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Monte Carlo model of the Elekta SLiplus accelerator: validation of a new MLC component module in BEAM for a 6 MV beam

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Abstract

A new component module (CM), called MLCE, has been implemented in the BEAM program. The CM takes into account the particular ‘tongue-and-groove’ design of the Elekta multi-leaf collimator (MLC) and the air gap between the leaves. The model was validated by two series of measurements and simulations. The first benchmarking series focuses on the interleaf leakage and the intraleaf transmission. The measurement showed a total transmission through the MLC of 1.42% of the open field dose. Two Monte Carlo (MC) simulations were made, the first with the new CM MLCE (inclusive of air gap) and the second with the CM MLCQ (exclusive of air gap), which is available in the BEAM distribution. When the air gap between the leaves was determined by varying the parameters of the leaf geometry within tolerance limits on the technical drawing, the total measured transmission of 1.42% was well reproduced by the CM MLCE. In contrast, MC simulations with MLCQ showed that the transmission through the MLC calculated without the interleaf leakage is only 44% of the total transmitted radiation. The relevance of the detailed MLC modelling was demonstrated also by studying the ‘adjacent’ tongue-and-groove effect, where two adjacent (not opposing) leaves are complementary, opened or closed. The two complementary leaf settings were simulated both with the CM MLCE and MLCQ. A comparison with measurements was made. In regions covered by two or more leaves, the dose increased by 14% for two leaves and by 40% for more than two leaves when the interleaf leakage was included in the transmission. The tongue-and-groove effect was perfectly reproduced by the MLCE module.

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1. Introduction

For several years now, the computer-controlled multi-leaf collimator (MLC) has been used for conformal radiotherapy as a replacement for metal alloy blocks. Recent advances in computer and linac technologies have provided the possibility of delivering optimized intensity-modulated radiotherapy (IMRT) in static mode (step-and-shoot mode) or dynamic mode (dynamic multi-leaf collimation: DMLC, or intensity-modulated arc therapy: IMAT) (De Neve et al 1996, 2001, De Gersem et al 2001). Several papers have discussed the dosimetric characteristics of MLCs, such as the transmission through the MLC, leaftip transmission, leaf scatter contributions (LoSasso et al 1998, Arnfield et al 2000, Kim et al 2001, Siebers et al 2002, Palms et al 2000, Jordan and Williams 1994, Huq et al 1995) and the tongue-and-groove effect (Webb 2001, Sykes and Williams 1998, Yu 1998, Huq et al 2002). When dose calculations are performed with a conventional dose computation algorithm these specific dosimetric characteristics are not—or only approximately—taken into account. With the introduction of the Monte Carlo method it is possible to make a more accurate simulation of the different dosimetric issues related to the treatment head. The transmission, consisting of intraleaf transmission and interleaf leakage, through the MLC has been studied by blocking open fields with the MLC. The results have been reported for the Varian MLC (LoSasso et al 1998, Arnfield et al 2000, Kim et al 2001). A total transmission through the MLC of 1.6–1.9% of the open field dose was reported for the Varian MLC (Arnfield et al 2000).

The main purpose of this paper is the presentation and commissioning of a MC model for the Elekta MLC in the Monte Carlo (MC) user program BEAM (Rogers et al 1995). The most recent BEAM distribution (BEAMnc-2002) incorporates three MLC models: the component module (CM) MLC, CM MLCQ and CM VARMLC. Only the last CM includes the particular tongue-and-groove design and the associated airgap between the leaves based on the Varian design. The rounded leaf end is included in MLCQ and VARMLC. The effects of introducing a rounded leaf end in the MC MLC model have been published previously (Palmans et al 2000). The new CM, called MLCE, includes the tongue-and-groove design, the rounded leaf end, the airgap between the leaves and a global MLC tilt based on the Elekta design. The commissioning of the CM MLCE is based on the simulation of two experiments strongly related to the leafbank geometry: (1) the measurement of intraleaf transmission and interleaf leakage and (2) the measurement of the adjacent ‘tongue-and-groove’ effect. By comparing MC simulations with measurements, the importance of an accurate MLC model in MC simulations (incorporating the air gap between the leaves and the tongue-and-groove design) is investigated. Uncertainties in Monte Carlo results are expressed as uncertainties of type A (u_A), as defined in the IAEA Technical Report No 398.

