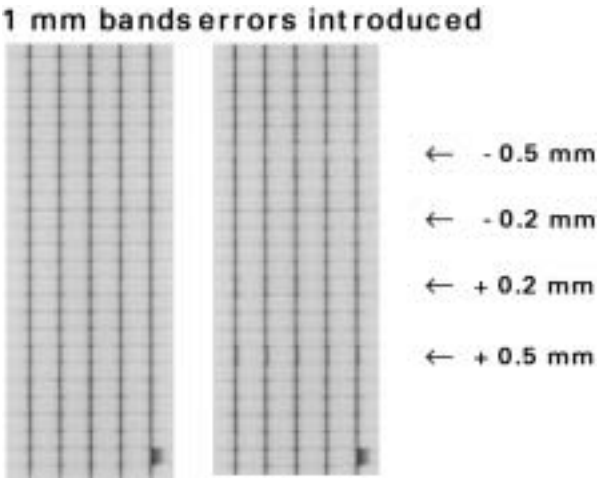

Figure 5. Film test to determine relative leaf positioning. The film image on the right has leaves intentionally shifted by –0.5 to +0.5 mm to demonstrate the method. The image on the left does not have errors. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

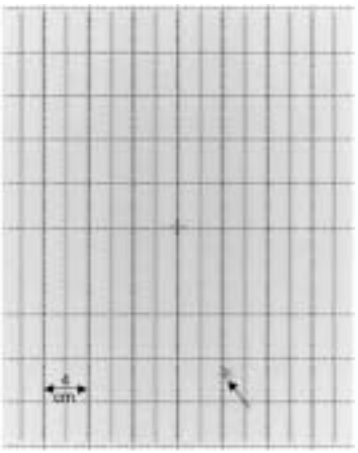

Figure 6. Film test to determine absolute leaf positioning accuracy. The bands extend to ±14 cm laterally for a Varian Millennium™ MLC. An accurate scale can be superimposed upon the film image to observe the absolute accuracy of the leaves; a 4×4 cm grid is superimposed on the bands in this image.

Clinically Oriented Test Fields

Identifying the source of a problem is not always straightforward, especially if more than one component of the IMRT process may be the source of the problem. A prerequisite for accurate IMRT treatment is careful and ongoing assessment of the dose delivery as compared with the dose calculations for standard treatment conditions. However, dose calculations are based upon assumptions and approximations, which may not hold under more rigorous conditions.

Hypothetical IMRT test cases and clinical dose distributions selected from actual patient's fields for a variety of simple to complex targets can be planned, delivered, and measured to evaluate the overall accuracy of the system (Xing et al. 1999; LoSasso, Chui, and Ling 2001; Van Esch et al. 2002). Verification of these fields using two-dimensional high-resolution techniques, such as film in flat, cylindrical, or cubic phantoms or electronic portal imaging devices (EPIDs), should be appended to a routine QA program. Methods are described in detail in the chapter ***Patient-Specific QA*** by Xia. Such dose distribution comparisons evaluate the overall performance of the MLC at the level of dose and dose variation actually received by the patient, and they provide a direct link to the treatment planning system dose calculations. Another advantage is that the use of dose distributions overlays and differences are more familiar than standard QA data to many physicians, therapists, and physicists alike. Repeated use of the same fields demonstrates the stability of the delivery system over time. For departments equipped with multiple MLC, they can also be the basis for an IMRT intercomparison of MLC. Discrepancies can be indicative of irregularities in the delivery system or the dosimetry measurement system, as well as the dose calculation algorithm or the leaf sequencer. Such tests should be performed periodically as well as for new MLC, new MLC software, and modifications of the treatment planning algorithms.

As is common in most new clinical treatment strategies, IMRT at Memorial Sloan-Kettering Cancer Center (MSKCC) began with a relatively undemanding treatment site, the prostate (Ling et al. 1996). Before IMRT treatments began at MSKCC, we acknowledged three specific parameters, which needed to be re-commissioned for the IMRT dose calculations. These were: (1) the MLC transmission (primary plus scatter) through the leaves and interleaf spaces; (2) the added transmission through the rounded leaf edges; and (3) output factor for small MLC-shaped fields simulated by an analytical source function (LoSasso, Chui, and Ling 1998). These factors have minor influences for conventional static fields as the average MLC transmission, 1.5% to 2.0%, is less than that for metal alloy blocks, ~3.5%, the round edge only slightly broadens the penumbra in these cases, and MLC output factor for a tertiary collimator can be ignored in most cases. In contrast for IMRT, transmissions through the leaves and the rounded leaf edges contribute 4% and 10%, respectively, to the delivered dose to the target volume in typical IMRT fields, and small variable gaps between leaves produce local output variations.

Concurrently, as IMRT fields increased in size, modulation, and irregularity, periodic QA for clinical fields showed increasing discrepancies in certain cases. QA was gradually intensified to look at different components of the MLC and to try to identify the problem. After some time we concluded that commissioning parameters needed to be reevaluated. The average value for MLC scatter, based upon prostate and head and neck field sizes, was included in the MLC transmission that is applied to all fields; however, it is not accurate for larger IMRT fields. We have refined the source function, to more accurately calculate MLC output for very small gaps. Additionally, we modeled the interleaf spaces giving the planner the option to evaluate tongue-and-groove effects in individual plans.

Clinical dose measurements indicate potential problems in highly modulated and irregularly shaped fields. Recently, a multi-institution comparison of calculated and measured clinical dose distributions indicated that the center-specific dose kernels derived from deconvolution of ion chamber profiles were inadequate (Van Esch et al. 2002). One of the more extreme cases at MSKCC, an IMRT lung field, calculated and measured in a flat homogeneous phantom, is illustrated in figure 7. The overlay of calculations and measurements shows large variations in dose, 15 to 60 cGy within the field, with an average dose of about 30 cGy. The dose difference in figure 7a shows that discrepancies can be 25% of the average dose (15% of the local dose) in such fields. Most differences are found near the high dose gradients and can be attributed to inaccuracies in the extra-focal source distribution. Calculations comparing the source distribution used for figure 7 with a new source distribution are shown in figure 8. The modification appears to have resolved most of the discrepancy. It should be noted that these discrepancies would be less in the composite dose distribution due to the smoothing influence of other fields.

