Calibration and quality assurance for rounded leaf-end MLC systems

Maria N. Graves,[a)] Antoinette V. Thompson,[b)] Mary K. Martel, Daniel L. McShan, and Benedick A. Fraass
Department of Radiation Oncology, University of Michigan Medical Center, Ann Arbor, Michigan 48109-0010

(Received 5 March 2001; accepted for publication 28 August 2001)

Multileaf collimator (MLC) systems are available on most commercial linear accelerators, and many of these MLC systems utilize a design with rounded leaf ends and linear motion of the leaves. In this kind of system, the agreement between the digital MLC position readouts and the light field or radiation field edges must be achieved with software, since the leaves do not move in a focused motion like that used for most collimator jaw systems. In this work we address a number of the calibration and quality assurance issues associated with the acceptance, commissioning, and routine clinical use of this type of MLC system. These issues are particularly important for MLCs used for various types of intensity modulated radiation therapy (IMRT) and small, conformal fields. For rounded leaf end MLCs, it is generally not possible to make both the light and radiation field edges agree with the digital readout, so differences between the two kinds of calibrations are illustrated in this work using one vendor's MLC system. It is increasingly critical that the MLC leaf calibration be very consistent with the radiation field edges, so in this work a methodology for performing accurate radiation field size calibration is discussed. A system external to the vendor's MLC control system is used to correct or handle limitations in the MLC control system. When such a system of corrections is utilized, it is found that the MLC radiation field size can be defined with an accuracy of approximately 0.3 mm, much more accurate than most vendor's specifications for MLC accuracy. Quality assurance testing for such a calibration correction system is also demonstrated. [DOI: 10.1118/1.1413517]

Key words: Multileaf collimator, calibration, quality assurance, intensity modulated radiation therapy (IMRT)

INTRODUCTION

Many multileaf collimator systems (MLCs) are designed such that the leaves of the MLC move linearly, perpendicular to the axis of the beam. This design is not only mechanically simpler than a double-focused design, which typically requires movements on an arc, but also conserves space in the collimator head. If a flat divergent leaf edge were used to match the divergent beam edge at a particular distance from the central axis of the field, then the linear motion of the leaves would cause a field size dependent penumbra. To offset this undesirable result, leaves with rounded ends are often used to keep the radiation penumbra relatively constant over the range of leaf travel. The general behavior of curved leaf end MLC systems has been described by Galvin *et al.*,[1] Jordan *et al.*,[2] and Klein *et al.*[3,4] These design considerations result in differences between the MLC leaf readouts and the projected light field edge locations, as has been demonstrated by Galvin *et al.*[5] The "effective widening of the MLC leaf openings" has been discussed for DMLC delivery by Wang, *et al.*,[6] curved "leaf end transmission offset" has been described by LoSasso *et al.*,[7] and the "set leaf gap" has been characterized for IMRT by Low *et al.*[8] These authors describe a difference between the light field size (or the leaf position readout) and radiation field size of varying severity ranging from 0.5 to 1.2 mm per side. As illustrated in Fig. 1, the geometry of the linear MLC motion and rounded leaf ends causes the projected light field, the radiation field, and the absolute linear position of the leaves to be different from each other. Thus, coincidence between the digital readouts for the MLC and the radiation field or light field must be achieved by using a calibration table in the control system software.

Because the coincidence between the leaf readout system and the field size cannot be taken for granted with this nondivergent geometry that is found in this curved leaf–linear motion type of collimator system, the MLC readout system must be verified during system acceptance, and during routine quality assurance checks. Corrections may be necessary if the calibration and readout systems are not adequately precise. For example, radiation field measurements of leaf position that were made early in the commissioning of one accelerator/MLC system indicated that the leaf positions were more than 1 mm wider than the readout showed. This was the result from the use of the standard light-field-based calibration procedure recommended by the vendor. The subsequent inability to use the vendor's calibration system to resolve the discrepancy between the measured radiation field size and the leaf position readout led to the work described in this paper.