2. Materials and methods

2.1. Monte Carlo code and computer hardware

The Monte Carlo user code BEAM/EGS4 (Rogers et al 1995) was used to simulate radiation transport through the accelerator head. For phantom dose calculations the user code DOSXYZ (Ma et al 1995) was applied. The calculations with the EGS4 based usercodes BEAM and DOSXYZ ran on a cluster of 18 computers (Pentium III, 1 GHz, dual processors) operating under a Linux system. BEAM and DOSXYZ were linked by means of linux-scripts so that there was no need for user-interaction between the fluence and the dose calculation.
2.2. Elekta SLiplus treatment head

2.2.1. Geometrical description of the treatment head. The Monte Carlo model for the 6 MV beam of the Elekta SLiplus linac, as used in this study, is similar to the model described in detail in a previous paper (De Vlamynck et al 1999). Some changes have been implemented in the flattening filter geometry since then, because new technical data have been provided regarding the exact geometry. The components independent of the field settings are the electron target, primary collimator, flattening filter, ionization chamber, backscatter plate, mirror and mylar foil exit window. The field-dependent part of the linac (figure 1) consists of the multi-leaf collimator (figure 1, A), the upper-jaws (called the back-up jaws in Elekta terminology: figure 1, B) and the lower jaws (called the X-jaws in Elekta terminology, figure 1, C). The MLC is the first field-dependent component, closest to the electron target. The field-dependent components of the linac and the mirror can be rotated. This rotation is referred to as the ‘collimator angle’. The leaves and the back-up jaws travel along the Y-axis, the X-jaws travel along the X-axis according to the Elekta convention. The Z-axis (=central axis, CAX) points downstream starting from the electron spot (figure 1).

2.2.2. Geometrical description of the MLC. The Elekta MLC consists of two banks of 40 independent leaves each. The leaf material is a tungsten alloy with density of 18.0 g cm$^{-3}$ ($\pm 0.2$ g cm$^{-3}$). The 40 leaves in one leafbank are sub-divided into four classes, depending on the position of the cut-away for the lead screw. Figure 2 shows a picture of a leaf from one sub-class where the cut-away for the lead screw is positioned in the top part of the leaf. The design of the stepped leaf sides (the tongue and groove) and the curved leaf tip are all identical for the leaves in one leafbank, except for the two outermost leaves of each leafbank which differ slightly from the other leaves. The inner leaves can travel 20 cm away from the central...
Figure 2. (a) Side view photograph of one Elekta leaf. 1 = the stepped leaf side (tongue-and-groove design), 2 = cut-away for lead screw and 3 = the rounded leaf end. (b) Side view of a leaf in the MC model MLCE. The cut-away for the lead screw has been neglected in the MC model. A view on the back of the leafbank (indicated by 'Obs') is given in figures 3(a), (b) and (c).

axis (CAX) and 12.5 cm across the CAX. The outer leaves have limitations on these values. Details about the curved leaf end and its effect on the penumbra were published previously (Palmans et al 2000). The Elekta MLC starts at $Z = 29.8$ cm ($=\text{ZSTART}$) and has a thickness of 7.5 cm. The projection of the leaf pitch (LP, figure 3) in the isocentric plane is ca 1 cm and the projection of the top leaf width (TLW) is ca 1.1 cm (figure 2(a) and Sykes and Williams (1998)). The tongue-and-groove design of the leaf sides is shown in figure 3(a).

2.2.3. MC model of the MLC and implemented approximations and simplifications. The MC model of the Elekta MLC was based on technical drawings provided by the manufacturer, Elekta Oncology Systems, Crawley, UK. Figure 2(a) shows a side view of one Elekta leaf: one can distinguish the stepped leaf side (1), the cut-away for the lead screw (2) and the curved leaf tip (3). The following assumptions have been made in the MC model: the opening in the leaves for the lead screw is not modelled and the two outermost leaves of each leafbank have been taken identical to all the other leaves in that leafbank. In this way, all the leaves in one leafbank are identical. Figure 2(b) shows a side view of one leaf in the MC model.

