A method for determining multileaf collimator transmission and scatter for dynamic intensity modulated radiotherapy

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The main purpose of this work is to demonstrate a practical means of determining the leaf transmission and scatter characteristics of a multileaf collimator (MLC) pertinent to the commissioning of dynamic intensity modulated radiotherapy, especially for the sweeping window technique. The data are necessary for the conversion of intensity distributions produced by intensity-modulated radiotherapy optimization systems into trajectories of MLC leaves for dynamic delivery. Measurements are described for two, tungsten alloy MLCs: a Mark II 80-leaf MLC on a Varian 2100C accelerator and a Millenium 120-leaf MLC on a Varian 2100EX accelerator. MLC leakage was measured by film for a series of field sizes. Measured MLC leakage was 1.68% for a 10 × 10 cm² field for both 6 and 18 MV for the 80-leaf MLC. For the 6 MV field, the 1.68% leakage consisted of 1.48% direct transmission and 0.20% leaf scatter. Direct transmission through the 80-leaf MLC, including the rounded leaf tip, was calculated analytically taking into account the detailed leaf geometry and a Monte Carlo-generated energy spectrum of the accelerator. The integrated fluence under the leaf tip was equivalent to an inward shift of 0.06 cm of a hypothetical leaf with a flat, focused tip. Monte Carlo calculations of the dose to phantom beyond a closed 80-leaf MLC showed excellent agreement with the analytic results. The transmission depends on the density of the MLC alloy, which may differ among individual MLCs. Thus, it is important to measure the transmission of any particular MLC. Calculated doses for a series of uniform fields produced by dynamic sweeping windows of various widths agree with measurements within 2%. © 2000 American Association of Physicists in Medicine. [S0094-2405(00)01810-1]

Key words: multileaf collimator, intensity modulated radiotherapy, dosimetry, Monte Carlo method

I. INTRODUCTION

The purpose of this paper is to provide an accurate, practical method for determining several of the most important dosimetric parameters of a multileaf collimator (MLC) that are needed for the clinical implementation of intensity modulated radiotherapy (IMRT).

The delivery of intensity-modulated radiotherapy beams may be accomplished using several different techniques, including physical compensators, tomotherapy, step-and-shoot technique and dynamic MLC. The MLCs are used for both dynamic and step-and-shoot modes. In the former, the beam is on while the leaves are in motion, whereas in the latter the beam is off while the leaves move. In either case, the accuracy of the dose delivered and the agreement between calculated and measured dose depend upon adequate accounting of the various effects associated with MLC characteristics. These include, for example, the rounded leaf tips, tongue-and-groove leaf design, leaf transmission, leaf scatter, and collimator scatter upstream from the MLC.

In IMRT, when intensity patterns are characterized by relatively large and closely spaced fluctuations, the average window width (the distance between leading and following MLC leaves) is small. Since the window width is smaller, for the same dose received by the tumor the treatment time is longer than for “smoother” intensity distributions. The increased treatment time results in an increase in leaf transmission, rounded leaf tip transmission, and leaf scatter contributions (“indirect contributions”) as a fraction of the total dose delivered. Knowledge of the magnitude of these effects is necessary for the conversion of intensity distributions produced by IMRT optimization systems into trajectories of MLC leaves. Leaf trajectories are also used in the final dose calculation. Since the corrections applied for these effects are approximate, the uncertainty in dose delivered increases as the average window width decreases.

This study is mainly directed at the dynamic sweeping window implementation of IMRT. The average window width for dynamic sweeping window delivery is smaller than in other techniques such as the step-and-shoot technique, due to a finer intensity grid. Since the window width is smaller, accurate accounting of the dosimetric properties of MLC leaves will have a greater effect for the sweeping window method. However, the dosimetric parameters established by our method are valid for other techniques, when needed.

Previous studies have examined some of the issues described by this paper, including leaf bank leakage, equivalent leaf shift, and the leaf tip transmission function for the 80-leaf Varian MLC. The present work differs from previous...
work in several respects, in addition to presenting data on the newer Varian 120-leaf MLC. This paper determines the total amount and the spatial distribution of the MLC leaf scatter portion of the leakage dose. The leakage consists of two components. The term direct radiation denotes the component that is transmitted through the MLC without interacting, the term leaf scatter denotes radiation exiting the MLC after interacting within it. Since both primary photons from the target and head scatter photons may or may not interact in the MLC, both will have leaf scatter and direct components. We have investigated the magnitude of MLC leaf scatter by measuring the MLC leakage as a function of field size. The experimentally determined values of leaf scatter were confirmed by analytic and Monte Carlo calculations. We have chosen to neglect the depth dependence of leakage, which has been studied previously.11 The depth dependence of leakage essentially demonstrates the effect on the accelerator beam quality (or, depth dose) of interposing a beam-modifying device (the MLC) in the beam.12,13

Sections II and III together comprise the technical aspects of the paper most directly applicable to commissioning a MLC for dynamic IMRT. In Sec. III, we illustrate our method with two examples: an 80-leaf MLC and a 120-leaf MLC.

