*The British Journal of Radiology, 000* (2010), 1–10

# Impact of the high-definition multileaf collimator on linear accelerator-based intracranial stereotactic radiosurgery

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**ABSTRACT.** The impact of two multileaf collimator (MLC) systems for linear accelerator-based intracranial stereotactic radiosurgery (SRS) was assessed. 68 lesions formed the basis of this study. 2.5-mm leaf width plans served as reference. Comparative plans, with identical planning parameters, were based on a 5-mm leaf width MLC system. Two collimation strategies, collimation fixed at 0° or 90° and collimation optimised per arc or beam, were also assessed. Dose computation was based on the pencil beam algorithm with tissue heterogeneity accounted for. Plan normalisation was such that 100% of the prescription dose covered 95% of the planning target volume. Plan evaluation was based on target coverage and normal tissue avoidance criteria. The median conformity index difference between the MLC systems ranged between 0.8% and 14.2%; the 2.5-mm MLC exhibited better dose conformation. The median reduction of normal tissue exposed to ⩾100%, ⩾50% and ⩾25% of the prescription dose ranged from 13.4% to 29.7%, favouring the 2.5-mm MLC system. Dose fall-off was steeper for the 2.5-mm MLC system with an overall median absolute difference ranging from 0.4 to 1.2 mm. The use of collimation optimisation resulted in a decrease in differences between the MLC systems. The results demonstrated the dosimetric merit of the 2.5-mm leaf width MLC system over the 5-mm leaf width system, albeit small, for the investigated range of intracranial SRS targets. The clinical significance of these results warrants further investigation to determine whether the observed dosimetric advantages translate into outcome improvements.

Received 19 September 2009
Revised 23 March 2010
Accepted 18 May 2010

DOI: 10.1259/bjr/19726857



The principal goal of stereotactic radiosurgery (SRS) is to provide a method for focal irradiation of target tissue to higher doses without increasing normal tissue complication. Historically, linear accelerator-based SRS treatment planning and delivery has relied upon non-coplanar arc therapy delivered through small (≤40 mm) circular collimators. However, over the last 15 years, multileaf collimators (MLCs), now a routine appendage to modern linear accelerators (linacs), have evolved in terms of both field size and width of the individual tungsten leaves, and it is intuitive to assume that target dose conformity and/or the steepness of the dose gradient can be influenced by decreasing MLC leaf width.

The advantage of the smaller leaf width has been studied by several groups [1–11], but with mixed results. Kubo et al [7] were the first to assess the conformity of three-dimensional (3D) conformal plans using 1.7, 3 and 10-mm leaf width MLC systems. The authors showed that the 1.7- and 3.0-mm MLCs met the Radiation Therapy Oncology Group guidelines for static-field SRS treatment planning [12, 13]. Subsequently, Fiveash et al [5] compared intensity-modulated radiotherapy plans between a 5-mm MLC and a 10-mm MLC in three cranial cases and observed noticeably better sparing of optic structures for the 5-mm MLC. Monk et al [8], in a study of 14 intracranial cases, showed that 3-mm MLC improves both planning target volume (PTV) conformity and normal tissue sparing over 5-mm MLC for intracranial static-field SRS. However, the authors concluded that quantitative differences between the 3- and 5-mm leaf MLC collimation (based on 5% for tissue sparing) may not be clinically significant for some cases. Jin et al [6], in an intensity-modulated radiotherapy and radiosurgery study of 54 patients, concluded that the 3-mm MLC has a better conformity index and better sparing of small organs at risk (OARs) than either the 5-mm or the 10-mm MLC with a target volume dependence. Burmeister et al [2], on the other hand, reported no apparent clinically significant difference between the 5- and 10-mm MLC systems on three patients treated with intensity-modulated radiotherapy, except for very small target volumes or those with concavities that are small with respect to the MLC leaf width. More recently, Wu et al [11], in a preliminary evaluation of the dosimetric impact of a 2.5-mm MLC over the 5-mm MLC for various treatment techniques and for a subset of five brain tumour cases abutting the brainstem, showed that the 2.5-mm leaf width MLC in combination with the intensity-modulated radiotherapy technique can yield dosimetric benefits to the treatment of small lesions in cases involving complex target/organ-at-risk geometry. The current study was

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designed to provide a more comprehensive assessment of the performance of the 2.5-mm leaf MLC system over the 5-mm leaf system for target volumes characteristic of intracranial SRS, and assess if potential gains realised may be clinically meaningful.

## Materials and methods

### *Patient population and treatment planning*

68 metastatic brain lesions of patients previously treated with SRS in the Department of Radiation Medicine at the Oregon Health and Science University in Portland, OR, USA, between June 2008 and July 2009 form the basis of the current retrospective study. The study was approved by the Oregon Health and Science University Institutional Review Board. Each patient was immobilised with a relocatable thermoplastic mask system (Orfit Industries, Wijnegem, Belgium) and underwent a high-resolution (1 mm slice thickness) CT scan on a dedicated 16-slice big-bore CT simulator (Philips Medical Systems, Cleveland, OH). High-resolution $T_1$ weighted post-contrast magnetic resonance (MR) images (1.3 mm slice thickness, 1.3 mm spacing) were also obtained for all patients, usually within a week of planned treatment. Both CT and MR images were electronically transferred to a radiation therapy planning system (iPlan RT Dose v3.0.2 and 4.1, BrainLAB AG, Heimstetten, Germany) for co-registration using the planning system's integrated intensity-based mutual information automatic registration algorithm. All fusions were visually inspected and approved by the radiation oncologist.

