The design and physical characterization of a multileaf collimator for robotic radiosurgery

To cite this article: G Asmerom et al 2016 Biomed. Phys. Eng. Express 2 017003

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The design and physical characterization of a multileaf collimator for robotic radiosurgery


Accuray Incorporated, 1310 Chesapeake Terrace, Sunnyvale, CA 94089, USA

1 Author to whom correspondence should be addressed.

E-mail: wkilby@accuray.com

Keywords: x-ray beam collimation, CyberKnife® System, robotic radiosurgery, stereotactic body radiation therapy, multileaf collimator

Abstract

A multileaf collimator (MLC) optimized for SBRT delivery with the CyberKnife® Robotic Radiosurgery System (Accuray Incorporated, Sunnyvale, CA, USA) is described. The MLC is exchangeable with the alternate fixed and variable circular aperture collimator systems. The non-coplanar workspace is effectively equivalent for all three collimation types. The same range of tracking options, including real-time respiratory motion tracking, and the same tolerance on beam pointing accuracy (≤0.95 mm) is maintained with all three collimation types. The MLC includes 52 flat-sided leaves, each of which is 90 mm tall and projects 3.85 mm width at the nominal treatment distance of 800 mm SAD. The design allows 100% overtravel and unrestricted interdigitation. Leaf position is determined by primary motor encoders and is checked with a secondary optical camera system. Maximum leakage, including inter-leaf and under the closed position leaf-tip gap was measured on three units tested. The leaf position accuracy measured over the full range of leaf positions, all robot and MLC orientations, and including variation with leaf motion direction and accumulated leaf motion after initialization had a mean error <0.2 mm, with 2%–98% range of ±0.5 mm (projected at 800 mm SAD) on three units tested. The only factor found to effect leaf positioning accuracy was sag under gravity, which systematically altered leaf positions by 0.1 mm. Tilting the leaves to reduce inter-leaf leakage results in 0.5 mm asymmetry in leaf-side penumbra at 100 mm depth, and a partial leaf-edge transmission pattern analogous to the tongue and groove effect observed with interlocking leaves.

1. Introduction

The CyberKnife® Robotic Radiosurgery System (Accuray Incorporated, Sunnyvale, CA, USA) is described in detail elsewhere (Kilby et al 2010). The rationale for adding a multileaf collimator (MLC) is to allow irregularly shaped fields to be delivered from a given robot orientation using fewer beams and lower total monitor units (MU) than is possible with either non-isocentric fixed circular or Iris™ variable aperture (Echner et al 2009) collimated fields. The first planning study to investigate this showed that for ten lung SBRT cases CyberKnife treatment using an MLC might allow a reduction in treatment time (including robot motion, beam delivery, and intra-fraction imaging) in comparison to a dosimetrically equivalent Iris collimator treatment of 29% for PTV <80 cm³ increasing to 55% for 152 cm³, and a mean reduction of 47% in total MU (van de Water et al 2011). The MLC model used in that study was entirely hypothetical, and MLC dose calculation used a beam model based on measurements with another vendor’s device and a flattened beam. More recent planning studies using actual CyberKnife beam data have compared MLC plans against those generated with fixed or Iris collimators for prostate (n = 5), brain metastasis (n = 5) (McGuinness et al 2015), and accelerated partial breast irradiation (n = 9) (Goggin et al 2015). For dosimetrically equivalent plans, MLC treatment times were lower by approximately 50% in all cases, and total MU were reduced by 40% (prostate), 70% (brain metastasis), and 50% (partial breast).
This paper describes the design goals, the mechanical and control system design, and the physical characterization of the InCise™ 2 MLC which is commercially available for the current CyberKnife M6™ System since 2015, and is intended to realize the clinical benefits shown in these planning studies. It should be noted that some published descriptions of a CyberKnife MLC refer to a slightly different design, InCise MLC, first installed in 2014 (Fuerweger et al 2015, Huq et al 2015).