Our method for determining the MLC characteristics requires two series of measurements. The first series consists of MLC leakage measurements as a function of field size, using film. This determines the direct transmission through the leaves and the MLC scatter as a function of field size. The second series of measurements, also using film, is of dynamic, uniform intensity fields. The purpose of these measurements is to determine the equivalent shift due to the rounded leaf tips of the Varian MLC design. This quantity has been previously measured by a static field technique and was called the leaf gap offset.11 A convenient means of approximately accounting for the rounded tip design in calculations is to regard the additional fluence through the tips as being equivalent to an effective increase in the window width between opposing leaves over the geometrical distance between leaf tips. This effective increase in the window width is equal to twice the equivalent shift of a single leaf. The equivalent shift (or leaf gap offset) in the boundary of the radiation field for the 80-leaf Varian MLC is about 0.1 cm or less per leaf.10,11 This effective widening has a negligible effect on treatments involving static fields shaped with MLCs. It must, however, be accounted for in intensity-modulated treatments delivered with a dynamic MLC, where it can be a significant fraction of the variable distance between the leaves.

Section IV presents an analytic method for calculating direct transmission of primary radiation through the MLC. Although such calculations are not always necessary for the implementation of IMRT, they are useful for determining the leaf tip fluence transmission function. Comparing the calculation with measurements shows that the measured leaf shift consists of two components: an intrinsic shift due to the rounded tip and an additional component related to mechanical tolerances. This has implications for quality assurance and output constancy.

Also presented in Sec. IV are Monte Carlo calculations of photon transport through the MLC. This Monte Carlo data illustrates the separation of the MLC-transmitted radiation dose into the direct and MLC scatter components and shows their spatial distribution. A conclusion from the analytic and Monte Carlo studies is that calculations cannot predict the MLC leakage without accurate knowledge of the MLC density. Significant differences in leakage among MLCs of the same design may arise from variations in the average density of the material composing the leaves.

II. METHODS

A. Measurements of MLC leakage versus field size

An 80-leaf multileaf collimator (Mark II MLC, Varian Medical Systems, Palo Alto, CA) mounted on a Varian Clinac 2100C linear accelerator and a 120-leaf Millenium MLC mounted on a Clinac 2100EX accelerator were used in this study. The MLCs were of tungsten-alloy composition. MLC leakage was measured with Kodak XV-2 film, at 100 cm source to axis distance and a depth of 5 cm in a water-equivalent epoxy/plastic phantom ("plastic water.") Nuclear Associates, Carle Place, NY). All films in a given experiment were from the same batch and a standard film calibration was performed.

The measured leakage through the leaves varies with the collimator-defined field size, since some portion is due to scatter from the leaves. The surface area of the MLC exposed to the beam increases with field size, hence the MLC scatter contribution increases with field size as well. In principle, the amount of scatter for a given field size can be obtained by subtracting the zero field size transmission from the measured transmission (leakage) for the field of interest. In an attempt to estimate the leaf scatter contribution, we measured the leakage for various field sizes.

The field size dependence of the leakage was determined by adjusting the jaw positions to various field sizes, and having the MLC set to block the entire open area. For field widths up to 10 cm, the field width (field dimension parallel to the direction of leaf travel) was varied, while the field length was kept at a constant 5 cm. The fixed field length of 5 cm ensured that the same four inner leaves were used to integrate the leakage. This avoids uncertainties introduced by variations in the interleaf gap and associated transmission. These measurements were carried out for both the 80-leaf and 120-leaf MLCs. For the larger fields, the width was held constant at 10 cm, while the field length was increased up to a maximum of 40 cm. In this case the width was limited in order to avoid overlap between the jaw-defined field and the line of abutment between the leaf banks. The large-field measurements, with variable length, were carried out only for the 120-leaf MLC.

The MLC-blocked field may be created by displacing the line of abutment between opposing leaf banks either to the right or to the left of central axis, or by displacing alternating leaves to the right and left. In any case the Varian MLC
design limits the maximum displacement between leaf banks to 14.5 cm. When shifting an entire bank to one side it is important that a single leaf (e.g., the one nearest the field edge) be displaced in the opposite direction from the other leaves. This prevents the leaf carriage from inadvertently being interposed in the field during leakage measurements. Having the carriage in the field causes the attenuation to increase by approximately 20%.

The leakage was determined by exposing a film to 900 monitor units (MU), with the MLC blocking the beam. Without changing the field size as defined by the collimator jaws, a second film was exposed to 25 MU, with the MLC retracted. This gave approximately the same optical density to both films. The film with MLC retracted was repeated in order to account for uncertainties due to film batch and processing variability. The central axis of the films was registered by marking the cross-hair locations or lasers on the film prior to their exposure. Using a scanning densitometer, on each film a profile along the field length, intersecting the beam central axis, was scanned. For the smaller field sizes, the average leakage of the MLC was taken as the mean value of the ratio of the two curves, over the central 4.0 cm of the curve. For larger fields, the central 80% of the field was used to determine the leakage.

For the 120-leaf MLC, ion chamber measurements were taken simultaneously with the film exposures. A 0.6 cm³ Farmer-type ion chamber was placed on central axis, at 6 cm depth, with the chamber axis perpendicular to leaf travel. The purpose of these measurements was as a check on the uncertainties associated with film-to-film variability, which are typically about 2%.