In this work, we illustrate some of the specific issues that should be considered if one attempts to make precise use of the radiation and/or light fields associated with curved leaf-end MLC systems. Although these differences between ra-

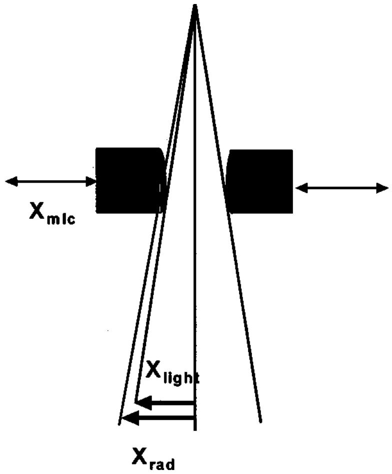

FIG. 1. For rounded leaf end MLCs, the actual field size calibration differs for light (X_{light}) and radiation field (X_{rad}) edges, and depends in a complex way on the motion of the leaves (X_{mlc}).

diation field size and digital readout could be considered small, they can be important in a number of clinical situations that require excellent precision. These may include conformal therapy with small fields, use of the MLC system for stereotactic radiosurgery, and multi-segment (segmental) and Dynamic MLC (DMLC) IMRT treatments.[5,8–11] A number of different approaches to IMRT are based on the use of numerous individual segments to create complicated intensity patterns that often resemble a checkerboard. If a MLC is used to create such intensity patterns, the precision of leaf placement must be accurate, since overlaps or underlaps between segments may lead to significant differences in the dose distribution, and the gradient at a field edge is often more than 10% per mm.[12–14]

Although in this paper we illustrate these calibration issues with one particular model of MLC, many issues addressed here should be investigated for any curved leaf-end MLC system. In this paper, we present a method for MLC leaf calibration that will correctly predict radiation field sizes to better than 0.5 mm, an accuracy that is more appropriate for much of the conformal therapy and IMRT that is currently performed. We also describe a method to correct for many possible MLC system calibration limitations. Finally, we present a simple film-based quality assurance check that is sensitive enough to detect calibration errors on the order of tenths of millimeters.

METHODS AND MATERIALS

The work presented here has been performed on a total of nine Varian accelerators (Clinac 2100 C/CD's accelerators, Varian Oncology Systems, Palo Alto, CA) equipped with 52 leaf, 80 leaf, and 120 leaf multileaf collimators. Photon energies of 6 and 15 MV were available on each accelerator. The vendor's leaf calibration and standard acceptance test procedure were used initially during accelerator installation and acceptance. Following the vendor's acceptance test procedures, the radiation field was used to check the collimator jaw and leaf position calibrations.

The vendor provides two control system computer files that can be edited to change the leaf calibration. The first file is inside the controller computer ("MLCXCAL.TXT") and includes values that can change the centerline offset, the "skew" of each side of leaves, and the "gap" between both sides of leaves. The second file is a calibration table in the MLC workstation ("MLCTABLE.TXT") and was designed to minimize the deviations of the digital MLC position readout from the light or radiation field edge positions over the entire range of leaf travel. Both tables were edited to optimize the light field calibration as much as possible, using the vendor's calibration procedure. After the light field met acceptance test criteria, we performed further measurements and an analysis to improve the radiation field calibration of the MLC system.

Radiation field size data were measured using two methods. The first method was based on water phantom scans. Computer-controlled water phantom scanning systems (WP-600 and WP-700 Water Phantom/Film Dosimetry Systems, Wellhofer Dosimetrie, Schwarzenbruck, Germany) utilizing 0.1 cm^3 ion chambers (IC-10 0.1 cm^3 ion chambers, Wellhofer Dosimetrie, Schwarzenbruck, Germany) (active cylinder length 3.3 mm) and photon diode detectors (Shielded Photon Diodes, Scanditronix Medical AB, Uppsala, Sweden) (diameter 2.5 mm) were used for measurements with each accelerator. Measurements were made with the diodes in air at 100 cm from the source, and with the ion chamber at the isocentric plane with water depths of 10 cm. All profiles were normalized on the central axis, except in cases where the leaves or jaws were near or crossed central axis. These were normalized at the center of the irradiated area. The field sizes and edge locations were defined at the 50% intensity points relative to the central value of the profile.

The second method utilized film. Pre-packed verification film (XV-2 Ready-Pack film, Eastman Kodak Co., Rochester, NY) was exposed to individual rectangular fields defined by the MLC. Each film was placed at the isocenter in a solid water phantom at a depth of 10 cm and exposed to an optical density of about 1.0. The radiation field sizes were obtained from each film by scanning across the center of each field using a computer-controlled film scanner (WP-600 Water Phantom/Film Dosimetry System, Wellhofer Dosimetrie, Schwarzenbruck, Germany) (spot size 0.8 mm). The width of the field was then obtained from the film scanning system software using the 50% intensities as described above. A correction of the optical density values to dose using a measured H/D curve was not necessary since conversion to dose makes an undetectable difference in the location of the field edge. This is due to the nearly linear response of this film for doses less than 50 cGy.[15] To check that transmission between the leaves or other artifacts at the leaf junctions were not affecting the results, field size scans were compared through the center of a leaf and at the leaf junction. The differences measured in this comparison were less than 0.2 mm.