2. Technical design description

2.1. Mechanical design

The main features of the design are summarized in figure 1 and table 1.

2.1.1. Tool plate

This provides an interface to the robotic tool exchange system which allows for automated swapping between MLC, fixed, and Iris variable aperture collimators as defined by each treatment plan. The tool plate ensures that the MLC is aligned to the beam axis reproducibly with no relative rotation between the beam and the MLC. During treatment delivery, rotational alignment of each beam to the target volume is achieved by adjustments of the robotic manipulator joints, and is maintained throughout treatment by continual image guidance and tracking.

2.1.2. Patient plane shield

The patient plane shield is a fixed secondary collimator. Its principle role is to provide additional shielding above the gap between the tips of opposing leaf pairs when they are parked outside the beam, to minimize leakage radiation to the patient. In the direction perpendicular to leaf motion the aperture is slightly larger than that formed by the side protection plates to avoid increasing beam penumbra.

2.1.3. Camera and illumination board

These are used by the secondary leaf position sensing system.

2.1.4. Leaves and guides

Each leaf is thicker at the bottom than the top, with each leaf side initially aligned with the radiation source. The leaf sides are flat and leaves do not interlock, which simplifies the manufacturing process and assists with robust interdigitation. To reduce inter-leaf leakage, the entire set of leaves is then tilted by 0.5° (figure 2). This angle was determined experimentally to be the minimum sufficient to achieve maximum inter-leaf leakage <0.5%. Each leaf is 90 mm tall, with minimal material removed to

<table>
<thead>
<tr>
<th>Table 1. MLC Design characteristics.</th>
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</thead>
<tbody>
<tr>
<td>Number of leaves</td>
</tr>
<tr>
<td>Leaf width (at 800 mm SAD)</td>
</tr>
<tr>
<td>Maximum treatment field size (at 800 mm SAD)</td>
</tr>
<tr>
<td>Leaf height</td>
</tr>
<tr>
<td>Leaf tip design</td>
</tr>
<tr>
<td>Leaf side design</td>
</tr>
<tr>
<td>Interdigitation</td>
</tr>
<tr>
<td>MLC assembly weight</td>
</tr>
<tr>
<td>Source to collimator distance (lower side of leaves)</td>
</tr>
<tr>
<td>MLC assembly physical envelope</td>
</tr>
<tr>
<td>Maximum leaf speed (at 800 mm SAD)</td>
</tr>
<tr>
<td>Maximum leaf over-travel (at 800 mm SAD)</td>
</tr>
</tbody>
</table>
accommodate the drive train and guiding features. The leaf tips are separated into three sections (figure 2). The lowest section is focused at the radiation source at a full open position, the centre section is aligned when the leaf is at the midpoint of travel, and the top section is focused at the fully closed position. Rigid guides provide support and alignment for the leaves. The leaves ride on low friction bearings mounted to the guides.

2.1.5. Side protection plates
These have the same height as the leaves and function as non-moving leaves determining the maximum field size in the direction perpendicular to leaf motion. The edge of the side protection plate is in the same location as the next leaf would be, matching side profile and focussing in order to yield the same penumbra as a leaf edge.

2.1.6. Motor and drive train
Leaves are driven via a motor and lead screw combination (Maxon Motor Ag, Sachsein, Switzerland). The motors are staggered to minimize their offset from the central axis of the leaf, which minimizes off-axis forces and improves efficiency. Stress-testing of the motors was performed under aggressive testing conditions, and expected life in the field is at least two years. The motors are designed for easy field replacement.

2.1.7. Workspace
The lower surface of the MLC leaves is at 400 mm SAD, providing the same patient clearance as fixed and Iris collimators. Treatment is performed from a set of specific points (nodes) defining positions for the Linac target around the patient that can be reached by the treatment robot and avoid collision with the patient, couch, and other fixed obstacles. There is a different node-set for treatments to the head and body. For
head, the MLC has 171 nodes, compared to 179 for the fixed or Iris collimators, and for body the MLC has 102 versus 117 for the fixed or Iris collimators. Overall, the density of nodes is reduced by between 4% and 13% but these are spread over an almost unchanged solid angle (figure 3).

