I. INTRODUCTION

Multileaf collimators (MLC) are widely used in radiotherapy and have a tremendous impact on the efficiency of care. Although their initial use was primarily as a device to replace cerrobend blocks, a more recent application of the MLC is to behave as a virtual compensator, allowing for the modulation of photon fluence maps in either a static or dynamic delivery mode. This is the key role of the MLC for the delivery of intensity modulated radiation therapy (IMRT). For conventional radiotherapy, Thompson et al. presented the routine daily quality assurance (QA) check of geometric parameters on computer-controlled accelerators and Klein et al. described the performance characteristics and QA tests to be performed during the commissioning of a MLC. However, MLC quality assurance for IMRT requires further study.

IMRT requires extensive knowledge of MLC leaf positioning accuracy, precision, and long-term reproducibility due to the extremely small field sizes (e.g., 1×1 cm) and the greater amount of MLC motion (at least one order of magnitude above conventional radiotherapy). When accurate leaf positioning is lost, significant dose delivery errors can occur. LoSasso et al. showed for the dynamic delivery mode MLC leaf position errors of 1 mm in a prescribed 1 cm sliding window produced dosimetric errors greater than 10%. Low et al. reported field abutment measurements produced dose errors of 16.7±0.7%/mm for 6 MV photon beams.

The recent publication of AAPM Task group 50 provides an excellent review of MLC design and QA issues. The TG-50 report does provide a test for determining errors in leaf positioning that is extremely sensitive to relative position errors, but it does not quantify the amount of error, identify the offending leaf, or demonstrate the absolute position of the leaves with respect to the central axis of the collimator. The objective of this work was to develop a technique to efficiently measure the absolute position of each MLC leaf, over the range of leaf positions utilized in IMRT, based on dosimetric information. Additionally, this technique should automate the MLC IMRT QA process to allow measurement and assessment of large amounts of data efficiently. This technique is used to determine the MLC leaf positioning accuracy, reproducibility of leaf positioning immediately following calibration, temporal stability/longevity of leaf calibration, and dependence of leaf position due to direction of travel.

II. METHODS

A. Experimental setup/design

Exposures were made with a Siemens (Siemens Medical Systems, Concord, CA) Primart linear accelerator that utilizes a MLC designed with 29 pairs of leaves: two leaves that project to 6.5 cm at 100 cm from the source (leaves 1 and 29) and twenty-seven leaves projecting to 1 cm width (leaves 2–28). Das et al. provided a complete description of the
-and the right-hand side from the X2 jaw. Delineate the left-hand side of each 1 cm travel position. As shown in Fig. 1, the leaves of the X1 jaw from 10.5 cm in the open position to 9.5 cm in the over-

This image, shown in the beams-eye view, steps the leaves marker tray present. The resultant pattern is shown in Fig. 1. Three strips formed by all leaves with a 1 cm gap between opposed leaf-pairs. The strips are separated by 2 cm and move parallel to the leaves, and with approximately 1% interleaf leakage and an exposure series delivered to each film of 580 MU, a dose of nearly 15% of the maximum is seen along the leakage lines.

An example of the two vertical dose profiles is shown in Fig. 2. Figure 2(a) represents two dose profiles, one through each leaf bank, separated by approximately 24 cm. In Fig. 2(a) the digitized image is rotated with respect to the collimator central axis of rotation, as seen by the difference in vertical distance of the leakage peaks from the top of the film. Conceptually, no rotation of the image would show the two dose profiles in phase with one another. An in-house computer code was written to identify the Cartesian coordinates of each interleaf leakage peak and from the two points identified along each common leakage line, from which the angle of the leakage line with respect to the horizontal axis of the digital image is calculated. The angle of rotation within the digital image data is calculated for all 26 leakage lines created between the 27 leaf pairs, and the average value is then removed from the digital image within the film dosimetry software. Figure 2(b) shows a second set of dose profiles, one through each leaf bank, for the digital image following rotational correction. The measured rotational error was never more than 2.2° for all films analyzed, and the standard deviation of the rotation calculated was 0.07°.

2. Translation of the digital image

The origin on the digital image was selected to coincide with the central axis (CAX) of the beam. The central marker of the radio-opaque marker tray was set to coincide with the design of this double-focused multileaf collimator. This double-focused leaf design contains a flat leaf end (not rounded) that tracks the divergence of the beam while the leaf moves in a pendulous motion (not linear).

