Dosimetric leaf gap and leaf trailing effect in a double-stacked multi-leaf collimator

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Short running title: DLG and trailing effect in a stacked MLC

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Abstract

Purpose: To investigate (i) the dosimetric leaf gap (DLG) and the effect of the 'trailing distance' between leaves from different multi-leaf collimator (MLC) layers in Halcyon^{TM} systems and (ii) the ability of the currently available treatment planning systems (TPS) to approximate this effect.

Methods: DICOM plans with transmission beams and sweeping gap tests were created in Python for measuring the DLG for each MLC layer independently and for both layers combined. In clinical Halcyon plans both MLC layers are interchangeably used and leaves from different layers are offset, thus forming a trailing pattern. To characterize the impact of such configuration, new tests called 'trailing sweeping gaps' were designed and created where the leaves from one layer follow the leaves from the other layer at a fixed 'trailing distance' t between the tips. Measurements were carried out on five Halcyons SX2 from different institutions and calculations from both the Eclipse and RayStation TPSs were compared with measurements.

Results: The dose accumulated during a sweeping gap delivery progressively increased with the trailing distance t. We call this 'the trailing effect'. It is most pronounced for t between 0 and 5 mm, although some changes were obtained up to 20 mm. The dose variation was independent of the gap size. The measured DLG values also increased with t up to 20 mm, again with the steepest variation between 0 and 5 mm. Measured DLG values were negative at $t = 0$ (the leaves from both layers at the same position) but changed sign for $t \geq 1$ mm, in line with the positive DLG sign usually observed with single-layer rounded-end MLCs. The Eclipse TPS does not explicitly model the leaf tip and, as a consequence, could not predict the dose reduction due to the trailing effect. This resulted in dose discrepancies up to +10% and −8% for the 5 mm sweeping gap and up to ± 5% for the 10 mm one depending on the distance t. RayStation implements a simple model of the leaf tip that was able to approximate the trailing effect and improved the agreement with measured doses. In particular, with a prototype version of RayStation that assigned a higher transmission at the leaf tip the agreement with measured doses was within ± 3% even for the 5 mm gap. The five Halcyon systems behaved very similarly but differences in the DLG around 0.2 mm were found across different treatment units and between MLC layers from the same system. The DLG for the proximal layer was consistently higher than for the distal layer, with differences ranging between 0.10 mm and 0.24 mm.

Conclusions: The trailing distance between the leaves from different layers substantially affected the doses delivered by sweeping gaps and the measured DLG values. Stacked MLCs introduce a new level of complexity in TPSs, which ideally need to implement an explicit model of the leaf tip in order to reproduce the trailing effect. Dynamic tests called 'trailing sweeping gaps' were designed that are useful for characterizing and commissioning dual-layer MLC systems.

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I. Introduction

A fast-rotating, enclosed, ring-mounted gantry system designed for intensity modulated radiotherapy/volumetric modulated arc therapy (IMRT/VMAT) delivery, the Halcyon (Varian Medical Systems, Palo Alto, CA), has been recently released[1,2]. The system incorporates some unique features different from traditional C-arm linacs, including a dual-layered stacked and staggered multi-leaf collimator (MLC). Its innovative design offers attractive features but also raises new challenges and requires some adaptation of the commissioning procedures[3,4].

The Halcyon is delivered with the Eclipse treatment planning system (TPS) from the same manufacturer (Varian Medical Systems), which includes a fully pre-configured photon beam model based on the reference beam data. Extensive validation tests have been performed and installed systems have been found to accurately match the reference beam data preconfigured in Eclipse, including percentage depth doses, profiles, and output factors[3,5]. It has also been reported that the system complies with commissioning criteria from international guidelines[6,7,8,9,10,11] and a good agreement between measurements and calculations for clinical plans was found in patient-specific quality assurance (QA) tests, end-to-end verifications and external audits[2,3,12].

RayStation (RaySearch Laboratories, Stockholm, Sweden), a TPS independent of treatment units' manufacturers, is also commercially available for the Halcyon. Saini et. al.[12] recently showed that RayStation provides excellent dose calculation accuracy for the Halcyon, offering the possibility to integrate equipment from different manufacturers in a clinical workflow. RayStation does not include any pre-configured beam model, thus requiring a more comprehensive data collection and commissioning effort.

In clinical plans for the Halcyon, leaves from the stacked layers closely follow one another to further reduce the interleaf leakage compared to the standard single-layer design. We will call the distance between the tips of the leaves from stacked layers the 'trailing distance'. The basic characteristics of the Halcyon's dual-layer MLC, such as leaf positioning reproducibility, transmission, and the dosimetric leaf gap (DLG[13]), which accounts for the transmission through the rounded leaf ends, have been reported[14,15]. However, all the studies to date investigated simplified geometries with either a single MLC layer or both layers with the same nominal leaf positions defining the aperture. This simplification is not generally applicable

to the clinical treatment plans. To achieve maximum fluence conformality (i.e. effective leaf width of 5 mm), the leaves from different layers must be offset somewhat when defining a curved aperture, thus forming a trailing pattern. Lim et al[15] postulated that leaf trailing could affect dose calculation accuracy, particularly for the highly modulated plans. However, how the trailing distance affects the effective transmission through the leaf tips has not been investigated in detail so far. Moreover, some authors have reported DLG values of opposite signs for certain aperture configurations[12,14], raising the conceptual question of the meaning of the DLG for the double-stacked MLC. The interplay between the MLC layers certainly presents new challenges in MLC modeling.

The primary goals of this study are to quantitate the dosimetric leaf gap in the presence of leaves from different MLC layers trailing each other and its effect on the dose calculations in the two TPSs currently supporting Halcyon. Secondary goals are to determine the consistency of the dosimetric leaf gap and the trailing effect across a number of Halcyon systems and to evaluate the feasibility of using a common preconfigured MLC model in the TPS.