2.2. Control system design

2.2.1. Primary leaf position control

The primary control system consists of electronics for motor drive, position processing and control, leaf alignment, safety loops, and communication with the treatment delivery system. Leaf positioning is achieved by actuating brushed DC motors, driven individually by full-bridge pulse-width modulating (PWM) motor drivers controlled by custom electronics. The motors have bi-directional quadrature encoders which are used to track the incremental motion of the leaf. Leaves are positioned with an encoder accuracy equivalent to ±50 μm. MLC leaves are controlled independently and all leaves can move simultaneously. Leaf speed and torque are controlled through a PWM drive scheme.

The motor encoders are relative, so before precise positioning can be accomplished, a homing operation is performed. To enable this, a light beam is positioned behind the rear face of each leaf bank, intercepted by an opposing detector (Omron Corporation, Kyoto, Japan). Each leaf is retracted sequentially until this beam is crossed, the beam interruption is detected, and a home position is set on the encoder. A verification procedure is also performed. To allow this there is another light beam and detector combination positioned in advance of the front face of each leaf. The baseline encoder count change between the rear beam and front beam intersections is recorded for each leaf at the time of MLC installation and after some adjustments that may be made in the field. Before each treatment fraction, after each leaf is retracted to set home position it is advanced until the front beam is broken. The change in encoder counts is compared to the baseline value and the system only allows treatment if this corresponds to a difference of less than ±200 μm. This protects against light beam shifts and other mechanical anomalies or changes from the time of system calibration.

2.2.2. Secondary leaf position sensing

A camera-based system provides a secondary mechanism of detecting MLC leaf positions with mechanical accuracy better than ±1.0 mm. The system uses an obliquely oriented wide angle lens (Computar Optics Group, Cary, NC, USA) located above the proximal side of the leaf bank as shown in figure 1. Illumination of the proximal MLC leaf surface is achieved via a custom-design LED illumination system. A diffuse non-specular illumination is achieved with two layers of matte white polyester sheeting.

The image processing pipeline consists of three algorithmic stages. In the first, lens radial and tangential distortions are removed using intrinsic camera parameters measured during camera assembly. To mitigate the effects of lens discoloration due to radiation and ambient light interference on position sensing, white balancing and ambient light suppression algorithms are also applied. White balancing involves computing correction parameters at the beginning of each treatment fraction. Ambient light suppression uses a custom-designed algorithm based on colour saturation of the light entering through the MLC aperture. In the second stage, an oblique-view image is transformed to a top-view representation using registration of visual features to a top-view template image (figure 4). In the third stage, the image is subdivided into leaf-specific subdomains and the system detects the position of leaf notches by maximizing the normalized cross-correlation coefficient between leaf notch template and a candidate notch position within the image subdomain. The resulting normalized cross-correlation coefficient is treated as the detection confidence and is represented on the user interface.

The system is capable of tracking individual leaf positions in real time with approximately 4 Hz update rate. Primary and secondary leaf positions are compared immediately before and after the delivery of every MLC aperture. In the event of a difference larger than 1 mm, a system interlock is raised. The system displays the processed image with optional graphic overlays of leaf positions as specified in treatment plan and as measured by the primary and secondary feedback systems (figure 4). Additionally, the system provides a real-time visual presentation of the video stream with similar information overlays.

