Klaus Bratengeier*, Sonja Wegener and Barbara Herzog

Distance-dependent penumbra and MLC-width: new insights in determinants of healthy tissue sparing in stereotactic irradiation

Arguments in favor of a virtual isocenter

Abstract: For stereotactic irradiation, both, penumbra and MLC leaf width make an impact on the sparing of healthy tissue around the target. Mostly, MLC design is regarded as the one influenceable parameter. However, also penumbra can be varied by choosing different distances between the source of radiation and the patient. The authors investigate the distance- dependent penumbra effects of idealized collimators as well as for real 5 mm MLCs. Test objects are small spherical targets of varying diameters to be irradiated under differing prescription conditions. A method to calculate exact stereotactic radial dose distributions from beam profiles or 2D dose distributions of single beams is developed for circular and MLC shaped targets. Also, a planning study is performed using a Pinnacle3™ planning system. Also, in a theoretical analysis perfect top hat profile beams and beams with varying penumbra are compared for better understanding of penumbra effects with respect to radial dose distributions. It is shown, that the penumbra changes for small targets are more relevant than the beam shaping by 5 mm MLCs. Quasi-isotropic irradiated MLC shaped (quadratic) beams at virtual SAD 700 mm produce steeper radial dose decrease than ideal circular beam shapes with a penumbra typical for SAD 1000 mm. A reduced source-to-patient distance allows better sparing of healthy tissue because of two reasons: The smaller effective leaf width but even more due to steeper penumbra. First, the authors suggest for future recommendations on stereotactic irradiations to specify not only MLC widths but also penumbra characteristics. Second, a so-called "virtual isocentre" could be useful to take advantage of the penumbra effect: Dependent on gantry angle and isocentric couch angle, the couch should be steered automatically in a way that the central axes of all beams always intersect in the same point at the same distance from the source.

Keywords: Stereotactic Irradiation, Multi-leaf Collimator, Penumbra, Virtual Isocentre, Robotic Table Motion, Planning Study, Radiotherapy.

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1 Introduction

To guarantee optimal ancillary conditions utilizing multi-leaf-collimators (MLC) in stereotactic radiotherapy (STX) mostly the leaf width of the MLC is taken into account. The beam profile parametrized by its penumbra is regarded as a fixed operand [1] which cannot be influenced.

Even in recommendations regarding STX, MLC is extensively discussed, MLC width requirements are defined; but no restrictions are proposed for penumbra [2].

Penumbra, however, can be strongly influenced by MLC design and even by changing the source-to-patient distance. The authors investigate the latter case in several ways. This contribution depends on two submitted papers [3–4] which describe each approach in detail; both aspects are brought together here to create an overall view on the problem.

First [3], film dosimetry of beam profiles combined with an algorithm to calculate the radial dose STX distribution from arbitrary beam profiles and shapes was used. It allowed comparing the radial distributions at different source to virtual isocentre distances (SVID) in relation to the original source to isocentre distance (SID).

Second [4], a planning study was performed to compare an optimal collimator shape to a MLC at several distances SVID compared with SID.

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2 Methods

During the theoretical considerations and in the planning study the irradiation was always assumed quasi-isotropic, directed to spherical targets. The isocentre depth for SID was placed in 10 cm water depth, though effects of penumbra would be less pronounced than for smaller depths. For SVID the distance was reduced, but all central beams again intersected in the centre of the PTV. Always a (isocentric) 5 mm MLC was assumed, a width above the 3 mm often recommended as an upper limit.

In [3], a formula was developed to calculate radial dose distributions from dose profiles in the target depth. Film dosimetry of quadratic beam shapes at SID 100 cm and SVID 70 cm at a target depth of 10 cm was performed. Furthermore, circular target shaped collimators were simulated assuming the penumbras of MLC and jaws.

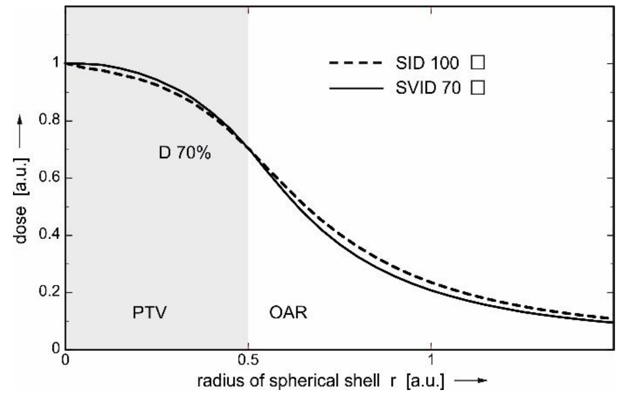
In [4], a planning study for spherical targets of several diameters (1.0 cm up to 1.7 cm) was performed for varying prescription types: 70% 80% and 90% of maximum dose as minimum for the planning target volume (PTV). An optimal circular collimator using the same penumbra and block thickness as the MLC was created to simulate optimal adjustment to the target shape. The mean dose to spherical shells of different radii was calculated for MLC and ideal collimator at SID 100 cm and SVID 70 cm and 50 cm (always in 10 cm target depth).

3 Results

3.1 Effect on varying SVID for MLC beams

Both studies showed qualitatively the same dependence of penumbra from SVID. Smaller SVID reduced the penumbra. Narrower penumbra reduced the dose in the healthy tissue (organ at risk, OAR), especially in the high dose area adjacent to the PTV (see i.e. Fig. 1 for quadratic shape, MLC not adapted to the target). The volume receiving 2/3 of the prescription dose was in all cases smaller for MLC at SVID 70 cm than for the ideal collimator shape at SID 100 cm [4].