II. Materials and Methods

II.A. Halcyon system and MLC characteristics

The Halcyon^{TM}system consists of a single-energy 6 MV flattening filter free linear accelerator that is isocentrically mounted on a covered fast-rotating ring gantry with a source-to-isocenter distance of 100 cm. The system is equipped with a stacked-and-staggered dual-layer MLC composed of 29 proximal leaf pairs ('upper' layer) and 28 distal leaf pairs ('lower' layer) that can produce a maximum field size of $28\times28\,cm^2$ at the isocenter plane. Leaves have a projected width of 1 cm, a maximum leaf speed of 5 cm/s and travel across the full 28 cm range (all values at the isocenter plane). The proximal layer is offset by 5 mm along the leaf width from the distal one. The first release of the Halcyon, version SX1, performed the field shaping with the distal leaves only, whereas the proximal leaves merely served as a backup collimator in order to reduce transmission. Halcyon SX2, on the contrary, performs the field shaping with both leaf layers independently, allowing for a finer shaping of the field apertures and reducing the effective leaf widths at the isocenter plane to 5 mm[1,15].

Both MLC layers are focused only in the direction perpendicular to the leaf motion and

the leaf ends are rounded. The curvature radius is 23.4 cm, which is larger than the radius for the standard Varian MLCs (8 cm and 16 cm for the Millennium and High-Definition MLCs, respectively). The leaves are also taller than in the other Varian MLCs (7.7 cm compared with 6.50-6.75 cm), contributing to a lower MLC transmission through a single leaf.

II.B. Tests and experiments

Sweeping gaps and transmission measurements were used to determine the DLG. The DLG is commonly used for the dosimetric characterization of the leaf tip[13] and accounts for the leaf position calibration and additional transmission through the rounded leaf ends[13,16]. Two types of DLG tests were devised for each MLC layer. The first one involved one MLC layer at a time and essentially duplicated the classical setup described for the single-layer MLCs. The second set of tests was designed to investigate the impact of the trailing distance between leaves from different MLC layers.

DICOM RT Plan files for the DLG determination were created in Python 3.7 with the MLC defining a rectangular aperture of a certain width or 'gap size' and a 10 cm length. Leaves moved at the same constant speed between all control points and for all gap sizes. The gap center moved from −6 cm to +6 cm with 13 control points, such that the shift in leaf positions between consecutive control points was 1 cm. The other MLC layer's leaves were kept fixed at ± 5 cm in order to crop the beam aperture to the central 10x10 cm^2 square region. By using this arrangement, the leaves fixed at ± 5 cm mimic the jaws commonly used in DLG measurements with Varian linacs, thus keeping the same scatter conditions. This configuration is illustrated in Fig. 1a. Two sets of gap sizes were defined: an extended set with gap sizes from 2 mm to 20 mm in 2 mm steps and a reduced set with gap sizes of 2, 5, 10, 15 and 20 mm. For comparison purposes, the DLG was also measured with the DICOM files provided by the manufacturer.

To investigate the impact of the trailing distance between leaves from different MLC layers, a variation of the sweeping gap test that we named 'trailing sweeping gaps' (tSGs) was designed where the leaves from each layer were separated by a fixed distance (a sketch is provided online as Supporting Information). While the leaves from one layer define the sweeping gap and move according to the classical sweeping sequence (these are the leading leaves), the leaves from the other layer follow them at a fixed trailing distance tip to tip

(these are the trailing leaves). To characterize this effect, experiments were performed for trailing distances of 0, 0.5, 1, 2, 3, 4, 5, 10 and 20 mm, fully covering the region spanned by the leaf tip widths, and were carried out twice, with reversed roles of trailing and leading layers. Since the transmission through both MLC layers simultaneously is practically negligible[15], only a fixed width of twice the trailing distance (one at each side of the sweeping gap aperture) effectively contributes to the transmission in these tests. Therefore, this transmission component is independent of the gap size and was directly measured away from the leaf tip. To crop the beam aperture to the central 10x10 cm^2 square region, the trailing leaves were kept at a maximum off-axis distance of 5 cm. Additionally, the sweeping gap size beyond this position was reduced to 1 mm in order to minimize transmission and scatter while fulfilling the minimum dynamic leaf gap of 0.5 mm. In these tests, a higher number of control points was used (between 25 and 27 depending on the gap size) to produce this cropped configuration while keeping the same constant leaf speed in the central 10×10 cm^2 region. The trailing sweeping gap test is sketched in Fig. 1b.

The MLC transmission was measured for each MLC layer and leaf bank (right A or left B) individually for the 10×10 cm^2 and several other field sizes. For each field size, measurements were carried out with the open beam and the beam closed by a different MLC bank. The transmission for each layer and field size was computed as the ratio of the average reading through the closed banks over the reading for the same size open beam.

The number of delivered monitor units (MU) ranged between 200 and 300, which produced leaf speeds below 1 cm/s. The DICOM files for the tests will be provided by the authors upon request.

II.C. Equipment and measurements

All the experiments were conducted on five Halcyon SX2 systems from different institutions. Two institutions used the Eclipse, two used RayStation and one institution used both Eclipse and RayStation. Details of the participating institutions, equipment and systems used are given in Table 1.

Measurements were performed either in water or in a water-equivalent plastic phantom and all centers used a Farmer chamber PTW 30013. Other detectors can be used for measur-

ing the DLG but the Farmer chamber is recommended because it provides a good assessment of the average dose due to its relatively large size[13,17]. Measurements were carried out at a source-to-surface distance of 90 cm, with the chamber placed at the isocenter at a 10 cm depth.

The DLG was determined from the chamber readings with the sweeping gaps. The MLC transmission component was subtracted from each reading. Next, a linear fit of the corrected readings as a function of the nominal gap size was performed. Finally, the DLG was defined as the negative of the gap axis intercept of this linear fit, such that a negative intercept sign corresponds to a positive DLG and vice versa[13,18].

All the Halcyon systems and TPSs used in this study were carefully commissioned according to international guidelines[6,7,8,10,11]. Calculations were carried out with the dose calculation algorithms clinically used at each institution (see Table 1). Two calculation grid resolutions were evaluated: 2.5 mm, which is commonly used in clinical practice,[19] and 1 mm, which is the finest resolution available in both TPSs. Calculated doses were obtained as the average doses over a delineated cylindrical structure mimicking the active volume of the Farmer chamber. Calculated doses (D_{calc}) were compared with measured doses (D_{meas}) and differences were computed as $(D_{calc} - D_{meas})/D_{meas}$ and expressed as percentage values.