2.2.3. Software and firmware motion control

Desired leaf positions are communicated via an Ethernet connection to the MLC control system firmware, which converts them from units of mm into units of encoder counts. For each leaf, an increase in encoder counts corresponds to motion towards the centre. The firmware executes trajectory planning for each leaf based on its current and desired positions, and a set of trajectory setpoints is generated before leaf motion starts. Trajectories are planned in two steps: a coarse-tuning step in which most of the displacement is covered by controlling the leaf’s velocity (rather than exact position), and fine-tuning in which the remaining displacement to the target is completed in position control. Once trajectory planning is completed, all leaves move to their desired position simultaneously. During motion, firmware monitors the actual positions of all leaves in order to detect following errors and to prevent collisions between opposing leaves. During motion, firmware also communicates position and other leaf status information to the software control layer at an interval of 16 ms or less. When all position targets are reached, firmware communicates
that motion is complete and final leaf positions are checked in both firmware and software. Beam can only be delivered if leaf motion is complete and all leaves are positioned within ±50 μm of the target position. Conversely, leaf motion can only be commanded when beam delivery is complete. In the event that uncommanded leaf motion is detected by primary position sensing during beam delivery, the system is interlocked and the beam is turned off. As such, the control system is configured for step-and-shoot treatment delivery but the architecture can support a dynamic delivery model.

2.3. Leaf position calibration scheme

The control system commands each leaf to a mechanical position of the leaf tip relative to the beam central axis based on the motor encoder count. If the distance of the rear optical beam from the central axis, the leaf length, and the pitch of the motor encoder (counts/mm) are known, the mechanical position of the leaf tip \( x_m \) can be easily calculated from the encoder.

The output of the treatment planning system contains the position of the radiation field edge associated with each leaf, projected to the reference treatment distance of 800 mm SAD \( x_i \). The conversion between these two leaf positions is achieved by

\[
x_m = G(i, x_i) (x_i + P(i, x_i) + C(i, j))
\]

where \( i \) is the leaf bank (X1 or X2) and \( j \) is the leaf number in that bank (1–26). \( G \) is simply a scaling factor to back-project the mechanical leaf edge at 800 mm SAD to its physical position, and is either 370/800 for a leaf that has not extended past central axis or 340/800 if it has. \( P \) is a correction offset to account for leaf tip partial transmission, which results in the radiation edge of the beam being slightly behind the mechanically projected leaf tip position to a degree that varies with leaf position. These offsets were obtained by modelling the leaf tip transmission as a function of leaf position using a simple ray-trace attenuation calculation and ignoring scatter. Finally, \( C \) is a calibration offset which can be adjusted to correct for uncertainties in the overall calibration, and is the only parameter that is adjusted on a unit-specific basis. This is determined independently for the two leaf banks. Although it could also be independent for each leaf, in the current implementation only a linear variation of offset with leaf number is allowed in order to correct for any angular offset between the rear beam and the perpendicular to leaf motion (i.e., to correct for skew in the rear beam).

3. Physical characterization

3.1. Measurement techniques

Film dosimetry was performed using Gafchromic® EBT3 film (Ashland Incorporated, Lexington, KY, USA) scanned using an Epson 10000XL optical scanner (Seiko Epson, Nagano, Japan) in transmission mode using the red channel. Scanning detector dosimetry was performed using a 60018 stereotactic diode oriented parallel to the beam axis, an MP-3
water tank, and Mephysto software (PTW, Freiburg, Germany). All measurements were conducted using one or more of a set of five MLCs at the vendors test facility.

### 3.2. Leakage and transmission

MLC leakage and transmission was measured by film dosimetry at 800 mm SAD and 15 mm depth in solid water, with the beam vertical and horizontal. Horizontal beam tests were performed with the leaves traveling parallel to the floor and towards the ceiling in order to investigate leakage variation with leaf deflection under gravity. During treatment delivery, leaf pairs that are not used to form an aperture are positioned with one fully retracted and the other fully extended so that the gap between leaf tips is shadowed by the patient plane shield. Each test was performed with the X1 leaves fully extended to the X2 side, and vice versa. In the beam horizontal, leaf vertical orientation the robot was positioned so that the extended leaves were moving towards the ceiling, so that any leaf sag under gravity would cause them to fall back away from the patient plane shielding and maximize leakage at the leaf tips. Maximum leakage was calculated by analysing the mean dose within a 1 mm ROI centred at every pixel in the image. Mean transmission and leakage was calculated over an ROI corresponding to the primary beam incident on the MLC (130 mm × 110 mm at 800 mm SAD). The values are relative to the dose at the centre of a 60 mm circular reference field. Measurements were performed on all five MLC units.

