Physical and dosimetric aspects of a multileaf collimation system used in the dynamic mode for implementing intensity modulated radiotherapy

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The use of a multileaf collimator in the dynamic mode to perform intensity modulated radiotherapy became a reality at our institution in 1995. Unlike treatment with static fields using a multileaf collimator, there are significant dosimetric issues which must be assessed before dynamic therapy can be implemented. We have performed a series of calculations and measurements to quantify head scatter for small fields, collimator transmission, and the transmission through rounded leaf ends. If not accounted for, these factors affect the delivered dose to the prostate by 5%–20% for a typical plan. Data obtained with ion chambers and radiographic film are presented for both 6 and 15 MV x-ray beams. The impact on the delivered dose of the mechanical accuracy of the multileaf collimator, achieved during leaf position calibration and maintained during dose delivery, is also discussed. © 1998 American Association of Physicists in Medicine. [S0094-2405(98)02510-3]

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I. INTRODUCTION

Recent advances in computer application and linac technology have provided new tools for creating and delivering optimized radiation treatments. Several groups have designed computer algorithms, based on the “inverse planning” method, which automatically generate optimized dose distributions by modulating the photon fluence in the radiation fields.1,2 In parallel, software for operating multileaf collimators (MLCs) in the dynamic mode (i.e., the leaves are in motion during radiation delivery) has been developed. (Varian Associates, Palo Alto, CA). Converting the radiation fluence profiles to the leaf motion patterns is a third software module.3 These capabilities, in combination, have been implemented in our center for the delivery of intensity modulated radiotherapy (IMRT).

MLCs are available from several manufacturers at this time. Their designs differ in the way they couple with conventional collimators and in their physical and dosimetric characteristics. MLC hardware is already familiar in many clinics, as MLCs have been used for static field therapy for several years. Several papers have discussed the dosimetry of these devices as a replacement for metal alloy blocks used for static fields.4–7 Varian MLCs (Varian Associates, Palo Alto, CA) have been used clinically at our institution to deliver static field treatments since 1992 and to deliver intensity modulated field treatments with dynamic multileaf collimation (DMLC) since 1995.8 In general, the dosimetry of radiation fields is similar whether shaped by the Varian MLC or metal alloy blocks. Specifically, factors such as geometrical accuracy, depth dose, transmission, and output are comparable.4–7 In addition, the dose distributions are similar for a multifield treatment at the boundary of the planning target volume, when electron transport and patient setup uncertainty are properly considered.7 However, based upon our experience, these studies are inadequate to predict the dosimetry of DMLC used for intensity modulated treatments. The application of MLCs to intensity modulation engenders a unique set of problems, relating to accurate and reproducible dose delivery, which need to be resolved before DMLC therapy can be successfully implemented in the clinic. Previously, we have reported the results of tests designed to examine certain mechanical aspects of DMLC and their implications on dose delivery.9 Tests examined the stability of leaf speed, the effect of acceleration and deceleration of leaf motion, the positional accuracy of the leaves, and the effect of lateral disequilibrium on dose profiles due to the varying intensity levels between adjacent leaves. Based upon the results, the mechanical aspects of the Varian MLC were judged to be accurate and reliable. Dosimetric verification of IMRT prostate fields in phantom have shown the dose accuracy achievable with this technique.10 It was also clear that further studies were needed in order to characterize fully the dosimetric aspects of DMLC.

In this study we carefully examined the accuracy and reproducibility of the leaf gaps, keeping in mind that the accuracy of the delivered dose with DMLC is directly dependent on the precision of the gap between opposed leaves. For the MLC used in our study, this depends upon the gap calibration methods of the manufacturer. Another factor which affects the gap precision is the ability of the leaves of the MLC to move to their prescribed coordinates at the prescribed times. For this reason, a proprietary software system interactively monitors the leaf motions and interrupts radiation delivery if the leaves are not at the specified positions to within a certain tolerance. Thus, we evaluate the impact of these factors on the dose delivery.