II.D. Description of the TPS MLC models

The Eclipse TPS uses three parameters to model the MLC: the DLG, the MLC transmission, and the tongue-and-groove width. Calculations in Eclipse are carried out considering all leaves with flat tips retracted by DLG/2 with respect to the nominal leaf positions. By applying this shift, the additional transmission through the rounded leaf end can be approximately compensated for and the integral fluence in the sweeping gap beams can be reproduced. The MLC transmission is defined for each MLC layer as the average leaf transmission and the tongue-and-groove width is subtracted from the fluence map at the exposed sides of the leaves[20,21]. The MLC model in Eclipse for the Halcyon uses a DLG = 0.1 mm, a transmission for a single MLC layer of 0.47% and a null transmission below both MLC layers. The tongue-and-groove widths for the proximal and distal layers are 0.56 mm and 0.40 mm, respectively. All these parameters are fixed and unmodifiable by the user[22].

The MLC model in RayStation has several user-definable parameters: leaf tip width, x-offset, MLC transmission, tongue-and-groove width, gain and curvature. The MLC transmission indicates the average transmission for a single MLC layer and a null transmission below both layers is considered. The leaf is represented in the model as a heightless rectangle with the defined transmission. The leaf tip width parameter defines a region near the tip where a constant transmission equal to $\sqrt{T}$ is assigned. A similarly reduced transmission is also assigned to the tongue-and-groove regions extending from the exposed leaf sides. Additionally, an effective leaf position is considered in the calculations where all leaves are shifted by a certain amount which at the central axis is equal to the 'x-offset' parameter and at the off-axis positions also depends on the 'gain' and 'curvature' parameters. A detailed description of these parameters can be found in the RayStation 10A Reference Manual[23].

The most recent version of RayStation (RayStation 10A) was included in this study, which implements separate configurations parameters for each MLC layer. Additionally, a prototype version was also evaluated where the transmission assigned to the leaf tip region was increased to a fixed value of 0.20 (corresponding to a 20% transmission). This prototype version will hereafter be referred to as RayStation 11P.

III. Results

III.A. Dosimetric leaf gap and MLC transmission

The results for the DLG and MLC transmission values obtained at each institution are given in Table 2. The average DLG value was 0.44 mm for the proximal layer (range 0.36-0.48 mm) and 0.28 mm for the distal layer (range 0.12-0.38 mm). At all institutions the measured distal DLG was smaller than the measured proximal DLG, differing by 0.16 ± 0.05 mm (average $\pm$ 1 SD). In all cases the Pearson's correlation coefficient r of the linear regression gave 1-r^2 values below 10^{-6}. The MLC transmission for a single layer was $0.33 \pm 0.01\%$ at all institutions.

For the sweeping gap beams with both MLC layers defining the aperture (i.e. leaves from both layers at the same position) the DLG ranged from -0.62 to -0.42 mm and was -0.49 mm on average. This value was 0.93 mm smaller than the average DLG of the proximal layer and 0.77 mm smaller than the average value of the distal layer. The MLC transmission

under both MLC layers was lower than 0.01% at all institutions (average of 0.005%), which can be considered negligible for practical purposes. The corrected readings for a representative case (Institution A), including the linear fits and the DLG derivation for each layer and both layers, are shown in Figure 2. The DLG values shown in Table 2 were obtained with gap sizes varying by 2 mm. At all institutions the DLG values obtained with the reduced set of gap sizes agreed within 0.01 mm with those measured with the extended set of gap sizes. Note that a negative DLG value corresponds to a positive gap axis intercept of the linear fit line (lower curve in Fig. 2).

For comparison purposes, the DLG and transmission were also determined with the DICOM files provided by Varian, which only include the DLG set for the distal layer. The DLG values obtained with these files differed from those obtained with our custom-made ones. The average MLC transmission between all centers was $0.47 \pm 0.01\%$, which was higher than the 0.34% value with the custom plan files. The DLG for the distal layer was -0.34 ± 0.10 mm, which was smaller than the 0.28 mm previously determined.

The disparity in the MLC transmission values obtained with our files and the ones provided by Varian was caused by the different field sizes used. The files provided by Varian use a field size around $27 \times 27\,\text{cm}^2$, which is close to the maximum field size for the Halcyon. However, the values given in Table 2 were obtained with a $10 \times 10\,\text{cm}^2$ field size (as defined by the other MLC layer) and it is well known that the MLC transmission depends on the field size[24]. To further investigate this dependence, MLC transmission was measured for various field sizes (5×5, 15×15, 20×20 and $25 \times 25\,\text{cm}^2$). As shown in Figure 3, MLC transmission varied from approximately 0.31% to 0.47% as the field size increased from $5 \times 5\,\text{cm}^2$ to $25 \times 25\,\text{cm}^2$. Note that when the exact field size in the direction perpendicular to the leaf motion could not be achieved due to the 1 cm leaf widths, slightly larger field sizes were used in that direction and MLC transmission was referenced to the corresponding equivalent square field.

A detailed analysis of the DICOM RT Plan files provided by Varian for the determination of the DLG revealed that the distance travelled by the leaves depended on the gap size. The leaves travelled 14.8 cm for the smallest gap size of 2 mm and this distance was progressively reduced with the gap size, going down to 13 cm for the 20 mm gap. With a constant number of MUs, such differences affect the leaf speed and thus the linearity of the corrected readings

as a function of the gap size, leading to the incorrect DLG values. Further details on the loss of linearity and on the structure of the corresponding residuals from the linear fit are provided online as Supporting Information.

III.B. Effect of the leaf trailing distance (trailing effect)

The DLG was also determined with the trailing sweeping gap tests, in which a certain trailing tip to tip distance is kept between the leading layer defining the gap size and the trailing layer. The results are reported specifying the leading layer used in each case: 'proximal layer' indicates that the proximal leaves were leading, with distal leaves trailing, and vice versa. As shown in Figure 4, the DLG exhibited a strong dependence on the trailing distance. For a zero trailing distance, the projections of leaves from each layer coincide and both layers define the sweeping gap simultaneously. In this case, a negative DLG was obtained (Table 2). The DLG increased with the trailing distance up to ~10 mm, after which it reached a plateau close to the single layer DLG value given in Table 2.