Figure 5 shows an example of MLC leakage and transmission. The increased leakage between leaves is clearly visible, although there is no increase where the tips of opposing leaves meet which indicates that this position is well shielded by the patient plane shield. The abrupt change in transmission observed about one third of the way back from the extended leaf tips is caused by the leaf design; the part closest to the tip is solid Tungsten alloy, the part towards the back of the leaf has slots cut into it to accommodate the drive mechanisms attached to it and adjacent leaves (figure 2). This is more clearly seen in the two leakage and transmission profiles shown in figure 6. Over all MLCs and robot orientations there were a total of 26 leakage and transmission measurements. The maximum leakage observed in these tests ranged between 0.34% and 0.44% (mean = 0.38%) and mean leakage and transmission ranged between 0.22% and 0.25% (mean = 0.23%). The variation between units is small, and there are no systematic variations with MLC or beam orientation indicating that any leaf deflection under gravity does not significantly alter the leakage pattern.

### 3.3. Leaf positioning accuracy

#### 3.3.1. Variation with leaf position

This was tested using scanning detector measurements at 800 mm SAD and 15 mm depth. Profiles were scanned across one leaf pair, parallel to the leaf motion direction, for a series of 10 mm wide strip fields that were centred from \( x = -50 \) mm to \( x = +50 \) mm in 5 mm increments. The full width at half maximum (FWHM) of each strip was measured and compared against the FWHM when centred at \( x = 0 \) mm. This test was performed on two MLC units, and was repeated on one of these units with the partial transmission correction removed from the calibration scheme (i.e., with all terms \( P(x, x_i) \) in equation (1) set to zero) in order to test the effectiveness of this correction.

The results are shown in figure 7. When the partial transmission correction is absent from the leaf calibration scheme the width of the strip increases by up to 0.55 mm as the leaves move away from central axis before decreasing again in a characteristic ‘M-shaped’ pattern. This variation is closely matched by the
prediction of the ray tracing attenuation algorithm used to correct for partial leaf tip transmission in the calibration scheme. As a result, when this correction is enabled the variation in strip width with leaf position is reduced to typically less than ±0.1 mm.

3.3.2. Variation with robot orientation

This was tested using the garden fence leaf positioning test (Bayouth et al 2003). Film was mounted just below the MLC at 433.5 mm SAD using a custom device that fixes mechanically to the accessory mounting points, incorporating radio-opaque markers to indicate central axis and film orientation. This arrangement allows the test to be easily and reproducibly performed at any robot orientation. Tests were analysed using FilmQA v3.0 (Ashland Incorporated). All calculated offsets between expected and measured leaf positions were projected to 800 mm SAD. Tests were performed in three robot orientations: beam vertical, beam horizontal with bank X1 towards the ceiling, beam horizontal with X2 towards the ceiling, with three tests at each orientation. The changes in leaf position between the horizontal and vertical beam orientations are shown in table 2. There was a systematic deflection

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**Figure 6.** Line profiles of the leakage and transmission pattern corresponding to the two white lines shown in figure 5 (with y increasing towards the top of that image). The front part of each leaf is solid Tungsten alloy 90 mm thick whereas the rear part has cut-outs reducing the Tungsten alloy thickness by 3–6 mm and therefore increasing the radiation transmission. It is also clear from these profiles and figure 5 that the inter-leaf leakage features for leaves in the top half of the image (i.e. above central axis) are more sharply defined than those in the bottom half (below central axis), which is a result of the leaf tilt.