Reference plans were computed for the 120-leaf high-definition (HD) MLC system (BrainLAB/Varian Novalis TX), characterised by a spatial resolution of 2.5 mm at the isocentre for the central 8 cm, and of 5 mm elsewhere [14]. To assure valid data generation, all reference plans were carefully selected from a larger library of SRS plans to ensure that target volumes were conformed by the central 2.5-mm leaves of the HD-MLC system. The gross tumour volume (GTV), delineated on MR images with no margin expansion to a PTV, was the basis of treatment planning. All plans were computed using a pencil beam algorithm for a 6-MV photon beam energy at a maximum dose rate of 1000 MU $min^{-1}$ such that the prescribed dose (PD) encompassed 95% of the PTV, with a heterogeneous dose distribution and a desired plan maximum of 150% of the PD. A dose resolution of 2 mm was set. To ensure accurate dose computation, an adaptive dose calculation grid function was enabled to automatically adjust the dose resolution such that a minimum of 10 voxels are always used for dose computation on each dimension inside a target of interest, irrespective of its geometry. Tissue heterogeneity was taken into account.

Planning techniques included static 3D conformal radiotherapy (3DCRT, $n = 9$), step-and-shoot intensity-modulated radiosurgery (IMRS, $n = 18$) and dynamic conformal arc (DCA, $n = 41$). For DCA planning, the default number and length of arcs were 5 and 120˚, respectively, equally space at 45˚ couch angles. In some patients, the number of arcs may be increased or decreased, or shorter arc length or changes in couch position may be used to avoid traversing OARs such as the optic nerve or chiasm, brainstem and eyes. For the current cohort, a median number of 5 (range 4–11) equally weighted arcs with a cumulative median number of 660 arc-degrees (range 500–990) was used for DCA planning. In the event that DCA proved unsuitable in terms of tumour coverage and normal tissue and/or OAR avoidance, 3DCRT or IMRS planning is used. A median number of 13 (range 9–18) equally weighted beams was used for 3DCRT or IMRS planning in the current cohort. Like the arcs in DCA, beams in 3DCRT and DCA were arranged in a practical manner according to tumour and critical organ location for the purpose of achieving maximal target coverage and optimal dose conformality while keeping doses to OARs below institutional dose limits. IMRS dose optimisation parameters typical of the current cohort included a 2-mm PTV grid size with adaptive resolution for small objects, a 3% sharp edge smoothing filter, a 30-segment step-and-shoot technique with 2-mm beamlets and MLC tongue-and-groove optimisation. Normal tissue restriction was applied with a 2-mm normal tissue dose grid size, 24- and 16-mm margins around the PTV with and without restriction, respectively. Hot beam MU was set at 150% and a Kernel resolution of 2.5 mm was used. The iPlan RT Dose inverse planning provides four constraint weighting methods, starting with a PTV-only optimisation (*i.e.* excluding OAR constraints). After the optimal PTV coverage is obtained, OAR constraints with different relative weight factors (or penalties) are included in the cost function, resulting in plans with an OAR of low, medium or high importance. Although OAR medium or high optimisation generally provided better OAR sparing, these optimisation methods compromised PTV coverage; hence, the selection of OAR low optimisation for the current cohort. A 0–2 mm margin was added around the PTV, with a median leaf edge to PTV contour-fitting technique for DCA and 3DCRT techniques.

Comparative plans were based on the 120-leaf Millennium MLC system (Varian Medical Systems, Palo Alto, CA), characterised by a spatial resolution of 5 mm at isocentre for the central 20 cm and of 10 mm elsewhere [15]. Comparative plans were generated by computing or re-optimising corresponding reference plans such that PTVs were conformed by only the central 5-mm leaves of the Millennium MLC system. In addition to the influence of the respective MLC systems on SRS dose distributions and normal and/or critical structure avoidance, the impact of collimation strategy was also investigated. Thus, besides the available 2.5-mm MLC reference plans and their corresponding 5-mm MLC comparative plans, all generated with collimation fixed at either 0˚ or 90˚, an identical set of plans was created with collimation optimised per field or arc to minimise field aperture as a result of improved MLC shaping around the PTV. In total, 272 treatment plans formed the basis of this study.

### *Evaluation parameters*

Studies were categorised into three groups according to PTVs: (1) PTV$<1$ cm$^3$ ($n = 34$), (2) 1 cm$^3$ $\leq$ PTV$<5$ cm$^3$ ($n = 25$) and (3) PTV $\geqslant 5$ cm$^3$ ($n = 9$). Each



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treatment plan was evaluated with respect to target coverage and normal tissue sparing criteria.

In terms of target coverage criteria, PTV dose–volume histogram (DVH) parameters including minimum dose (or $D_{min}$, defined in this study as dose to 99% of the PTV) and maximum dose (or $D_{max}$, defined in this study as dose received by the ''hottest'' 3% volume of the PTV) were computed and recorded. Dose conformity was quantified using a robust conformity index (CI) formulation (Equation 1) that takes into account the location of the prescription isodose surface with respect to the PTV, as well as the volume of normal tissue being treated [16–17]

$$\mathrm{CI} = \frac{V_{\mathrm{PTV}} \times V_{\mathrm{PIS}}}{[\mathrm{PTV}_{\mathrm{PIS}}]^2} \qquad (1)$$

where PIS is the prescription isodose surface, $V_{PTV}$ is the magnitude of the planning target volume, $V_{PIS}$ is the volume encompassed by the prescription isodose surface and $PTV_{PIS}$ is the planning target volume encompassed within the prescription isodose surface.

A peritumoural rind volume (PRV), defined in the current study as a 20-mm wall from the surface of the PTV, was used to evaluate and quantify healthy tissue sparing. Of interest were $PRV_{100}$ (PRV receiving $\geqslant$100% of the prescription dose), $PRV_{50}$ (PRV receiving $\geqslant$50% of the prescription dose) and $PRV_{25}$ (PRV receiving $\geqslant$25% of the prescription dose). A gradient score index by Meeks et al [18] and Wagner et al [19], defined as

$$G = 100 - [100 \cdot [(R_{\mathrm{eff},\,Rx} - R_{\mathrm{eff},\,50\%Rx}) - 0.3] \qquad (2)$$

where $R_{eff,Rx}$ is the effective radius of the prescription isodose volume and $R_{Eff,50\%Rx}$ is the effective radius of the isodose line equal to one-half of the prescription isodose line, was also used to quantify dose fall-off in normal tissue. The effective radius was quantified by