All five Halcyon systems exhibited the same behavior and differences between the curves were only due to the variations in the DLG values at different institutions (Table 2). To illustrate this similarity, all the curves were vertically shifted to match a common average DLG for each layer at the 20 mm trailing distance. This resulted in overlapping curves (see Figure 4c).

The variations in the DLG for the tSG tests were caused by differences in the doses measured for different trailing distances. The measured sweeping gap doses as a function of the trailing distance at a representative institution (center E) are illustrated in Figure 5. As the trailing distance decreased, the sweeping gap doses were progressively reduced. For trailing distances between 20 mm and 5 mm this reduction was small and nearly linear, while for trailing distances below 5 mm the dose reduction was larger and progressively steeper.

The dose variations shown in Figure 5 were independent of the gap size; therefore, the linear fit line used to determine the DLG (corrected readings as a function of the gap size in Fig. 2) was shifted downwards as the trailing distance was reduced, resulting in a lower (more negative) DLG value. Since the dose variations were the same for all gap sizes, the corresponding relative variations ended up much higher for the small gaps: the relative

variation between the trailing distances of 0 and 5 mm was approximately 5% for the 20 mm gap, 10% for the 10 mm gap, and as high as 20% for the 5 mm gap. The dose versus trailing distance curves at all centers were very similar, with only a scaling difference due to the different calibration setups (associated with nominal dose rates) and each machine-specific DLG.

To investigate the reason behind this effect, the variation of the transmission through the leaf ends for different trailing distances was investigated by ray tracing computations. The results for direct transmission considering photons with a vertical (non divergent) incidence and a simple exponential attenuation through the leaves are given in Figure 6, where a linear attenuation coefficient $\mu = 0.74\,\mathrm{cm}^{-1}$ was chosen to obtain a transmission of 0.33% for a leaf height of 7.7 cm. As the projections of the leaves from each layer get closer, the additional fluence through the rounded leaf ends is reduced due to the combined attenuation from both leaves. Thus, when the leaf projections coincide (trailing distance = 0), the transmitted photons must pass through the leaf tips from both layers, which increases attenuation and reduces the DLG.

Figure 6 illustrates the transmission computed with ray tracing for different trailing distances, as well as the corresponding integral transmission and equivalent offset. The integral transmission was obtained from accumulating the transmission profile and subtracting the transmission corresponding to that of flat and double-focused leaves, hence the offset indicates the leaf tip transmission component to the DLG[16]. The intrinsic DLG can be computed as twice this offset[16] and strongly depends on the trailing distance (see Fig. 6c), which approximately explains the variation in the measured DLG. For further details on the relationship between the DLG, the integral transmission and the offset, the readers are referred to Arnfield et al[16]. This offset has also been called intrinsic offset and its relationship with the 'x-offset parameter' in RayStation was recently provided by Saez et al[17].

III.C. Modeling the trailing effect in the TPSs

The sweeping gap and trailing sweeping gap plans were imported and calculated in Eclipse and RayStation. The calculated doses and the derived DLG values were compared to the experiments.

The calculated doses for the sweeping gaps in Eclipse were independent of the MLC layer and varied slightly with the trailing distance. As shown in Figure 7, the calculated dose varied linearly with the trailing distance and Eclipse underestimated the dose for trailing distances $\gtrsim$1 mm and overestimated it for trailing distances $\lesssim$1 mm. Differences depended on the gap size and were as high as +10% and −8% for the 5 mm gap and ± 5% for the 10 mm gap.

The results in RayStation depended on the version used. In version 10A the calculated doses varied smoothly for trailing distances t larger than the 'leaf tip width' parameter configured in the system and showed a more pronounced variation for trailing distances below this value (see dashed lines in Fig. 7). The TPS underestimated the dose for $t \gtrsim 1$ mm, with differences around −3%, and overestimated the dose for $t \lesssim 1$ mm with discrepancies up to +9%. This represented a clear improvement with respect to Eclipse for $t \gtrsim 1$ mm (discrepancies were approximately halved) but only a minor improvement for $t \lesssim 1$ mm.

In RayStation 11P the dose increase between trailing distance = 0 and trailing distance equal to the 'leaf tip width' was steeper (dotted lines in Fig. 7) due to the higher transmission (20%) assigned to this region compared to the previous value of $\sqrt{T}$ (5.7% for T = 0.33%). This resulted in a better agreement across the entire range of trailing distances. The only substantial differences with the measured doses were obtained between $t = 0.5$ mm and 3 mm but all differences were within ± 1%, ± 2%, and ± 3% for the gap sizes of 20 mm, 10 mm and 5 mm, respectively.

The calculated doses were independent of the grid size in both TPSs. Figure 7 shows the measured and calculated doses for the 10 mm sweeping gap. Sweeping gaps of other sizes produced similar dose variations, but the relative dose differences depended on the gap size: the smaller the gap size, the larger the relative dose difference. More information on other gap sizes and their corresponding dose differences is provided as Supporting Information (Figures S3, S4 and S5).

To better characterize the modeling of the trailing effect a 'calculated DLG' was derived from the calculated doses and compared with the measured DLG. The calculated DLG from Eclipse was 0.13 ± 0.01 mm for all the tests regardless of the MLC layer, of the trailing distance and of the version of Eclipse (Fig. 8). This 0.13 mm value was only slightly larger than the fixed 0.10 mm parameter preconfigured in the TPS. The DLG from RayStation 10A

decreased somewhat for small trailing distances, but not sufficiently to match the experiment. RayStation 11P exhibited a steeper variation in the DLG for small trailing distances, which improved the agreement between the calculated and measured DLG for large trailing distances (single layer DLG) as well as for a trailing distance $t = 0$ (DLG for both layers combined).

IV. Discussion

The Halcyon^{TM} has a double-layer MLC and in v2.0 clinical plans the leaf positions from both layers are kept as close as possible to achieve the effective 5 mm resolution, as well as to reduce the effective MLC transmission. The leaves from one MLC layer follow the leaves from the other layer at a close 'trailing' distance with proximal and distal layers interchangeably taking leading and trailing roles. The trailing distance t affects the doses delivered by dynamic fields; hence the stacked MLC introduces new characterization and modeling challenges.

As the trailing distance t was increased, the doses delivered by the sweeping gaps increased. For $t > 5$ mm the increase was nearly linear with t, corresponding only to the added transmission of one layer compared to two, and did not affect the measured DLG values. However, as the trailing distance was reduced below 5 mm, there was a steeper decrease in the measured doses and the corresponding DLG also decreased, which suggested some modification of the effective transmission through the overlapping leaf tips.