We compared the measurement techniques on the first MLC by measuring the same field sizes with each method. These field sizes measured with film agreed with the same field sizes measured with water tank scans to within 0.3 mm.

After verifying that the film method achieved the same results as the water tank method, we used the film method on the remaining MLC systems studied, since it proved to be more efficient.

For the MLC radiation field calibration measurements, each bank of MLC leaves was measured separately, with respect to the position of a common reference point, the opposite (lower) collimator jaw. The first step in the profile measurements was to determine the exact location of the reference jaw. The reference jaw was set to 19 cm from the central axis, and was then unchanged during the remainder of the measurement set. The absolute location of the reference jaw was obtained by measuring the position of the jaw at both ends of a 180 degree collimator rotation and taking half the distance between the two edges. Subsequent profiles were measured with the opposite set of leaves at different positions, keeping the reference jaw unchanged. For an analysis, these profiles were aligned to the field edge that was defined by the reference jaw. Using this method, the absolute position accuracy of the leaf edges with respect to the accelerator collimator isocenter is precisely defined by the determined location of the reference jaw. Comparisons of the results from the different MLCs, repetition of measurements, set-up of the scanners' coordinate systems, and other tests determined that the accuracy of the radiation field edge locations was performed reproducibly to better than 0.3 mm. Overall, the accuracy of the measurements and corrections, taken together, is approximately 0.5 mm.

Once it was determined that corrections were necessary to achieve accurate leaf positions, two attempts were made to apply the corrections inside the vendor's software. The first attempt was to change the leaf gap value in the MLCXCAL.TXT, but because of the rounded leaf ends, the most accurate "leaf gap" value would cause the leaves to collide when closed, so the software prevents such a value. The second attempt was to change the values in MLCTABLE.TXT table ("internal correction", but the software in the 52 leaf and 80 leaf MLCs does not allow positive values in this table, therefore only the most positive ($>+10$ cm) and most negative (<-10 cm) leaf positions could be corrected for in this table. Therefore, we applied an "external" (outside Varian's software) correction to fix the remaining leaf positions. In this external software, we included a factor to ensure that closed leaf pairs do not collide. This external correction was applied on machines both with and without computer-controlled delivery.[16–18] In both situations, the corrections were implemented using automatic software routines external to the planning system, in such a way that the users do not have to do any additional work. See Fig. 2 for an illustration. The external correction routine is run after the treatment plan is done but before the leaf positions are sent to the MLC. In the Varian 120 leaf software, the software allows for the entire correction to be made inside the vendor software. However we have chosen to be consistent and use the external correction on all our MLCs.

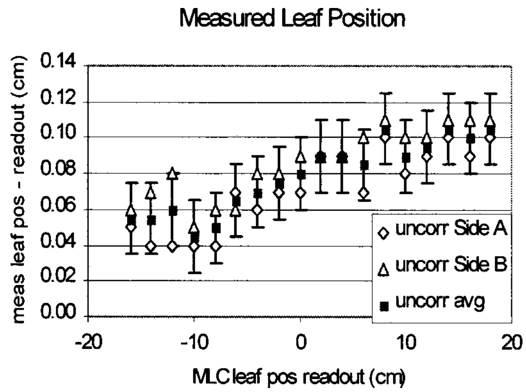

FIG. 2. A block diagram describing two methods of implementing the final leaf position correction: (a) Internal correction: The vendor's calibration table should be edited at all leaf positions if possible. (b) External correction: Used if internal correction is not possible or is not complete.