We also assessed how the MLC design influences the photon fluence produced by DMLC with the “sliding window” technique.3 In this method, because of the relatively small gaps between opposed leaves and because most re-
regions are shielded by leaves much of the time, the delivered photon fluence is quite sensitive to the transmissions through the leaves and the rounded leaf ends, the leakage between the leaves, and the head scatter, factors which are of lesser significance in the use of static fields. If not properly accounted for, these influences could result in substantial errors in dose delivered. Whereas this study involves only MLC of a specific design, the concepts and findings have broad implications for intensity modulated therapy with DMLC and may be applicable to MLC of other designs as well.

II. MATERIALS AND METHODS

A. MLC description

The Varian MLC (Mark II) is mounted below the conventional block collimators on a Varian C-Series accelerator. It consists of 26 pairs of tungsten alloy leaves, approximately 6 cm thick, each projecting a 1.0 cm leaf width at isocenter, with the midleaf position at about 51 cm from the source. The leaves, mounted within carriages, move in a rectilinear fashion, in the same direction as the lower block collimators. The range of travel of individual leaves is approximately 15 cm at isocenter relative to the carriage, and +20 to −16 cm about isocenter when combined with carriage motion. Maximum leaf speed is 3 cm per second at isocenter. For DMLC operation, only the leaf motion is permitted (with the current version of the software); the carriages remain fixed during dose delivery. The upper collimators define the superior and inferior borders, and the lower collimators are positioned 0.5 cm distal to the most retracted leaf position at each side of the field, similar to the procedure for static fields. In order to ensure a relatively constant penumbra at different positions in the beam, the ends of the leaves are rounded as shown in Fig. 1(a). The central 3 cm portion of each leaf end is circular with a radius of curvature of 8.0 cm. Beyond this, the leaf end is straight, and at an angle of 11.3° relative to the vertical axis. Leakage between adjacent leaves is minimized by an interlocking tongue and groove arrangement [Fig. 1(b)].

The rectilinear leaf motion and the rounded leaf edge, in combination, introduce a nonlinear dependence of field size on leaf position. As a leaf is retracted away from the central axis, the field-defining point on the rounded end is no longer the center of the leaf, but moves away from the source. As a leaf is extended across the central axis, the field-defining point moves toward the source. In either case, the resulting field size is slightly smaller than that predicted by the linear change in leaf position. Varian provides a generic correction file to compensate for the nonlinear dependence of field size with leaf position. In this way, the digital readout is linked to the light and radiation fields, and not the physical displacements of the leaves. Since the MLC leaves are precisely machined, the parameters in this file are common to all Varian MLCs and should not require adjustment. A second file, the Positioning Calibration File, allows the user to compensate for misalignment between the MLC and the central axis. This is performed by adjusting four parameters, the skewness of the left and right leaf banks individually, the gap between opposed leaf banks, and the centering of the leaf banks on the central axis. It is notable that the gap adjustment, which is most critical for dynamic dose delivery, can be accurately performed using a feeler gauge for a small field size (e.g., 0.1 cm). Other fields sizes are set relative to this reference field relying upon the precision of the individual leaf motor encoders. After these correction files are activated, the digital readout should agree with the projected light field.

The planning and execution of intensity modulation treatment at Memorial Sloan–Kettering Cancer Center (MSKCC) is based upon an inverse plan optimization which strives to achieve a uniform dose within the target while keeping the normal tissue doses below their specified tolerances. Dose calculations are performed using the convolution of an optimized intensity distribution with a pencil beam kernel. The “sliding window” technique, where all leaves start at one end of the field and move unidirectionally, with different speeds, to the other end, is used to deliver the intensity modulated profiles.