To construct the leafbank in the MC model, we define one reference leaf around the CAX. All the other leaves will be positioned by translation and rotation of this reference leaf. Figure 3(a) shows a view on the reference leaf as seen by observer (Obs) in figure 2(b). The parameters which describe the reference leaf are: the top leaf width (TLW), the tongue-and-groove width (TGW) and the bottom leaf width (BLW). In this way the leaf pitch (LP) is defined as TLW − TGW (figure 3(a)). Every parameter (TLW, BLW and TGW) can be varied within tolerance limits mentioned on the technical drawings. The outer lines in figure 3(a) (dashed vertical lines) are positioned symmetrically around the CAX. For this reference leaf, the midline coincides with the CAX.

The positioning of the other leaves in the MC model consists of three steps:

1. The reference leaf (figure 3(a)) is translated 40 times so that the midline of the $N$th leaf (figure 3(b), $N = 1, \ldots, 40$), which is still parallel to the CAX, is positioned at $X_N = -19.5 + (N - 1)\text{ZSTART}/100$, with $N = 1, \ldots, 40$ the number of the leaf (numbering from negative to positive axis) and ZSTART is the starting position of the leafbank on
the CAX (figure 3(b), translation). The size of the air gap (AG) between the leaves is defined as follows: 
\[ AG = X_N - X_{N-1} - (TLW - TGW) = X_N - X_{N-1} - LP. \]
The size of the air gap can be varied since the technical drawings mention tolerance limits on the dimension of TLW and TGW. At this point, adjacent leaves have overlapping regions since the bottom part of the leaves is wider than the top part.

2. The translated leaves are then rotated around \( X_N \) so that the midline of every leaf is focused to the target (\( Z = 0 \)) (figure 3(b), rotation). After this rotation the leaves have no overlapping regions anymore. The air gap is not constant along the leaf side, since adjacent leaf sides are not parallel. Due to the rotation of every leaf, the bottom of the leafbank becomes curved (figure 1, A).

3. The MLC as a whole is slightly tilted by an angle of 0.3°, so the midline and the leaf sides are focused away from the electron spot (figure 3(c)). (Personal communication with Elekta Oncology Systems, Crawley, UK.)

In the final leafbank, the projection of the TLW in the isocentric plane should be ca 1.1 cm and not exactly 1.1 cm, since all leaves have the same TLW and start at the same position on the CAX (29.8 cm). The density of the tungsten alloy has been taken 18.0 g cm\(^{-3}\).

In the MLCQ model, used further on in this study and part of the BEAM distribution, the leaves are not identical. The leaf sides are all focused to \( Z = 0 \) and the TLW is determined by: 
\[ \text{TWIDTH} / \text{NUM_LEAF} \]
with TWIDTH being the total width of the leafbank and NUM_LEAF the number of leaves (for the Elekta MLC = 40). The start position of the leaves on the Z-axis corresponds with ZSTART, the end position of every leaf corresponds with ZSTART + 7.5 cm. In this way,
Figure 4. Leaves (white) and back-up jaws (grey) settings for the measurement of intraleaf transmission and interleaf leakage. This configuration was simulated with CM MLCE and CM MLCQ.

The bottom of the leafbank is flat. The isocentric projection of every leaf is 1 cm. The MLCQ model does not model the air gap between adjacent leaves, nor the tongue-and-groove design (figure 3(d)). As a consequence this model only accounts for intraleaf transmission and not for interleaf leakage.

2.3. Experimental investigations

The first experiment for commissioning of the CM MLCE concerns the measurement and simulation of intraleaf transmission and interleaf leakage. Figure 4 shows the isocentric projection of the leaves and back-up jaws settings applied to determine the transmission through the MLC. The lower jaws were maximally retracted. As a reminder: the leaves move along the Y-axis and the X-axis is perpendicular to the leaves. These field settings were applied to the Elekta SLiplus linac for a 6 MV photon beam at the GUH for collimator angle 0° and 90°. X-profiles were considered in the isocentric plane, at a phantom depth of 5 cm and for an off-axis position of 5 cm (at position of the dotted line in figure 4). To avoid an important contribution from the part that is shielded only by the back-up jaws, the right edge of the phantom was aligned at \( y = -0.5 \) cm. In this study we will make a distinction between intraleaf transmission (indicated with line 1 in figure 3(c)) and interleaf leakage (line 2 in figure 3(c)) as defined in AAPM Report No 72.