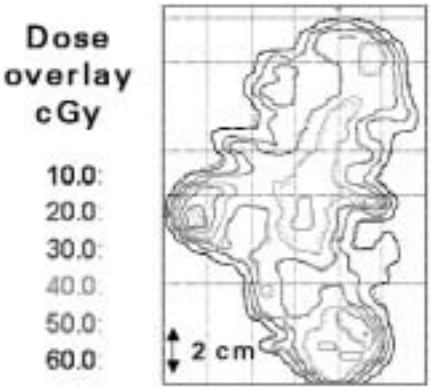

Figure 7. Overlay comparison of calculation (solid lines) and film measurement (dotted lines) for a posterior-anterior (PA) lung field used in an IMRT treatment. The intensity-modulated dose varies from 10 to 60 cGy.

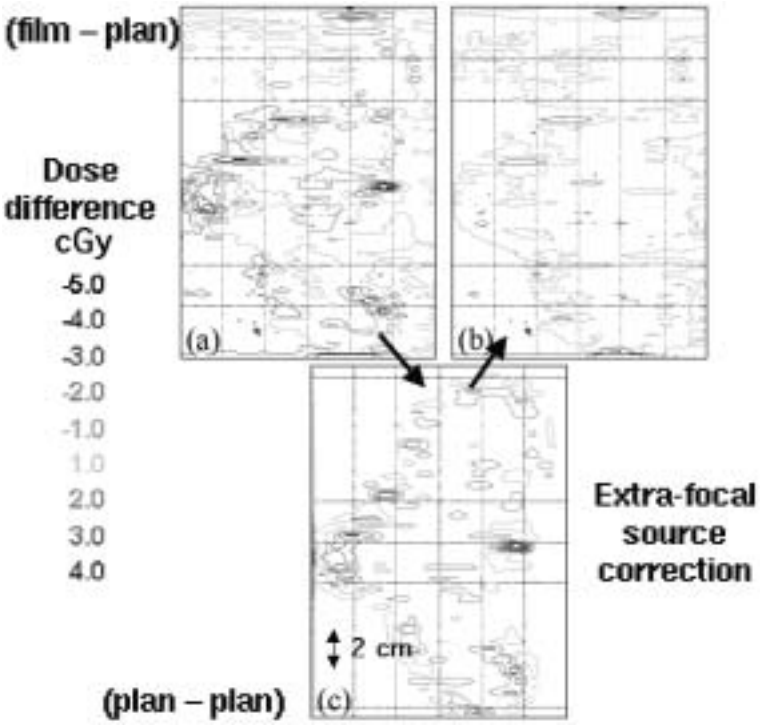

Figure 8. Comparison of dose differences (film-calculation) for the field in figure 6 using the (a) old source function and the (b) modified source function. The dose differences between the two calculations are shown in (c).

Gap Width (DMLC Procedures – Varian Only)

Narrow Sliding Window

If dynamic capabilities are supported, as for the Varian MLC, then alternate dosimetric methods with much greater precision are available in addition to the static methods described in the previous section. As these tests are more quantitative, they allow tracking of long-term stability. Given that the fluence (and consequently the dose measured) through a narrow gap is critically dependent on gap width, inversely, dosimetric measurements can be used as a sensitive monitor of gap width (Wang et al. 1996; LoSasso, Chui, and Ling 1998; Arnfield et al. 2000; LoSasso, Chui, and Ling 2001). For example, an output variation of 1%, which is easily measured, corresponds to a variation of ~0.05 mm for a 5.0 mm wide gap (with the round edge transmission not factored in). Based upon this relationship, we developed a number of dosimetric procedures utilizing an ion chamber or diode array.

DMLC Output Vs. Static Field

The stability of the gap can be monitored utilizing an ionization chamber and a 5 mm sliding window beam delivery to measure the output. At the time of monthly x-ray beam output calibration, ion chamber readings for the narrow DMLC field are normalized to that measured in the static beam calibration field, using the same setup geometry to avoid uncertainties arising from changes in monitor chamber calibration; temperature and pressure corrections, and precise setup accuracy are also unnecessary. The long-term results, over a 4-year period from 1998–2002, for several treatment machines at MSKCC are displayed in figure 9. Here we plot the ratio of the DMLC output to static field output versus time. The variation in radiation output during this period is <1% for all three machines, and is less than that corresponding to the 0.2 mm tolerance on gap width (indicated by the vertical arrow marked 0.2 mm). Given the <1% output variation for the gap width of 5 mm used for the reference DMLC field, the variation would be even less (<0.3%) for typical clinical fields with a gap width of ~2 cm. The dashed lines in figure 9 indicate adjustments to the calibration parameters, which led to small changes in the DMLC outputs.

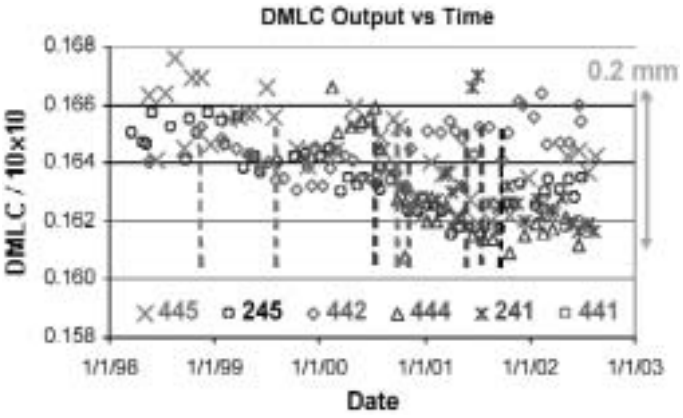

Figure 9. DMLC output stability over time. The ratios of the dynamic field to the reference field are plotted for six Varian MLCs. The 0.2 mm range in gap width corresponds to a 3% change in the ratio. The dashed lines indicate changes to the calibration parameters in the MLCXCAL files. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

DMLC Output Vs. Gantry And Collimator Angles

Leaf position variations imposed by the effects of gravity at different gantry angles should be documented periodically. Changes in leaf position between gantry angles are indicative of problems with leaf drive assemblies or carriage supports and can lead to significant dose errors. For SMLC these effects can only be observed with film

techniques, using the doubly exposed film test described earlier or using the "picket fence" or similar pattern. Variation in fixed gaps at four orthogonal gantry angles should be observed. Scanning is advisable as the changes associated with skewness cannot be quantified visually. When DMLC is available, dosimetry is an option using ion chambers or diode arrays to measure output changes from narrow gaps at different points along the gap.

A standard monthly DMLC test for this purpose uses a cylindrical ion chamber (with appropriate buildup cap) at the isocenter; a fixed dose using the 5 mm sliding window field described above is delivered, and normalized to the dose from a fixed static field, at different gantry and collimator angles. The time trends of dose output for six combinations of gantry and collimator angles for four MLC are presented in figure 10. It is apparent that each MLC has a distinctive pattern. The horizontal dashed lines represent the output range that ±0.2 mm gap variation would impose. The vertical dashed lines are the adjustments to the calibration as in figure 9. These graphs show that for any specific set of gantry and collimator angles the clinical output is stable over time to within about 1%. Furthermore, since daily treatments are generally delivered with multiple gantry angles that compensate each other, the deviation due to carriage instability is usually much less than 1%.