B. Mechanical accuracy

Given its importance in IMRT with the sliding window technique, the accuracy in leaf position and the related gap width were studied and monitored by several techniques. First, the reproducibility of the leaf position readout is routinely checked by static light field projection at isocenter, with a spatial uncertainty of about 0.25 mm. Second, a test has been devised to check the accuracy and reproducibility of leaf positions and gap widths in DMLC mode. Briefly, an intensity-modulated radiation field consisting of narrow bands (1 mm wide) of exposure spaced at 2 cm intervals is
produced on film. By this method, it is possible to visually detect errors greater than 0.2 mm in an individual leaf position or gap width.

A third test involves periodically measuring with an ion chamber the dose for a uniform field delivered dynamically with a small, 0.5-cm-wide, sweeping gap, and normalizing it with the dose from a static 10×10 cm² field defined by the jaws. Since the dose can be measured precisely and since it is very sensitive to any width change of this small gap, this test is capable of detecting less than 0.1 mm deviation. The above test, performed with a cylindrical ion chamber in air at the isocenter, was also repeated for different gantry angles (0°, 90°, 180°, and 270°) to assess the effect of gravity on the performance of the MLC in the dynamic mode. Other factors which could affect the delivered dose, such as chamber position and beam output variation with gantry angle, were accounted for by repeating the measurements with the fixed reference field defined by the jaws.

The accuracy of dose delivered during DMLC operation is dependent, in part, on a proprietary software module which controls the movement of the individual leaves during radiation delivery, according to the data in a DMLC file which specifies the leaf positions as a function of monitor units (MU). As described in our previous publication, the DMLC file is generated, based on the intensity modulated beam profiles produced by an inverse planning algorithm, by a software module designed by Spirou and Chui at MSKCC. Every 55 ms during DMLC delivery, the control software monitors the leaf positions and compares them to their prescribed positions. The beam is interrupted momentarily if any leaf position is outside a user-defined tolerance, selectable from 0.1 to 5.0 mm. In theory, this should never happen because in designing the MSKCC software which creates the DMLC file, the capability of the MLC in the dynamic mode (i.e., the maximum leaf speed), was explicitly considered. In actuality, there are occasional “out-of-tolerance interrupts” for reasons which are not fully understood, but which could be due to MLC motor fatigue and effects of leaf acceleration and deceleration. To assess the influence of leaf position tolerance on DMLC operation, relative dose measurements were made for a range of tolerance settings at the central axis. Since the chamber’s diameter spanned several leaves, the measurement averages over midleaf and interleaf transmission. For the measurements on the axis, for “closed” MLC, in order to avoid leakage between the rounded ends, the junction between the opposed leaves was placed off axis and under the jaw. For measurements at 7 cm off axis, the lower jaws were positioned asymmetrically. Measurements on the axis were made for jaw settings of 6×6, 10×10, and 14×14 cm², and at depths of d_max through 30 cm, for 6 and 15 MV x-rays; off-axis measurements were made for 10×10 cm² fields only.

Additional measurements were made with radiographic film to separately quantify midleaf and interleaf transmissions for both 6 and 15 MV x rays. For jaw settings of 10×10 cm², Kodak XV2 film was placed at 15 cm depth in a polystyrene phantom perpendicular to the central axis and irradiated to the same average optical density, ~1.0, for both the open and closed MLC fields by adjusting the MU. The film was scanned with a scanning densitometer with a 1 mm aperture. Doses were derived from densities using film calibrated at 15 cm depth for a 10×10 cm² field. The transmission profile for the leaves was obtained by dividing the transmitted dose profile by the open field dose profile after correcting for the relative MUs delivered.

### D. Head scatter

An intensity modulated (IM) field generated by the sliding-window technique is essentially a composite of many relatively small fields. Accurate dose calculations for an IM field, given the rapid change in output factor with field size for small fields, requires detailed knowledge of the “extended source” distribution. Thus, we measured in-air photon output and extracted the source distribution from the derivative of the measured output as a function of field size. The derivative is approximated with primary and scatter components. In our current model, the primary component is assumed to be a delta function, and the scatter is described by two conic distributions. The heights and base radii of the two cones were chosen so that the calculated and measured output factors agree to within 1% for field sizes up to 15×15 cm². The primary fluence at any point can then be computed by integrating the source function over the part of the source seen by the point through the aperture.