RESULTS AND ANALYSIS

In addition to the vendor's standard acceptance procedures, numerous studies of the locations of the light field and radiation field edges versus the digital readouts from the control systems of the MLC were performed. As was discussed in the Introduction, the radiation field measurements made after the vendor performed the standard calibration procedure (Fig. 3) show that the actual radiation field edges can deviate from the MLC readout by more than 1 mm for a single bank of leaves. These data were measured with the vendor's standard calibration table in place (see the lowest

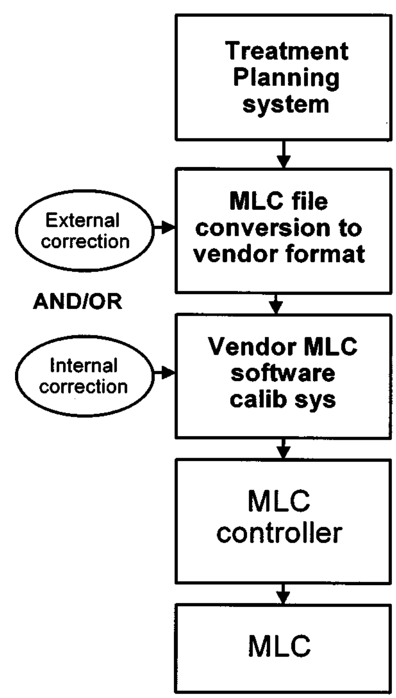

FIG. 3. Initial measurements of leaf positions based on radiation field size checks when using the light-field-based vendor MLC calibration table. The difference between the radiation field sizes and the digital field size is plotted versus digital readouts from the MLC control system.

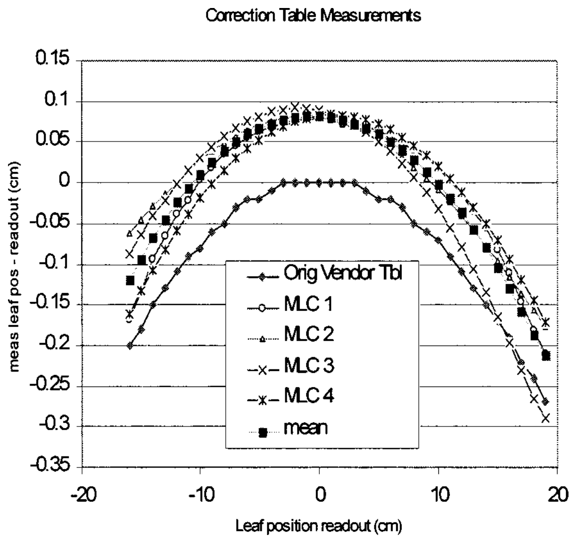

FIG. 4. Results of correction table measurements for 4 MLCs of the same type. These are 4th order polynomial fits to the measured data. Also shown is the mean of the 4 MLCs, and the vendor's original correction table, based on a light-field calibration procedure.

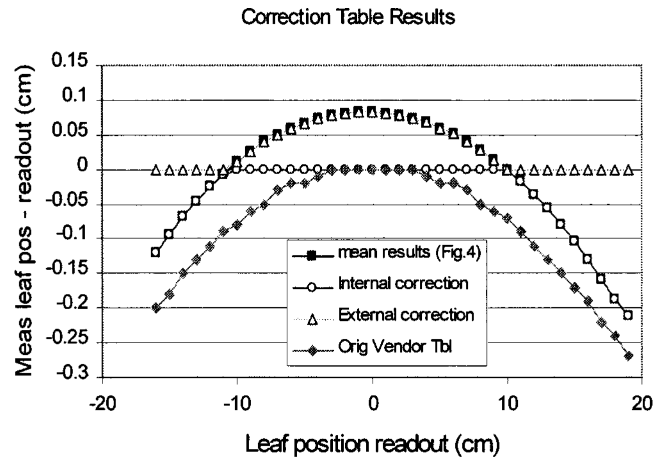

FIG. 5. A summary of new calibration results. Shown are the original vendor calibration table, the new vendor calibration table (internal), and the additional corrections that are implemented outside the vendor's software (external).

curve in Fig. 4). When using both banks of leaves to define the field size, the deviations add, forming a total deviation of 2–3 mm.

Figure 3 shows data for one 52 leaf MLC. The same post-acceptance test measurements were performed on our first four Varian MLCs (all 52 leaf). These data were used to derive the necessary correction tables for each of these MLCs. These curves are shown in Fig. 4. Also plotted is the original vendor-supplied calibration table (MLCTABLE.TXT). In order to achieve accurate leaf positions using a radiation field calibration, the vendor's table needed to be edited to reflect the measured data shown.