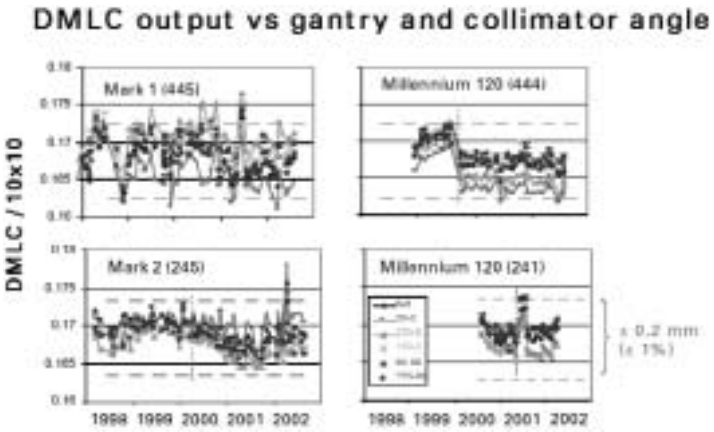

Figure 10. DMLC output stability vs. gantry and collimator angle for four MLCs over time. The DMLC outputs are normalized to the outputs for the static reference field at each angle. The dashed lines represent ±0.2 mm range in gap width (1% clinical dose variation).

DMLC Output, Off-Axis Perpendicular To Leaf Motion

Off-axis dosimetry measurements indicate the relative skewness at a number of gantry and collimator angles. Data obtained with a linear diode array for a Varian MLC for gantry angles of 90° and 270° are shown in figure 11. The individual diode readings

are normalized to the readings with both the gantry and collimator at 0°. The diodes see varying amounts of interleaf leakage. Fitting these data points to straight lines yields the dashed lines for gantry angles of 90° and 270° relative to the 0°-gantry position. Some backlash is unavoidable in mechanical systems. Fortunately, such variations, as observed here at 90° and 270°, tend to compensate each other during treatment. Nevertheless, output vs. gantry angle is variable among the MLC, and output changes over time may indicate mechanical problems.

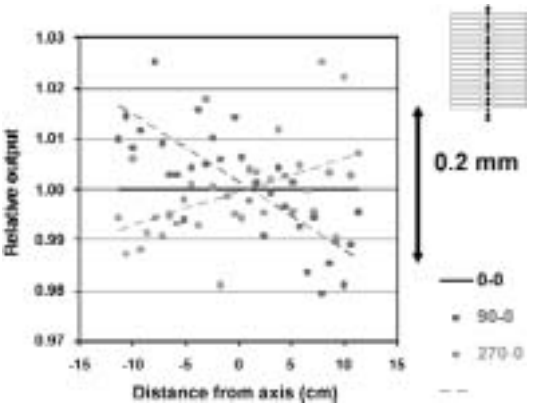

Figure 11. DMLC output stability vs. gantry angle measured with a linear diode array. The array is mounted in the blocking tray holder and aligned perpendicular to the direction of leaf motion. DMLC outputs are first normalized to the static reference field at each angle and then normalized to the output at 0°. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

DMLC Output, Off-Axis Parallel To Leaf Motion

A dynamic slit field can be used to verify the off-axis gap width accuracy dosimetrically. The method compares symmetry and flatness of relative dose profiles for an open field with that for a 1.0 cm wide dynamic field moving at a constant speed (cm/MU). Measurements may be obtained at arbitrary intervals with an ion chamber, a detector array, or film. Ideally, the normalized dose profile for the dynamic field should mimic that for the open static field.

The gap-width accuracy at off-axis positions verified with ionization measurements for one MLC is shown as relative dose profiles (i.e., normalized to the dose at the central axis) in figure 12a and 12b for 6 MV X-rays. Figure 12a shows the static field and DMLC field profiles and the ratios of these profiles for each of three fields, centered at the axis and at ±8 cm off-axis at a depth of 10 cm. Near the central axis, the open field and dynamic profiles agree within 0.5%; however, at 10 cm from the

axis, the ratio of the profiles decreases by ~2%. This decrease is not due to changes in the gap-width, the measured transmission also decreases with increasing off-axis distance, to 92% of the central axis transmission at 10 cm off-axis. Figure 12b shows that the ratios of the profiles for the DMLC fields and the static fields are much flatter, once the transmitted component of the dose is removed from the DMLC readings. Thus, the width of the gap for this MLC is relatively constant across the field.

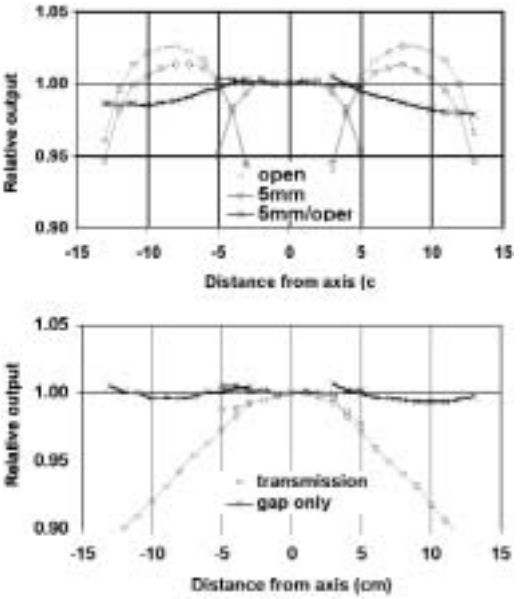

Figure 12. Measured dose profiles for a narrow, 0.5 cm, DMLC field are compared with those for an open static field. Due to the 15 cm field width limitation, fields are centered at the central axis and at ±8 cm off axis. (a) Ion chamber measurements at 1 cm intervals are normalized to the central axis. (b) The ratio of DMLC to open field is flat once the variation in off-axis transmission is measured and corrected for. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

Beam Characteristics For Small MUs

The delivery of IMRT using SMLC with Siemens and Elekta requires that the beam be cycled off and on (step and shoot). As the number of segments increases providing more control points, the monitor units (MUs) per segment will decrease. For complex intensity-modulated patterns with many subfields, large numbers of segments may be delivering small MU values, less than 2 MU (Ezzell and Chungbin 2001; Xia, Chuang, and Verhey 2002). For example, a 200 cGy prescribed daily fraction delivered with a

100 segment plan will average only 2 MU per segment. Since such small MU settings are outside the range of conventional treatments, the scope of acceptance testing and QA procedures do not normally address this issue.