**Figure 7.** The change in FWHM for a requested 10 mm strip width as a function of the strip position relative to beam central axis (x = 0) measured with two MLC units. When no position dependent correction is applied in the leaf calibration a clear pattern is seen for the strip width to increase by up to 0.55 mm for strips centred approximately 30 mm off-axis before decreasing back to the width seen on central axis when the strip is about 55 mm off-axis. This is in good agreement with the FWHM variation predicted by a simple ray-tracing attenuation model through the leaf-tips. When that model is incorporated in the leaf calibration scheme the measured FWHM variations become much smaller (typically <±0.1 mm).
Accuracy change after simulated treatment
Variation with leaf motion direction

- MLC5 0.17 0.15
- MLC4
- MLC3

(MLC unit 800 mm SAD. Positive offset indicates that leaf position is closer to the X1 side than expected.)

Table 3. Summary of 6240 measurements of individual leaf offsets from expected positions repeated on three MLC units, projected to 800 mm SAD. Positive offset indicates that leaf position is closer to the X1 side than expected.

<table>
<thead>
<tr>
<th>MLC unit</th>
<th>Mean offset (mm)</th>
<th>Std. dev. (mm)</th>
<th>2% offset percentile mean offset (mm)</th>
<th>98% offset percentile mean offset (mm)</th>
<th>Minimum offset—mean offset (mm)</th>
<th>Maximum offset—mean offset (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLC3</td>
<td>−0.04</td>
<td>0.19</td>
<td>−0.38</td>
<td>0.39</td>
<td>−0.59</td>
<td>0.60</td>
</tr>
<tr>
<td>MLC4</td>
<td>−0.02</td>
<td>0.14</td>
<td>−0.30</td>
<td>0.27</td>
<td>−0.35</td>
<td>0.71</td>
</tr>
<tr>
<td>MLC5</td>
<td>0.17</td>
<td>0.15</td>
<td>−0.34</td>
<td>0.31</td>
<td>−0.92</td>
<td>0.54</td>
</tr>
</tbody>
</table>

(MLC sag of leaves towards the floor in the horizontal beam tests, of approximately 0.1 mm relative to the vertical beam. Offset variability was slightly smaller in the horizontal beam orientation, with standard deviations decreasing by between 0.01 and 0.04 mm.)

3.3.3. Variation with leaf motion direction

To minimize the effect of hysteresis on leaf positioning, leaves always approach their commanded positions by extending. To test the effectiveness of this approach garden fence tests were performed with the strip pattern moving from left to right and from right to left. Two tests were performed for each motion direction. No significant changes in mean bank offset or offset variation with leaf motion direction were observed (see table 2).

3.3.4. Variation with leaf motion after initialization

Leaf position initialization is performed immediately before each treatment. To test whether accuracy degrades with prolonged leaf motion after initialization, garden fence tests were performed with a vertical beam immediately before and after simulated treatment deliveries without re-initialization after treatment. Three treatment plans were simulated using a phantom, ranging from 30 to 88 MLC segments per plan and 30 to 63 beam orientations. The treatment simulations included full robot, MLC motion and beam delivery. No consistent changes were seen in mean bank offset or offset variability after treatment, and the largest change in mean bank offset was 0.07 mm (see table 2).

3.3.5. Variation of small field output factors due to leaf position reproducibility

Output factors were measured with a vertical beam at 15 mm depth in the water phantom for the smallest MLC aperture 7.6 mm × 7.7 mm. This was repeated ten times, with the leaves were fully opened and then closed to form the aperture again before each measurement. The variation between the largest and smallest measured output factor was 0.1%.

