Mini and Micro Multileaf Collimators

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1. Motivation

Multiple arc or multiple field convergent beam irradiation techniques have been used extensively for stereotactic radiosurgery (SRS) or radiotherapy (SRT) of small lesions. A major problem is that dose distributions produced by employing rectangular or circular collimators are of simple convex shape and therefore do not allow conformal treatment of irregularly shaped lesions. The use of multiple overlapping spherical treatments results in some field shaping advantages and permits the treatment of larger tumors. Disadvantages of this multiple isocenter technique include the increased treatment time and the substantial dose inhomogeneity that is the result of overlap of multiple fields. This dose inhomogeneity correlates significantly with side-effects and increased morbidity for those patients, as has been shown by Nedzi et al. [10]. Improved tumor dose homogeneity can be accomplished by using a field shaping device, which can form the optimal field shape for each beam direction.

Several techniques to implement field shaping for SRT have been proposed. An obvious approach is to use custom-shaped apertures. However, it is difficult and cumbersome to manufacture a custom-shaped aperture accurately [1]. In another approach, the fields are shaped with a manually adjustable multileaf collimator (MLC) [15,12] that can be used through an entire arc without shape modification during the arc. This technique has been applied successfully to several cases, however, in many cases the beam’s eye view projection of the target can change significantly during a single arc, as well as from one arc to the next. Therefore, it is more practical to use a computer-controlled field-shaping device to achieve optimal dose distributions.

Built-in computer-controlled MLCs are supplied by the major linac vendors. However, with a projected leaf width of 1-1.25 cm, the resolution is generally too coarse for the treatment of small irregularly shaped lesions in SRT. Recently Varian has started to produce a new MLC in which the inner leaves project to 5 mm. This is a marked improvement as compared to the conventional 1 cm resolution, however, it is still sub-optimal for the treatment of very small or very complex lesions with SRT.

In this course we will concentrate on add-on MLCs with projected leaf widths below 5 mm that are attached to the linac’s accessory device holder. We will term MLCs with leaf widths between about 2 mm and 5 mm as mini MLCs (mMLC) and below about 2 mm as micro MLCs (μMLC). The advantage of the use of mMLCs as compared to circular collimators with single or multiple isocenters has been nicely demonstrated for example by Shiu et al. [17] and Kubo et al. [6]. Basically, the mMLC allows to achieve an excellent target coverage without any hotspots, and at the same time it yields a reduced dose load for normal tissues.