The second experiment is the measurement of the tongue-and-groove effect of the Elekta MLC. This effect was defined by Webb (1997, 2001) as follows: ‘When a field is comprised of matched components in which either the tongue or the groove projects into the open part of the field, the resulting junctioned field may have an underdose in the region of interlock.’ These tongue-and-groove interlock regions can be comprised with either adjacent leaves or adjacent plus opposite leaves. Sykes and Williams (1998) performed extensive measurements of this effect for two Philips accelerators. The effect showed up as underdosage regions of 15% to 28% (Sykes and Williams 1998, Webb 2001). In this study the interlock regions are comprised with adjacent leaves (no opposite leaves). Therefore, two complementary fields were applied to the SLiplus linac. One of the two fields, referred to as field 1, is shown in figure 5. Field 2 is the complement of this leaf configuration (leaves which were opened in field 1 are closed in field 2 and vice versa). These leaf settings for fields 1 and 2 include regions covered by one, two, three and six leaves. For both fields, profiles were considered in the isocentric plane, at a depth of 1.5 cm and at \( Y = 0 \) cm.
2.4. Phantom and methods of dose measurements

Measurements of the leakage were performed with radiographic films (KODAK X-Omat V) of $33 \times 41$ cm. The films were placed in a polystyrene phantom, perpendicular to the beam axis. Optical density (OD) data were obtained with a 12 bit CCD based Vidar VXR-12 digitizer (Vidar Systems Corporation, VA, USA), using the method described in Martens et al (2002). The scans were performed at 300 dpi. The films were calibrated in a $10 \times 10$ cm field at the measuring depth of 5 cm (SSD = 95 cm).

To assess the reproducibility, profiles for collimator angles $0^\circ$ and $90^\circ$ were measured three times on a day. In addition, measurements were performed for the other leaf bank, only for collimator angle $90^\circ$ (Y1 and Y2 swapped in the collimator settings and profile measured at off-axis position of +5 cm).

As the X-Omat V films are known to have an energy and dose-rate-dependent response (Martens et al 2002), we performed comparative measurements with a diamond detector (PTW, Freiburg, Germany, type 60003) for a limited number of points. The diamond detector was oriented for maximum spatial resolution in the scan direction. This detector has in addition to a high spatial resolution (thickness of active volume is 0.21 mm) also an energy-independent response at megavoltage photon beams (Laub et al 1997, Mobit and Sandison 1999). The data obtained with the diamond detector were corrected for dose-rate dependence (Hoban et al 1994, Laub et al 1997). Note that using the diamond detector to measure all the profiles was not possible because of the required high spatial resolutions in combination with the low dose rate and thus the long measuring time per point.

The measurement of the tongue-and-groove effect was executed with a diamond detector in an automatic MP3 water phantom (PTW, Freiburg, Germany) for an SSD of 98.5 cm and the detector was placed in the isocentric plane (1.5 cm depth). The detector was oriented for maximum spatial resolution in the scan direction and a correction for dose-rate dependence was applied. The profile for each field configuration was measured independently from the other. In this way, by summing the two profiles, a direct comparison with MC simulations can be made.

2.5. MC computation technique and parameters

MC simulations with the linac model described in section 2.2 were split up into three parts. In the first step 18 Monte Carlo runs were performed with different random number seeds,
starting from a uniformly distributed parallel electron beam incident on the electron target. The energy of the incident electrons was sampled from the energy distribution published by Knight (1996). The electrons' path was modelled as an elliptic source, with longest axis 2 mm (along \( Y \)-axis) and short axis 0.9 mm (along \( X \)-axis). EGS4 transport parameters \( ECUT \) and \( PCUT \) were set to 700 keV and 10 keV, respectively, and the electron transport algorithm PRESTA (Bielajew and Rogers 1987) was enabled. The variance reduction methods for bremsstrahlung splitting (each bremsstrahlung photon was split into 25 photons with reduced weight) and range rejection (Rogers et al 1995) were enabled as well. For each of the 18 runs a phase-space file, containing information about \( 6 \times 10^7 \) particles, was scored under the mirror, in front of the field-dependent part of the treatment head (plane 1 in figure 1). Total calculation time for step 1 was 82 h on 18 individual calculation engines. For step 2 in the simulation process, these phase space files were used as a particle source for radiation transport through the field-dependent components. Depending on the field configuration, the particles in the phase space file were re-used several times. A second phase space file was scored at the front surface of the phantom (plane 2 in figure 1). The space between the mylar foil exit window and the phantom surface was modelled with a slab, set to medium air. The third step involves a dose calculation in DOSXYZ.

