Characteristics of popular photon beam collimators

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Abstract. Purpose: To compare the physical and dosimetric aspects of radiation beam collimation systems that may affect the stereotactic radiosurgery and radiotherapy of small lesions. Methods: Gamma knife (GK) cones, Cyber-knife Iris/InCise collimators, popular Varian and Elekta multi-leaf collimators (MLCs) were theoretically analyzed. Leaf-edge effects (Inter- and intra-leaf leakages, field penumbras, and dosimetric leaf gap - DLG) and transmission through some collimators were measured with ion chambers and films in phantoms and electronic portal imagers in an extended distance. GK plans and IMRT/VMAT plans were generated for ten patients and conformity index (CI) and dose drop (DD) from target to 5-mm ring were compared. Results: New MLCs have improved field shaping conformity, reduced transmission but not field penumbras and DLG. The measured DLG changed with time of usage and varied across the field. GK plans had better CI and DD for small lesions of < 1 cm while MLC-based VMAT/IMRT plans improved CI for large lesions of > 2 cm. Conclusions: New thinner and taller MLCs have improved the field shaping conformity and transmission but not leaf edge effects. Cone-based irradiation is still the best to small lesions of < 1 cm while VMAT/IMRT using new MLCs provide more conformal dose to irregular target usually with size of > 2 cm.

1. Introduction
I should like to begin by describing MLC leaf-edge effects on delivered dose on which we have some theoretical study twenty-two years ago [1]. As you know that MLC has made IMRT [2] and VAMT [3] possible and new collimation systems have been designed in recent years. To select a machine to treat intracranial and extracranial lesions, there are extensive options of GK, cyber knife, tomo-type and c-arm-type linear accelerators equipped with MLCs for 3DCRT, IMRT, VMAT, SRS and SBRT. Understanding the characteristics of equipped collimators could be the key factor in purchasing the machine. This pilot study is by no means exhaustive to cover all clinical aspects of MLCs but the dosimetric impacts or differences of MLCs.

2. Characteristics of Popular Collimation Systems

2.1 Summary of popular Collimation Systems
Table 1 listed the technical specifications of some popular collimation systems with reference [4] for Gamma Knife, [5] [6] for Cyber Knife, [7] for Varian MLC and [8] for Elekta MLC. There are Siemens MLC, Tomotherapy MLC, Brainlab micro MLC, and other MLCs. To address the clinical impacts, an algorithm in round-end leaf control was described in subsection 2.2. Measurements of leaf edge effects
and their influences on treatment plans were explored in other sections.

2.2 Theory of Physical Leaf Tip vs Nominal Leaf Lateral Position

Exact 3D solution for tracing X-rays tangent to a rounded leaf end with the leaf tip position for left and right leaves had been first derived by the author \[1\] \[9\] and utilized by AAPM TG 50 report \[10\].

\[
X = W + \delta = W \cdot \sin(\theta) + R(1 - \cos(\theta)) \quad \text{for left leaf}.
\]

\[
\delta = X - W = W \cdot \sin(\theta) - R(1 - \cos(\theta)) \quad \text{for right leaf}.
\]

The field edge position $X = W + \delta$ is the nominal leaf position. Standard Varian MLC leaf tip was pushed away by $-0.2$ mm (about $0.4$ mm on SAD plane) to avoid collision of closing leaf pair at the central region. Some new MLC chamfers the tip to avoid collision. The $\delta$ values for Elekta MLC was experimentally determined with MLC calibration. Theoretically, radiation field edge should be the ray through a half value layer (HVL) chord into the MLC for the $50\%$ transmission. Additional shift for $2.3$ HVL chord into the leaf corresponds the increase of penumbra. Non-focus surfaces at the end and sides of a leaf increased scattering and transmission at the edges in comparison with that from the focus jaws. That have been quantified as intra- or inter- leaf leakages under blocking area, enlarged penumbra at the edges and Dosimetry Leaf Gap (DLG) within dynamic IMRT fields \[11\].
2.3 Leaf Edge Effects (LEEs) on Dose Delivery
LEEs are sensitive to the submillimeter leaf position uncertainties. Thus, measurements are required to quantify LEEs particularly for weariness of extensive use or recalibration. Figure 3 and 4 demonstrate that measured LEEs using an on-board electronic portal imager (EPI) after geometric conversion to SAD and dosimetric renormalization to the ion chamber doses at $d_{\text{max}} = 16$ mm. The penumbras at 10 cm depth can be determined with scans in a water tank or films in a solid phantom.

Figure 3. EPI uniform response to 6X 21x16 cm open field (a), % transmission in a closing field (b), % interleaf leakage distribution (upper) and 3D plot (c), and normalized intensity distribution in dynamic Picker Fence irradiation (upper) and 10 time % end leakage by subtracting closing field intensity (d).
Figure 4. Measured cross-plane penumbras 4.8 mm vs in-plane penumbras 4.0 mm for a 1x1 cm field using a vertically mounted pinpoint ion chamber scanned at SSD = 90 cm and depth = 10 cm.