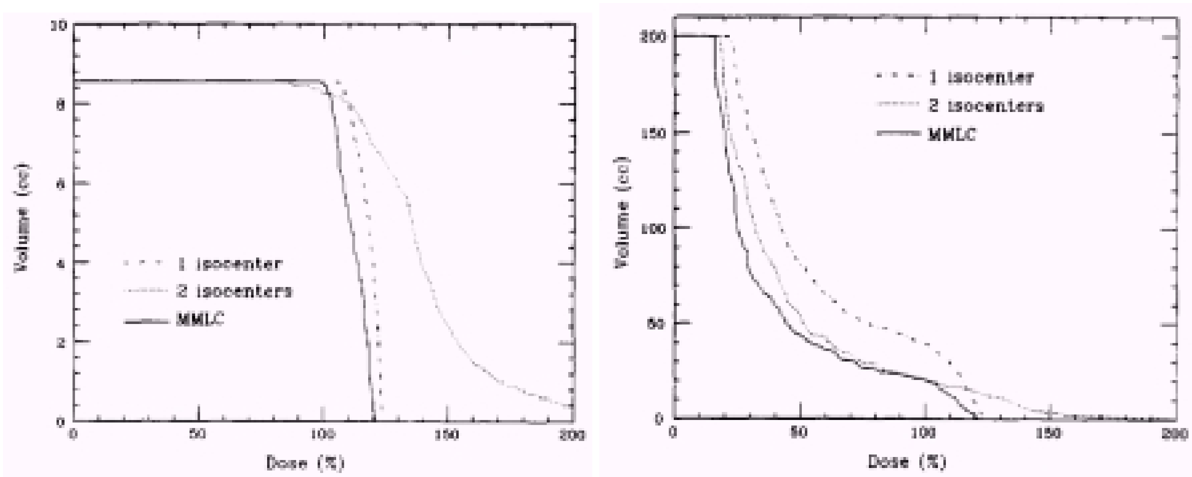

Figure 1: Comparison of dose-volume histograms (DVHs) for the treatment of an 8.5 cm^3 brain metastasis with circular fields using one or two isocenters, and an 18 field mMLC treatment. Left: target, right: normal tissue. Source: Shiu et al. [17].

Despite the attractiveness of MLCs, Leavitt at al. [7] showed that even simpler collimator designs have significant field shaping advantages over circular collimation. They built a device with four independent rotatable jaws with an auxiliary circular collimator and demonstrated a conformal advantage compared with a circular collimator for a representative target. However, it was shown that an “ideal” collimator is superior to this device in minimizing the dose to normal tissue [11].

2. Required features of motor-driven mMLCs and μMLCs

Some important criteria that MLCs have to fulfill in order to be applied efficiently in SRT are given below. The respective features of commercial MLCs are summarized in a table in the appendix.

Maximum Field size

Typically SRS and SRT is used for the treatment of small intracranial lesions. The field sizes normally used for this type of treatment are below 5 x 5 cm^2. This field size is easily covered by all commercially available mini and micro MLCs. When one starts thinking about new applications such as stereotactic treatments in the body stem, larger fields sizes may become necessary. On the other hand, lesions with diameters above about 10 cm hardly ever require the fine resolution of an mMLC and can well be treated with conventional large-field MLCs.

Overcenter travel

For very irregular target shapes with strong indentations, it may become necessary to move some of the leaves across the central axis, which is called overcenter travel. From our experience in non intensity-modulated SRT we never found it necessary to have an overcenter travel of more than 2 cm.

Projected leaf width

The leaf width determines the resolution with which a field can be shaped. To achieve the highest possible degree of conformation, the width should be as small as possible. Thorough studies investigating the merit of going to ever smaller leaf widths are rare. From physical reasons it is clear that the degree of conformation achievable by reducing the leaf width must reach a plateau. It is reasonable to expect that this plateau must start at widths close to the beam penumbra, which is in the order of 2-2.5 mm for 4-6 MV photons, and which is roughly the lateral electron range.

Leaf transmission

As add-on MLCs are generally backed up by the rectangular jaws of the linac, leaf transmission is not as critical as for large field MLCs that replace one pair of jaws. Nevertheless, the value should not exceed 5%. An important related issue is leakage between neighboring leaves, called interleaf leakage. The specified values of this quantity should be evaluated with care, because it is difficult to measure and it depends on the alignment of the MLC as well as on the position within the field. In any case, interleaf leakage should not be much higher than leaf transmission.

Maximum leaf speed

In multiple static field treatments, the leaf speed affects only the total treatment time and becomes critical only when very many fields are used (>20). Because the field sizes are much smaller than in conventional radiotherapy, a maximum leaf speed of 1 cm/s is generally more than sufficient. The situation gets a little more involved if the MLC shall be used for dynamically shaped arc treatments. Here the shape of the beam's eye view projection of the target can change significantly during an arc, and the MLC must be able to adjust its shape correspondingly. For this purpose higher leaf speeds of up to 1.5 cm/s are desirable. However, a clear advantage of the dynamically adjusted arc technique as compared to multiple static fields has yet to be shown.

Clearance to isocenter

The isocenter clearance should clearly be as large as possible. However, for treatments in the head a value of 30 cm suffices even for large-angle non-coplanar beam orientations. In the body stem a larger clearance is sometimes required. The clearance is mainly determined by the position at which the accessory holder is mounted in the linac, and by the height of the MLC. One has to be aware though that a larger clearance compromises the penumbra to some degree. Furthermore, a smaller height of the MLC generally leads to larger transmission.