The two experiments (measurement of intraleaf transmission and interleaf leakage and the tongue-and-groove effect) were simulated with CM MLCQ and the new CM MLCE. The CM MLCQ represents the ‘ideal’ situation where the air gap is zero, while CM MLCE simulates the situation with a non-zero air gap. Thus CM MLCE simulates both intraleaf transmission and interleaf leakage while CM MLCQ simulates transmission through the MLC. The geometric parameters for CM MLCQ were chosen so that the MLCQ leaf sides intersect the tongue-and-groove region of CM MLCE symmetrically.

For simulation of the intraleaf transmission and interleaf leakage, particles from the phase space file under the mirror were re-used three times with different random number seeds to ensure independent histories. The option of range rejection was enabled in the simulation. The resulting phase-space file in the simulation of the transmission contained about \( 1 \times 10^6 \) particles when the simulation was done with CM MLCE and \( 0.37 \times 10^6 \) when simulated with CM MLCQ, at the front surface of the phantom (at 95 cm, plane 2 in figure 1). The phase space files fully characterize the incident radiation fluence on the phantom surface. These phase space files were used as an input for in-phantom dose calculations with DOSXYZ. The voxels for both MLCQ and MLCE simulations were 0.1 cm wide in the direction perpendicular to the leaf motion, 0.4 cm thick along the CAX where the isocentric plane intersects the voxel in the middle and 1 cm in the direction of the leaf motion. The phantom was represented by a homogeneous polystyrene medium with an experimentally determined density of 1.04 g cm\(^{-3}\). The transport parameter for EGS4 were set to \( ECUT = 561 \) keV and \( PCUT = 10 \) keV in DOSXYZ.

The tongue-and-groove effect was also simulated with both CM MLCQ and CM MLCE. Simulations with CM MLCE incorporate the tongue-and-groove design of the leaves and the interleaf leakage. Comparison with the MLCQ simulations indicate the influence of both the tongue-and-groove design and the air gap. The phase space file at the back of the mirror was used once. The resulting phase space file at the front surface of the phantom contained about \( 2.6 \times 10^7 \) particles for field 1 and \( 2.4 \times 10^7 \) for field 2, for both CM MLCQ and CM MLCE. These phase space files were used for in-phantom dose calculations with DOSXYZ. The voxels were 0.1 cm wide in the direction perpendicular to the leaf motion, 0.2 cm along the CAX with the isocentric plane intersecting the middle of the voxel and 1 cm in the direction of the leaf motions. The medium in all voxels was set to water.
To compare the performance of the CM MLCE, a fluence simulation was made for a 10 x 10 cm² field. No dose calculation was performed in these simulations. With the new CM MLCE, 3.5 h of calculation time was necessary, compared to 1.44 h with CM MLCQ and 1.22 h for CM MLC.

3. Results and discussion

3.1. MLC leakage and transmission

3.1.1. Dose distribution at 5 cm depth. Figure 6 shows the measured intraleaf transmission and interleaf leakage for the leaf configuration of figure 4. The dose profiles are expressed as a percentage of the open field dose (dose for a 10 x 10 cm² on the CAX at 5 cm depth for SSD = 95 cm). A very good agreement between the relative profiles as measured with film and with diamond detector was found. However, when comparing the profiles in an absolute way, we found a 3% lower response for film than for the diamond detector. Therefore a correction of 3% was applied to all film measurements represented in this manuscript. All profiles were reproduced perfectly in the two additional measurements with radiographic film on the same day at the Y1 (90° collimator angle) and Y2 (0° and 90° collimator angles) side. The film measurements at the Y2 side showed an average transmission of 1.42% for collimator angle 90° and 1.40% for collimator angle 0°. The position and shape of the peaks were perfectly reproduced at both angles. The little difference of 0.02% in the average transmission is not noticeable in figure 6. At the Y1 side of the MLC, a transmission of 1.57% was measured for collimator angle 90°. The difference with the measurements at the Y2 side at both 0° and 90° is clear in figure 6. The differences in leakage between Y1 and Y2 leafbanks are within manufacturing tolerances. The Monte Carlo simulations will be referred to the measurement at the Y2 side at collimator angle 90°.