Radiographic images were acquired to dosimetrically determine the position of each leaf using Kodak XV Ready-Pack film (Eastman Kodak Company, Rochester, NY) placed at 5 cm depth in a polystyrene phantom and perpendicular to the central axis of the beam. A single radiographic film was exposed to two sets of exposures: the first creates a dose pattern utilizing the MLC leaves, the second allows determination of the central axis of the collimator of rotation. The first set of exposures are created using 6 MV x rays for eleven static exposures of 50 MU: each is given by a strip field of 1 cm×28 cm strips formed by all leaves with a 1 cm gap between opposed leaf-pairs. The strips are separated by 2 cm center to center in the X-jaw direction. Without moving the film or phantom an additional exposure of 30 MU is delivered: an open field 23×28 cm with a radio-opaque marker tray present. The resultant pattern is shown in Fig. 1. This image, shown in the beams-eye view, steps the leaves from 10.5 cm in the open position to 9.5 cm in the overtravel position. As shown in Fig. 1, the leaves of the X1 jaw delineate the left-hand side of each 1 cm×28 cm exposure, and the right-hand side from the X2 jaw.

B. Digital data manipulation

Each film was digitized with 0.17 mm resolution using commercial film dosimetry system [Vidar 12-plus digitizer with Radiological Imaging Technology RIT 113 Film Dosimetry Software (Colorado Springs, CO)] and converted to a dose. The digital images were manipulated to reduce noise (3×3 median filter) and remove translation and rotation of the film data with respect to the collimator coordinate system, as described in the following.

1. Rotation of the digital image

With respect to the collimator axis of rotation, there exists several potential opportunities for introducing rotation: the phantom, the Ready-Pack, the film within the Ready-Pack, the film while digitized, etc. The orientation of the digitized image with respect to the collimator axis of rotation is determined by measuring the interleaf leakage along each edge of the film. This is accomplished by manipulation of the digitized image, as shown in Fig. 1. Two dose profiles in the direction perpendicular to the direction of leaf travel are acquired, one along the outer edge of each side of the film. This is seen as the vertical lines along the outer edge of the image in Fig. 1. Since the greatest width of the two exposures is 23 cm and the film is 25.4 cm wide, there is a strip along the outer edge of the film that is exposed exclusively to interleaf leakage. This leakage is measurable because the MLC design used in this study does not have a set of diaphragms that move parallel to the leaves, and with approximately 1% interleaf leakage and an exposure series delivered to each film of 580 MU, a dose of nearly 15% of the maximum is seen along the leakage lines.

Translation of the digital image

The origin on the digital image was selected to coincide with the central axis (CAX) of the beam. The central marker of the radio-opaque marker tray was set to coincide with the...
CAX of the beam (described in Sec. II C), so the center of mass of the central marker of this marker was specified as the origin of the digital image. The film dosimetry software automated the translation of the data set to the user’s specified origin.

### 3. Dosimetric determination of leaf position

With the rotation removed from the image and the origin (CAX) of the beam defined, the horizontal dose profile along each leaf pair was acquired. This process is easily automated with the knowledge of the location of the center of the second leaf pair (13.5 cm from the origin) and the 1 cm widths of the leaves. The film dosimetry software allows the user to extract up to 15 dose profiles simultaneously, so measurements for leaf pairs 2–15 and then 15–28 were smoothed (5 point) and extracted. The x value of the extracted data represents the x coordinate of each profile with respect to our newly defined origin, and the y value is the absolute dose measured across the horizontal dose profile. A composite of these dose profiles is shown in Fig. 3. The left-hand side of each peak of dose is caused by the position of the X1 bank leaf and the right-hand side is caused by the position of the X2 bank leaf.

The dosimetrically determined position of each leaf was determined from an in-house code. Consider a function \( f(x) \) to represent the value of dose measured at point \( x \) along the dose profile. To find the maximum and minimum values of each peak, the code finds a point \( x_i \) where the sum of the values of dose for \( N \) points is nearly equivalent in either direction,

\[
\sum_{h=-1}^{N} f(x_{i+h}) = \sum_{h=-1}^{N} f(x_{i-h}) \leq \epsilon,
\]

where \( \epsilon \) is a user’s specified residual. Because the profiles are slightly asymmetric, the value of \( \epsilon \) is nonzero even at the peak or valley. As the resolution of the digitized image is 0.176 mm/pixel, a value of \( N = 10 \) pixels provides sufficient reduction of noise without extending beyond 2 mm from pixel \( x_i \). Whether the point \( x_i \) is located at a peak or valley is determined by the sign of Eq. (1) as one progressed from pixel \( x_{i-1} \) to pixel \( x_i \). If the difference was positive, the point \( x_{i-1} \) is on the left-hand side of a peak and the satisfaction of Eq. (1) yields a maximum; if negative, then Eq. (1) locates a minimum.