However, positive values were not allowed inside MLCTABLE.TXT for the 52 and 80 leaf MLCs, so the positive deviations could not be corrected with use of the vendor's table alone. Therefore, for these earlier MLCs, the options were to either edit MLCTABLE.TXT (''internal correction'') for the nonpositive values and add an external correction table for the positive values, or to apply the whole correction in the external table (see Fig. 2). The 120 leaf MLC software does allow the entire correction to be made inside their table. In the event that the vendor denies permission to edit this calibration file, the whole correction may be made externally. Figure 5 illustrates the new average calibration correction, and how it may be applied in two separate tables (internal and external) if necessary.

The final results of our correction process are shown in Fig. 6 (radiation field–digital readout deviation). Here, a final set of measurements of the radiation field edge location have been obtained, but using the new MLCTABLE.TXT and an additional external correction table from Fig. 5. The radiation field data in Fig. 6 are in much better agreement with the digital readouts than the original data shown in Fig. 2, and are well within the experimental error of 0.5 mm.

Figure 6 shows the results from one of the 52 leaf MLCs. Instead of measuring a separate calibration curve for all of our more recent MLCs, we simply applied the average curve from the first four 52 leaf MLCs. We then measured the corrected field sizes to verify that this correction was accurate for each individual MLC. For three 80 leaf MLCs and two 120 leaf MLCs, this same correction curve achieves measured field sizes that agree with the digital position readouts to within 0.5 mm.

The agreement between light field and digital readout in Fig. 7 now shows the systematic difference that is the result of using a radiation field-based calibration system. The light field data have been shown in Fig. 7 only for reference. The MLC calibration with respect to the light field is not of major importance for treatments in our clinics. For conformal therapy, in which apertures are designed inside the three-dimensional (3-D) treatment planning system and complex field arrangements are used, it is the radiation field size versus the digital machine control and readout which is important, not the accuracy of the light field. The light field (in Fig. 7) now demonstrates expected deviations from the digital readout (which now defines the radiation field edges).

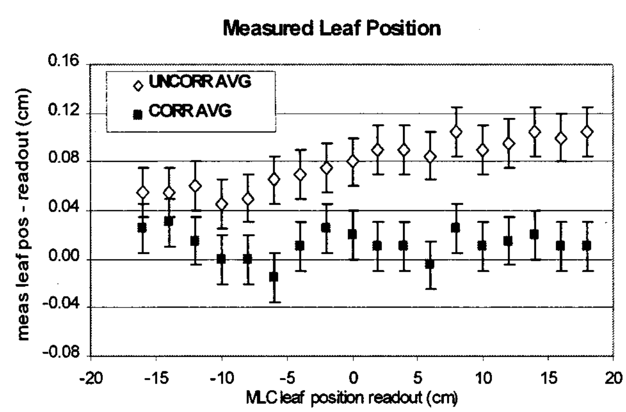

FIG. 6. Pre- and post-correction radiation field measurements with each leaf carriage measured separately, across its entire range of travel.

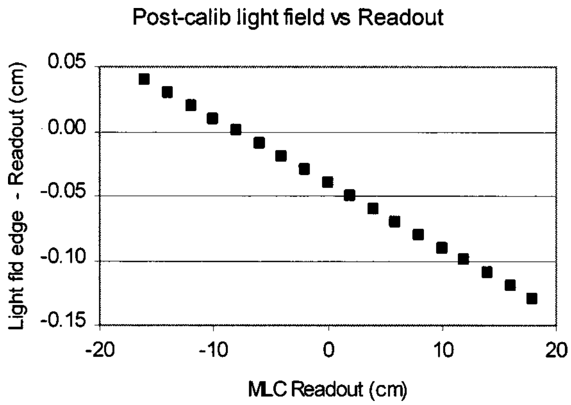

FIG. 7. A comparison of light-field and radiation-field calibration of digital MLC readout, after calibration and corrections.

Table I summarizes our processes for calibration of the rounded leaf MLC systems in our clinics. We have found that we can use the average of these first few MLCs results to apply to the rest of our MLCs. We currently use a correction table that is the average of the curves in Fig. 4 as our standard correction. This saves the time of performing steps 2 through 4, then steps 5 through 7 are performed to check the validity of this average correction table. This standard correction achieves accurate results for all of the MLCs from this vendor, including the 52 leaf, the 80 leaf, and the 120 leaf versions.

TABLE I. Steps summarizing our calibration process for rounded leaf MLC systems.