A comparison between the Monte Carlo simulation with CM MLCQ and CM MLCE is shown in figure 7, together with the measured profile for collimator angle 90° at the Y2 side. The average transmission of radiation calculated with MLCQ is 0.622% (±0.021%) which is only 44% of the measured transmission at the Y2 side for collimator angle 90°, indicating...
that the transmission is significantly underestimated when the air gap is neglected. The MC calculation with CM MLCE has been repeated with several air gap sizes. Recall that the variation of the air gap size corresponds with the variation of the leafpitch (LP) size within tolerance limits of technical drawings (2.1.2). The variation of the average total transmission (=intraleaf transmission and interleaf leakage) with the air gap size as derived from the MC calculations is: 

\[ D = 3.6 \times 10^{-5} \ AG + 6.12 \times 10^{-3} \]  

with \( D \) the total transmission in per cent of the open field dose and \( AG \) the air gap size in \( \mu \text{m} \). With a measured transmission of 1.42% the air gap size is taken 224 \( \mu \text{m} \) in CM MLCE. The result of the MC simulation with this air gap size is plotted in figure 7 (full black line). The maximum dose peaks are equally spaced by 1 cm in the isocentric plane, as could be expected from the MLCE model. The positions and widths of the peaks agree well with the measured profile. The average height of the measured dose peaks (peak to valley) is 0.33% with a standard deviation of the mean \( (\mu_A) \) of 0.16%, while the average calculated height is 0.78% with \( \mu_A = 0.07\% \). This great difference in peak heights between calculation and measurement may be caused by mechanical displacement of every individual leaf and by fluctuations of the dimension of the TGW, the TLW and the BLW (and as a consequence fluctuations in the AG size).

The full lines in figure 7 represent quadratic fits to the different components contributing to the total transmission through the leafbank (measured transmission, MLCE and MLQ calculation and calculated scattered radiation). The calculated scattered radiation accounts for on average 0.25% \( (\mu_A = 0.02\%) \) of the total transmission. The transmission without the interleaf leakage and with the scattered photons incorporated accounts for 0.62% \( (\mu_A = 0.02\%) \) on average (calculated with MLQ). The total transmission is 1.42% \( (\mu_A = 0.05\%) \), so the leakage component contributes another 0.80% \( (\mu_A = 0.07\%) \) to the total transmission. For comparison, the full grey line is a quadratic fit to the measured dose profile (collimator angle 90°, Y2 side). The quadratic fit to the measurement (grey) agrees well with the quadratic fit to the calculated dose profile (black).

3.1.2. Energy aspects of leakage and transmission. The effect of the air gap on the energy distribution of photons at the phantom surface is shown in figures 8(a)–(c).
Figure 8(a) shows the photon energy distribution at the phantom surface for a $10 \times 10$ field. Figure 8(b) shows the energy distribution of photons at the phantom surface for a MLC-blocked field (described in figure 4) calculated with MLCQ (grey) and MLCE (black). The vertical axis shows the percentage photons per energy-interval of the total number of transmitted photons (for MLCQ the total number of transmitted photons was $0.37 \times 10^6$ while for MLCE we obtained $1 \times 10^6$). This spectrum was taken over energy-intervals of 10 keV, the total sum over these intervals gives 100%. In the MLCE calculation the number of transmitted high-energy photons is much larger than in the MLCQ calculation, due to the presence of the air gaps, showing a lower contribution of the low-energy photons to the total number of transmitted photons in the spectrum. The average photon energy in a $10 \times 10$ field is 1.83 MeV (calculated) while the average energy of the transmitted photons is 2.17 MeV ($\mu_A = 0.03$ MeV) when calculated with MLCQ (no interleaf leakage) and 2.32 MeV ($\mu_A = 0.02$ MeV) when calculated with MLCE (interleaf leakage incorporated). In both cases blocking a half-open field causes beam hardening. Due to the presence of the air gaps much greater high-energy photons are transmitted through the leafbank. Thus, incorporation of this interleaf leakage induces an additional beam hardening with an average energy increase of 150 keV. In figure 8(c) the average photon spectrum for the 20 central peaks is plotted together with the average photon spectrum of the 20 central valleys. The average energy of the peaks is 2.45 MeV ($\mu_A = 0.02$ MeV) while the average energy of the valleys is 2.22 MeV ($\mu_A = 0.02$ MeV). The greater average photon energy in the peaks
can be contributed to the larger number of transmitted high-energy photons through the air gap compared to the situation where there is no air gap present. The low-energy photons are mostly Compton-scattered and are deviated from their original direction of flight, contributing both to the low-energy part in peaks and valleys. The additional beam hardening can be fully contributed to the inclusion of the interleaf leakage component in the transmission. The monochromatic line at 511 keV results from positron annihilation photons.