Now for each peak we can dosimetrically determine the edge of the leaf by finding the 50% value of the dose profile within that peak. But because the film has been double exposed (see Sec. II A) the background dose must be removed. Consider the dose profile through the \( j \)th peak; there are five points of interest moving from left to right: the minimum \( (x_{L,\text{min}}^j) \) and 50% dose point \( (x_{L,50}^j) \) on the left-hand side of the profile, the maximum dose point \( (x_{\text{max}}^j) \), and the 50%

![Fig. 2. Vertical dose profiles for calculating rotation.](image1)

![Fig. 3. Horizontal dose profiles. Data are exported from RIT 113 and an in-house code analyzes each peak to determine the spatial location where the dose is 50% of the peak value (after background subtraction). Each peak has two sets of these values, one from the X1 bank leaf (left of the peak) and one from the X2 bank leaf (right of the peak).](image2)
\( x_{R-50} \) and minimum \( x_{R-min} \) dose points on the right-hand side. The dosimetrically determined edge of the leaf is then calculated as

\[
x_{L-50} = \frac{x_{max} - x_{L-min}}{2}
\]

and

\[
x_{R-50} = \frac{x_{max} - x_{R-min}}{2}.
\]

All points \( x_j \) contain a baseline dose from the first exposure and the tails of the dose from the other 10 1×28 cm exposures, which is assumed to be equivalent for all five points described above for each \( j \)th peak, and removed in Eqs. (2) and (3). The dosimetrically determined position of all 54 leaves of the MLC was measured for each of the 11 prescribed positions: 10.5, 8.5, 6.5, 4.5, 2.5, 0.5 cm (the “open” direction) and −1.5, −3.5, −5.5, −7.5, and −9.5 cm (in the overtravel or “closed” direction).

C. MLC performance studies

The above-described were performed weekly to study the performance of the MLC. The resultant images were analyzed to determine the MLC leaf positioning accuracy, reproducibility of leaf positioning immediately following calibration, temporal stability/longevity of leaf calibration, and dependence of leaf position due to direction of travel.

In order to determine the absolute position of a leaf the origin, defined as the central axis of the beam, had to be determined. The central axis of the beam was demonstrated to coincide with the central marker of the radio-opaque marker tray using a double exposure delivered to a separate film. The first exposure of 30 MU was delivered to an 11×11 cm field with the collimator set to 0°, the second exposure of 30 MU was for a 30×30 cm field with the collimator set to 180°. In addition to the field size and collimator angle change, the second exposure was performed with an 11×11 cm lead block (5 cm thick) placed over the center of the field. The resultant image is shown in Fig. 4. When the radio-opaque markers of the inner and outer image are collinear the radio-opaque marker tray is properly positioned. Although this is easily seen visually, the center of mass of each marker can be measured and compared to demonstrate alignment. The accuracy of this CAX determination technique is one pixel, i.e., 0.176 mm.

The initial MLC leaf position measurements followed the calibration of the MLC by the field service engineer. Currently the field service engineer calibrates the Siemens MLC manually, the most common technique utilizes the light field projected on a piece of graph paper placed on the treatment couch in the isocentric plane. The light field is a reasonable surrogate for the radiation field due to the double-focus design. This design characteristic also includes a nonlinear (pendulous) travel-motion of the leaves, requiring four motor/potentiometer calibration points: 20, 10, 0, and −10 cm. All leaves of each leaf bank are driven to the calibration point and the actual position is captured, becoming the calibration position for the leaf.

Immediately following the field service engineer’s calibration of the MLC the positions of each leaf were measured. The reproducibility of leaf positioning immediately following calibration was assessed by repeating the QA exposure series five separate times, with all leaves moving from left to right in the beams-eye view. A second set of 5 QA exposure series was performed with leaves moving in the opposite direction to allow assessment of the dependence of travel direction. Temporal stability/longevity of leaf calibration was determined by repeating the QA exposure series approximately every 10 days for a 90 day period. The overall accuracy of this technique is 0.35 mm.