3.3.6. Overall leaf positioning accuracy

To test overall leaf positioning accuracy a set of 24 garden fence tests were performed. This test set included (a) beam vertical, (b) beam horizontal with leaves running parallel to the floor, (c) beam horizontal with leaves running vertically and X1 bank closest to ceiling, and (d) as (c) but with X2 closest to ceiling. At each orientation tests were performed with X1 leaves moving towards X2 and vice versa. There were three repeats of each test, and all tests were performed without re-initialization. In total, these tests provide 6240 measurements of individual leaf positioning accuracy. This dataset includes all of the sources of position variation investigated previously plus any
systematic variation between leaves (i.e. jaggedness of strip edges) and reproducibility of individual leaves. Analysis was performed using RIT Complete v6.3 (Radiological Imaging Technology Incorporated, Colorado Springs, CO, USA). The same measurement series was repeated for three MLC units, and the results for each are shown in table 3 and figure 8.

3.4. Penumbra
Beam profiles were measured for a set of centred rectangular apertures using a scanning detector at 100 mm depth. Because of the unflattened beam, 20%–80% penumbra was calculated for each side of the beam after renormalizing the profile to twice the dose at the relevant inflection point based on a method developed for unflattened beams (Pönisch et al 2006) and subsequently used in similar studies (Cashmore 2008). Since no flattened beam is available with CyberKnife®, $D_{\text{CAX}}/D_{\text{I}}$ in the original formula was assumed to be equal to 2 (i.e. the inflection point in the unflattened beam and the 50% dose edge in a hypothetical flattened beam with the same collimation were assumed to be coincident), as in (Fuerweger et al 2015). The results are presented in figure 9. In the $y$-direction (perpendicular to leaf motion) there is a systematic difference between the two sides of the beam, with penumbra larger by 0.5 mm on average at the Y2 edge than Y1. The leaf tilt means that the measured $y$-profiles are asymmetric, and also that measured beam width is reduced in comparison to a

Figure 8. Distribution of individual leaf position offsets from expected positions measured on three MLC units in a series of garden fence tests combining measurements of reproducibility, jaggedness, variation with leaf position, with robot and MLC orientation, with leaf motion direction, and with accumulated leaf motion since initialization. Positive offsets indicate that the measured leaf position is closer to the X1 side than expected. Offsets are projected to 800 mm SAD.
simple geometric projection of the leaf aperture if the tilt were ignored. The tilt also means that at the junction between two adjacent leaves fluence is attenuated by both leaves rather than just one or the other as would be the case for focused leaves without a tilt. This gives rise to something analogous to the 'tongue and groove' effect seen with interlocking leaves when leaves are opened sequentially (see figure 10).

The variation in leaf tip penumbra with leaf position was assessed using the offset 10 mm strip scans shown in figure 7 (with partial transmission correction enabled). The results show that penumbra is constant to $\pm 0.2$ mm at all leaf positions. However, leaf tip penumbra is systematically higher when a leaf has extended beyond central axis, which may be due to the geometric penumbra component increasing as the collimating surface of the leaf tip shifts closer to the source. In addition, the average penumbra follows a similar 'M-shaped' pattern to the position offsets caused by partial transmission through the leaf-tip which suggests that the same cause is responsible.

3.5. Beam pointing accuracy
The three secondary collimator systems have different masses and to compensate for any impact of this on

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**Figure 9.** Penumbra at 800 mm SAD and 100 mm depth for symmetric apertures about central axis. The average x-penumbra (i.e. across both sides of the field parallel to leaf motion) is shown, together with penumbra at the Y1 and Y2 beam edges (perpendicular to leaf motion). Fits to the data are shown to aid clarity: average X (dashed), Y1 (dotted), Y2 (solid).

**Figure 10.** Top left and right: two leaf patterns were exposed sequentially onto film in order to analyse the partial transmission effect at leaf edges. Bottom: the resulting vertical beam profile (shown as a white line) exhibits a dose reduction of about 20% at the inter-leaf junctions between apertures. This is caused by the leaf tilt, and is analogous to the 'tongue and groove' effect observed with interlocking leaf designs.
robot deflection a separate set of positional offset calibrations is performed for each collimator type during installation. With this set of corrections applied, total targeting error with MLC was measured using end-to-end tests (Yu et al 2004, Antypas and Pantelis 2008, ) for all tracking modes including with real-time respiratory motion tracking. The results shown in table 4 demonstrate that the total targeting error remains ≤0.95 mm in all cases, the same tolerance that is applied to fixed and Iris collimator treatments.