$$R_{\mathrm{eff}} = \sqrt[3]{\frac{3V}{4\pi}} \qquad (3)$$

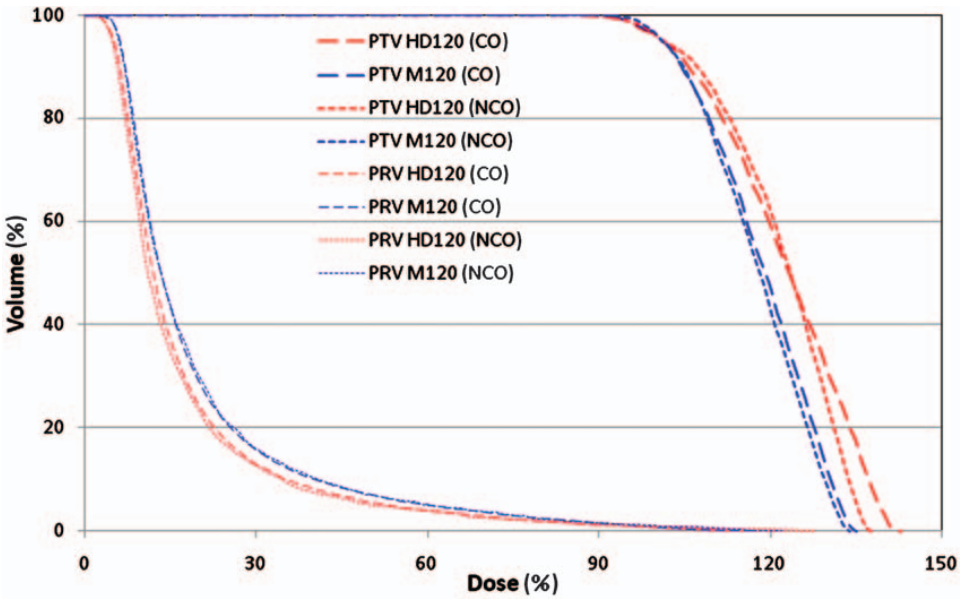
### Statistical consideration

The Wilcoxon signed rank test was performed to assess differences between the 2.5 and 5-mm MLC systems, with a $p$ value $<0.05$ defining statistical significance.

## Results

### Target dose–volume parameters

The median PTV was 1.0 $cm^3$ (range 0.1–11.1 $cm^3$); 1.7 $cm^3$ (range 0.4–3.3 $cm^3$) for 3DCRT, 2.9 $cm^3$ (range 0.1–11.1 $cm^3$) for IMRS and 0.7 $cm^3$ (range 0.06–9.1 $cm^3$) for DCA planned cases, respectively. The median prescription dose was 22 Gy (range 15–24 Gy). The DVHs for all involved treatment planning techniques are shown for a representative case in Figure 1. Tables 1 and 2 summarise the mean and median differences in the minimal, mean and maximal PTV doses, including the dose conformity index, as a function of PTV. Table 1 indicates small absolute, but unequivocal statistically significant, differences between the 2.5 and the 5-mm MLC systems for PTVs $<1$ $cm^3$ in terms of minimal, mean and maximal PTV doses. Table 2 shows unequivocal statistically significant differences between the MLC systems, albeit small in absolute terms, for the DCA and 3DCRT techniques, unlike the IMRS technique. Regarding isodose conformation, while there was a




COLOR FIGURE

**Figure 1.** Normal tissue (PRV) and target volume (PTV) dose-volume histograms generated from a dynamic conformal arc planning technique for the two MLC systems with collimation either optimised (CO) or not (NCO).



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**Table 1.** Difference in target dose–volume parameters as a function of planning target volume. Differences presented as mean ± standard deviation, with median differences and their corresponding median per cent differences presented in parentheses

| Category | [a]$D_{min}$ (Gy) | [b]$D_{mean}$ (Gy) | [b]$D_{max}$ (Gy) | [b]Conformity index |
|---|---|---|---|---|
| **No collimation optimisation** | | | | |
| Overall ($n$ = 68) | 0.09 ± 0.40 | 0.36 ± 0.48 | 0.91 ± 0.52 | 0.32 ± 0.78 |
| | (0.15, 0.7%) | (0.41, 2.0%) | (0.82, 3.5%) | (0.11, 7.0%) |
| | 0.010 | <0.001 | <0.001 | 0.001 |
| I ($n$ = 34) | 0.16 ± 0.36 | 0.58 ± 0.42 | 1.10 ± 0.58 | 0.56 ± 1.05 |
| | (0.19, 0.9%) | (0.55, 2.5%) | (1.10, 3.8%) | (0.24, 11.3%) |
| | <0.001 | <0.001 | <0.001 | <0.001 |
| II ($n$ = 25) | 0.16 ± 0.37 | 0.27 ± 0.42 | 0.73 ± 0.33 | 0.09 ± 0.09 |
| | (0.22, 1.2%) | (0.39, 1.9%) | (0.75, 3.4%) | (0.08, 5.2%) |
| | 0.037 | 0.007 | <0.001 | <0.001 |
| III ($n$ = 9) | −0.34 ± 0.42 | −0.21 ± 0.35 | 0.66 ± 0.47 | 0.07 ± 0.05 |
| | (−0.38, −2.6%) | (−0.25, −1.3%) | (0.60, 3.2%) | (0.07, 4.6%) |
| | 0.051 | 0.138 | 0.009 | 0.008 |
| **Collimation optimisation** | | | | |
| Overall ($n$ = 68) | −0.09 ± 0.28 | −0.07 ± 0.27 | 0.15 ± 0.38 | 0.15 ± 0.34 |
| | (−0.05, −0.3%) | (−0.08, −0.4%) | (0.05, 0.2%) | (0.05, 3.0%) |
| | 0.010 | 0.007 | 0.004 | <0.001 |
| I ($n$ = 34) | −0.13 ± 0.34 | −0.16 ± 0.25 | 0.26 ± 0.48 | 0.26 ± 0.45 |
| | (−0.09, −0.4%) | (−0.15, −0.7%) | (0.23, 0.9%) | (0.15, 14.2%) |
| | 0.022 | <0.001 | 0.004 | <0.001 |
| II ($n$ = 25) | −0.09 ± 0.18 | −0.00 ± 0.30 | 0.11 ± 0.21 | 0.05 ± 0.09 |
| | (−0.06, −0.3%) | (−0.06, −0.3%) | (0.05, 0.2%) | (0.03, 2.7%) |
| | 0.010 | 0.294 | 0.028 | 0.007 |
| III ($n$ = 9) | 0.10 ± 0.19 | 0.09 ± 0.17 | −0.12 ± 0.09 | 0.01 ± 0.04 |
| | (0.14, 0.8%) | (0.05, 0.3%) | (−0.13, −0.8%) | (0.01, 0.8%) |
| | 0.192 | 0.086 | 0.015 | 0.635 |