We used a simple ray tracing code to show that such a trailing effect could be due to the interplay between the attenuation at the leaf tips of both MLC layers and to the transmission through their rounded leaf ends. When the trailing distance is zero, the leaves from both layers define the gap size and the transmission through the leaf tips is reduced due to the combined attenuation of two MLC layers. Without accounting for other phenomena such as MLC scatter, source size or changes in the energy spectrum, simple ray tracing was sufficient to qualitatively show the impact of the leaf trailing distance on the integral transmission and on the DLG (see Fig. 6).

For the specific TPSs, Eclipse failed to model the steeper dose reduction for small trailing distances ($t < 5$ mm). The reason for this is that Eclipse accounts for the additional

transmission through the rounded leaf end by retracting the leaf positions a certain distance (DLG/2), but it does not implement any explicit model of the leaf tip, effectively considering it flat. To better replicate the interplay between the leaf tips from different MLC layers, a better MLC model for the Halcyon system would likely be necessary.

The main advantage of RayStation is that it includes a more detailed, although still rudimentary, model of the leaf tip. It uses a two-step function where a constant intermediate transmission is assigned to a certain length at the end of the leaf equal to the 'leaf tip width' parameter configured in the system. For trailing distances below the leaf tip width this model produced a steeper dose reduction for the sweeping gap doses, as well as a linear reduction in the corresponding DLG (see Figures 7 and 8). The best results were obtained with RayStation 11P, because the higher transmission assigned to the leaf tip produced a steeper dose variation for small trailing distances. RayStation 11P yielded an agreement within $\pm 3\%$ even for the 5 mm sweeping gaps. To further improve this agreement a more sophisticated leaf tip model would likely be required, which could go from the implementation of a three-step function (with two intermediate transmission levels at the leaf tip instead of only one) to a continuous variable transmission through the curved portion of the leaf.

The MLC transmission values obtained at all centers were consistent. For both MLC layers combined the transmission was negligible ($\sim 0.005\%$) and for a single layer the transmission varied between approximately 0.30% and 0.50% depending on the field size. For the field sizes below 20x20 cm^2, the MLC transmission for the proximal layer was smaller than for the distal one, which can be plausibly explained by the former's closer position to the source (fewer scattered photons reaching the detector). However, Fig. 3 shows a slightly greater transmission for the proximal layer for the 25x25 cm^2 field size. The exact reason for this reversal is unknown, but the differences were minimal and should have no practical implications. Since in clinical plans the area shielded by only a single MLC layer is limited to a small region around the beam aperture, it is reasonable to consider the average MLC transmission in clinical plans to be close to 0.30%.

The DLGs measured in the present study were quite homogeneous across five institutions. The DLG for the proximal layer was consistently higher on average than for the distal layer by 0.16 ± 0.05 mm, which should ideally be taken into account by the TPS. Some difference was expected because for the same physical leaf height and tip radius, the different

IV. DISCUSSION

distance from each MLC layer to the isocenter plane impacts the trailing effect and the DLG. The geometrical projection of the leaf tip width at the isocenter is larger for the proximal layer. As a consequence, the plateau is reached at a larger trailing distance (see Figures 4-5) and the DLG value of the proximal layer is larger compared to the distal one. The measured DLGs for different treatment units ranged between 0.36 mm and 0.48 mm for the proximal layer and between 0.12 mm and 0.38 mm for the distal layer. These results support the assumption that a common preconfigured MLC model for the Halcyon system is feasible. However, differences in the measured DLG around 0.2 mm were found, which are equivalent to systematic differences of 0.1 mm in leaf positions. Such differences are experimentally detectable in Halcyon plans and can produce average ion chamber point dose difference-saround 0.8% in clinical cases[12]. To minimize these differences, a slight modification of the MLC modeling parameters should be allowed.

A wider range of DLG values for the Halcyon has been reported in the literature for the distal layer, with values ranging between −0.23 and +0.27 mm[2,3,12,15]. Kim et al.[14] measured the DLG for single layers and both layers combined and reported a larger DLG for both layers (0.96 mm) than for each single layer (−0.20 mm), which is the opposite of what we found. We believe that these discrepancies are mainly due to methodological and perhaps reporting differences, rather than to actual differences between the MLCs. It is important to determine the DLG with sweeping gaps of all sizes traveling at the same speed; otherwise, the linearity of the corrected readings as a function of the gap size is reduced and systematic errors are introduced (see Fig. S1 in the Supporting Information). We also want to note that with DLG values so close to zero it is necessary to carefully determine the sign of the DLG.

Negative DLG values are counterintuitive. The DLG accounts for the additional transmission through the rounded leaf end and is expected to be positive for the leaf positions calibrated by visible or infrared light. Negative values could in principle be due to differences between the leaf position origins of each MLC layer, but in reality such differences were very small (<0.2 mm as estimated by additional measurements) and could not explain by themselves the negative DLG values around −0.5 mm. We believe that another contributing factor could be the photon source occlusion: when both MLC layers define the sweeping gap (trailing distance close to zero), the combined source occlusion by each layer reduces the sweeping gap doses and could contribute to a negative DLG.

Despite the large discrepancies found between calculated and measured doses for small trailing distances, a good agreement in clinical plans has been reported for both Eclipse and RayStation in patient-specific QA verifications, end-to-end tests and certification audits[2,3,12]. The reason for this is probably that the MLC models were configured with parameters that partially compensate for the limitations in each TPS. Several authors have shown that the DLG parameter that maximizes the clinical dose calculation accuracy may not necessarily be the same as the measured DLG[25], which can be used to compensate for limitations in the MLC model[26]. Of note, the DLG value of 0.1 mm preconfigured in Eclipse is an intermediate value between the DLG per layer and for both layers (see straight line in Fig. 8). This value is probably a good compromise for Eclipse that provides acceptable accuracy in typical clinical plans. Of course the influence of the trailing interplay is reduced, as any other leaf penumbra effect, in the clinical plans containing a relatively large proportion of wide apertures.