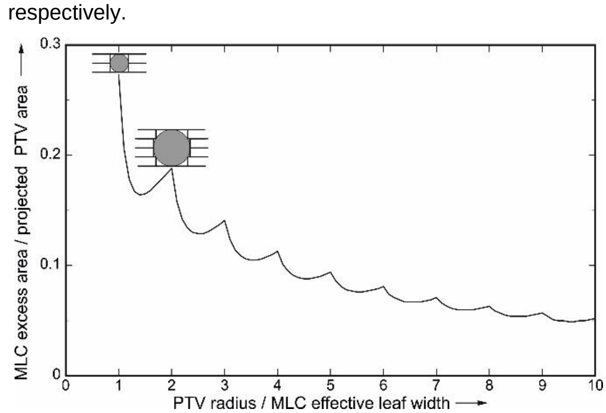
Fig. 1: Target diameter 1 cm, 5 mm MLC: radial dose distribution at SVID 70 cm (continuous line) vs. SID 100 cm (dashed line). The beam shape was always quadratic.



3.2 Finer MLC resolution at reduced SVID

The effect of beam shape adaption of the MLC must be recognized in addition to the SVID/SID effect from section 3.1 Fig. 2. depicts the excess area. For SID 100 cm a PTV of diameter 1 cm had an excess area of 27 % which was reduced to 17 % for SVID 70 cm.

Fig. 2: Excess area for MLC adapting a circular PTV shape in beams eye view (BEV) projection.
Insets: Two examples for PTV radius / MLC width = 1 and 2, respectively.



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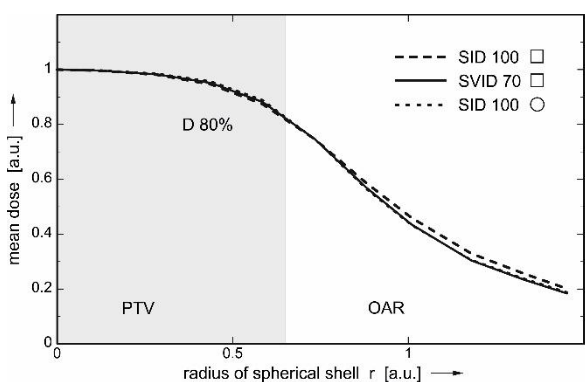
3.3 Optimal beam shaper at SID 100 cm vs. MLC at SVID 70 cm

Both approaches, calculation directly from measured profiles and the planning study came to equivalent results: The reduction of SID 100 cm to SVID 70 cm compensated the roughness of a 5 mm MLC completely. In any case (varying PTV diameter, varying prescription), the combined effect of steeper penumbra and finer effective resolution lead to the same or better healthy tissue sparing than a perfect collimator shape at standard distance SID 100 cm. Fig. 3 depicts an example. The radial dose distribution for quasi-isotropic irradiation for a circular (perfectly adapted) collimator at standard distance is almost identical with the distribution for a MLC collimator at SVID 70 cm.

Fig. 3: Planning study. PTV diameter 1.3 cm, 5 mm MLC.
Dashed line: SID 100 cm using MLC.
Dotted line: optimal beam shape at SID 100 cm.
Continuous line: SVID 70 cm using MLC.



(1)

4 Discussion and outlook

Penumbra has an impact on the steepness of dose distributions of small targets. Penumbra effects seem to be underestimated in STX literature and should be quantitatively included in recommendations.

Penumbra can be influenced by changes of source to target distance. A reduction from SID 100 cm to 70 cm would compensate the excess area of a MLC compared to an optimal beam shaper. A virtual isocentre could be useful to realize reduced SVID (see Appendix).

5 Appendix: virtual isocentre

5.1 The concept of the virtual isocenter

Let the virtual isocenter (VI) be defined as a point on the central axis in a fixed source to-virtual-isocenter distance SVID. SVID is chosen larger than the usual source to axis distance SAD (identical to the source to isocenter distance SID). The VI will always be placed at the setup-point in the patient in the same way as the isocenter for conventional isocentric techniques. Neither the planning system nor the record and verify-system need to be modified, both work with a virtual linac with increased SAD.

5.2 Planning system configuration

The commissioning of a virtual linac with increased SID in the Therapy Planning System (TPS) is straightforward. In the following we illustrate it for Philips Pinnacle3™ TPS. The linac with SVID < SAD can simply be generated from the standard linac with SAD = 100 cm by:

- decrease of the virtual linac "SAD" to SVID;
- corresponding change to the MLC geometry: the dimensions of the BEV (perspective) projection of the structures decrease, which is reflected by the proportionally decreased MLC leaf width;
- - increase of the Dose/MU factor at calibration point according to the inverse-square law at a calibration point distance SVID.

The new output factors for the square fields have to be interpolated from known output factors, or, ideally, re-measured in a water-equivalent phantom, together with the new MU/Gy factor. The VI is implemented in the planning system like any other isocentre. The planning process itself differs in no way from normal isocentric planning. Such a linac configuration procedure had been successfully tested in our clinic for Pinnacle3™ and an Elekta Synergy™ linac. It can be stated that the Philips Pinnacle3™ planning system for a VI-linac behaves exactly like a conventional linac with adequately shifted isocenter.

5.3 Couch positioning

For given SVID, the physical couch position has to be calculated by the couch positioning system from the gantry angle and couch rotation angle: realisation of the VI should completely be integrated in the couch positioning software.

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Neither planner nor the record and verify system have to be involved. The couch position in the room coordinate system is a unique function of the gantry and the couch angle and can be calculated by simple trigonometry.

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