For these measurements the upper and lower jaws were set to 15 cm at the isocenter. The MLC was used to define fields from 10×10 cm² to less than 1×1 cm² with square and rectangular shapes. Two methods have been used to measure output in air. In one method, a small cylindrical ion chamber was used with a 3-mm-thick brass buildup cap with a combined outer diameter and axial length of 1.2 and 1.5 cm, respectively. For field sizes of 3 cm and less in either dimension, a film technique was used to supplement the ion chamber measurements. Kodak XV2 film in ready pack was suspended in air perpendicular to the beam central axis between a pair of 0.5-mm-thick polystyrene plates. To achieve sufficient buildup for 15 MV x rays, lead disks, 6 mm in diameter and 3 mm in thickness, were placed at the field center in contact with the film jacket, upstream and downstream from the film, with slight pressure asserted by the plates. In this configuration, the density at the center of the field was converted to dose, extending the output in-air mea-
measurements to field sizes less than 1 cm². Relative outputs were measured for 6 and 15 MV x rays.

E. Rounded leaf end transmission

MLCs with rounded leaf ends are offered by several manufacturers. Two approaches were used to assess the contribution of the radiation transmitted through the rounded leaf ends. First, photon attenuation by the leaf end was calculated based on an accurate description of the MLC leaf geometry [Fig. 1(a)] and the measured linear attenuation coefficient. The attenuation coefficient was derived from the measured average MLC transmission and the known leaf thickness for the manufacturer’s design. Whereas an individual leaf is nominally 6 cm thick, we calculated the average thickness to be only 5.65 cm, due to guides at the top and the bottom, and the tongue and groove at the sides [Fig. 1(b)]. Profiles were calculated for leaf ends positioned on the central axis and at 10 cm off axis.

A second approach involves measuring the in-phantom dose profiles of static MLC fields with gap widths of 0–10 cm, and then integrating over the measured profile. The integration should yield the sum of (a) the fluence transmitted through the MLC leaves, (b) the fluence through the gap opening, and (c) the fluence transmitted through the rounded leaf ends. The sum of (b) and (c) should be proportional to the effective gap opening, i.e., the nominal gap plus an offset. The assumption that the offset is a constant, largely independent of leaf position, is a good approximation within ±5 cm about the central axis, as our calculated results will show.

For both 6 and 15 MV x rays, Kodak XV2 film was placed at 100 cm from the source at a depth of 5 cm in a polystyrene phantom. The upper and lower jaws were set to 5.0 and 14.0 cm, respectively, in symmetric mode. The MLC gaps, symmetric about the central axis, varied from 0 cm (with opposing leaf ends in contact) to 10 cm (to give a 5 × 10 cm² field). A WP102 scanning film densitometer (Wellhofer, West Germany) was used to scan each film parallel to the leaf motion. Each film was scanned ten times, with each scan separated by 1 mm in the direction perpendicular to the leaf motion) covering the 1 cm region around the central axis, to include midleaf and interleaf contributions. After conversion to dose, all ten scans for each field were integrated over the 12 cm region, symmetric about the central axis.

Another measurement was made to obtain the MLC transmission for this experimental geometry. The MLC was set to zero field size and its center positioned 7.5 cm off the central axis (and 0.5 cm into the shadow of the lower jaw). The exposed film was scanned and integrated over the 12 cm extent about the central axis. This transmission, calculated per unit length of leaf, is then used to subtract the contribution of MLC transmission (a) from the integrated dose for each of the open fields described above. A plot of the net integral dose (b) plus (c) versus gap width, should yield the offset to the nominal gap width, when extrapolated to zero dose.