Such compromises are, however, not optimal. The 'optimal' configuration parameters may depend on the characteristics of each individual clinical plan and, as a consequence, they may be technique and even case-dependent[27,28]. We believe it is important to use tests specifically designed for dynamic treatments for characterizing and commissioning MLC models, such as the recently proposed asynchronous sweeping gaps[20] and the trailing sweeping gaps specific to the double-stacked MLC described in the present study. These tests facilitate the configuration of MLC models in the TPS, standardizing the configuration process[17] and guiding future model developments[21]. MLC models that are able to reproduce the results obtained with these dynamic tests should, in principle, provide a better accuracy in a wider range of treatment techniques and plan characteristics. As an example, in RayStation 11P configuring the system to reproduce the measured DLG for each MLC layer separately provided a good agreement not only for each independent layer, but also for the trailing effect (see Figures 7 and 8).

The dose accuracy in clinical plans was not included in the current study, as it focused on the characterization of the DLG and the trailing effect and their modeling in the TPSs. However, several authors have already reported good dosimetric results in clinical Halcyon plans with both Eclipse and RayStation[12,29]. We believe that as MLC models evolve, helped by detailed measurements including those in the current study, the dose calculation accuracy in clinical plans will also improve, especially for cases with small dynamic leaf gaps and trailing distances, which produced the largest discrepancies. Further improving the MLC

IV. DISCUSSION

model and evaluating the benefits in clinical plans will be the subject of future work.

V. Conclusions

In the present study we described the previously unreported trailing effect in a stacked MLC system, which is primarily due to the intricate interplay between the primary photon fluence attenuation by the rounded leaf ends from different layers. This effect produces important differences in the doses delivered by sweeping gaps with the Halcyon^{TM} system depending on the distance between the leaf tips from each layer (trailing distance). Additionally, it also affects the measured DLG, which strongly depends on the arrangement used in its determination. To maximize the DLG measurement accuracy it is important to use sweeping gap plans that maintain the same MLC speed for different gap widths. This is not the case with the DICOM RT Plan files currently supplied by the vendor.

The performance of a TPS in reproducing the trailing effect depended on the leaf tip model implemented in each system. Eclipse has no explicit model of the leaf tip and could not replicate this effect. RayStation implements a simple model of the leaf tip that could partially replicate the trailing effect, especially with the modifications introduced in the presented prototype.

The MLC dosimetric characteristics across five different Halcyon systems were quite homogeneous, but differences around 0.2 mm were found in the measured DLG values. The DLG for the proximal layer was always larger than for the distal one, on average by 0.16 ± 0.05 mm. A common preconfigured MLC model for the Halcyon system is feasible, but these differences should ideally be taken into account by the TPS.

Double-stacked MLCs introduce new challenges such as the need for separate TPS parameters for each MLC layer and the trailing effect, which should be carefully considered when these systems are evaluated. The proposed trailing sweeping gap tests are useful for characterizing and commissioning dual-layered MLCs.

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Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Data sharing

The data and DICOM files that support the findings of this study are available from the corresponding author upon reasonable request.

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Institution	TPS	Algorithm	Phantom
Centre Oscar Lambret, Lille, France (A)	RayStation 9A	CC	Water (MP1, PTW)
Institut Sainte Catherine, Avignon, France (B)	Eclipse 15.6	AAA	Water (myQA HALO^{TM}, IBA)
IUCT Oncopole, Toulouse, France (C)	Eclipse 15.6	AAA	Water (BeamScan^{TM}, PTW)
Moffitt Cancer Center, Florida, USA (D)	RayStation 9B	MC	Plastic (Plastic Water®, CIRS)
Radiotherapy Center of Mâcon, France (E)	Eclipse 15.6	AAA	Water (1D SCANNER^{TM}, Sun Nuclear)
	RayStation 10A	CC	

Table 1: Institutions and equipment used in the study. The dose calculation algorithms were: Anisotropic Analytical Algorithm (AAA), Collapsed Cone (CC) and Monte Carlo (MC).

	Proximal layer (upper)		Distal layer (lower)		Both layers	
Institution	DLG (mm)	T	DLG (mm)	T	DLG (mm)	T
A	0.47	0.32%	0.32	0.34%	-0.44	0.006%
B	0.46	0.33%	0.28	0.34%	-0.48	0.005%
C	0.36	0.32%	0.12	0.34%	-0.62	0.005%
D	0.42	0.32%	0.28	0.33%	-0.48	0.005%
E	0.48	0.32%	0.38	0.33%	-0.42	0.005%
Average	0.44	0.322%	0.28	0.336%	-0.49	0.005%
Standard deviation	0.05	0.002%	0.10	0.003%	0.08	0.0003%

Table 2: Dosimetric leaf gap (DLG) and transmission (T) obtained at each institution for each layer and both layers combined.