B. Equivalent leaf shift

1. Measurements on uniform intensity fields created by dynamic sweeping windows

The equivalent leaf shift has been previously measured by a least-squares fit to the integrated dose of different size static fields. Another possible technique for measuring the shift is by exposing film in phantom to adjacent half-fields with an overlap equal to the shift. We have chosen a method based on simple, dynamic uniform fields. This method has the advantage of high sensitivity. A disadvantage is the necessity of creating several dynamic MLC files, which are described next.

Dynamic MLC (DML) files are files that contain leaf positions as a function of monitor units, and are used by the MLC controller to position the MLC leaves dynamically during beam delivery. DML files were designed with the intention of creating a series of 10 × 10 cm² uniform fields. Each field was created by a sweeping window formed by the central ten pairs of opposing leaves, with fixed separations between the leaf banks ranging from 0.5 to 10 cm. This represents a typical range of window sizes for clinical fields. For a given window width, all ten leaves moved with the same constant velocity across the treatment field. Similar fields have been described by Stein. Such files are readily created using a text editor. Each of these fields was designed to deliver the equivalent of 25 MU to a 10 × 10 cm² area, assuming idealized doubly focused leaves (i.e., no leaf tip curvature) with zero leaf transmission. To determine MU settings for a given window width, it was assumed that the leaves start with the window closed on the left edge of the square field. The leading (L) leaf begins to travel at a constant velocity until the window opening is equal to the desired width. Then both L and the following (F) leaves begin to move at the same velocity until the L leaf followed by the F leaf reach the right boundary of the field. Figure 1 illustrates graphically the trajectory in terms of leaf position versus MU for the 0.3 and 10 cm window fields.

Under these conditions, dose greater than 25 MU received at the isocenter plane is due to transmission and scatter from the leaves. Further details of leaf velocity, etc., are given in Mohan et al. The analysis of dose measurements of the (nominally) uniform fields must take into consideration a “ripple” effect superimposed on the beam profile that results from intra- and interleaf variation in transmission. This effect increases with decreasing window width due to the extra beam-on time. Due to this effect, measuring the dose using an ion chamber is problematic unless an integral number of leaf cycles is subtended on the chamber. With film measurements, this problem can be easily dealt with by averaging. Film measurements for each field were taken at the isocenter plane, at 5 cm depth in water-equivalent plastic phantom. For both 80-leaf and 120-leaf MLCs, the dose to the film was taken as the average of a linear scan through the central axis perpendicular to leaf motion, encompassing eight leaves. This avoided the penumbra region of the 10 × 10 cm² field. For calibration purposes, the dose was measured at the same depth for an open, static 10 × 10 cm² field. A standard film calibration was performed to convert optical density to dose.

![Diagram of leaf position vs MU for two of the uniform fields produced by constant velocity sweeping windows. All 40 leaf pairs move with the same trajectory. The open field MU at each point is equal to the vertical distance between the lines representing the leading (L) and following (F) leaf in each pair.](image-url)
2. Best fit analysis of equivalent shift

We use the term “opening density,” $M_{\text{open}}$, at a point in the field as the portion of total “beam on time” for which the point is exposed to the source of primary radiation, unobstructed by dynamic leaves. The units of opening density are MU. During beam on, the point will also receive indirect radiation due to direct transmission through and scatter from the MLC leaves. The total of primary radiation and indirect radiation is denoted as “effective opening density,” $M_{\text{eff}}$.

For uniform fields created in the above given manner, the central axis fluence is considered to be equivalent to dose. We also assume for simplicity that an opening density of 25 MU gives a fluence/dose of 25 at the measurement point at 5.0 cm depth. For the fields described previously, with all leaves moving in tandem at constant velocity, the average dose over the central portion of the field is given by

$$M_{\text{eff}} = \left( M_{\text{open}} + \frac{2 \, \delta \, R}{60 \, \text{V}} \right) (1 - T) + MT,$$

where $M_{\text{open}}$ is the nominal opening density, $M$ is the total beam on-time in units of MU, $T$ is the average measured leakage for the field of interest, $\delta$ is the (apparent) equivalent leaf shift in cm, $R$ is the accelerator dose rate in MU/min, and $V$ is the leaf velocity in cm/s. $M_{\text{open}}$ is constant for the 10×10 cm² fields considered here. For each field represented in Fig. 1 it is equal to the vertical distance between the graph lines that correspond to each pair of leaves. It should be mentioned that $M_{\text{open}}$ is termed the “nominal” opening density because it is not corrected for that portion of the leaf shift that is due to systematic errors in leaf position (i.e., the leaf gap error, see Sec. IV). This portion of the leaf shift contributes some open field dose.

In Eq. (1), the factor of 2 in the second term accounts for the additional dose due to the outward shift of both leaves. It should be noted that a more accurate way of accounting for the fluence transmission though the leaf tip is to model the transmission as a function of position, rather than as a simple shift. The transmission function for the 80-leaf MLC is discussed in Sec. IV. The fluence at a point is then calculated by integrating the transmission function as the tip passes the point of interest. However, for the case of leaves moving at constant velocity, as considered here, if the integral of transmission through the tip region is known, the total calculated fluence on central axis will be the same whether it is calculated by an equivalent shift or using a tip transmission function.