$n$, number of cases; PTV, planning target volume; MLC, multileaf collimator; HD120, high-definition 120-leaf MLC; M120, millennium 120-leaf MLC; $D_{mean}$, sum of the product of dose value and percent volume in each dose bin; $D_{min}$, dose to 99% of the PTV; $D_{max}$, dose to the ''hottest'' 3% of the PTV.
[a]HD120 minus M120.
[b]M120 minus HD120.

quantitative and statistically significant difference between the MLC systems, this difference was most noticeable for PTVs <1 $cm^3$ and the DCA technique (Figure 2).

### *Normal tissue sparing*

Table 3 and 4 show quantitative evidence of improved normal tissue sparing of the 2.5-mm MLC system over the 5-mm MLC system for small and large PTVs alike. The median reduction of normal tissue exposed to ⩾100%, ⩾50% and ⩾25% of the prescription dose was 14.9%, 29.7% and 22.4%, respectively, without collimation optimisation. With collimation optimisation, the median reduction was 13.4%, 14.3% and 13.4%, respectively. When combining all isodose levels, the median dose reduction decreased from 17.4–34.6% (for PTVs <1 $cm^3$) to 8.1–13.8% (for PTVs >5 $cm^3$) with use of the 2.5-mm MLC system and no collimation optimisation, compared with 19.8–21.2% to 2.3–5.2% with collimation optimisation. The DCA technique resulted in the largest overall improvement in normal tissue avoidance of the 2.5-mm MLC over the 5-mm MLC system (Table 5 and 6).

Regarding dose fall-off, the gradient was steeper for the 2.5-mm MLC system with an overall median absolute difference of 1.2 mm (~24% difference) without collimation optimisation and 0.4 mm (~8% difference) with collimation optimisation (Table 3). While the differences between the MLC systems were consistently statistically significant, the IMRS technique showed the smallest median difference (0.3 mm or ~5%) with application of collimation optimisation.

## Discussion

Modern linac-based SRS technology is characterised by tremendous flexibility in treatment options. Treatments can be administered by means of circular or multileaf collimator-based forward planning strategies or multileaf collimator-based inverse planning methods, with patients immobilised by frame-based or frameless techniques employing image guidance methodologies [20]. At present, several treatment planning techniques are available for linac-based SRS, but in an individual case the best choice for one or other of these techniques is not always obvious, in spite of several planning studies that have been published [21–26].

At our institution, the default SRS delivery technique uses the 2.5-mm leaf width Varian/BrainLab high-definition MLC system [14] to conform to the beam's-eye view of the target with the shape changing every arc degree throughout the treatment. Although this results in a highly conformal treatment, location in close proximity of OAR(s) may preclude some tumours from being treated safely with the DCA technique. In such circumstances, including the treatment of irregularly shaped targets, IMRS may provide a more superior option [27–29], because being an inverse planning



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**Table 2.** Differences in target dose–volume parameters as a function of treatment planning technique. Differences presented as mean ± standard deviation, with median differences and their corresponding median percent differences presented in parentheses

| Category | [a]$D_{min}$ (Gy) | [b]$D_{mean}$ (Gy) | [b]$D_{max}$ (Gy) | [b]Conformity index |
|---|---|---|---|---|
| **No collimation optimisation** | | | | |
| 3DCRT ($n$ = 9) | 0.26 ± 0.13 (0.24, 1.4%) 0.008 | 0.52 ± 0.20 (0.48, 2.5%) 0.008 | 0.80 ± 0.27 (0.72, 3.5%) 0.008 | 0.20 ± 0.21 (0.13, 6.8%) 0.008 |
| IMRS ($n$ = 18) | −0.27 ± 0.46 (−0.34, −1.9%) 0.039 | −0.10 ± 0.52 (−0.18, −0.9%) 0.223 | 0.77 ± 0.61 (0.66, 2.8%) <0.001 | 0.41 ± 0.98 (0.09, 5.5%) 0.006 |
| DCA ($n$ = 41) | 0.21 ± 0.32 (0.22, 1.2%) <0.001 | 0.53 ± 0.37 (0.53, 2.3%) <0.001 | 0.99 ± 0.51 (0.90, 3.5%) <0.001 | 0.31 ± 0.76 (0.12, 7.1%) <0.001 |
| **Collimation optimisation** | | | | |
| 3DCRT ($n$ = 9) | −0.17 ± 0.23 (−0.06, −0.4%) 0.009 | 0.13 ± 0.40 (0.00, 0.0%) 0.593 | 0.05 ± 0.18 (0.00, 0.0%) 0.761 | 0.05 ± 0.04 (0.03, 2.1%) 0.021 |
| IMRS ($n$ = 18) | −0.05 ± 0.34 (−0.08, −0.4%) 0.879 | −0.08 ± 0.21 (−0.12, −0.6%) 0.078 | 0.09 ± 0.30 (0.00, 0.0%) 0.663 | 0.05 ± 0.16 (0.02, 1.5%) 0.296 |
| DCA ($n$ = 41) | −0.09 ± 0.26 (−0.07, −0.3%) 0.018 | −0.10 ± 0.25 (−0.15, −0.4%) 0.012 | 0.20 ± 0.44 (0.22, 0.9%) 0.005 | 0.21 ± 0.41 (0.08, 5.0%) <0.001 |

$n$, number of cases; PTV, planning target volume; MLC, multileaf collimator; HD120, high-definition 120-leaf MLC; M120, millennium 120-leaf MLC; $D_{mean}$, sum of the product of dose value and percent volume in each dose bin; $D_{min}$, dose to 99% of the PTV; $D_{max}$, dose to the ''hottest'' 3% of the PTV; IMRS, intensity-modulated radiosurgery; 3DCRT, three-dimensional conformal radiotherapy; DCA, dynamic conformal arc.