First 4 MLCs	Next 5 MLCs
1. Optimize the calibration values in the vendor's MLC controller, using radiation field techniques whenever possible. 2. With the vendor's calibration table in place, use the radiation field size films (as described earlier) to measure leaf positions across their range of travel. 3. The differences between the digital readout and measured radiation field edges are plotted, as displayed in Fig. 4. 4. A fourth order polynomial fit to these data is used to smooth the corrections and avoid putting random measurement-based deviations into the correction tables. Use this curve to determine the corrections to the calibration table that will remove the deviations (as in Fig. 5).	**Instead of 1–4**: Apply average calibration curve resulting from measurements of first four MLCs.
5. Apply the corrections in the vendor table where possible, and use the secondary correction table to fix the regions that cannot be corrected in the vendor table (Fig. 5). 6. With the new corrections in place, re-measure the leaf positions and verify that they are now within 0.5 mm of the desired position. 7. Perform a final verification with the QA film described below.	

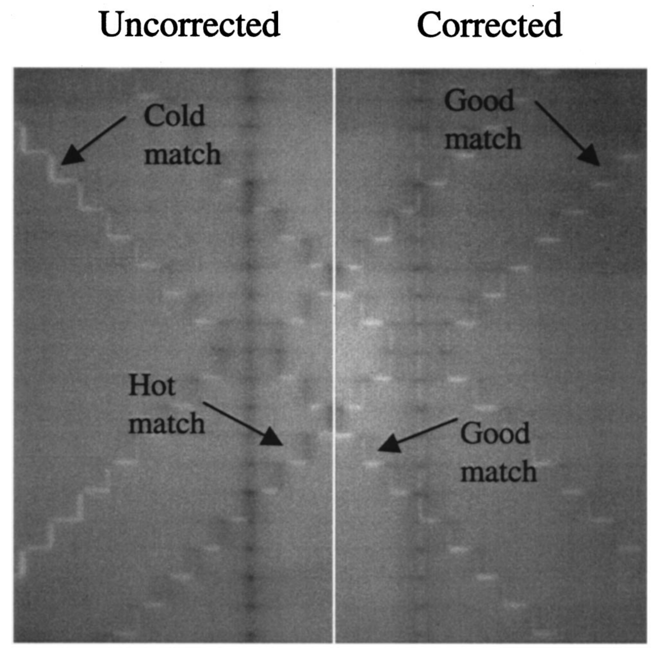

FIG. 8. The film image taken from the daily MLC calibration QA test, created with 4 pairs of segments. The left side shows the leaf matches when no corrections are applied. The hot spots centrally and cool spots laterally indicate that the leaf positions could be better. The right side is the film after the correction. It has uniform matching throughout.

DISCUSSION AND QUALITY ASSURANCE

As mentioned earlier, accurate calibration methods such as those described in this work are of more clinical importance for small fields, conformal therapy, and IMRT than for many standard therapy treatment techniques. The maximum difference between the actual radiation field size and the desired (planned) field sizes found in each of the systems studied can be more than 3 mm with the typical light-field-based calibration method. For large field, less conformal treatment delivery schemes, this 3 mm difference may not be clinically significant. However, such size differences are potentially significant for high dose conformal therapy or radiosurgery-type applications. For multisegment IMRT delivery, where many different MLC patterns may be used to make a complex intensity pattern, the potential of several mm of overlap between opposing sets of leaves may lead to larger dosimetric differences than may be desired.

Routine quality assurance testing of the MLC calibration can be performed quite accurately using a multisegment film for MLC checks. To improve our quantitative MLC checks, the routine daily QA check of geometric parameters on computer-controlled accelerators, described by Thompson *et al.*,[19] can be modified to include a MLC calibration check film specifically designed for accelerators equipped with rounded-leaf-end MLC systems. The MLC QA film (Fig. 8) is comprised of complementary jagged diagonal patterns. The idea is to view the match between opposite sides of leaves when both sides are sent to the same leaf position. This test relies on the very precise alignment of the leaves of the Varian MLC system (using an internal laser system), so that a significant range of the position versus readout table