The simple formula, Eq. (1), can be used to determine the equivalent shift in the tip position from the measurements on dynamic, uniform fields produced by constant velocity leaves, as follows. The average dose to the central portion of the field, as measured by film, is represented by $M_{\text{eff}}$ in Eq. (1). The measured values of $M_{\text{eff}}$ are substituted into Eq. (1), which is solved for the equivalent shift, $\delta$, using for $T$ in the formula the measured leakage for a 10×10 cm² field. This is carried out for each uniform field. For each uniform field, the calculated width of the sweeping window is equal to the set (nominal) window width, plus twice the equivalent shift, $\delta$.

A linear regression analysis of the calculated versus the set window width gives the average or best-fit equivalent shift, as the $y$ intercept.

III. RESULTS

A. Measurements of MLC leakage versus field size

1. 80-leaf MLC

Figure 2 shows measured MLC cross-leaf leakage profiles through the closed MLC, for a series of collimator jaw-defined fields with a common length of 5 cm and four different widths ranging from 0.5 to 10 cm, for 6 and 18 MV. Inspection of the graphs shows that the line average of leakage increases with increasing field size. This increase in effective transmission reflects the increased scatter from the MLC leaves when a greater surface area of the leaves is exposed to the beam, for the larger openings as defined by the collimator jaws. Figure 3 shows the line-averaged cross-leaf leakage as a function of field width. Two sets of measurements taken 18 months apart show excellent reproducibility. The 18 MV leakage data are similar to the 6 MV results.

The difference in transmission between a finite field size and a “zero area” field (representing the primary beam) is the component of dose due to scatter from the MLC leaves for that field size. It was not feasible to extend the experiment to field widths narrower than 0.5 cm, due to measurement uncertainties and the mechanical limitations of the accelerator jaws. Linear extrapolation to zero field width gave a
direct transmission of $1.48 \pm 0.01\%$. The leaf scatter can then be found from the graph, by subtracting the direct transmission from the apparent transmission (leakage) for the field of interest. For example, the leaf scatter of a $10 \times 10 \text{cm}^2$ field is $0.20 \pm 0.01\%$. These and other MLC dosimetric parameters are summarized in Table I. The spatial distribution of the leaf scatter will be discussed in Sec. IV.

2. 120-leaf MLC

Figure 4 shows the leakage profile for a $10 \times 40 \text{cm}^2$ field, for the 120-leaf MLC in the direction perpendicular to leaf motion. The variability of the intraleaf transmission is less regular than for the 80-leaf MLC, because of substantial differences in the leaf cross-sectional design of the two MLCs. Since Fig. 4 represents the ratio of transmitted to open beam profiles, the shape of the open beam cannot account for the pronounced rounded shape. The shape is partly due to greater leakage through the 40 central leaves with isocentric widths of $0.5 \text{ cm}$ than through the outer leaves with widths of $1.0 \text{ cm}$. Also, some of the differential attenuation across the profile is from the spatial distribution of scatter, which has its largest contribution in the center.

Figure 5 encompasses the line-averaged, cross-leaf transmission versus field size data for $6 \text{ MV}$, for the 120-leaf MLC. Figure 5(a) shows the large field data, where the field width was held constant at $10 \text{ cm}$, and the length varied from 10 to 40 cm. Figure 5(b) shows the data for small fields where, similar to the 80-leaf MLC, the field length was held constant at $5 \text{ cm}$ and the width was varied from $0.5$ to $10 \text{ cm}$. Independent measurements of the right and left leaf banks gave similar results. Extrapolation to zero field size gave a direct transmission of $1.34 \pm 0.03\%$ for the 120-leaf MLC. The estimated value of leaf scatter, averaged over right and left leaf banks, was $0.21 \pm 0.03\%$ for a $10 \times 10 \text{cm}^2$ field and $0.40 \pm 0.03\%$ for a $10 \times 40 \text{cm}^2$ field (Table I). It is notable

![Fig. 3. Measured leakage vs field size, through the closed, 80-leaf MLC for 6 MV and 18 MV. Each point represents the line-averaged transmission over the central 4 cm of the fields shown in Fig. 2. The two sets of data at 6 MV represent the same measurements, repeated after 18 months. Extrapolating to zero field width gives the approximate direct component of radiation transmission through the MLC.](image1)

![Fig. 4. Measured leakage dose at 5 cm depth in phantom through the 120-leaf MLC at 6 MV, for a $10 \times 40 \text{ cm}^2$ field. The more irregular pattern of inter- and intraleaf transmission vs the 80-leaf MLC reflects differences in leaf structural design. Note the greater leakage through the inner 20 cm of the MLC which consists of $0.5 \text{ cm}$ leaves vs the outer part of the MLC which consists of $1.0 \text{ cm}$ leaves. A fitted curve has been superimposed to show the trend of the leakage profile, averaged over inter- and intraleaf.](image2)

| Table I. Measured and calculated multileaf collimator characteristics for $6 \text{ MV}$. The MLC direct transmission was found by extrapolating the measured leakage to zero field width. MLC scatter for a specific field size was found by subtracting the direct transmission from the measured leakage for that field size. The equivalent shift, $\delta$, consists of the sum of the intrinsic tip shift and the leaf gap error (see the text). The equivalent shift was determined by a least-squares analysis of uniform, dynamic fields (Fig. 6). The leaf gap error was measured directly using a mechanical gauge. |