[a]HD120 minus M120.

[b]M120 minus HD120.

technique, constraints can be set to modulate the intensity of the beam accordingly. Notwithstanding, like many other clinics, our institutions is also equipped with the 5-mm leaf-width millennium MLC system, giving us the flexibility to deliver treatment plans originally designed with a 2.5-mm MLC on the 5-mm MLC platform in the event of equipment failure. It is therefore equally important to characterise intracranial tumours into groups that will or will not benefit adequately from being treated by either collimation systems.

In the current work, we focused on the dosimetric differences between the 2.5-mm HD-MLC and the 5-mm Millennium MLC systems for the generation of DCA, 3DCRT and IMRS plans. The dosimetric changes from the 2.5 to the 5-mm MLC system were quantified in terms of differences in DVH parameters, target volume conformation, normal tissue avoidance and dose fall-off for patients treated with either of these techniques, categorised in different target volume groups.

The results demonstrated a trend between target conformation, expressed as a conformity index, and target volume, a pattern most exhibited by the DCA technique (Table 1 and Figure 1). For target volumes defined as small (*i.e.* <1 $cm^3$ in the current study), conformity index difference between the MLC systems was relatively large, and relatively small for target volumes defined as large (>5 $cm^3$), favouring the 2.5-mm MLC system with or without collimation optimisation (Table 1). Furthermore, the conformity index difference between the MLC systems was smaller for IMRS than for 3DCRT and DCA techniques for three seasons. First, target dose conformation in IMRS is partially contributed by beam modulation around the target boundary. The flexibility of beam modulation in any one dimension (direction of leaf motion, for example) is the same for all two MLC systems. Second, highly modulated beams are required to spare the OARs, which could put high dose in other area of normal tissue outside the target and, hence, could influence the conformity index a lot. While the 2.5-mm MLC may in general have more flexibility to block OARs, hence, higher dose to the other area of normal tissue outside the target, this might not be as significant an issue in the current study since OAR low optimisation as well as a large number of beams were used for IMRS planning. Finally, as presented in the results section, targets volumes associated with the IMRS technique were generally relatively larger than those of 3DCRT and DCA techniques [6].

In terms of DVH parameters including minimum, mean and maximum doses, the differences between the MLC systems were consistently statistically significant, except for target volumes >5 $cm^3$ (Table 1). Nonetheless, it was noticed that collimator optimisation reversed which of the two MLCs resulted in lower minimum and mean dose values. Furthermore, the minimum dose for the 5-mm MLC system was higher for IMRS than for 3DCRT/DCA in the absence of collimator optimisation (Table 2). This could be attributable to variation in the MLC margins (0–2 mm) set around PTVs to account for penumbra [6]. A more systematic study of the implications of MLC margins on DVH parameters would be needed to validate this assertion. Notwithstanding, absolute differences between the MLC systems were



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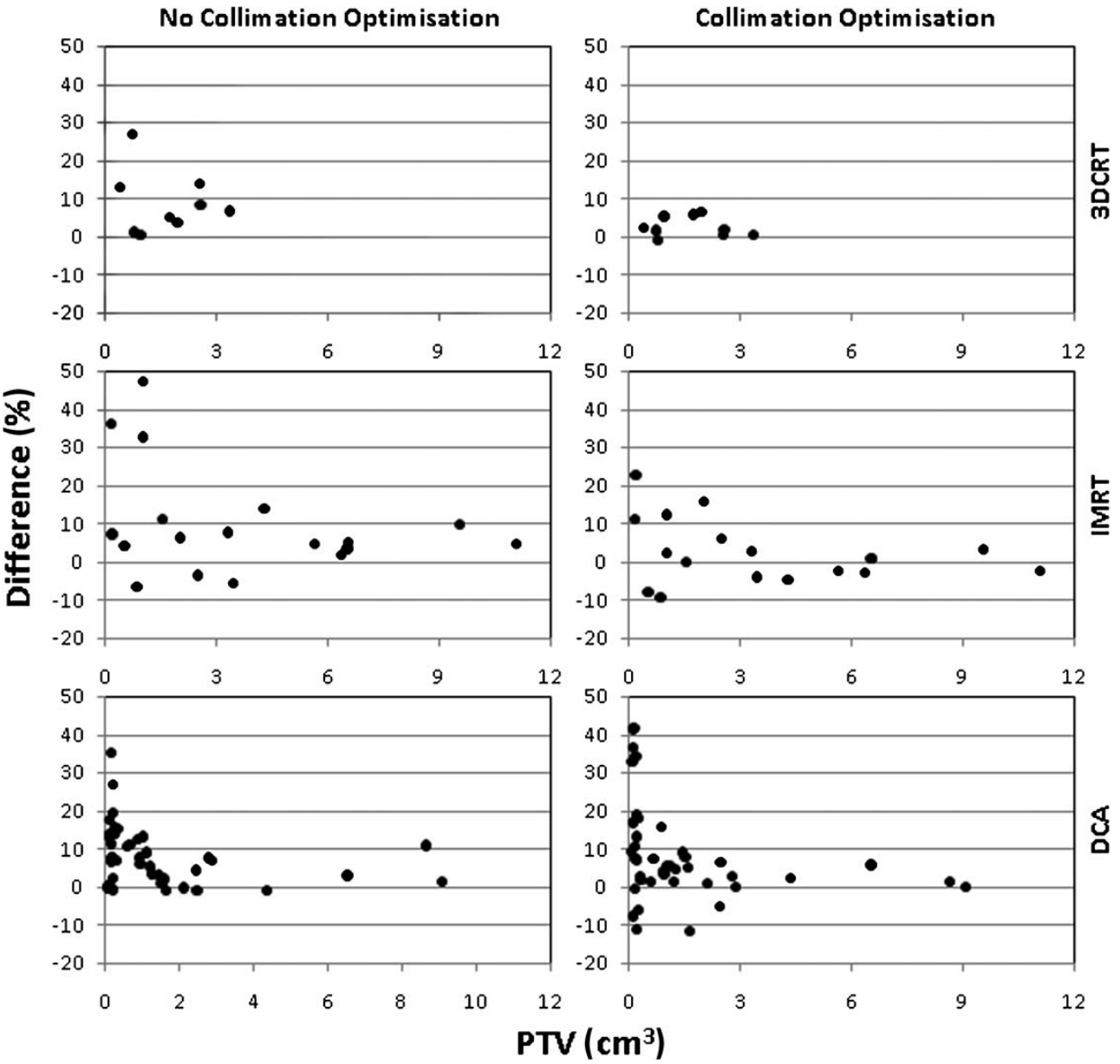