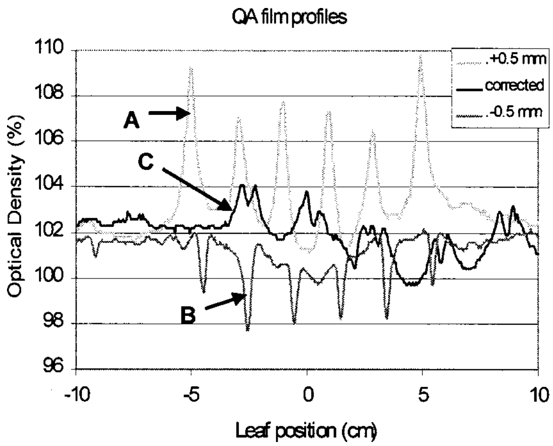

FIG. 9. Optical density profiles obtained from a scan of QA films made with three different MLC calibration tables: (a) 0.5 mm wider than correct, (b) 0.5 mm smaller than correct, (c) best result.

can be performed with one set of segments. Deviations on the order of 0.2 mm or smaller can be detected by eye using this film test. The film study, which includes irradiation of a stored series of segments using the computer-controlled MLC and the accelerator, film development, and visual analysis, takes only ten minutes to complete. This film technique can complement other IMRT MLC QA films that have been mentioned in the literature.[11,20] It is also possible to use a simple MLC light field check to confirm the calibration constancy, since the light field versus MLC readout curves are well-defined (Fig. 7).

Currently, this QA film (Fig. 8) is incorporated as part of the monthly machine QA check. Minimally, this film check should be performed monthly and after MLC maintenance or service. A ''base'' film, obtained at the time of the MLC calibration procedure, can be used as a reference for these routine checks. The film is then run routinely and after MLC maintenance, and the hot/cold spots at the leaf match junctions can be observed for changes.

The QA film is very sensitive to differences in calibration. By deliberately changing the MLC calibration by set amounts and irradiating the multi-segment QA film, we have determined that changes as small as 0.2 mm can be seen by eye on the film. Scans across the film can quantify more accurately the amount of change that occurred in the calibration (Fig. 9). Curve A shows the hot spots that occur when the leaf positions are too wide by 0.5 mm. Curve B shows cold spots that occurred when the calibration was made too small by 0.5 mm. Curve C shows the best match achievable with this curved leaf system. This result is beneficial, as it means that a simple visual inspection of the film can confirm the accuracy of the calibration very quickly. When converted to dose, the hot spots in curve A and the cold spots in curve B translate to 8–10%. Therefore, the 1 millimeter difference in leaf calibration between curves A and C creates a 15–20% dose difference in the matchline. The same film can also be used to assess gantry and collimator angle dependence of the leaf positions, and other such geometrical stability tests.

CONCLUSIONS

Agreement between planned and delivered dose distributions is a critical part of quality radiation therapy. In this report we illustrate that good agreement between the radiation field and the planned treatment field may not always be easy to assure for MLC systems unless careful calibration and quality assurance procedures are used. Each MLC system has different mechanical, hardware, software, and implementation limitations. In the case studied here, a software limitation makes a correction of the radiation field settings a little more difficult, and some of the radiation field calibrations of the MLC system must be done outside the vendor's software.

Some of the details in this work are specific to one vendor's MLC implementation, but those specific details are not the main point of this paper. We use results from one MLC vendor to illustrate the point that careful checks of the radiation field edge location are important, and cannot be assumed to be good enough for treatments such as IMRT after one uses a standard light-field-based calibration procedure. A careful calibration of the MLC control system's digital readouts to the radiation field produced by the MLC can be achieved. However, this calibration requires precise measurements and careful analysis in order to achieve the accuracy that could be required for high dose conformal therapy or IMRT applications. For many kinds of IMRT treatment delivery, these kinds of precise calibrations may be essential.

We have illustrated a number of measurement techniques that can be used to determine the agreement between the various representations of the field edges, and analysis and quality assurance techniques which illustrate the degree of agreement or disagreement between the various results. With careful measurements and a method to implement the corrections into the usual flow of patient treatment plan information into the MLC control system, it is possible to achieve agreement between the indicated field edge locations and the radiation field edges to better than 0.3 mm.

ACKNOWLEDGMENT

This work was supported in part by NIH Grant No. NCI POI-59827.

[a]Author to whom correspondence should be sent. Department of Radiation Oncology, University of Michigan Medical Center, Room B2C490, Box 0010, 1500 E. Medical Center Dr., Ann Arbor, Michigan 48109-0010. Telephone: 734-936-4309; fax: 734-936-7859; electronic mail: mgraves@roa.msu.edu
[b]Currently at Hospitals of the University of Pennsylvania.