III. RESULTS

A. Mechanical accuracy

A number of characteristics are important in the use of an MLC in the dynamic mode: mechanical precision, stability, and electromechanical reliability. Routine quality assurance has been performed with the Varian MLCs at our institution for several years before the commencement of DMLC operation. These tests have indicated that the calibration of the MLC is very stable. Based upon visual examination of the light fields, the reproducibility of leaf positioning is, generally, ±0.25 mm. Furthermore, the operation of the MLCs have been very reliable, i.e., essentially trouble free operation with an average use factor for the MLCs on three machines of approximately 70%.

During the development of the DMLC program at MSKCC, a number of acceptance and QA tests were devised using the dynamic functions.9 One QA test which is routinely used consists of narrow bands of radiation produced on film by a start and stop leaf pattern in dynamic mode. The test results confirmed that the precision of leaf position is
For one of these MLCs, more sensitive measurements of the gap width, based upon the output measured with an ion chamber for a small scanned field, were made at different gantry angles. The results showed that the precision with which the gap of the Varian MLC can be set and maintained has been found to be better than 0.1 mm, independent of gantry angle. Measurements using the same field at off-axis points are consistent with the reduced off-axis leaf end transmission presented in Sec. III E.

In the test of the effect of the tolerance setting, as the tolerance was decreased from 5.0 down to 0.1 mm, the beam hold off invoked by the software becomes more frequent, indicating that the leaves are at times unable to reach their prescribed positions, and that such incidences are more likely at tighter tolerance settings. The effect of tolerance on delivered dose is shown in Fig. 2(a) for two of five fields used to deliver 1.8 Gy in our standard five field intensity modulated prostate plan.12 The maximum dose variation is less than 1% for each field, occurring for tolerances between 0.1 and 2.0 mm. Further testing revealed that this variation is not due to error in gap width, but to beam instability caused by the increase in beam hold off incidence at the tighter tolerance setting.

B. Treatment time

As shown in Fig. 2(b), the treatment time is essentially constant for tolerances greater than 2 mm. As the tolerances are reduced, the beam was increasingly held off, thereby lengthening the treatment time. For the two examples shown the treatment time more than doubles, as the tolerance is reduced from 2.0 to 0.1 mm.

C. MLC transmission

The average of midleaf transmission and interleaf leakage is shown in Figs. 3(a) and 3(b) for 6 and 15 MV x rays, respectively, normalized to the output of the open field. The transmission, over a range of clinically useful field sizes (6 × 6 to 15 × 15 cm²) and depths (d_{max} to 20 cm), is about 2.0%. The transmission increases with jaw opening for both energies; the exact relationship is not known, although increased scatter from the MLC is likely. The transmission for 6 MV x rays also increases with depth of measurement, while for 15 MV x rays it is almost constant. This may be due to beam hardening for 6 MV x rays within the MLC resulting in a more penetrating transmitted beam than the open beam. The increase in pair production within the MLC for the higher energies in the 15 MV beam may have offset the beam hardening effect, as there is little change with depth. The transmission at 7 cm off axis is essentially the same as it is on the central axis for each energy.

Transmission profiles obtained for a 10×10 cm² field at 15 cm depth in polystyrene using film are displayed in Fig. 4. The average transmissions were 2.0% and 2.1% for 6 and 15 MV x rays in good agreement with the values found with the ion chamber. The range of transmission over the central por-
tion of the MLC was from 1.7% at midleaf to 2.7% between leaves. The variation in transmission through different leaves is less than 0.1%, while interleaf values vary by as much as 0.5%. For purposes of treatment planning calculations, 2% is used for static transmission to points outside the field. However, for DMLC fields using the “sliding window” technique, each point in the field is shielded for a longer time by the leaves relative to the time it spends under the window, resulting in an effective transmission of 4%–6% of the total fluence.