**Figure 2.** Conformity index differences between the 2.5- and the 5-mm MLC systems as a function of planning target volume (PTV) for treatment planning techniques including static conformal beams (3DCRT), step-and-shoot intensity-modulated beams (IMRS), and dynamic conformal arcs (DCA), with collimation either optimised or not.

quite small, more so with use of collimation optimisation, attributable in part to uniform target volume coverage as a result the large number of beams or arc-degrees used per treatment plan.

The creation of PRVs for different levels of dose allowed for the quantification of normal tissue sparing. This concept of PRV was adapted from works by Lee et al [30] and Chern et al [31] Unlike the study by Wu et al [11] in which the authors specifically measured the dose to the brainstem, the PRV was used in the current study to provide a more general framework to evaluate the effect of leaf width on the tissues immediately adjacent to the target, especially since there is little or no consistency in relative PTV critical structure proximity among the cases considered in the current study. Although the clinical importance of the differences between the MLC systems with regards to the radiation tolerance of OARs may be difficult to assess, the 2.5-mm width MLC system demonstrates an advantage in terms of normal tissue avoidance as confirmed by the mean difference in the volume of normal structure encompassed by the 25%, 50% and 100% isodose levels. Specifically, the overall median differences between the MLC systems were 22.4%, 29.7%, and 14.9% with fixed collimation, and 13.4%, 14.3%, and 13.4% with optimised collimation (Table 2). This difference is attributable, in part, to improvements in the design of the 2.5-mm MLC with reduced inter- and intraleaf leakage and smaller penumbra [22], although the latter will have less impact on a 3D dose distribution for a multiple beam arrangement when the contributions from the other beams are considered. Nonetheless, this difference in penumbra is expected to principally affect the volume of normal tissue encompassed by lower value isodoses, as is corroborated by results in Tables 3 and 5.



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**Table 3.** Difference in normal tissue avoidance parameters as a function of planning target volume. Differences presented as mean ± standard deviation, with median differences and their corresponding median percent differences presented in parentheses

| Category | [a]$PRV_{100}$ ($cm^3$) | [a]$PRV_{50}$ ($cm^3$) | [a]$PRV_{25}$ ($cm^3$) | [a]Gradient (mm) |
|---|---|---|---|---|
| **No collimation optimisation** | | | | |
| Overall ($n$ = 68) | 0.17 ± 0.32 | 2.96 ± 1.36 | 7.52 ± 2.66 | 1.26 ± 0.36 |
| | (0.08, 14.9%) | (2.39, 29.7%) | (6.91, 22.4%) | (1.23, 23.8%) |
| | <0.001 | <0.001 | <0.001 | <0.001 |
| I ($n$ = 34) | 0.17 ± 0.31 | 2.61 ± 1.47 | 7.51 ± 3.36 | 1.33 ± 0.37 |
| | (0.07, 17.4%) | (2.27, 37.4%) | (6.62, 34.6%) | (1.28, 22.5%) |
| | <0.001 | <0.001 | <0.001 | <0.001 |
| II ($n$ = 25) | 0.11 ± 0.21 | 3.05 ± 1.07 | 7.51 ± 1.81 | 1.19 ± 0.33 |
| | (0.10, 9.4%) | (2.76, 23.7%) | (7.30, 20.0%) | (1.19, 24.7%) |
| | 0.007 | <0.001 | <0.001 | <0.001 |
| III ($n$ = 9) | 0.38 ± 0.54 | 4.06 ± 1.16 | 7.59 ± 1.59 | 1.06 ± 0.48 |
| | (0.25, 8.1%) | (4.53, 23.9%) | (7.41, 13.8%) | (0.98, 28.8%) |
| | 0.066 | 0.008 | 0.008 | 0.108 |
| **Collimation optimisation** | | | | |
| Overall ($n$ = 68) | 0.06 ± 0.16 | 1.20 ± 1.00 | 2.97 ± 1.73 | 0.49 ± 0.28 |
| | (0.04, 13.4%) | (0.93, 14.3%) | (2.69, 13.4%) | (0.44, 8.1%) |
| | <0.001 | <0.001 | <0.001 | <0.001 |
| I ($n$ = 34) | 0.05 ± 0.10 | 0.79 ± 0.45 | 2.76 ± 1.51 | 0.54 ± 0.32 |
| | (0.03, 19.8%) | (0.77, 21.8%) | (2.60, 21.2%) | (0.59, 12.4%) |
| | <0.001 | <0.001 | <0.001 | <0.001 |
| II ($n$ = 25) | 0.08 ± 0.19 | 1.35 ± 0.79 | 3.55 ± 1.87 | 0.44 ± 0.24 |
| | (0.09, 9.8%) | (1.31, 13.2%) | (3.12, 11.5%) | (0.41, 7.5%) |
| | 0.027 | <0.001 | <0.001 | <0.001 |
| III ($n$ = 9) | 0.06 ± 0.26 | 2.34 ± 1.84 | 2.17 ± 1.79 | 0.42 ± 0.23 |
| | (0.06, 2.3%) | (2.62, 10.8%) | (2.34, 5.2%) | (0.43, 5.6%) |
| | 0.594 | 0.011 | 0.015 | 0.101 |

$n$, number of cases; PTV, planning target volume; MLC, multileaf collimator; HD120, high-definition 120-leaf MLC; M120, millennium 120-leaf MLC; PRV, peritumoral rind volume or a 20-mm wall from the surface of the PTV; $PRV_{100}$, PRV receiving ⩾100% of the prescription dose; $PRV_{50}$, PRV receiving ⩾50% of the prescription dose; $PRV_{25}$, PRV receiving ⩾25% of the prescription dose.
[a]M120 minus HD120.