Testing the accuracy of beam fidelity, i.e., dose output, symmetry, and flatness, for small MU can be done with an ion chamber positioned sequentially at the central axis and at four orthogonal off-axis points in a static field. At each point the dose for a fixed number of MU, X MU, is measured. At each point for X-1 MU segments the dose is also measured and then summed for comparison. Measurements may also be made with 2-D detector arrays or film. A summary of the experiences of small numbers of monitor units for several different machines concluded that individual centers need to make such measurements on their particular accelerator approximately monthly to ensure reliability (Webb 2001).

Leaf Motor Issues

Leaf Speed

Leaves have a maximum speed that is specified by the manufacturer. On occasion, leaf motors will not be able to maintain this speed during normal operation. Slowing is a symptom of excessive wear of the motor or other leaf assembly components. A buildup of dirt and grease migrating between the flat leaf surfaces from components of the drive mechanism may also tend to bind adjacent leaves; this possibility should be eliminated first. Variation in the maximum available leaf speed of individual leaves will influence treatment times since segments within an SMLC field will require longer leaf setup times.

For DMLC, which is only currently available with the Varian MLC, the reduction of the maximum leaf speed will have two possible effects. If a leaf is unable to maintain its programmed speed while the beam is on, then the MLC software will modulate the dose rate by increasing the number and duration of beam holdoffs during delivery, and thereby increase treatment times. More importantly, the delivered intensity profile may also differ from the prescribed profile if a leaf is lagging behind due to leaf speed issues, with or without beam holdoff indication. Thus, leaf speed is considered a more important QA issue for DMLC than for SMLC delivery, where the dose is unaffected. Detection of reduced leaf speed for an individual motor should be part of a QA program, so that the problem may be rectified by a service engineer.

The stability of leaf speed and the effects of leaf acceleration and deceleration on the delivered intensity profiles for DMLC have been recognized for several years (Chui, Spirou, and LoSasso 1996). To test the stability of leaf speed, specially designed leaf sequence files move pairs of leaves at constant speeds ranging from low to maximum speed. If the leaf speeds are constant across the field, then the measured dose profiles should be uniform. If leaf speeds are unstable, fluctuations would appear in the delivered profiles. Since leaf speeds are varied between programmed DMLC segments, the significance of acceleration and deceleration was also tested by inten-

tionally interrupting the beam and then resuming the irradiation, which was judged not to be a concern.

Sub-par leaf speed can often be visually detected relative to other leaves when the leaves are moved at their maximum velocity during field setup or leaf retraction or by using a leaf exercise pattern designed for this purpose, which moves leaves in and out of the field. If the problem is subtle, it may only be noticeable during leaf movements at certain gantry angles when gravity is a compounding factor.

During a DMLC treatment with the Varian MLC, excessive beam hold-offs for one or more fields are an indication of such a problem. The therapists performing the treatments should have an ear open for these telltale signs and report them for servicing. A more objective approach is to evaluate DMLC leaf positions recorded by the Varian MLC controller in log files during delivery. The Dynalog File Viewer[3], a software tool for evaluating leaf positioning during IMRT delivery, tabulates leaf position errors [root mean square (rms) deviation of monitored and actual leaf positions for individual leaves] based upon their magnitude and frequency of occurrence during treatment. A test file which moves all the leaves in and out of the field in an alternating pattern at a speed close to the maximum can then be evaluated with the Dynalog File Viewer to identify errant leaf behavior. Individual leaves are suspect if their deviations appear significantly larger than the average for all the leaves. Performing such a leaf speed test at gantry angles of 90° and 270° may be best to incorporate the gravity factor as well.

Motor Calibration Failures

Electromechanical components of the MLC may fail at any time. This may take the form of an abrupt failure, requiring immediate replacement of the part before treatment can resume, or, perhaps more troubling, it may be a gradual deterioration, requiring careful monitoring. Deterioration of motor speed has been described earlier. Another concern has to do with the long-term reliability of the primary encoders affixed to the Varian leaf motors; it is apparently related to the amount of usage of individual leaf motors. Chronic drift of the calibration of the leaf position encoder has been the principal symptoms of leaf motor failures for this MLC design until recently.

The data in figures 13 and 14 summarize the history of MLC leaf motor failures on three Varian MLC machines used primarily for DMLC treatments since 1996 at MSKCC. Approximately 80% of patients—~30 patients/day, 5 fields/patient—on two machines, 245 and 445, have been IMRT prostate patients (prior to this time, 1992–1995, these MLC have been used primarily for static MLC treatments). In figure 13, the increased frequency of motor failure near the central axis, indicated by color, and multiple failure, indicated by numbers, is consistent with those leaves used for prostate fields. The solid lines in figure 14 graph the chronology of motor replacements. For each MLC, leaf motor failures became more frequent after the initiation of DMLC treatment. Leaf position errors, caused by calibration drift, were increas-

[3] "Dynalog File Viewer, Reference Guide," (2001) Varian Associates, Inc., Oncology Systems, Palo Alto, CA.

ingly detected during QA procedures and patient treatments. The frequency of MLC reinitialization was gradually increased during the treatment day. Eventually, beginning in 1998 the replacement of marginally performing motors became part of the QA program. With DMLC QA specifically targeting this problem, leaf drive motors were replaced at a steady rate between 1998 and 2001. Based on our QA records we have estimated what the MLC motor replacement rate would have been had we initiated this prophylactic motor replacement policy in 1995. These are shown as dashed lines in figure 13. It is postulated that the repeated abutment of opposing leaves especially during IMRT delivery caused many of these leaf motors to fail prematurely. New software developed by the manufacturer, with a 0.5 mm minimum gap criterion, was installed in June 2001, indicated by the vertical dashed line in figure 13. While it is too early to be definitive, the rate of motor replacement appears to have decreased at about the same time. Furthermore, the primary cause of leaf motor failure is no longer calibration drift.