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<tr>
<th></th>
<th>80 leaf MLC Measurement</th>
<th>80 leaf MLC Analytic calculation$^a$</th>
<th>80 leaf MLC Monte Carlo Calculation$^b$</th>
<th>120 leaf MLC Measurement</th>
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<tbody>
<tr>
<td>MLC direct transmission</td>
<td>$1.48 \pm 0.01$</td>
<td>$1.48$</td>
<td>$1.495 \pm 0.005$</td>
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<td>(% of open field dose)</td>
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<td>MLC scatter, $10 \times 10 \text{ cm}^2$ field</td>
<td>$0.20 \pm 0.01$</td>
<td>$0.21 \pm 0.03$</td>
<td>$0.185 \pm 0.002$</td>
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<td>(% of open field dose)</td>
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<tr>
<td>MLC scatter, $10 \times 40 \text{ cm}^2$ field</td>
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<td>(% of open field dose)</td>
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<tr>
<td>Intrinsic tip shift (cm)</td>
<td>$0.06$</td>
<td>$0.06$</td>
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<tr>
<td>Leaf gap error (cm)</td>
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<td>$0.041 \pm 0.004$</td>
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<tr>
<td>Equivalent shift, $\delta$ (cm)</td>
<td>$0.114 \pm 0.004$</td>
<td>$0.114 \pm 0.004$</td>
<td>$0.114 \pm 0.004$</td>
<td>$0.088 \pm 0.003$</td>
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$^a$In this calculation the assumed MLC density needed to reproduce the measured direct transmission was 17.7 g/cm$^3$.

$^b$In this calculation the assumed MLC density needed to reproduce the measured leakage of 1.68% was 17.6 g/cm$^3$.
that the amount of leaf scatter for a $10 \times 10 \text{cm}^2$ field determined by this method was the same for both 80-leaf and 120-leaf MLCs. This is consistent with the fact that the bulk properties of the two MLC designs affecting leaf scatter are essentially the same.

B. Equivalent leaf shift

1. 80-leaf MLC

Values of equivalent leaf tip shift were determined experimentally for the 80-leaf MLC for each dynamic uniform field, as described in Sec. II. Figure 6(a) shows a regression analysis of these values. Extrapolation to zero window width yielded a value of $0.114 \pm 0.004 \text{cm}$ for the equivalent shift. Others have measured a leaf shift of $0.08 \text{cm}$ for the 80-leaf Varian MLC, using a static field technique.$^{10,11}$ In one of these studies the leaf shift was also measured by a dynamic uniform field method, with a resulting value of $0.12 \text{cm}$.\textsuperscript{10,11} This value agrees with our result.

As a check, the value of the equivalent shift as determined by linear regression was used to calculate for each uniform field the effective monitor units (or dose), $M_{\text{eff}}$, by Eq. (1).

These values of $M_{\text{eff}}$ agreed within 1% with the average dose values as measured by film.

2. 120-leaf MLC

Figure 6(b) shows a regression analysis of the equivalent leaf shift for the 120-leaf MLC. In this case the equivalent shift was determined to be $0.088 \pm 0.003 \text{cm}$. For the 120-leaf MLC, the values of $M_{\text{eff}}$ calculated by substituting this result in Eq. (1) agreed within 2% with the average dose values as measured by film.

Considering the 2% agreement with all measurements for both MLCs, we conclude that the accuracy of Eq. (1) for uniform fields is excellent even for narrow sweeping windows, where transmission and scatter is a relatively large part of the total dose. It should be noted that the apparent difference between the values of equivalent shift for the 80-leaf and 120-leaf MLCs is not determined by the shape of the tips, which is identical for the two leaf designs (although the cross-section differs, the tip curvature does not). As is discussed in Sec. IV C, this difference can be explained by differences in mechanical tolerances between the two MLCs.
IV. CALCULATIONS

A. Analytic calculation of leaf transmission for the 80 leaf MLC

One of the complications in calculating the overall transmission of the leaf bank is in accurately accounting for the complex leaf shape. The individual tungsten alloy leaves have a projected nominal width of 1 cm at isocenter (100 cm) and a physical thickness of 6.13 cm at their thickest point. The leaves of the MLC are single focused, i.e., the sides are shaped to converge at the source but each tip is rounded in the vertical direction in order to present an approximately constant penumbra at the isocenter plane. The radius of curvature at the center of the leaf profile is 8 cm. The remainder of the tip profile is defined by two lines, each being tangent to the circular arc and at an 11.3° angle to the vertical. The detailed physical shape of the tungsten leaves was obtained from drawings provided by the vendor. A simplified rendition of the leaf tip shape and cross section can be found in LoSasso, Chui, and Ling. A relatively simple analytic model was used to calculate the transmission as a function of position, through a given leaf of the 80-leaf MLC. In the following, we discuss the transmission through the leaf in directions parallel to, and perpendicular to the direction of leaf travel. An equivalent analysis was not performed for the 120-leaf MLC; such an analysis would be more difficult to carry out since there are three different leaf designs incorporated in that MLC.