Using the gradient function by Meeks et al [17] and Wagner et al [18], it was noted that there was a minimum mean gradient improvement of ~6%, corresponding to an approximate 0.4 mm change in gradient, with the 2.5-mm MLC system, when collimation was optimised. With a fixed collimation angle, the gradient improved by a minimum mean value of ~22%, corresponding to an approximate 1.3-mm change in gradient.

**Table 4.** Absolute normal tissue avoidance parameters as a function of planning target volume; numeric values presented as mean ± standard deviation, with median values in parentheses

| Category | $PRV_{100}$ ($cm^3$) | | $PRV_{50}$ ($cm^3$) | | $PRV_{25}$ ($cm^3$) | |
|---|---|---|---|---|---|---|
| | HD120 | M120 | HD120 | M120 | HD120 | M120 |
| **No collimation optimisation** | | | | | | |
| Overall ($n$ = 68) | 1.0 ± 0.9 (0.8) | 1.2 ± 1.0 (1.0) | 7.5 ± 3.9 (6.7) | 10.4 ± 4.7 (9.8) | 24.6 ± 12.9 (22.6) | 32.2 ± 13.8 (29.6) |
| I ($n$ = 34) | 0.4 ± 0.2 (0.3) | 0.5 ± 0.5 (0.4) | 4.4 ± 1.7 (4.1) | 7.0 ± 2.8 (6.5) | 15.5 ± 8.5 (12.9) | 23.1 ± 10.5 (21.0) |
| II ($n$ = 25) | 1.3 ± 0.7 (1.1) | 1.4 ± 0.7 (1.3) | 9.4 ± 2.2 (9.3) | 12.4 ± 2.9 (12.9) | 30.0 ± 7.8 (29.5) | 37.5 ± 8.7 (37.0) |
| III ($n$ = 9) | 2.4 ± 0.7 (2.1) | 2.8 ± 0.9 (2.4) | 13.8 ± 2.0 (13.5) | 17.9 ± 2.7 (17.4) | 44.1 ± 7.2 (41.0) | 51.7 ± 7.2 (47.5) |
| **Collimation optimisation** | | | | | | |
| Overall ($n$ = 68) | 0.7 ± 0.9 (0.5) | 0.8 ± 0.9 (0.5) | 8.8 ± 8.7 (6.2) | 10.0 ± 9.2 (7.2) | 21.9 ± 14.3 (20.9) | 24.9 ± 14.6 (23.4) |
| I ($n$ = 34) | 0.2 ± 0.2 (0.1) | 0.3 ± 0.2 (0.2) | 3.3 ± 1.8 (3.1) | 4.1 ± 1.8 (3.9) | 11.4 ± 6.2 (9.5) | 14.2 ± 6.4 (12.8) |
| II ($n$ = 25) | 0.9 ± 0.7 (0.7) | 1.0 ± 0.7 (0.8) | 10.1 ± 4.1 (9.4) | 11.5 ± 4.1 (10.2) | 28.7 ± 9.3 (25.7) | 32.2 ± 10.3 (30.0) |
| III ($n$ = 9) | 2.0 ± 1.4 (1.5) | 2.1 ± 1.4 (1.4) | 26.4 ± 9.5 (22.6) | 28.7 ± 9.7 (23.7) | 42.7 ± 13.7 (35.3) | 44.9 ± 14.2 (36.0) |

$n$, number of cases; PTV, planning target volume; MLC, multileaf collimator; HD120, high-definition 120-leaf MLC; M120, millennium 120-leaf MLC; PRV, peritumoral rind volume or a 20-mm wall from the surface of the PTV; $PRV_{100}$, PRV receiving ⩾100% of the prescription dose; $PRV_{50}$, PRV receiving ⩾50% of the prescription dose; $PRV_{25}$, PRV receiving ⩾25% of the prescription dose.



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**Table 5.** Difference in normal tissue avoidance parameters as a function of treatment planning technique. Median differences and corresponding median percent differences are presented in parentheses

| Category | [a]$PRV_{100}$ ($cm^3$) | [a]$PRV_{50}$ ($cm^3$) | [a]$PRV_{25}$ ($cm^3$) | [a]Gradient (mm) |
|---|---|---|---|---|
| **No collimation optimisation** | | | | |
| 3DCRT ($n = 9$) | 0.24 ± 0.21 (0.15, 13.0%) 0.010 | 2.81 ± 1.51 (0.48, 22.0%) <0.001 | 6.67 ± 2.01 (6.55, 3.5%) <0.001 | 0.98 ± 0.44 (0.95, 17.9%) <0.001 |
| IMRS ($n = 18$) | 0.27 ± 0.51 (0.20, 12.4%) 0.041 | 3.87 ± 1.30(3.96, 27.4%) <0.001 | 8.59 ± 3.03 (8.01, 2.8%) <0.001 | 1.34 ± 0.34 (1.36, 24.2%) <0.001 |
| DCA ($n = 41$) | 0.12 ± 0.21 (0.08. 15.9%) <0.001 | 2.60 ± 1.17 (2.30, 35.7%) <0.001 | 7.24 ± 2.50 (6.85, 3.5%) <0.001 | 1.29 ± 0.34 (1.28, 24.0%) <0.001 |
| **Collimation optimisation** | | | | |
| 3DCRT ($n = 9$) | 0.06 ± 0.14 (0.08, 3.1%) 0.104 | 1.31 ± 1.00 (0.99, 12.1%) 0.003 | 3.52 ± 2.43 (2.52, 11.7%) 0.001 | 0.40 ± 0.17 (0.34, 6.4%) <0.001 |
| IMRS ($n = 18$) | 0.03 ± 0.24 (0.01, 2.8%) 0.458 | 1.19 ± 1.55 (0.71, 7.2%) 0.005 | 2.44 ± 2.23 (2.09, 5.1%) <0.001 | 0.33 ± 0.32 (0.30, 4.8%) 0.004 |
| DCA ($n = 41$) | 0.04 ± 0.17 (0.03, 11.2%) 0.0003 | 1.20 ± 0.67 (1.12, 18.8%) <0.001 | 3.22 ± 1.59 (3.00, 16.7%) <0.001 | 0.58 ± 0.25 (0.54, 11.7%) <0.001 |