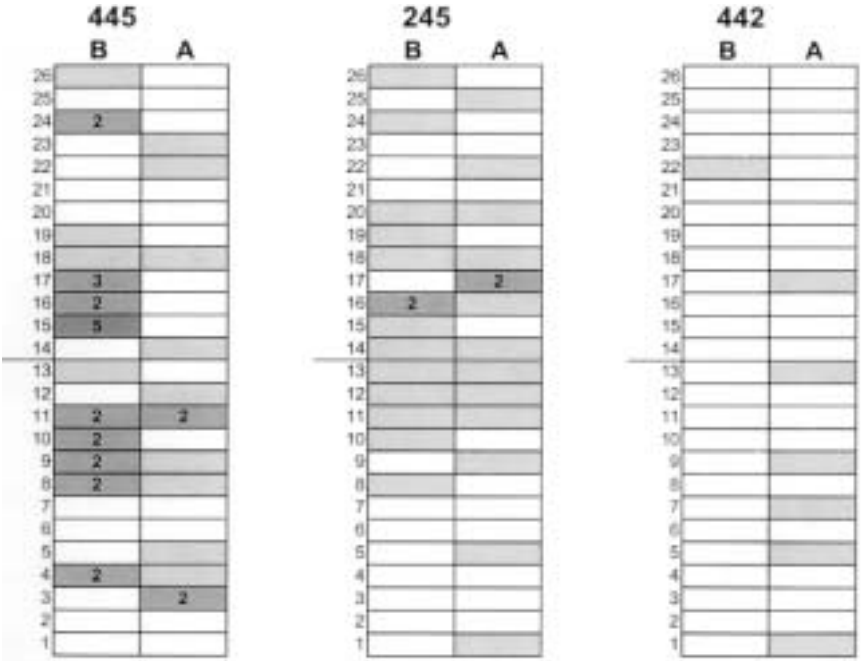

Figure 13. Leaf positions where motors have been replaced are shown in color for three MLC. Numbers indicate multiple motor replacements. The pattern of replacing centrally located motors for the MLCs in rooms 445 (left) and 245 (center) is consistent with the use of these MLCs almost exclusively for prostate treatments. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

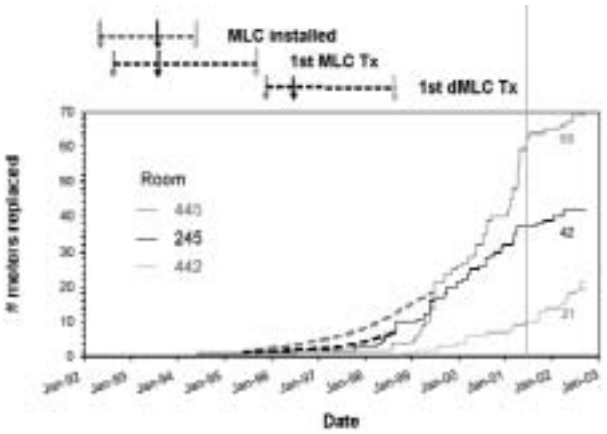

Figure 14. Cumulative motor replacements vs. time for three MLCs. The solid curves are the actual replacements. The dashed curves indicate that some motors would have been replaced earlier based upon the replacement criteria adopted in 1998. The vertical dotted line indicates the introduction of the 0.5 mm minimum gap criterion for moving leaves. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

The problem just described for the Varian MLC stems from the count losses by the primary encoder, an integral part of the motor assembly. It becomes more severe during the course of the treatment day, assuming the MLC is initialized (self-calibrated) in the morning using its internal optical calibration system. On occasion that the count losses of a primary encoder become excessive, leaf position errors could exceed 0.5 mm at isocenter. Reinitializing the MLC will temporarily alleviate the problem, but position errors may go unnoticed since the secondary position interlock is triggered only when the discrepancy between the primary and secondary readouts reaches ~2 mm at isocenter. To safeguard against such errors, potential encoder problems are identified using the picket fence film test described earlier on a semi-weekly schedule. The film test is performed by a therapist, evaluated by a physicist, and questionable motors are then replaced at the earliest convenience. This condition may exist intermittently for several days before detection.

Communication/Timing Errors

A number of studies have recently addressed the subject of communication delays, also referred to as timing errors, overshoot phenomenon, and latency issues, and the subsequent leaf position errors for the Varian MLC in dynamic mode. The concern arises due to the 55+ msec delay before the MLC control system can acknowledge and respond to the instruction for the next MU segment. In effect, the leaf lags behind its prescribed position, defined by the index, or fractional MU, in the leaf sequence file,

at each moment of the delivery. It may appear as though the leaf speed is the issue, but rather the deviation in leaf position is caused by the communication delay.

For the SMLC mode, these errors mainly affect the delivered dose in the first and the last segment, which deliver slightly greater and less dose than planned, respectively. Intermediate segments also experience these delays; however, approximately the same "overshoot," i.e., the ΔMU which is added to the end of each segment, is missing from the beginning of each segment. In this case two wrongs make it right; the intermediate segments generally receive the correct MU (Ezzell and Chungbin 2001; Xia, Chuang and Verhey 2002). This is demonstrated in figure 15, where the total MU per segment is varied from 0.25 to 25 at a delivery rate of 400 MU/min. For the smallest MU per segment such that the "overshoot" exceeds the planned MU for the segment, one or more of these intermediate segments may actually be skipped. The graphics in figure 16 illustrates this very clearly. In the upper diagram the planned segments are equal in MU per segment; the first segment delivers more dose and the last segment less than planned, while intermediate segments receive the correct dose. In the center diagram, a small intermediate segment, 3, is bypassed as a result of the overshoot. The lower diagram indicates the variable nature of the overshoot and the corresponding uncertainty this introduces to all delivered segments.

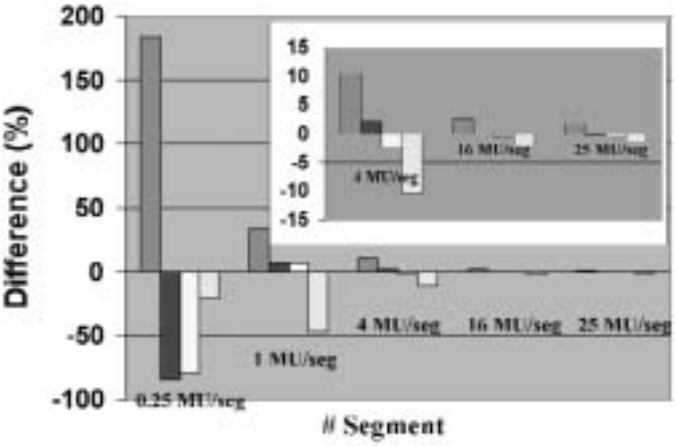

Figure 15. The relative dose variations among four segments as a function of MU per segment. The dose rate is 400 MU/min on a Varian 2300CD at 6 MV. [Courtesy of Ping Xia, UCSF.]