3.2. The ‘tongue-and-groove’ effect

3.2.1. Dose distribution at $d_{max}$ The dashed lines in figures 9(a) (MLCQ) and 10(a) (MLCE) are the calculated dose distributions for field 1 (leaf configuration in figure 5) at a depth of 1.5 cm along the $y = 0$ axis. The full grey line indicates the result of the measurement with the diamond detector. The regions covered by two or more leaves in field 1 show an underdosage when the dose is calculated without the interleaf leakage incorporated (MLCQ, figure 9(a)). With the MLCE model these low dose regions agree better with the measured profile (MLCE, figure 10(a)). The dose increase due to the incorporation of interleaf leakage is on the average 14% for regions covered by two leaves and 40% for three or more leaves. The dose increase is less pronounced for less than three closed leaves because of lateral scattering of radiation from the open leaf regions. The same results are seen in figure 9(b) for the field 2 configuration (the complement of leaf configuration in figure 5): regions covered by three or more leaves have an underdosage. These artefacts have disappeared when the simulation is repeated with MLCE (figure 10(b)). The penumbras in the profiles calculated with MLCE
agree better with the measured profile, indicating that the tongue-and-groove design has a significant effect on the shape of the penumbra.

3.2.2. The tongue-and-groove effect. By summing the dose profiles of fields 1 and 2 at 1.5 cm depth in the water phantom, the tongue-and-groove effect shows up as underdosage dips in regions where adjacent leaves are complementary opened or closed. The full grey line in figures 9(c) (MLCQ) and 10(c) (MLCE) is the sum of the measured profiles. The tongue-and-groove effect appears as underdosage dips from 22% up to 44% in the outer regions of the profile. As can be seen from figure 10(c), the underdosage dips are accurately reproduced when the dose profiles are calculated with MLCE. The MLCQ module is not able to predict the underdosage dips in the profile.

The appearance of the tongue-and-groove effect can be explained when we look closer at the projected leaf width in the isocentric plane. We consider leaves 12, 13 and 14 in detail. In figure 11(b), the full black line is the calculated dose profile for field 1 and the dashed black line is the calculated profile for field 2, when calculated with CM MLCQ. The full grey line indicates the projected width of the closed MLCQ-leaves in field 1 (leaf 12 and 14, see figure 5), while the dashed grey line indicates the projected width of the closed MLCQ leaf in field 2 (leaf 13). Recall that the projected leaf width of the MLCQ leaves in the isocentric plane is 1 cm (figure 11(a)). From figure 11(b) it can be seen that the projected leaves predict the position where the penumbra falls to 50% for both fields 1 and 2. Since the projected leaves do not overlap, the position of the 50% penumbra is the same for fields 1 and 2, leading to a more or less flat profile when the profiles are summed (grey dotted line in 10(b)). The same plots are made for MLCE in figure 11(c). The MLCE leaves all have an isocentric projected leaf width of ca 1.1 cm (figure 11(a)). It can be seen that the projected leaf widths overlap, but...
still predict the position of the 50% penumbra. Due to this overlap between adjacent projected leaves, the penumbras of fields 1 and 2 do not fall to 50% at the same position. This shift of the 50% penumbra causes the tongue-and-groove effect (dotted line in figure 11(c)).

4. Conclusions

With the BEAM program it is possible to simulate a clinical linac and a realistic fluence output from the treatment head. When an MLC is used to define irregular field shapes, some attention should be paid to the model used in the Monte Carlo simulation. In this paper we demonstrated that a detailed component module which incorporates an air gap and the tongue-and-groove design is necessary and should be preferred to a simplified model which does not take into account the exact geometry of the leaves. The effect of including the interleaf leakage in the simulation, an additional 0.80%, is significant. The modelling of the tongue-and-groove design is important for an accurate simulation of the penumbras. The new MLC model for the Elekta MLC in BEAM (called MLCE) is able to predict the total transmission (intraleaf transmission and interleaf leakage) through the MLC and the tongue-and-groove effect. When IMRT fields are simulated with the BEAM code, a detailed MLC model such as MLCE is needed to make a realistic calculation.

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