[1] J. Galvin, A. Smith, and B. Lally, ''Characterization of a multileaf collimator system,'' Int. J. Radiat. Oncol., Biol., Phys. **25**, 181–192 (1993).
[2] T. Jordan and P. Williams, ''The design and performance characteristics of a multileaf collimator,'' Phys. Med. Biol. **39**, 231–251 (1994).
[3] E. Klein, W. Harms, D. Low, V. Willcut, and J. Purdy, ''Clinical implementation of a commercial multileaf collimator: dosimetry, networking, simulation, and quality assurance,'' Int. J. Radiat. Oncol., Biol., Phys. **22**, 1195–1208 (1995).
[4] E. Klein, D. Low, D. Maag, and J. Purdy, ''A quality assurance program for ancillary high technology devices on a dual-energy accelerator,'' Radiother. Oncol. **38**, 51–60 (1996).

[5] X. Wang, S. Spirou, T. LoSasso, J. Stein, C. Chui, and R. Mohan, ''Dosimetric verification of intensity-modulated fields,'' Med. Phys. **23**, 317–327 (1996).
[6] T. LoSasso, C. Chui, and C. Ling, ''Physical and dosimetric aspects of a multileaf collimation system used in the dynamic mode for implementing modulated radiotherapy,'' Med. Phys. **25**, 1919–1927 (1998).
[7] D. Low, J. Sohn, E. Klein, J. Markman, S. Mutic, and J. Dempsey, ''Characterization of a commercial multileaf collimator used for intensity modulated radiation therapy,'' Med. Phys. **28**, 752–756 (2001).
[8] A. Boyer and C. Yu, ''Intensity-modulated radiation therapy with dynamic multileaf collimators,'' Semin Radiat. Oncol. **9**, 48–59 (1999).
[9] R. Mohan, ''Field shaping for three-dimensional conformal radiation therapy and multileaf collimation,'' Semin Radiat. Oncol. **5**, 86–99 (1995).
[10] S. Spirou and C. Chui, ''Generation of arbitrary intensity profiles by dynamic jaws or multileaf collimators,'' Med. Phys. **21**, 1031–1041 (1994).
[11] Y. Chen, A. Boyer, and C. Ma, ''Calculation of x-ray transmission through a multileaf collimator,'' Med. Phys. **27**, 1717–1726 (2000).
[12] C. Chui, S. Spirou, and T. LoSasso, ''Testing of dynamic multileaf collimation,'' Med. Phys. **23**, 635–641 (1996).
[13] J. Kung and G. Chen, ''Intensity modulated radiotherapy dose delivery error from radiation field offset inaccuracy,'' Med. Phys. **27**, 1617–1622 (2000).
[14] G. Budgell, J. Mott, P. Williams, and K. Brown, ''Requirements for leaf position accuracy for dynamic multileaf collimation,'' Phys. Med. Biol. **45**, 1211–1227 (2000).
[15] M. Evans and L. Schreiner, ''A simple technique for film dosimetry,'' Radiother. Oncol. **23**, 265–267 (1992).
[16] B. Fraass, D. McShan, G. Matrone, T. Weaver, and J. Lewis, ''A computer-controlled conformal radiotherapy system: I. Overview,'' Int. J. Radiat. Oncol., Biol., Phys. **33**, 1139–1157 (1995).
[17] G. Budgell, J. Mott, P. Williams, and K. Brown, ''Requirements for leaf position accuracy for dynamic multileaf collimation,'' Phys. Med. Biol. **45**, 1211–1227 (2000).
[18] D. L. McShan and B. A. Fraass, ''UM-CCRS/SP: sequence processor for computer-controlled radiotherapy treatment delivery,'' in *Proceedings of the XIth International Conference on the Use of Computers in Radiation Therapy*, edited by A. Hounsell, J. Wilkinson, and P. Williams (Medical Physics Publishing, Madison, WI, 1994), pp. 210–211.
[19] A. Thompson, K. Lam, J. Balter, D. McShan, M. Martel, T. Weaver, B. Fraass, and R. TenHaken, ''Mechanical and dosimetric quality control for computer controlled radiotherapy treatment units,'' Med. Phys. **22**, 563–566 (1995).
[20] C. Mubata, P. Childs, and A. Bidmead, ''A quality assurance procedure for the Varian multi-leaf collimator,'' Phys. Med. Biol. **42**, 423–431 (1997).