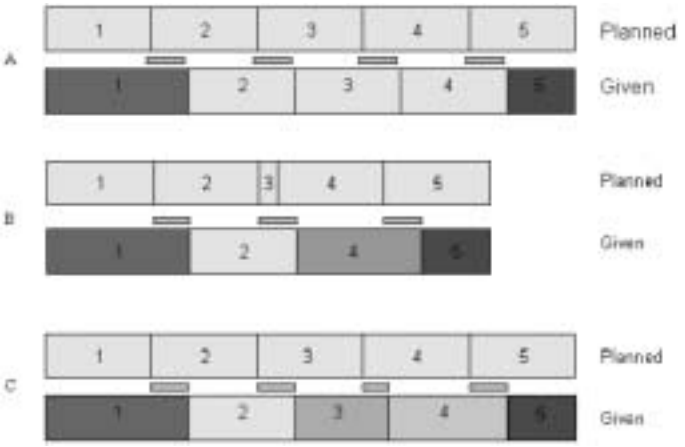

Figure 16. Schematic showing the effect of an overshoot in the MU delivery. (a) Overshoot is constant. Segment 1 is long, 5 is short, 2–4 are unaffected. (b) Overshoot exceeds the planned MU for segment 3, so it is skipped. (c) Overshoot is variable, so segment 3 is shorter than planned and segment 4 is longer. (Reprinted from *Journal of Applied Clinical Medical Physics*, vol. 2, issue 3, G. A. Ezzell, and S. Chungpin, "The Overshoot Phenomenon in Step-and-Shoot IMRT Delivery," pp. 138–128. © 2001, with permission from G. Ezzell and the *Journal of Applied Clinical Medical Physics.*]

In the DMLC mode, if leaf speeds are allowed to exceed their maximum values, dose rate modulation will result (Low et al. 2001). In this situation the dose is delivered in pulses as the beam holdoff is repeatedly invoked and the leaf deviation varies within each pulse; a rippled dose distribution results even though the intended leaf sequence is smooth. Another study offers a detailed description of the limitations of the delivery control system and proposes sequencing solutions to overcome these limitations (Litzenberg, Moran, and Fraass 2002b). However, the fluence modulation introduced by communication delays into DMLC delivery should also cancel for leading and trailing leaves.

Thus, it may be concluded that for typical clinical situations, i.e., when very small MU per field and MU per segment are avoided for SMLC and when appropriate leaf sequencing parameters (dose rate, leaf tolerance, and maximum leaf speed) are chosen for DMLC, timing errors will not lead to significant dose errors. There is some concern if these leaf sequences are used for QA purposes, where film and EPID may require shorter MU; the dose rate should be reduced in this case such that the maximum leaf speed is not exceeded.

Log File Analysis (Varian Only)

Log files are generated by the Varian MLC control software after each IMRT field is delivered. These files contain the leaf positions as indicated by the primary leaf position

encoder attached to each leaf motor. These monitored leaf positions and the prescribed leaf positions are recorded every 55 msec for each leaf. Analysis of these data can be a very useful QA tool, provided the information is properly interpreted. In this regard, it is important that the user understand that these are "monitored" leaf positions do not represent the "actual" positions of the leaves. They are the positions of the leaves from the perspective of the primary leaf position encoder attached to the leaf motor. Log files do not consider errors in the absolute leaf calibration, drift in the leaf calibration over time, or backlash in the leaf drive mechanism. Nevertheless, analysis of this data can provide information on the performance of MLC leaves individually.

Several applications of these log files have already been developed. During DMLC acceptance testing, log files were analyzed to study the impact of gantry and collimator rotations on leaf positioning (MSKCC 2003). The DMLC log files may also be converted to leaf sequence files which, with the prescribed MU and field size, permit the calculation of the "delivered" dose distributions (within the uncertainty due to leaf calibration and mechanical backlash) by the treatment planning system. The comparison of the delivered dose distributions with the planned dose distributions are useful to verify normal beam delivery and to study the effects of repeated beam holdoffs, invoked by gating signals, on IMRT dose delivery has been reported (LoSasso et al. 2001; Yorke et al. 2000). An example of such a comparison is shown as the dose overlay and difference in figure 17 for the posterior field of a 5-field DMLC prostate treatment. The dose difference distribution indicates discrepancies between the planned and delivered dose distributions of less than 1%.

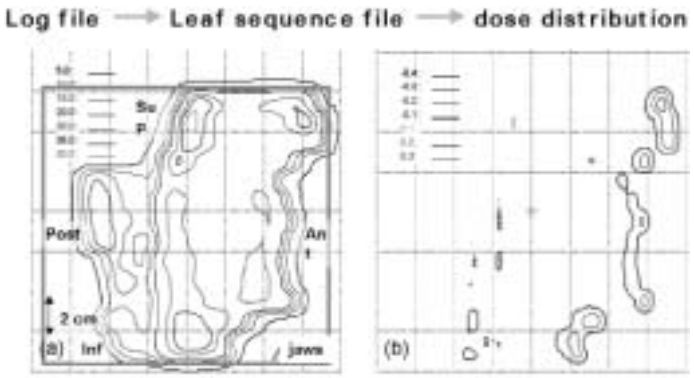

Figure 17. Comparison of a "delivered" dose distribution derived from a Dynalog file with the planned dose distribution. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

Varian has provided a software package, the Dynalog File Viewer, to summarize the deviations of the leaves from their prescribed positions for leaves that were moving during the DMLC treatment. These treatment summaries currently only provide numerical scores, rms leaf position deviations, which are not directly correlated to dose

delivery errors. However, they can be used to evaluate MLC in conjunction with appropriate test files to identify leaf motors that are not able to maintain their maximum speed.

A very detailed analysis of the Varian Dynalog files has been made to assess routine QA. (Litzenberg, Moran, and Fraass 2002a). In this study the authors derive, tabulate, and graphically display such quantities as leaf position and velocity deviations, gap deviations, and dose discrepancy profiles. They suggest that a routine of QA sequences be tested and analyzed daily to evaluate MLC performance. Although many of these features would overwhelm the average IMRT user, no doubt a modified version of this software, selecting specific parameters, targeting known problems would be a valuable QA and troubleshooting tool for the manufacturer to provide with each IMRT installation.

Interleaf Transmission

All MLC are focused in the direction perpendicular to leaf motion. This requires that the leaves are divergent and that the sides of the leaves have an overlapping component, tongues and grooves or just a single step midway, to reduce the interleaf transmission through the narrow air spaces between the leaves. Variation in transmission for a specific MLC in the direction perpendicular to leaf motion is caused by differences between the midleaf thickness and the combined thickness of tongues and grooves, plus the transmission through the narrow air spaces, which is not completely blocked by the tongues and grooves. The overlap, which also adds stability, can take a number of shapes, but generally keeps the measured interleaf transmission to less than 3%, which is lower than for metal alloy blocks (Boyer et al. 2001).