In principle, the leaf transmission function can be computed analytically with the knowledge of the shape of the leaf and the energy spectrum. We used the Monte Carlo-generated energy spectrum for our treatment machine (Varian Clinac 2100C) for such computations. The photon energy fluence transmission function below a single leaf, \( T(x,y) \), in a plane 100 cm from the target, at displacement \( x \) in the direction of leaf motion, was calculated by

\[
T(x,y) = \frac{\sum_{i=1}^{N} E_i N(E_i) \exp(-\mu_w l(x,y))}{\sum_{i=1}^{N} E_i N(E_i) / H_9262},
\]

where \( E_i \) is the photon energy, \( \mu_w \) is the linear attenuation coefficient of tungsten, \( l(x,y) \) is the path length through the leaf of a ray originating at the target and passing through position \( x, y \), and \( N(E_i) \) is the energy spectrum (in terms of number of photons in the energy bin \( E_i \) and \( E_i + \delta E \)). The \( y \) coordinate designates the direction perpendicular to leaf motion, accounting for the leaf cross-sectional design. We use only the primary portion of the energy spectrum generated by Monte Carlo simulations, averaged over 10 cm diameter in a plane through the isocenter. The reason for choosing a 10-cm-diam field is that on average the IMRT beam is approximately 10×10 cm wide. The widest IMRT beam possible with Varian MLC is 14.5 cm. The scattered portion of the incident beam was omitted because it has a significantly lower energy and a large angular spread. This portion of the beam is attenuated more strongly in the MLC leaves. We also neglect beam hardening effects, which would affect the calculation by introducing the energy absorption coefficient of water at the depth of measurement into the calculation.

The 80-leaf cross-section incorporates a tongue-in-groove design, to prevent unimpeded radiation transmission through the interleaf gap. The design of the leaf bank provides for a narrow interleaf gap between adjacent leaf surfaces. The machine drawing shows that the leaf cross section can be represented by four distinct sections, denoted \( j = 1, 2, ..., 4 \), with different thicknesses in the vertical direction and fractional widths \( w_j \). The breakdown into four sections is somewhat of a simplification, but is sufficiently accurate for these purposes. By definition, the sum of the fractional widths \( w_j \) is unity. Since the projected width of a single leaf plus the interleaf gap at isocenter is 1.0 cm, the partial width of each section is \( w_j \times 1.0 \) cm. In Eq. (2) the \( x \) dependence of the path length \( l(x,y) \) is along the leaf length and the \( y \) dependence is across the leaf width. Thus \( l(x,y) \) can be replaced by \( I_j(x) \), where \( j \) refers to the \( j \)th leaf section.

The rounded leaf tip was dealt with by computing the transmission curve from the open field region to several centimeters under the leaves according to

\[
T_{av}(x) = \sum_{j=1}^{4} T_j(x) w_j,
\]

where \( T_j(x) \) is given by Eq. (2), with the subscript \( j \) replacing the \( y \) coordinate in both \( T(x,y) \) and \( l(x,y) \).

At distances greater than 1 cm from the tip the path length through the leaf of a ray originating at the source is equal to the full effective thickness of the respective section and is constant in the \( x \) direction, neglecting divergence. The effective thicknesses varied from 2.55 cm for the section including the overlap of the tongue of a leaf with the groove of the adjoining leaf, to 6.13 cm, which is the thickness through the central part of the leaf.

The nominal interleaf gap at isocenter is 0.014 cm, but the actual partial width, \( w_j \), of the interleaf gap is larger than this due to details of the tongue-in-groove geometry. The primary transmissions through the interleaf gap and the leaf center regions were calculated to be 12.6% and 0.83% respectively, a difference of a factor of 15. However, the interleaf gap component of transmission does not dominate the overall transmission due to its narrow partial width.

The effects of the intra- and interleaf sections on transmitted dose can be seen in Fig. 2. Because of the smearing of fluence caused by lateral transport of radiation in the phantom, the measured value at each point does not represent the pure transmission. For instance, the measured value would be higher than the calculated transmission in the middle of a leaf and lower than the calculated value between leaves. The interleaf transmitted fluence is 15 times greater than the intraleaf transmitted fluence, but because of the small interleaf gap and effects of lateral electron transport in phantom, the transmitted dose at the peak is only about a factor of 1.5 greater than the dose in the valley.

B. MLC density

The average transmission is sensitive to the physical density of the MLC. Since in order to make it machinable the
MLC composition is a tungsten alloy, assuming the MLC to be pure tungsten with density of 19.3 g/cm³ will give erroneous results for the calculated transmission. Tungsten material, per Mil spec T-21014D, is 90%–95% tungsten plus alloying elements and may vary in density within the range 17–18 g/cm³. The simplest way to modify Eq. (2) to account for the lower density is to retain the attenuation coefficients and multiply the path lengths $l(x,y)$ by a density scaling factor less than unity. In practice, short of dismantling the MLC the alloy density can be determined for a particular MLC by matching the calculated direct transmission to the measured direct transmission (i.e., for a hypothetical zero-area field). Thus, the density becomes the only free parameter in the calculation. To match the measured direct transmission of 1.48% required an assumed MLC physical density of 17.7 g/cm³. This is in excellent agreement with Monte Carlo calculations described in the following, which required the assumption of a density of 17.6 g/cm³ to reproduce the measured leakage dose for a 10x10 cm² field of 1.68%.