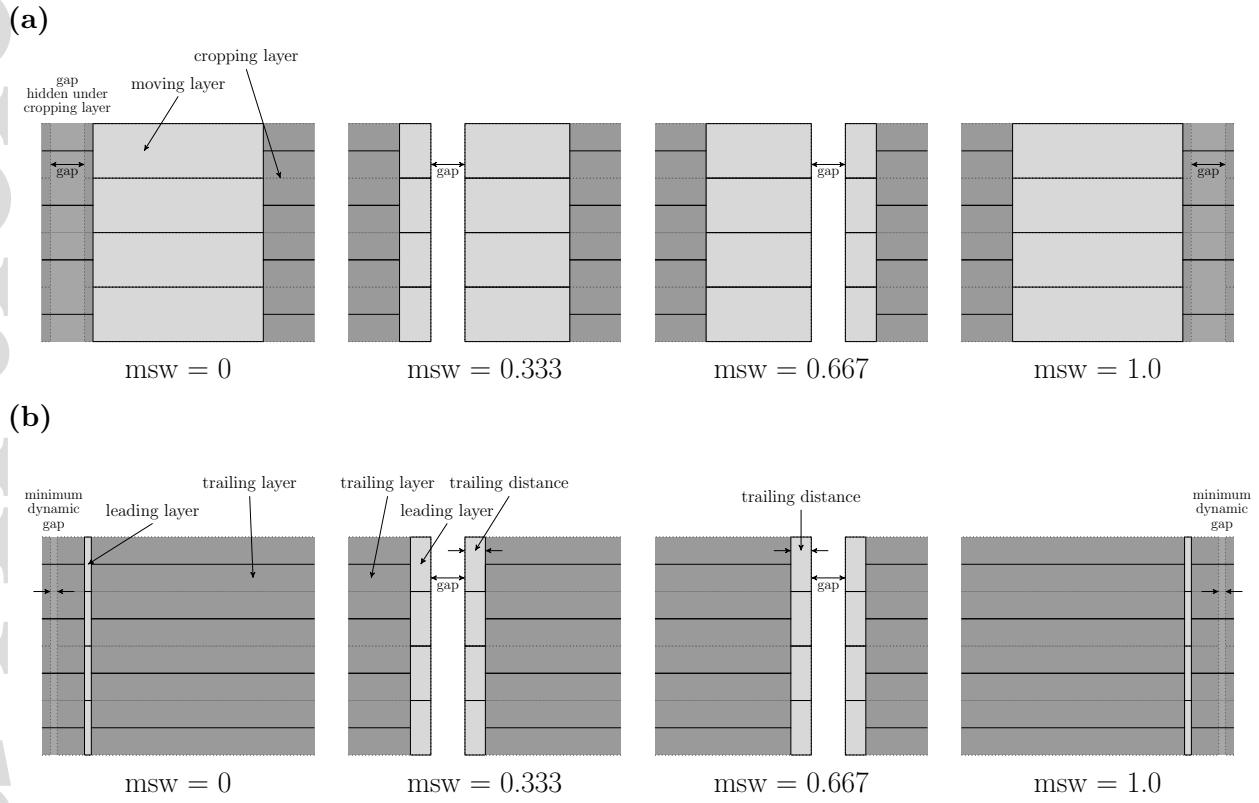

Figure 1: Sketch illustrating (a) the sweeping gap test and (b) the trailing sweeping gap test in the beam's eye view. The leaf positions are shown for different meterset weights (msw). Two versions of the tests were designed with the proximal and distal layers interchanging the leading and trailing roles.

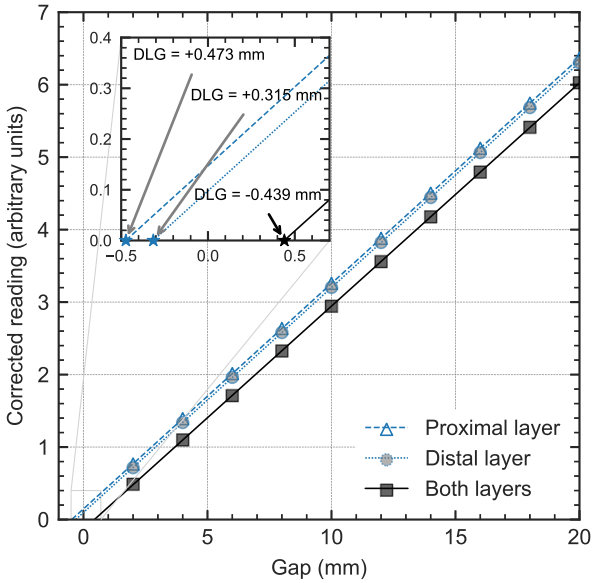

Figure 2: Results of the sweeping gap tests for the proximal and distal layers and for both layers combined (center A). The corrected readings (after subtracting MLC transmission) are plotted as a function of the gap size. The negative of the x-axis intercept of the linear fit defines the dosimetric leaf gap (DLG).

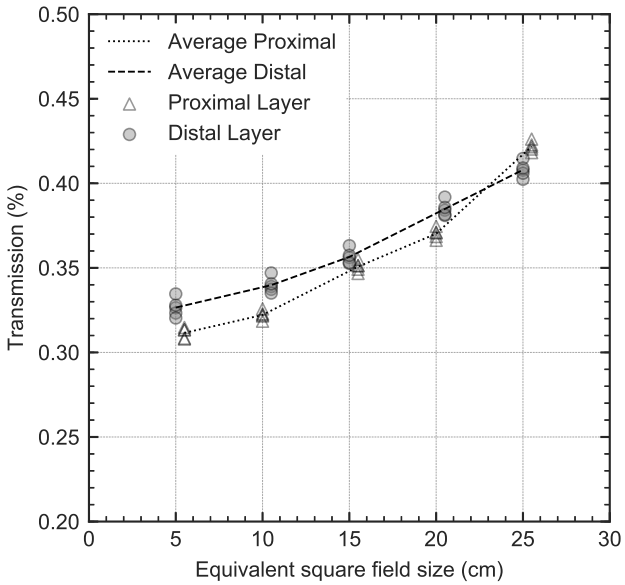

Figure 3: MLC transmission as a function of the field size. Symbols represent the values measured at each institution and dashed lines indicate the average values.