Notice that high interleaf leakage at some points (Fig. 1b) may affect measurement of DLG. A pin-point chamber was placed at the points of interest and doses from 2, 5, 10, and 20 mm width sliding window through a 20-cm square field for Agility (AG) MLC and 21 x 16 cm field for beam modulate (BM) MLC at 90 cm SSD. For 6-MV X-ray beams, the DLG are 0.26, 0.18, and 0.07 mm for BM MLC and 1.7, 0.5, and 1.1 mm for AG MLC. Similar measurement was performed on Varian machine with HD 120 MLC with the DLG of 0.39 and 0.27 mm for 6X and 6X FFF beams, respectively. However, the DLG in Eclipse TPS system had to be 1.1 mm in order to match the plan dose with delivered dose [6]. Both DLG variations across the fields and dose calculation differences support the author’s question for the concept of DLG to be briefly described in the next subsection.

2.4 What is the “DLG”

The concept of DLG was introduced by LoSasso et al [11] for adding intra-leaf leakage in dynamic IMRT fields. DLG was measured by the distance of the point with a zero dose from linear extension of the plot of dose vs sliding window widths. The dose for zero width of the sliding window should be the convolution of the radiation intensity I(x,y) with the additional scattering and transmission kernels at the leaf ends to the depth of interest. The subtracted profiles for a field defined by those focus jaws from the profiles for the same field defined by the MLC could provide the kernel and that could be approximated by two rectangle triangles (referring to Fig 2(d) for two end edges): one transmission through the leaf tip with a base size of τ and the height of kτ and the other mainly for more scattering from the leaf tip into the open area with a base size of σ and height of kσ. Integration provided:

$$DLG(x,y) = (k_τ τ + k_σ σ) I(x,y) / I_o$$

Where kτ and kσ ∈ (0,1) were ratios of the transmission and scattering peaks to the dose at CAX. If k were a constant, DLG would only change with radiation intensity such as FFF beams. Changes of the leaf end positions and the sides of the leaf as well as dose rate (MU) at the location (X,Y) could all affect the amount of scattering and transmission. Thus, a constant DLG does not truly represent LEEs and measured inter- and intra-leaf leakages should be included in the TPS commissioning.

3. MLC effects on Treatment of Small Lesions

3.1 Field Shape Conformity Using Various Collimators
We have $\text{CI}_{\text{IRIS}} \approx \frac{3}{\pi} = 0.95$. $CI_{\text{MLC}} = 4w \sum_{i=1}^{R/w} \sqrt{R^2 - i^2 w^2} / (\pi R^2)$. For $R = 20$-mm target, CI are 0.90, 0.79 and 0.55 by using a MLC with width $w = 2.5$, 5.0 and 10 mm, respectively.

3.2 Actual Coverage for small spherical targets using Cones or MLCs
Coverage of small spherical targets by the prescription does using single GK shot, MLC shaped field or arc were validated with film dosimeters. GK cones sizes are circular shapes while accelerators can change the field shape and size through adjusting leaves. The dose distributions from available GK shots and beam-modulate (BM) and agility MLC (AM)-shaped fields and arcs using Gafchromic EBT3 films placed within a spherical phantom as shown in Fig. 6.
Table 2. Results of the measured penumbra, FWHM, symmetry, and peak dose values.

| Mode      | Size (mm) |
|-----------|-----------|
| GK shot   | 4 2.7     |
| BM arc    | 4 8.1     |
| BM field  | 4 16.5    |
| AM arc    | 5 3.0     |
| AM field  | 10 3.2    |

|            | Transverse Penumbra | Transverse FWHM | Transverse Flatness % | Transverse Symmetry % | Longitudinal Penumbra | Longitudinal FWHM | Longitudinal Flatness % | Longitudinal Symmetry % | Max Dose (cGy) |
|------------|---------------------|----------------|------------------------|-----------------------|-----------------------|--------------------|------------------------|------------------------|----------------|
| GK shot    | 4 2.7               | 5.6            | 12.3                   | 0.1                   | 1.2                   | 4.7                | 9.4                    | 1.1                    | 362           |
| BM arc     | 4 8.1               | 8.8            | 21.8                   | 8.2                   | 2.1                   | 4.1                | 16.2                   | 8.8                    | 177           |
| BM field   | 4 16.5              | 13.2           | 20.0                   | 6.2                   | 2.4                   | 7.5                | 12.1                   | 3.3                    | 363           |
| AM arc     | 5 3.0               | 9.2            | 19.2                   | 2.5                   | 2.6                   | 4.6                | 17.8                   | 2.6                    | 250           |
| AM field   | 10 3.2              | 10.5           | 10.4                   | 3.0                   | 2.8                   | 2.8                | 19.7                   | 6.2                    | 137           |

a) All GK shots used the same treatment time of 1.25 min for dose of ~410 cGy from 18-mm helmet.

b) All beam-modulate (BM) and agility MLC (AM) arcs/fields were irradiated with 600 MU of 6X.

c) Transverse Penumbra for shots and arcs were larger than corresponding longitudinal penumbras.

d) Full-Width-Half-Maximum (FWHM) were larger than longitudinal values by beam overlapping.

e) The maximal doses on the films were the maximal dose value without using smooth filtering.