It is interesting to apply Eq. (3) to the results of LoSasso, Chui, and Ling for the Varian 80-leaf MLC. For a 6 MV, 10x10 cm² beam at 5 cm depth, a leakage dose of 1.85% was reported in that study. Considering our results it is reasonable to assume a value of leaf scatter of 0.2%, which gives a direct transmission for their MLC of 1.65%. To match this value by applying the foregoing analysis requires a MLC physical density of 17.1 g/cm³. Comparing this result with the density and transmission values for our own MLC suggests that variations in the average material density, and consequently the transmission, could be significant among individual MLCs. This finding suggests it is necessary that the transmission properties of every MLC be individually measured.

C. Tip transmission and equivalent shift

If the leaf tip were flat and focused, the fluence transmission would be unity on the open side of the leaf and equal to the full-thickness transmission on the side under the leaf. However, due to rounding, there is a distance of about 1 cm in the isocenter plane over which the transmission decreases precipitously from unity to the full thickness value of 0.0148. At present, some IMRT planning systems take the effects of leaf tip curvature into account by assuming an equivalent shift in the position of the field edge. A more accurate means of accounting for the leaf tip shape is by modeling it with a transmission function. The use of a transmission function rather than a simple equivalent shift may in some circumstances improve the accuracy of fluence calculations in the dynamic sweeping window technique. It will have less significance in the step-and-shoot technique.

The curve for the 80-leaf MLC calculated by Eq. (3) is pictured in Fig. 7(a). The leaf tip is assumed to align with the central axis. Equivalent curves to that in Fig. 7(a) were computed for displacements of 3 and 10 cm from isocenter. Currently, the curve which represents a displacement of 3 cm from isocenter is used in our clinical software to incorporate leaf transmission and rounded leaf tip effects in the computation of leaf trajectories for the 80-leaf MLC.

If the full thickness 0.0148 transmission is subtracted from the leaf transmission curve and the remaining transmission integrated, the integrated amount constitutes the additional transmission that is solely due to leaf tip curvature. This integrated amount may then be equated to a fractional transmission of unity, multiplied by a distance that represents the inward displacement (intrinsic shift) of a hypothetical flat leaf tip. The calculated intrinsic shift was found to be 0.060 cm.

The intrinsic shift of 0.06 cm is significantly less than the equivalent shift of 0.114 cm derived empirically from the sweeping window data for the 80-leaf MLC. This is because, for Varian MLCs the empirical or measured shift is comprised of two components: the intrinsic shift due to the rounded tip and an additional component related to mechanical tolerances. The latter component is termed by Varian the “leaf gap error,” and represents a small offset that is added to the nominal window width (leaf gap) in order to prevent collisions. The leaf gap error depends on software settings and thus may change, which is significant for quality assurance since the output constancy of dynamic fields depends on the constancy of leaf position settings. We have measured
the leaf gap error by terminating dynamic treatments using 0.5 and 1.0 cm moving windows. The cover was removed from the accelerator head and a precise measurement of the separation of the leaf banks was made. The average leaf gap error from two measurements was found to be 0.041 ± 0.004 cm. The combined displacement of the calculated intrinsic leaf shift plus this measured offset gave an equivalent shift per leaf of 0.10 cm. Considering mechanical tolerances and the small distances involved, this is in good agreement with the shift of 0.114 cm determined by sweeping window measurements. These values are summarized in Table I. The leaf gap error of the 120-leaf MLC was not measured, but it is smaller than that of the 80-leaf MLC because of closer mechanical tolerances. This is consistent with the 0.088 cm equivalent shift of the 120-leaf MLC being smaller than the 0.114 cm shift of the 80-leaf MLC.

D. Monte Carlo calculations for the 80-leaf MLC

Monte Carlo calculations using MCNP Version 4b2 were performed to evaluate the MLC leaf transmission and scatter for 6 MV x rays from a Varian 2100C accelerator, incident upon the MLC. This MCNP4B code has been shown to give similar results to those of the EGS4 Monte Carlo code for dose computations in phantom.20 The problem was broken up into four stages: modeling of the accelerator head, jaws, MLC, and phantom. The MLC geometry was reproduced using the manufacturer’s drawings. Further details of the Monte Carlo modeling of the MLC have been published.21 Data from Siebers et al.21 that is pertinent for interpreting and comparing to our other results is reproduced in the following.

1. Transmission through the leaf tip

In this calculation the details of the leaf cross section were neglected. For simplicity each leaf bank was modeled as a single leaf, semi-infinite in the direction perpendicular to leaf motion, of thickness equal to the central part of the leaf (6.13 cm). Therefore interleaf leakage was not accounted for in this calculation, resulting in decreased transmission. The MLC was modeled to produce a 10-cm-wide opening between the opposing leaf banks and the jaws were set to produce a 40×40 cm² field size at isocenter. The rounded leaf profile near the end of the leaf was modeled using the drawings referred to previously. In this simulation the transmission of primary fluence through the leaf tip was tallied at the isocenter plane, in order to compare with the analytic calculation. Scattered and non scattered events were separated by location of last interaction.