n, number of cases; PTV, planning target volume; MLC, multileaf collimator; HD120, high-definition 120-leaf MLC; M120, millennium 120-leaf MLC; PRV, peritumoral rind volume or a 20-mm wall from the surface of the PTV; $PRV_{100}$, PRV receiving ⩾100% of the prescription dose; $PRV_{50}$, PRV receiving ⩾50% of the prescription dose; $PRV_{25}$, PRV receiving ⩾25% of the prescription dose; IMRS, intensity-modulated radiosurgery; 3DCRT, three-dimensional conformal radiotherapy; DCA, dynamic conformal arc.

[a]M120 minus HD120.

### *Limitations*

The comparison presented in the current work is purely a computer-based treatment planning study on a single radiotherapy planning platform for two radiotherapy dose delivery systems with no attempt to investigate the isodose distributions delivered in practice by the two systems. The dosimetric differences reported here are believed to be solely due to the different leaf widths used in the treatment planning, since our comparisons were performed on the same treatment planning system for two treatment platforms with similar open-field beam characteristics, using the same beam configurations, optimisation parameters (for IMRS) and dose constraints. Nevertheless, it should be pointed out that leaf width is not the only parameter that is different between these MLC systems. Factors such as the leaf transmission and leakage (a function of leaf height, material constituent and tongue-and-groove) and source-to-MLC distance are also different and affect dosimetric parameters. Therefore, it is worth noting that the current planning study is not a simple comparison for different MLC leaf widths, but rather a complex comparison of two dose delivery systems with different leaf width MLCs [6, 32]. Finally, the perceived differences in the current study do not address set-up

**Table 6.** Absolute normal tissue avoidance parameters as a function of treatment planning technique; numeric value presented as mean ± standard deviation, with median values in parentheses

| Category | $PRV_{100}$ ($cm^3$) | | $PRV_{50}$ ($cm^3$) | | $PRV_{25}$ ($cm^3$) | |
|---|---|---|---|---|---|---|
| | HD120 | M120 | HD120 | M120 | HD120 | M120 |
| **No collimation optimization** | | | | | | |
| 3DCRT ($n = 9$) | 1.2 ± 1.0 (0.9) | 1.5 ± 1.1 (1.0) | 8.7 ± 3.0 (8.9) | 11.5 ± 4.1 (11.4) | 28.7 ± 12.0 (25.5) | 35.4 ± 13.5 (33.0) |
| IMRS ($n = 18$) | 1.5 ± 1.0 (1.5) | 1.8 ± 1.1 (1.7) | 9.8 ± 4.0 (10.4) | 13.7 ± 4.6 (13.7) | 31.4 ± 12.2 (33.7) | 40.1 ± 11.8 (41.4) |
| DCA ($n = 41$) | 0.7 ± 0.7 (0.4) | 0.8 ± 0.8 (0.5) | 6.2 ± 3.5 (5.9) | 8.8 ± 4.2 (7.9) | 20.8 ± 12.2 (18.9) | 28.0 ± 13.2 (24.2) |
| **Collimation optimisation** | | | | | | |
| 3DCRT ($n = 9$) | 0.7 ± 0.5 (0.5) | 0.8 ± 0.5 (0.8) | 8.2 ± 3.9 (8.1) | 9.5 ± 4.5 (9.1) | 27.9 ± 14.6 (24.2) | 31.6 ± 16.1 (24.2) |
| IMRS ($n = 18$) | 1.1 ± 0.9 (0.8) | 1.1 ± 0.8 (1.0) | 15.0 ± 11.2 (12.5) | 16.2 ± 11.8 (13.2) | 30.9 ± 15.5 (29.5) | 32.9 ± 15.9 (32.0) |
| DCA ($n = 41$) | 0.5 ± 0.9 (0.2) | 0.6 ± 0.9 (0.3) | 6.3 ± 6.9 (3.5) | 7.5 ± 7.4 (4.5) | 16.7 ± 11.1 (12.7) | 19.9 ± 11.6 (16.1) |

*n*, number of cases; MLC, multileaf collimator; HD120, high-definition 120-leaf MLC; M120, millennium 120-leaf MLC; PRV, peritumoral rind volume or a 20-mm wall from the surface of the PTV; $PRV_{100}$, PRV receiving ⩾100% of the prescription dose; $PRV_{50}$, PRV receiving ⩾50% of the prescription dose; $PRV_{25}$, PRV receiving ⩾25% of the prescription dose; IMRS, intensity-modulated radiosurgery; 3DCRT, three-dimensional conformal radiotherapy; DCA, dynamic conformal arc.



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uncertainty and intrafraction motion, which, if not adequately accounted for, will lead to discrepancies between calculated and actually delivered dose.

## Conclusion

The current study has demonstrated dosimetric merit of the 2.5-mm leaf width MLC system over the 5-mm leaf width system for stereotactic radiosurgery targets. The clinical significance of these results warrants further investigation in order to determine whether the observed dosimetric advantages translate into outcome improvements.

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