3.3 Comparison of patient SRS plans

We expanded our study to treatment planning for complete coverage of various targets while sparing nearby function structures. Deformable image registration software (Velocity, Varian Inc.) was used to transfer patients’ GK plans with cranial volume MRI, structures, and dose matrix. Patient CT scans were then used for dose calculation for non-coplanar beams or arcs in Pinnacle P3RTP system. If there was no head CT scans, we had overwritten MRI with uniform density of 1 g/cc as Fig. 7.

Figure 7. A single iso IMRT/VMAT plans and DVHs (left penal) for 6 lesions with sizes from 0.2 to 3.2 cm³ and prescription dose (PD) of 20 Gy and two iso IMRT/VMAT plans and DVHs (right penal) for another patient with a right acoustic neuroma for PD of 15 Gy and a small recurrent GBM in the right parietal lobe for PD of 20 Gy. Dash/Solid DVH lines are for IMRT/VMAT plans, respectively. All plans had coverage of > 95% and optimized conformity index defined as C.I. = coverage² x Target Volume / Prescription Isodose Volume [12] and the peripheral dose drop-off: DD = % (mean dose of TV – mean dose of 5-mm margin ring) / mean dose of TV.

The results for tested 11 cases (some cases had multiple lesions as a single target) were listed in Table 3 (AM for agility MLC and BM for beam modulator MLC) with red numbers indicating poor values in a standard SRS treatment. For small lesions (TV < 1 cc or size of <1 cm), GK has better CI and DD than that of VMAT or IMRT while IMRT/VMAT provide high CI for large lesions (6 or 8 cc for size of ~2
cm). As we already know if Varian HDMLC or Elekta dynamic MLC with 2.5 mm leaf width are used, CI would be further improved.

| Location       | PD (Gy) | TV (cc) | AM VMAT | BM VMAT | AM IMRT | BM IMRT | GK      | \( \text{DD} = \% (\text{MDt}_v - \text{MDt}_{5mm}) / \text{MDt}_v \) |
|----------------|---------|---------|---------|---------|---------|---------|---------|------------------|
| Pons           | 15.00   | 0.05    | 0.19    | 0.19    | 0.20    | 0.45    | 0.45    | 84.90            |
| SCLC met       | 20.00   | 0.10    | 0.45    | 0.24    | 0.28    | 0.45    | 0.45    | 79.20            |
| Recu. GBM      | 18.00   | 0.60    | 0.95    | 0.64    | 0.65    | 0.93    | 0.95    | 51.00            |
| 5 Mts           | 20.00   | 1.20    | 0.50    | 0.64    | 0.65    | 0.93    | 0.95    | 51.00            |
| Lt Occip.      | 20.00   | 1.30    | 0.43    | 0.64    | 0.65    | 0.93    | 0.95    | 51.00            |
| 5 Mts           | 20.00   | 1.40    | 0.50    | 0.64    | 0.65    | 0.93    | 0.95    | 51.00            |
| Rt Ac. Ne.     | 14.00   | 1.90    | 0.64    | 0.65    | 0.66    | 0.65    | 0.66    | 51.00            |
| Pit Aden.      | 18.00   | 2.10    | 0.65    | 0.64    | 0.66    | 0.65    | 0.66    | 51.00            |
| Soli. Met.     | 15.00   | 5.20    | 0.65    | 0.64    | 0.66    | 0.66    | 0.66    | 51.00            |
| Rt Front Met.  | 18.00   | 6.40    | 0.28    | 0.33    | 0.35    | 0.51    | 0.52    | 42.40            |
| Sup. Mening.   | 18.00   | 8.60    | 0.52    | 0.68    | 0.65    | 0.66    | 0.66    | 51.00            |

4. Conclusion
New MLCs had improved field CI but leaf edge effects (LEEs) varied significantly with a long-time usage and/or recalibrations as well as changing across the fields particularly for the new FFF beams. Theoretical comparisons and experimental verification are both useful in quantification of LEEs and the LEEs made GK still the best choice for small brain lesions (<1 cm) while new MLC provided more conformal dose to lesions > 2 cm. DLG concept was created to compensate differences in planning commissioning using the profiles of beams shaped with the focus jaws while real delivered IMRT/VMAT beams with the edges shaped by rounded leaf ends. Thus, conceptually, DLG should not be used if the measured LEEs can be included in the next generation planning systems.

5. Acknowledgement
This research was partially supported by a pilot grant from Elekta Inc.

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