Total weight

The weight of the equipment attached to the accessory holder is generally limited to values around 25 kg. However, experiments have shown that most gantries work well even with loads of 50-60 kg. The problem is not so much the stability of the gantry itself but the accessory holder. Nevertheless, special permits allow basically all commercial mini and micro MLCs to be mounted on all linacs. There is no reason to expect that the additional weight will compromise the isocentric precision of the gantry [4].

Geometric design

In the geometric design we distinguish between parallel, single focused, and double focused design. *Parallel* means that the leaves are aligned in parallel and move linearly. *Single focused* means that the leaf sides are aligned with the source but the leaves move linearly, i.e. the leaf ends are aligned with the source only at the center position. To achieve that the leaf end penumbra is independent of the leaf position, the leaf ends are generally curved. As a consequence, however, two opposing leaves cannot be closed altogether. In *the double focused* design both the leaf sides and the leaf ends are aligned with the source, i.e. the leaf trajectories are elements of a sphere. The latter is the "best" design leading theoretically to the smallest possible penumbra, but it is also the most demanding from a technical point of view. Since we are talking about small fields of typically less than 7x7 cm^2, the beam geometry can be roughly approximated as parallel. Therefore, for the creation of irregularly shaped but

uniform intensity beams in SRT, even the parallel design is adequate. For such small fields the penumbra is influenced much more by the size of the source, the energy, and the MLC location than by the MLC geometry.
However, the situation looks much different if one goes to intensity modulated beams (see below).

3. IMRT with an mMLC or μMLC

Recently the potential merit of using intensity modulated radiotherapy (IMRT) for stereotactic treatments has been investigated. Two studies considered the Nomos Mimic device with a leaf width of 1 cm for this purpose [20,9]. They come to the conclusion that for small lesions (diameter < 4cm) there is no advantage of IMRT as compared to conventional uniform beam treatments. In another study by Cardinale et al. [3] stereotactic IMRT with a mini MLC was simulated. These authors found superior normal tissue sparing for some of the targets in comparison with conventional uniform beam techniques. Similar results were obtained by Bues et al. [2], who found both a significant reduction of hotspots in the target volume and a significant increase in healthy tissue sparing. Altogether, the use of intensity modulation in SRT with an MLC seems to be a promising approach if the resolution, i.e. the leaf width of the MLC, is only fine enough.