In Fig. 7(b) the data points represent the Monte Carlo results for 6 MV, averaged over the two penumbrae regions produced by the leaf tips. Also shown in Fig. 7(b) is an analytic calculation of the leaf tip transmission curve through the thickest section of the leaf. In both Monte Carlo and analytic calculations the projection of the leaf tip was 5.0 cm lateral to the central axis. The analytic calculation used the energy spectrum corresponding to primary radiation only, within the central 5 cm radius of the beam, with this spectrum averaged into energy bins. The Monte Carlo calculation used the same energy spectrum, but each particle was tracked separately. Even with these approximations, the analytic calculation shows excellent agreement with the Monte Carlo results, the value of integral transmission under the leaf differing only 3% from the average Monte Carlo value in that region. The analytic calculation was performed with no free parameters or other modifications to published attenuation coefficients. This agreement to the physically reliable Monte Carlo calculations is strong evidence of the validity of the analytic method.

It should be noted that in both analytic and Monte Carlo calculations the same erroneous density value of 19.3 g/cm³ was assumed in these early calculations. This means that although the two methods agree, in both cases the calculated transmission is lower than the actual transmission through the center of the leaf. The correct density to be used in calculations can only be determined by comparison with transmission measurements, as discussed previously.

2. Transmission and scatter of a 10×10 cm² field through the closed MLC

The above-mentioned calculation of fluence transmission through the leaf tips considered an open MLC field and a simple model of the MLC itself. For the calculation of transmission through the closed MLC leaf bank, a more sophisticated model was developed that incorporated the full geometry of the MLC leaves, including tongue-in-groove. Also, in this case dose in phantom rather than energy fluence was tallied, making possible a direct comparison with measurements. Sufficient particles were run to keep statistical uncertainties below 1%. The MLC composition by weight was assumed to be 90% tungsten, 6% nickel, 2% iron, and 2% copper. The calculation was iterated using different values of alloy density until the calculated leakage dose at isocenter matched that of measurements. The required density to reproduce the measurements was 17.6 g/cm³.

Figure 8 shows a histogram of the dose at 5.0 cm depth in phantom due to different portions of the 10×10 cm², 6 MV beam, after penetrating the closed MLC. Each portion is reported as a fraction of the open field dose. The three curves
represent (1) the total of all photons that penetrated the MLC, (2) photons originating from the target that interacted in the MLC ("MLC scatter"), and (3) head scatter photons that are transmitted through the MLC. The Monte Carlo calculation gave a leakage of 1.68 ± 0.006% for a 10 × 10 cm² field of which 0.185 ± 0.002% was leaf scatter, in excellent agreement with experiment (see Sec. III and Table I). The MLC scatter contributes 11% of the MLC leakage dose, or 0.185% of the open field dose. Figure 8 shows that the spatial distribution of MLC scatter is relatively constant over the 10 cm field.

This level of MLC leaf scatter is insignificant for static fields, but it becomes significant in dynamic IMRT treatments with large field sizes and low efficiencies. Leaf scatter increases with field size due to the increased MLC surface area exposed to the beam. For dynamic IMRT, efficiency refers to the ratio of the monitor units for a static field to the total monitor units for a dynamic field that delivers the same dose. Low efficiency denotes fields with a long beam-on time relative to dose delivered, which occurs for fields with strongly fluctuating intensity patterns. The contribution of MLC transmission and scatter increases as efficiency decreases. For example, for the uniform field created by a 0.5-cm-wide sweeping window, leakage radiation contributes 36% of the dose at isocenter. This was calculated using Eq. (1). In Eq. (1) the leaf gap error component of the equivalent shift contributes to the open field dose, since the actual window width is increased over the set window width by an amount equal to the leaf gap error. The remainder of the equivalent shift, the intrinsic part, contributes to the leakage dose.

V. SUMMARY AND CONCLUSIONS

In this paper we have presented detailed measurements of leakage radiation through Varian multileaf collimators. Experimentally derived values of direct transmission and MLC scatter were confirmed by analytic and Monte Carlo calculations. Leaf scatter photons are diffusely distributed, their magnitude varying slowly as a function of position in the field. The measured MLC scatter is small: only 0.20% for a 10 × 10 cm² field, or approximately 12% of the total leakage for that field size. The amount of MLC scatter probably does not vary much among individual Varian MLCs. The small magnitude and relatively weak spatial variation of the leaf scatter in the Monte Carlo results, suggests that leaf scatter corrections in IMRT calculations may be simply implemented as an offset.

Scatter from leaves contributes dose even when a point is within the open window, whereas radiation directly transmitted through leaves without interaction contributes only when the point is in the shadow of the MLC. Analytic calculations showed that interleaf transmission of energy fluence was greater than intraleaf transmission by a factor of 15. However, because of the lateral transport of radiation the measured dose under the MLC varied by only up to a factor of 1.5. The direct transmission is sensitive to the average density of the MLC. The alloy density may vary among individual MLCs, thus it is important to measure the transmission of any particular MLC.

We have demonstrated a sensitive and accurate means of measuring the equivalent shift due to rounded leaf tips, based on dynamic uniform fields. When leaves move at constant velocity, a simple formula can predict the dose from these fields within 2% accuracy. Since part of the equivalent shift may vary based on software setting, regular measurements of dynamic window width constancy are a necessary part of quality assurance. In this study we have not addressed the issue of the relative accuracy for clinical IMRT of using an equivalent shift versus a full transmission function for the rounded leaf tip. The capability of using such data may or may not be available in a particular IMRT system.

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