4. Discussion

This paper describes a new MLC designed for robotic radiosurgery. It is important to note that the MLC provides an additional treatment option, but does not remove or alter any functionality previously available with the fixed or Iris collimators. This is principally achieved by the automated collimator exchange mechanism, whereby the treatment robot picks up whichever of the three collimation systems is needed for each treatment automatically at the start of each fraction. In addition, MLC treatments can be delivered to the same set of clinical indications using the same range of tracking methods, including real-time respiratory motion tracking, as was previously possible with fixed and Iris collimators, and with the same beam pointing accuracy (total targeting error ≤0.95 mm). Non-coplanar beam orientations are an important component of CyberKnife® treatment, and a key design goal was to ensure that the range of beam orientations available with MLC should not be smaller than with fixed or Iris collimators. This places considerable constraints on the physical size of the MLC, but as shown in figure 3 this goal was achieved by the final design.

Leaf positioning accuracy was found to be very high. A systematic sag of the leaves towards the floor when oriented vertically of only 0.1 at 800 mm SAD (relative to horizontal orientation) was observed, and there was no accuracy degradation associated with hysteresis or accumulated motor turns and leaf motion during treatment (table 2). Figure 7 shows that accuracy variation with leaf position is reduced from <0.3 to <0.05 mm by including position dependent offsets generated by a model of partial leaf-tip transmission in the MLC control system, as previously predicted (Hartmann and Föhlisch 2002). In a large set of over 6000 individual leaf position measurements repeated on three MLC units, that incorporated multiple MLC and robot orientations, multiple leaf positions, and both leaf motion directions, the mean positioning accuracy on all units was <0.2 mm with a standard deviation of <0.2 mm and a 2%–98% percentile range of <±0.5 mm (table 3 and figure 8). The camera based secondary position feedback system provides a robust check of leaf positions during treatment that is fully independent of the primary position measurement, and is sensitive to the worst case scenario of a motor or pusher rod becoming physically disconnected from a leaf. In addition, with this system the user can visually inspect and confirm leaf positions at any point during treatment.

Mean MLC leakage and transmission was 0.23% averaged over 26 tests, which can be compared with 0.12% for fixed CyberKnife collimators and 0.05% for the Iris collimator (Echner et al 2009). In order to minimize inter-leaf leakage where opposing (closed) leaves meet, the leaf over-travel capability is exploited to position this junction outside the edge of the largest treatment beam where it is shadowed by the fixed patient plane shield. Interleaf leakage between adjacent leaves in each bank is minimized by tilting the leaf sides through 0.5° away from their initial source focus. Maximum leakage is consistently <0.5% for all tests performed on multiple units. Maximum leakage variation with MLC and robot orientation was 0.1% over a set of 26 tests indicating that manufacturing variations and leaf deflection under gravity have relatively little impact on the leakage pattern. While the leaf tilt effectively limits leakage it also causes asymmetry in the leakage pattern and a change in leaf penumbra between leaves on one side of the central axis (i.e. leaves 1–13) and those on the other side (14–26), as shown in figures 5, 6, and 9. Penumbra across the leaf sides changes by 0.5 mm between the two halves of the beam.

Each of the collimation systems now available with the CyberKnife® System has technical advantages and disadvantages relative to the others. The collimator selection will be determined on a clinical application-specific or patient-specific basis by clinical user experience and treatment planning studies.

Acknowledgments

The authors would like to recognise the contributions to the MLC development made by their colleagues Matt Core, April Dutta, Wael Elbhassi, Haroldo Filho,

References