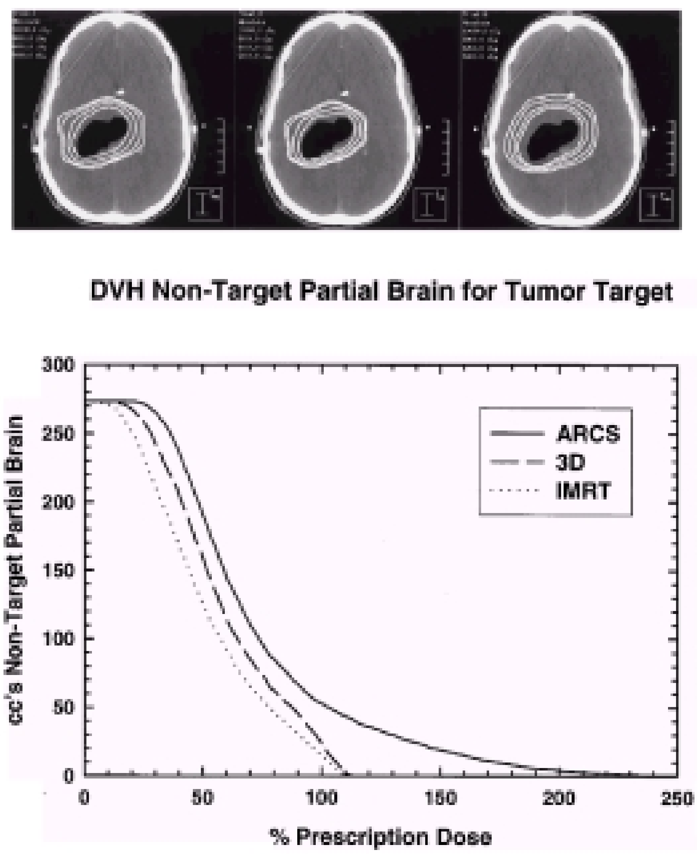

Figure 2: Comparison of techniques for the treatment of a brain tumor: a) 6 non-coplanar irregularly shaped beams (top left, “3D”); b) IMRT (top middle, “IMRT”); c) 3 isocenters with 5 arcs each using circular collimators (top right, “ARCS”). Isodose lines: 10, 8, 6, and 5 Gy. Source: Cardinale et al. [3].

The practical delivery of IMRT with an mMLC or μMLC would proceed just as in large field IMRT, i.e. either by a uni-directional dynamic sweep of the leaves or with “the step and shoot” approach, as shown in Figure 3. To make this possible in an efficient way, the MLCs have to fulfill some requirements in addition to the ones already mentioned.

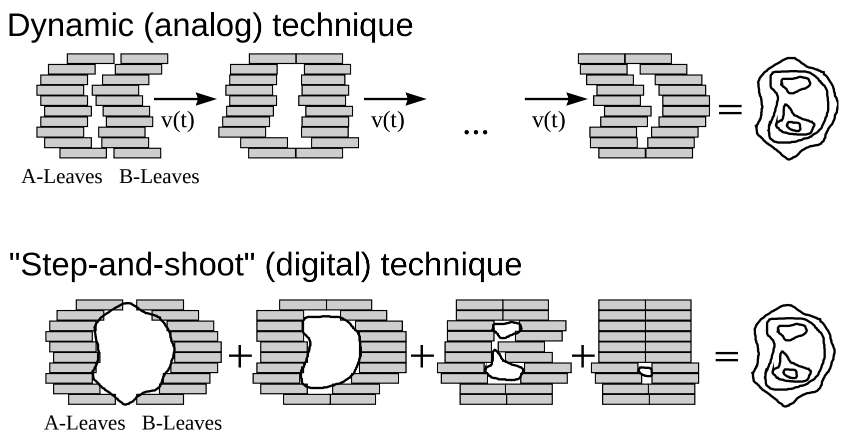

Figure 3: Principles of intensity modulation with an MLC.

3.1 IMRT-specific features of mMLC and μMLC

Overcenter travel
IMRT allows to sharpen the dose gradients by increasing the fluence especially at the field edges. To create narrow intensity peaks at the field boundaries, it may be necessary to move the leaves across the central axis and almost all the way to the opposite side. Hence the “overtravel” should be in the range of half the maximum field size.

Projected leaf width
To exploit the full potential of stereotactic IMRT, a high resolution, i.e. small leaf width, is more important than for uniform beam treatments. Some recent studies show that significant improvements in the dose distribution are obtained by reducing the leaf width from 4 to 2 mm, and even at 2 mm the plateau is not yet reached [13]. Figure 4 shows a comparison of DVHs for IMRT of a 40 cm^3 vertebral column metastasis with MLCs of different leaf sizes. Inverse planning was done with the KonRad program for 7 evenly spaced, coplanar, intensity modulated beams. It can be seen that the 1 cm MLC is worse than the 5 mm MLC both in sparing critical structures and in the PTV coverage, as well as due to the existence of hotspots in the target. The 5 mm and 1.6 mm MLCs are comparable in sparing critical structures, but the 1.6 mm μMLC yields a clearly higher target dose homogeneity.