III. RESULTS

Dosimetric analyses of the leaf positions were performed for 594 locations on each film (27 1 cm leaves per bank, 2 banks, 11 prescribed locations). The entire process, from initial phantom setup to the final analysis, was completed in approximately 30 min. The steps and time required to perform them are listed in Table I. This process was followed to assess MLC leaf positioning accuracy, reproducibility of leaf positioning immediately following calibration, temporal stability/longevity of leaf calibration, and dependence of leaf position due to direction of travel. The results of each test are provided in the following.
**A. MLC leaf positioning accuracy**

Figure 5 shows the absolute positioning accuracy of MLC leaves immediately following calibration by the field service engineer, who used the light field to position the leaves as described earlier. Figure 5(a) shows the measured leaf position of the 27 leaves of 1 cm width within bank X1 (X1.2 through X1.28). The prescribed position for all leaves of the X1 bank was 10.5 cm in the “open” direction. All 27 leaves were within 1.2 mm of the prescribed position, however the data demonstrate a clear trend. This effect can be created by a slight rotation of the MLC calibration tool (in our case, the graph paper) during the calibration procedure. If we assume the rotation is centered on the CAX, the results shown here can be caused by 0.4° rotation: a 1 mm leaf position error is produced 10.5 cm away from midline for the 1 cm leaf that resides 13 cm from the central leaf. Figures 5(b)–5(d) show the absolute leaf position error of the X1 leaf bank, calculated by subtracting the measured from the prescribed leaf position. These results are for all 11 prescribed leaf positions; where each line represents a different leaf: Fig. 5(b) shows leaves 2–10, Fig. 5(c) shows leaves 11–19, and Fig. 5(d) shows leaves 20–28. All measured values are within 1.5 mm of the prescribed leaf positions. At 10.5 cm the results are evenly distributed around zero, where once again we can see the rotational trend in the data by observing the systematic error in the leaf positions from leaf X1.2 to X1.28 for a given programmed leaf position. An additional characteristic of these data is that each leaf demonstrates a constant error from 10.5 to 0.5 cm, and then positive shifts in the error as the leaves continue to −9.5 cm. The shape of the error results are likely due to the calibration procedure, which contains calibration points at three points (−10, 0, and 10 cm) through this region. The fourth MLC leaf calibration point (+20 cm) is outside our region of interest.

**B. Reproducibility of leaf positioning**

Figure 6 shows the reproducibility of leaf position for all leaves immediately following calibration by the field service engineer. The QA film test pattern was created 5 times with the leaves traveling from the X1 bank toward the X2 bank, and the mean value of measured position of each leaf was calculated. The randomness/reproducibility of leaf positioning was expressed as a frequency distribution shown in Fig. 6. Wide variation of any measurement from its mean is indicative of poor reproducibility. MLC leaf positioning was

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**Table I. MLC leaf position determination process.**

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Time required to perform (min)</th>
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<tbody>
<tr>
<td>Verification of radio-opaque marker tray positioning</td>
<td>5</td>
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<tr>
<td>Film exposure to create test pattern</td>
<td>5</td>
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<tr>
<td>Extracting dose profiles from digitized film</td>
<td>5</td>
</tr>
<tr>
<td>Film data corrections</td>
<td>5</td>
</tr>
<tr>
<td>Data analysis and documentation</td>
<td>10</td>
</tr>
</tbody>
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Fig. 5. The absolute positioning accuracy of MLC leaves immediately following calibration. (a) The prescribed leaf position was 10.5 cm in the “open” direction for all 27 leaves within bank X1. All 27 leaves were within 1.2 mm of the prescribed position, but the slope of the data implies a slight rotation of the MLC calibration tool during calibration caused by 0.4° rotation. (b)–(d) Absolute leaf position error of the X1 leaf bank, calculated by subtracting the measured from the prescribed leaf position: (b) leaves 2–10, (c) leaves 11–19, and (d) leaves 20–28. Results are for all eleven prescribed leaf positions; where each line represents a different leaf.
found to be reproducible to within 0.3 mm precision for 95% of the measurements immediately following calibration.

C. Temporal stability/longevity of leaf calibration

To characterize the temporal stability of the MLC calibration, the accuracy of leaf calibration was measured 9 separate times over a 90-day period. Figure 7(a) shows the results of a single leaf, X2.28, where the spatial difference from desired leaf position is shown for multiple points in time. Each of the eleven lines represent a specific desired leaf position, and demonstrates that leaf X2.28 held its initial calibration position over the course of measurements at all eleven positions. The largest variations are approximately 0.5 mm and appear to be a systematic result around day 21, as they are resolved in subsequent measurements. Figure 7(b) shows the results for all leaves of the X1 and X2 leaf banks. Here the longevity of leaf calibration was expressed as the difference between the measured leaf position at any point in time and the measured position at the time of initial calibration. Approximately 95% of the measurements were within 0.6 mm of the initial calibration position for 9 separate measurements over a 90-day period. As expected, the results for the two leaf banks are similar and symmetric, but unexpectedly we see a systematic shift in the positive direction. This systematic error was likely introduced in the determination of the initial calibration positions.