D. Head scatter

Relative output measurements were made in air using an ion chamber and radiographic film to extend the measurements to fields less than 1 cm². The results are shown in Figs. 5(a) and 5(b) for fields of various sizes and shapes. Relative to that of a 10 × 10 cm² field, the output for a 3 × 3 cm² field is reduced by 2%, and for a 1 × 0.6 cm² field by 5%–6%. This reduction is small, about half that reported by others when fields were defined by the jaws for a similar machine. This difference is probably due to the fact that the Varian MLC is located below the lower jaws, and therefore, the field size dependence is less sensitive to the distributed source and head scatter.

E. Leaf end transmission

Based upon the measured average transmission through the MLC of 2.0% and the calculated effective leaf thickness of 5.65 cm, the linear attenuation coefficient is taken to be 0.692 cm⁻¹. Using this value and assuming a point source, the photon transmission profiles are calculated for the leaf edge positioned at the central axis and at 10 cm off axis (Fig. 6). The primary transmission under the leaf falls off to 50% at 0.3 mm (projected distance at isocenter), to 20% at 1.5 mm, and to 4% at 6 mm. Beyond 8 mm the transmission falls to 2%. The falloff is slightly faster when the leaf edge is off axis.

The effect of the transmission through the rounded leaf on the dose delivered by DMLC can be approximated by a 1 mm offset applied to the leaf position. The offset is represented in Fig. 6 by the rectangle, which is equal to the area under the transmission curve for the leaf end, except for the 2% MLC transmission. Thus, the added transmission due to the rounded leaf ends is equivalent to enlarging the field size of a focused collimator by 2.0 mm (1.0 mm for each opposed leaf). As an example of the significance of this, the transmission through the leaf ends will contribute 10% of the total dose delivered by a nominal 2.0 cm gap moving at a constant speed across the field, since the effective gap is 2.2 cm. Although the “offset” varies slightly with leaf position (at 10 cm off axis, it is 0.8 mm), a single value is a good approximation.

The results of film dosimetry, i.e., integrating cross-field dose profiles of static MLC fields of various widths, are
given in Fig. 7, with the relative integral dose plotted against the nominal field width. Regression analysis of the data yielded offsets of 2.0 and 1.7 mm for 15 and 6 MV, respectively, in excellent agreement with that derived from calculated transmission curves of the MLC leaf end.

IV. DISCUSSION

In the sliding window technique of DMLC application, the delivered dose is directly related to the gap between opposed leaves as they sweep across the field. To appreciate the importance of gap width accuracy in DMLC, we related error in delivered dose to error in gap width for different nominal window widths. As shown in Fig. 8, the dose error is large for small gap width and large gap error. However, as presented earlier, the MLC position precision is better than 0.1 mm. In addition, for clinical intensity modulated treatments at this time, relatively little dose is delivered with gaps <1 cm. Therefore, the dose error due to gap error is not an issue. It is noteworthy that subtle changes in individual leaf positions may be caused by gravity, drag due to friction, or simply misalignment with the central axis; however, each of these factors tends to shift both leaves in the same direction, with the result that the gap width is unchanged.

Figure 2(b) indicated that a leaf position tolerance setting of 0.1 mm could increase the treatment time of a typical prostate field from about 30 to 80 s. On the other hand, accuracy in delivered dose either on the central axis [Fig. 2(a)] or at off-axis points (data not shown) is hardly affected by the choice of tolerance setting. Therefore, for reasons of treatment time efficiency, dose accuracy, and potential hardware problems with the leaves during DMLC operation, 2 mm was chosen as the leaf position tolerance. Thus, under normal operating conditions the leaf position tolerance is nearly passive; however, it acts as a safety interlock should a leaf behave abnormally, e.g., becoming stuck during irradiation.