Another by-product of the overlapping portions of the leaves is the so-called "tongue-and-groove" effect, which can produce an underdose in the interleaf space (van Santvoort and Heijmen 1996; Webb et al. 1997). Interleaf transmissions and tongue-and-groove effects fluctuate between adjacent leaf pairs. They have a more pronounced effect in IMRT than in 3DCRT because the MU are greater for IMRT and because the leaves shield the target for a significant portion of the IMRT treatment. For this reason, the range of interleaf transmission should be determined for all the leaves at acceptance testing; variations may also be observed at different gantry and collimator angles. Later, these findings may explain discrepancies between measured and calculated doses for individual fields. Fortunately, the magnitude of interleaf transmission and tongue-and-groove effects tend to negate each other as fields are combined in the composite plan.

Interleaf transmission is most easily quantified with film dosimetry using a tissue equivalent phantom and a high-resolution scanner. In general, the interleaf transmission exceeds the midleaf transmission for MLC as shown in figure 18 for Varian Mark 2 and Millennium MLC, where the transmission profiles for the blocked fields are normalized to that for the open field. As measured in phantom, the maximum interleaf transmission should not be more than twice the midleaf value. The full-width-half-maximum (FWHM) values are ~ 2.5 mm measured in phantom for 6 and 15 MV X-ray beams (LoSasso, Chui, and Ling 1998).

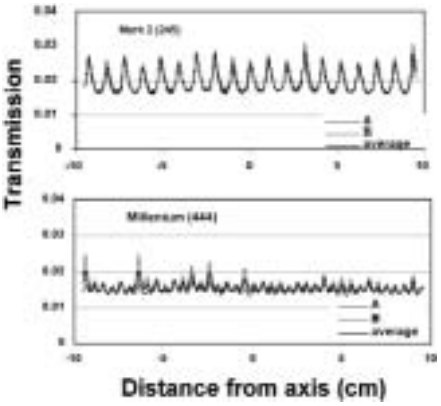

Figure 18. Interleaf and midleaf transmission profiles (A-side, B-side, and average) for the (a) Mark 2 and (b) Millennium™ 120 MLC. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

MLC Intercomparison

For centers with multiple MLC-equipped linacs, a diligent QA program will compare MLC parameters that affect the dose delivered. Values of parameters, such as midleaf and interleaf transmissions, variations in leaf position calibration, and output factors for small fields, are usually measured with static fields when commissioning the MLC; their comparison is straightforward.

A major concern for IMRT is the fluence through the leaf face. Each MLC design can be classified as either single- or double-focused. In the double-focused configuration (Siemens), the leaves move in an arc; the leaf face and the leaf sides nominally match the beam divergence. Single-focused leaves (Elekta and Varian) only have sides that are divergent. Since they move in a plane, they have rounded faces, allowing the leaves to maintain a constant penumbra width as the non-focused leaves move away from the central axis in a simple rectilinear motion. This is a complicating factor for dose calculation as the round leaf end transmits more of the primary beam than a flat leaf end, and the transmission is varying with distance from the edge. For the Varian and Elekta MLC, this added fluence will contribute a significant amount of the delivered dose within typical IMRT fields, perhaps 10% or more depending upon the degree of modulation in the plan. This transmission may vary somewhat with energy, MLC model, and distance from the central axis due to oblique path length through the leaf face and off-axis spectral changes. For the Siemens MLC, although the leaf faces are flat and focused to the source, even slight misalignment may introduce additional fluence.

Transmission through the leaf ends can be quantified with measurements of the effective gap offset (LoSasso, Chui, and Ling 1998; Arnfield et al. 2000; LoSasso,

Chui, and Ling 2001). An effective offset for a leaf can be thought of as the amount that a leaf would need to be retracted to add the same fluence as is transmitted through the leaf end. In one method film is used to measure integral dose in phantom for a set of nominal static gap widths including the smallest gap setting allowed with the leaves not touching. Leaf sequence files have been created for moving gaps with different fixed widths and constant leaf speed centered at 0, 5, and 10 cm from the central axis. An integrating ion chamber, either in a phantom or in air, serves the same purpose as film in the previous method. For each field, static or dynamic, the integrated reading is the sum of the fluence through the gap, the leaf end transmission, and the full leaf transmission. Full leaf transmission is measured using the same jaw setting and detector setup (note: measured transmission is dependent upon irradiation and geometry due to scatter and interleaf transmission), but with the leaves of the MLC blocking the field completely. The full leaf transmission varies for each gap field and must be subtracted from the measurement. This is derived from the average of the measured transmission for the two leaf banks with an adjustment for the spatial (film) or temporal (ion chamber) fraction that the detector is shielded by the leaves. The net ion chamber outputs, normalized to a static 10×10 cm^2 static field at the central axis and a depth of 10 cm for 6 MV and 15 MV beams, are displayed in figure 19. They are plotted against the nominal gap width and fit with straight lines. The intercept at zero dose yields the effective gap offset. Note that this measurement includes the effect from the uncertainty of the leaf gap calibration, the variations in attenuation due to energy and leaf design, and the limitations of the mechanical components of the MLC system.

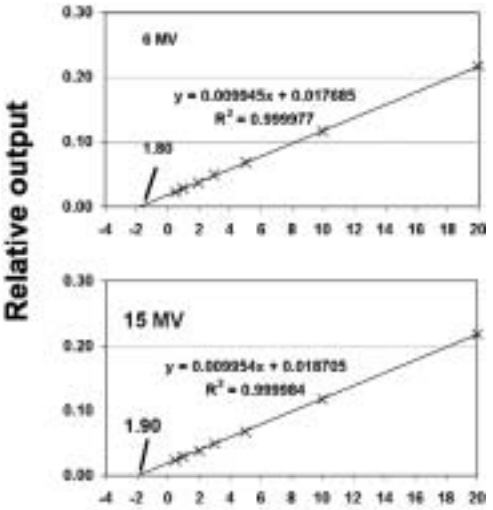

Figure 19. Output vs. DMLC gap width. The x-intercept is the effective gap offset due to the round leaf ends. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

Effective gap offsets can then be compared for various rooms, MLC models, energies, and off-axis positions. Figure 20 summarizes measured offset values at the central axis, 5 cm, and 10 cm off-axis, parallel to leaf motion, for five Varian MLCs with three different leaf designs. For the same nominal energies, variation in the offset value was within ±0.15 mm at all positions. Except for the MLC in room 442, the variation in the offset value at the central axis is within ±0.05 mm. The lower offset for the MLC in room 442, in part, is due to the slightly lower beam energy observed for this 6 MV beam.