With the knowledge of the longevity of the leaf position calibration, the compiled results over a 90-day period were analyzed to determine the MLC leaf calibration accuracy. Analysis of the difference of the leaf positions from their desired position (as described in Sec. III A), provided in Fig. 7(c), reveals 86.6% of the position measurements were within 1.0 mm and 98.2% were within 1.6 mm. All but three measurement points were within the manufacturer’s specification of 2 mm for this 90-day period. Once again we see a systematic shift in the data sets, but here the shift is in the opposite direction for each leaf bank. This error could be introduced due to the subjectivity of determining the location of the field edge based on the light field during the initial calibration.

D. Dependence of leaf position due to direction of travel

Figure 8 shows the reproducibility of leaf position for all leaves for opposing directions of leaf travel. The QA film test
pattern was created 5 times with the leaves traveling from the X1 bank toward the X2 bank—films 1–5, and then a second set of 5 QA exposure series with leaves moving from the X2 bank toward the X1 bank—films 6–10. The mean value of measured position of each leaf was calculated. The results show reproducibility of 0.25 mm for a single direction of leaf motion, and 0.5 mm when introducing hysteresis.

E. Recalibration using the MLC QA technique

The reproducibility can be exploited to allow a superior calibration procedure to the present system offered by the manufacturer. To this end, we utilized the measured leaf position information to perform a new calibration of the MLC. Since the MLC leaf positions are repeatable, we performed a MLC leaf positioning study and determine the position error for each leaf, then used that information to place the leaves. An additional correction of 0.3 mm was required to account for the nonlinear addition of scatter from each exposure into each dose profile. We then captured the leaf positions and calibrated. The results of this approach are shown in Fig. 9. Figure 9(a) shows the measured position of all 1 cm leaves on the leaf X1 bank for a prescribed position of 10.5 cm. The recalibration procedure has removed the trend in measured leaf position error and all values are now within 0.5 mm. The results for all calibration positions for all leaves are shown in Fig. 9(b). Following this technique 91.5% of all leaves/positions were within 0.5 mm, with a mean error of 0.1 mm and a maximum error less than 1.0 mm. This is a significant improvement from the results shown in Fig. 5(b).

IV. CONCLUSIONS

The tool presented here has become a critical component of our IMRT toolbox, as it allows the absolute position of each MLC leaf to be determined dosimetrically with efficiency and accuracy. Data acquisition can be accomplished in 5 min using auto-field sequencing and analysis requires approximately 30 min, providing a dosimetrically determined position of each leaf for 11 different locations. Furthermore, by superimposing the radio-opaque marker tray in every image, the absolute location of each leaf can be determined with respect to the beam’s central axis.

Our results do show a measurable variation in the position of the leaves. The initial calibration performed by the field service engineer set most leaves within 1 mm (87%) and nearly all leaves within 1.6 mm (98%). The positioning of the MLC leaves studied here was reproducible (0.3 mm precision w/95% confidence), both immediately following calibration and within 0.6 mm (95% confidence) for 90 days postcalibration. The data demonstrate the double-focus MLC system is capable of maintaining leaf position calibration for a three-month period, allowing monthly verification of MLC leaf positioning for IMRT applications. Furthermore, the data show reproducibility of leaf position is acceptable regardless of leaf travel direction (with 84% of leaves within 0.2 mm and 99% within 0.4 mm).

Because the leaf positioning of the MLC proved to be reproducible, the measured positional errors of the leaves could be used to recalibrate the MLC. Following this technique 91.5% of all leaves/positions were within 0.5 mm,
with a mean error of 0.1 mm and a maximum error less than 1.0 mm. This is similar to the values published by Graves et al.\textsuperscript{18} for a rounded leaf-end system, after using the manufacturer’s specified correction table, resulting in errors that exceed 1 mm. However, following a correction process developed at their institution they reduce the error to within 0.5 mm. The single-focus MLC systems require a correction table to account for differences between the light and radiation field, but Graves et al.\textsuperscript{18} and our work here show an additional correction may be necessary to account for difficulties in the initial calibration of any multileaf collimator. Thus, the correction table required would be unique for each double focus MLC system and would require modification after each new calibration.

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\textsuperscript{17}J. E. Bayouth and S. M. Morrill, “MLC dosimetric characteristics for small field and IMRT applications,” Med. Phys. (submitted).