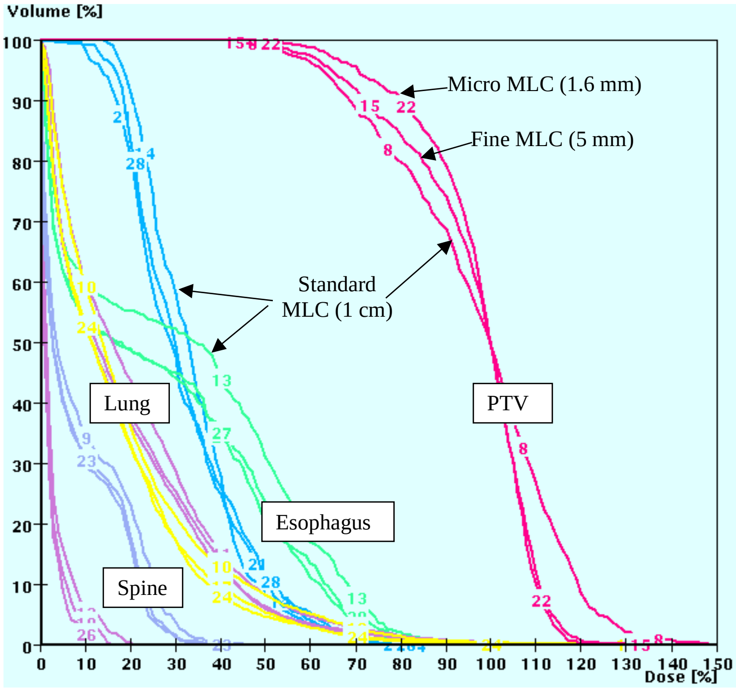

Figure 4: Comparison of DVHs for the treatment of a vertebral column metastasis with IMRT using MLCs with different leaf sizes.

Leaf transmission

The total irradiation time in IMRT is about 3 times longer than in uniform beam therapy. Hence, the effective leakage is proportionally higher. To keep the effective leakage below about 5%, the leaf transmission should be less than 2%.

Leaf speed

A leaf speed of 1.5 cm/s is sufficient even for dynamic IMRT.

Geometric design

Current algorithms for the calculation of the leaf trajectories from the desired intensity map are based on the assumption that each pair of opposing leaves produces a one-dimensional intensity profile more or less independent of the neighboring leaf pairs. This assumption is only fulfilled if the MLC geometry is at least single-focused. This requirement may be relaxed if more sophisticated trajectory calculation algorithms become available.

Leaf positioning accuracy

The accuracy of leaf positioning is even more important in IMRT than in uniform beam therapy. Since many small subfields are superimposed to obtain the desired intensity modulated field, positioning errors may causes matchline problems. Moreover, since the subfields may often be less than 1 cm wide, a positioning error of only 1 mm may cause a dose error of more than 10 %. Therefore, the positioning error should be smaller than 0.5 mm.

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Appendix

	BrainLAB m3	Radionics	MRC (Leibinger)	3D Line (Wellhöfer)	Direx AccuLeaf
# Leaf pairs	26	31	40	24	36
Field size (cm^2)	10 x 10	10 x 12	7.3 x 6.4	11 x 10	11 x 10
Overcenter travel (cm)	5	No data	2.4	2.5	No data
Leaf width (mm)	3.0 – 5.5	4.0	1.6	4.5	No data
Leaf transmission (%)	< 4	< 2	< 1	0.5	< 2
Maximum speed (cm/s)	1.5	2.5	1.5	1	1.5
Clearance to isocenter (cm)	31	35	30	30	31
Total weight (kg)	35	35	38	35	27
Geometric design	Single focused	Single focused	Parallel	Double focused	Two sets of leaf pairs at 90°
Web address	www.brainlab.com	www.radionics.com	www.mrc-heidelberg.de	www.3dline.com	www.direx.co.il

Table 1: Features of commercially available add-on mini-MLCs.