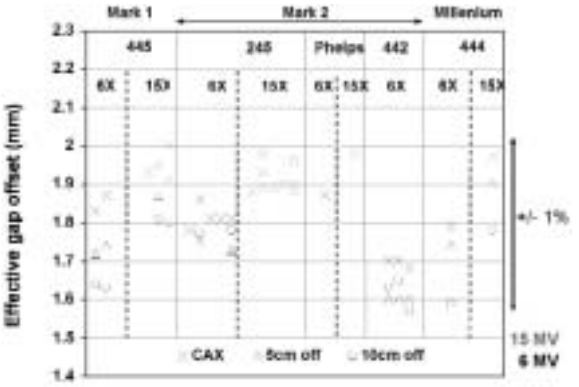

Figure 20. Comparison of measured effective offsets for five MLCs at the central axis and at 5 and 10 cm off-axis for 6 and 15 MV X-rays. [Reprinted from *A Practical Guide to Intensity-Modulated Radiation Therapy*, MSKCC staff. © 2003, with permission from Medical Physics Publishing.]

Auxiliary Systems

Where the tumor and/or critical organs are potentially affected by respiratory motion, respiratory gating may be applied during simulation, scanning, and treatment to minimize movement. Gating during tumor localization will affect the apparent tumor size and location (Nehmeh et al. 2002). Gating during IMRT delivery has an added benefit, as intrafraction organ motion can distort the temporal and spatial dependent dose delivery. Figure 21 illustrates the cyclical motion of a point in the field, perpendicular and parallel to the leaf motion, caused by respiration. The impact on dose delivery of gating the accelerator beam with a respiratory monitoring system should be tested. This can be performed with film dosimetry techniques or by analyzing log files.

For large target volumes it is sometimes necessary to split fields into two subfields (figure 22) due to limitations in the field width used for IMRT. Dose distribution accuracy in the overlap region of split fields should be tested for clinical cases (Wu et al. 2000).

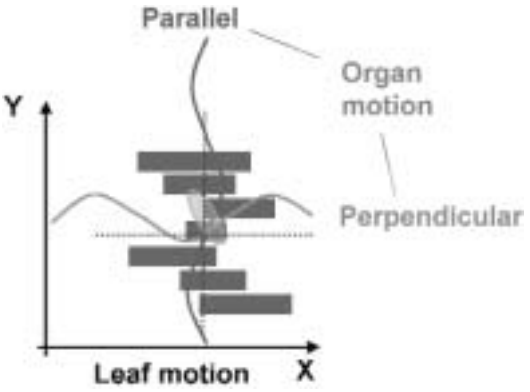

Figure 21. Diagram illustrating the motion of a point in the tumor due to respiratory motion relative to leaf motion for the sliding window type of treatment. Note: Step-and-shoot delivery is sensitive to respiratory motion as well.

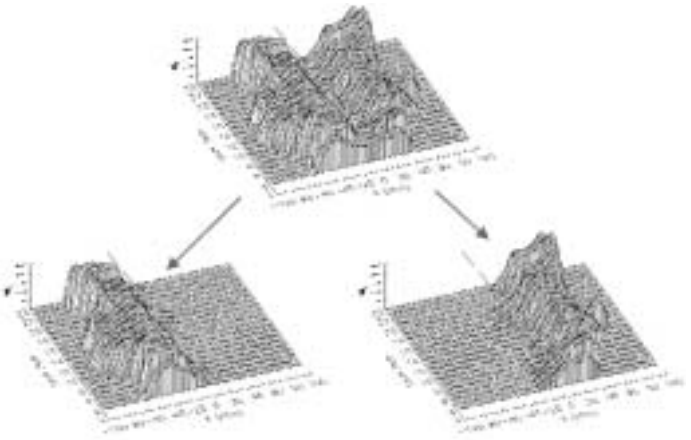

Figure 22. Diagram illustrating the splitting of large intensity pattern into two subfields.

Frequency Of Checks

It is difficult to set a standard for frequency of performing QA. The frequency will vary with a number of factors including the type of delivery, i.e., SMLC or DMLC, the MLC design, the variety of tests used, the length and breadth of experiences of the individual institution, and the feedback of the composite experiences of all institutions with the MLC hardware and software. Ergonomic issues include the speed and simplicity of the tests, the stability of the parameters being tested for the individual MLC, and the significance of deviations on the delivered dose to the target and normal tissues.

Initially, the type and frequency of tests are performed on a schedule which reflects unfamiliarity with both the delivery problems and the clinical significance of apparent irregularities. Verification of all clinical fields for patient's plans, though labor intensive, is invaluable in the early stages of IMRT to evaluate the entire planning and delivery process. Gradually this heightened guard can be relaxed as understanding and confidence builds in the inherent safety features and a more efficient QA process.

Using MSKCC as an example, where thousands of patients have been treated with IMRT since 1995 and where the current rate is about 200 treatments per day on 14 MLC-equipped machines at the center and satellite facilities, routine QA requires less than 2 hours per month per MLC or about one-fifth of the daily and monthly QA for the linac. It is relatively rare that we verify clinical dose distributions for IMRT patients, currently less than 5% of patients have dose verification. Dosimetric evaluation of the entire field of each IM beam for each patient, using standard verification tools, would have overtaxed our medical physics resources and was judged not to be necessary. Individual patient dosimetry is currently relegated to new treatment sites, new MLC, or new software. Our current approach integrates existing methods, combining periodic QA and computer verification, to provide the necessary quality assurance in a safe and efficient manner (LoSasso, Chui, and Ling 2001). However, in the years surrounding the initiation of IMRT, QA with ion chamber and/or film dosimetry was performed for each field for hundreds of patients. This QA process has obviously evolved with time; it is likely that this program will be further refined in the future.

This startup intensity should be unnecessary considering the composite experiences of such institutions with these devices. Nevertheless, individual treatment centers should expect a learning curve for understanding novel treatment planning and QA issues. The urge to implement IMRT at individual therapy centers should be tempered while these issues come into focus and are addressed at each center.

Summary

This chapter has addressed the quality assurance issues specific to IMRT delivery with an MLC, both for the SMLC and the DMLC modes. It does not address acquisition of commissioning parameters for the treatment planning system or the routine verification of treatments, which are discussed in other chapters.

One of the principal concerns for IMRT relative to conventional 3DCRT is the mechanical accuracy of the MLC. Leaf positioning and gap width are critical to the accuracy of the delivered dose in IMRT. Alignment of the MLC to the accelerator, direct and indirect measurements of leaf positions and gap widths, verification of reference static and dynamic fields, and analysis of feedback information provided by the MLC software are discussed. Procedures and results for a variety of mechanical, light field, and radiation field measurements using a feeler gauge, graph paper, film, and dosimeters have been presented.

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