The implications of MLC transmission and transmission through the rounded leaf end are more serious for DMLC than for static MLC treatments. The transmissions through the leaves and the leaf ends contribute to the dose throughout the target, not just near or outside the field boundary as for static MLC fields. Furthermore, the relatively small fields associated with the “sliding window” technique of DMLC treatments tend to amplify the importance of the transmitted photons. Typically 1- to 4-cm-wide gaps are used for the treatment of the prostate, which are uncommon for static field treatments. The idealized curves in Fig. 9 indicate the magnitudes of these effects for a typical prostate treatment with 15 MV. The curves are based upon the assumption that a gap of fixed width moves with constant speed across the target. The fractional contribution of the rounded leaf end is approximately the ratio of the effective gap offset, 2 mm, to the gap width. The dose transmitted through the MLC, will typically vary from 3%–6% of the total target dose and is related to the target width (7 cm for this example) divided by the gap width. For DMLC in the treatment of prostate can-
cer, these combined transmissions will add 5%–20% of the target dose for 1- to 4-cm-wide gaps. For static fields, on the other hand, the transmissions produce only slight broadening of the penumbra and 2% primary fluence outside the field, both of which can be managed as for cerrobend blocking.

For a dynamic field, the influence of the MLC on output is much less than the curves in Fig. 5 suggest. As the leaf window moves across the target, each point in the target "sees" overlapping portions of the extended source at different times. As a result, the source distribution associated with a dynamic field as a whole is nearly the same as that for a static field with the same outer shape. It follows then, as for static fields for this MLC design, that overall head scatter for a dynamic field is essentially independent of the MLC as shown in Fig. 9; head scatter is defined mainly by the jaw setting. Actually, due to the nonuniform intensity patterns within a dynamic field, the contribution of head scatter will vary slightly within the field.

In our scheme, the head scatter and leaf transmissions are accounted for during the conversion from optimized intensity profiles to leaf motion patterns. The inclusion of MLC transmission is explained in detail in a previous publication. The effects of head scatter and leaf end transmission are handled in the following manner. First, without considering these effects, the leaf motions are generated from the "intended" intensity distribution. Then the head scatter contribution at each point, calculated by backprojecting the field opening, defined by MLC and jaws, onto the source plane, and the leaf end transmission profile are convolved with the leaf motion patterns to produce a "delivered" intensity distribution. Leaf motions are then generated from a third "working" intensity distribution, which is modified until the "delivered" and "intended" distributions agree to within 1% ($\leq$3 iterations). That the corrections are properly applied is evidenced by routine comparisons of measured and calculated dose. In one verification study, shown in Fig. 10, the five intensity modulated fields for a particular prostate patient were used to expose radiographic film parallel to the central axis in a cylindrical polystyrene phantom, 25 cm in diameter. The film densities were converted to dose by calibrating the film at 12.5 cm depth. Dose calculations were then performed for the five fields in a similar phantom geometry using the three-dimensional treatment planning system. The agreement within and around the target region is very good.

Finally, something should be said about tongue and groove effects. These effects have been evaluated for the clinical fields used for the intensity modulated prostate treatments of our patients. They result in a reduction in the dose between leaves, which tends to counteract the interleaf leakage. For all the DMLC patients treated to date, film dosimetry has been performed in a flat homogeneous phantom for each field and the measured dose distributions are compared with similarly calculated dose distributions. For the majority of the fields, the measured dose variation at the interleaf regions is not detectable. The maximum variation observed was a 5% dose reduction along a line 3 cm in length with a full width at half-maximum of 2 mm for one of five prostate fields for an intensity modulated plan. Obviously, the severity is lessened when the composite dose for all five fields is considered. In addition, a new optimization strategy has been introduced which should alleviate tongue and groove effects. This will be tested in conjunction with our inverse planning optimization algorithm to determine its benefits.

**V. SUMMARY**

Commissioning a MLC for DMLC application requires considerable effort. This paper addresses the important issues confronting the Varian MLC user. The results presented above can be divided into two categories. Those which are related to the alignments and calibration of the MLC need to be monitored carefully by the user to establish their accuracy and precision, since the DMLC application is much less tolerant of misalignment and poor calibration than conventional static field treatments. The second category comprises unavoidable factors which affect the output and which must be accurately quantified and accounted for during the plan optimization or dose delivery process. These include head scatter and transmissions associated with midleaf, interleaf, and leaf end components of the MLC.

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