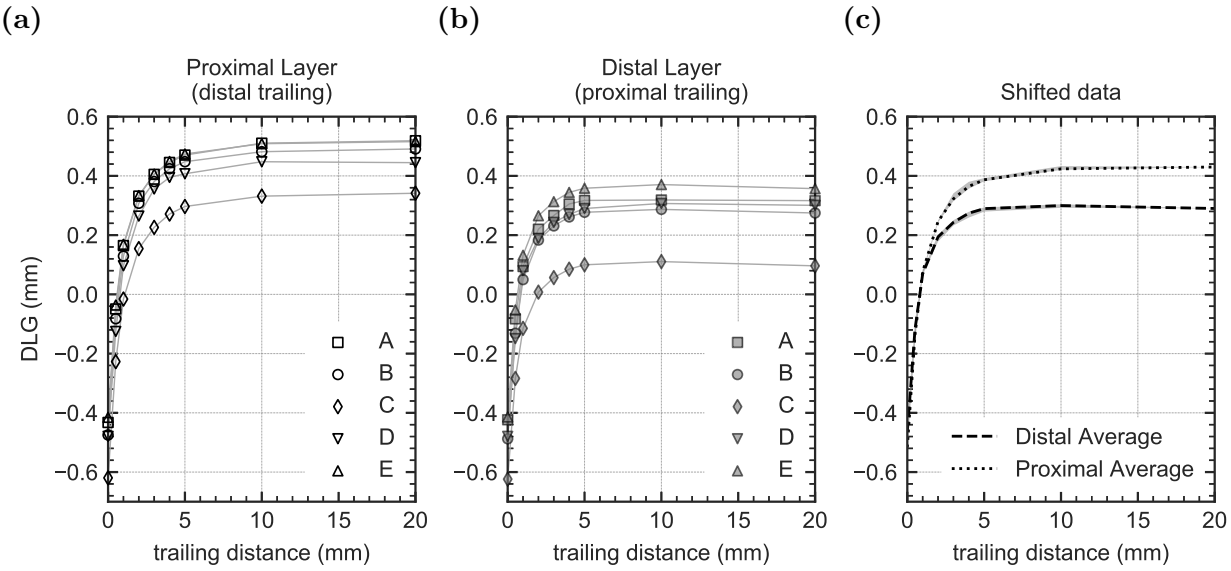

Figure 4: Dosimetric leaf gap (DLG) values obtained at the five institutions as a function of the trailing distance t for the (a) proximal and (b) distal layers. In (c) the DLG curves from each institution were shifted vertically so that the DLG for $t = 20$ mm matches the average DLG given in Table 2. The lines in (c) represent the average curves and the shaded areas indicate the range of variability between different institutions.

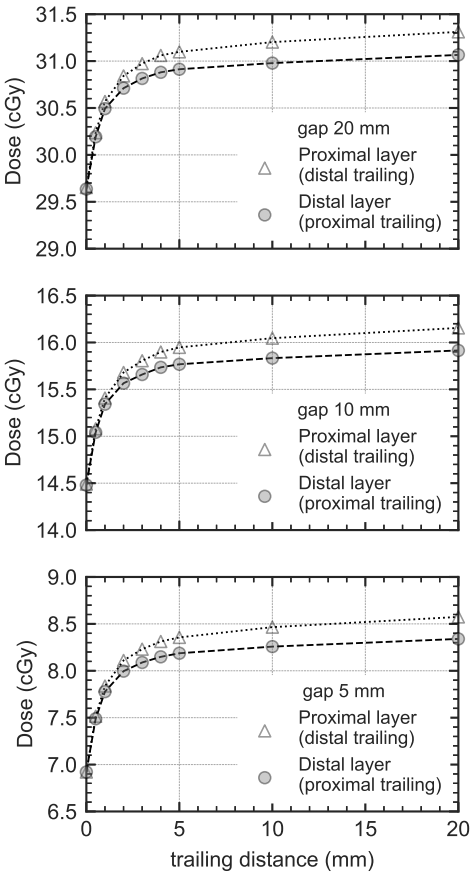

Figure 5: Measured sweeping gap doses as a function of the trailing distance for different gap sizes. A common dose scale was used in all plots to illustrate that dose variations were independent of the gap size. The doses shown correspond to 100 MU.

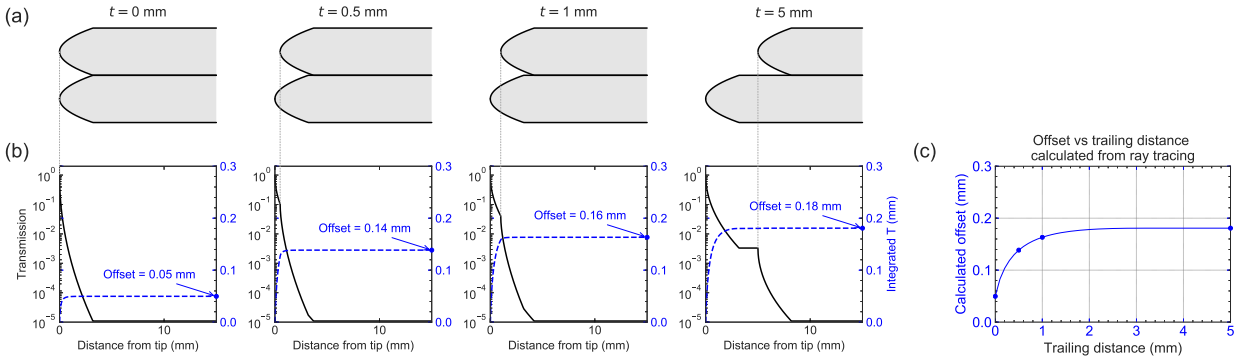

Figure 6: Results obtained with ray tracing. In (a) a sketch of the leaves from each layer for different trailing distances is illustrated. The computed transmission through the leaves and the corresponding integral transmission (dashed lines) are shown in (b). In (c) the leaf offset computed with ray tracing is plotted as a function of the trailing distance.

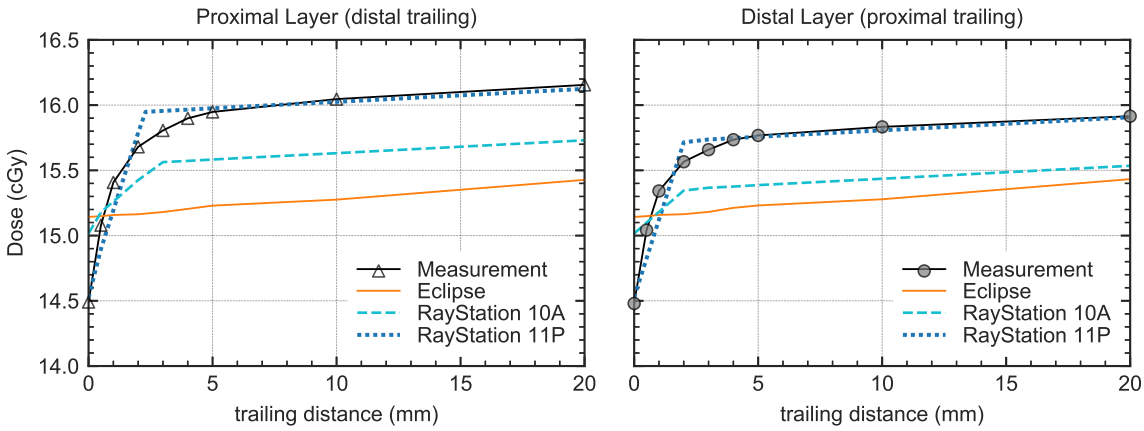

Figure 7: Measured and calculated doses for a 10 mm sweeping gap as a function of the trailing distance. The doses shown correspond to 100 MU.

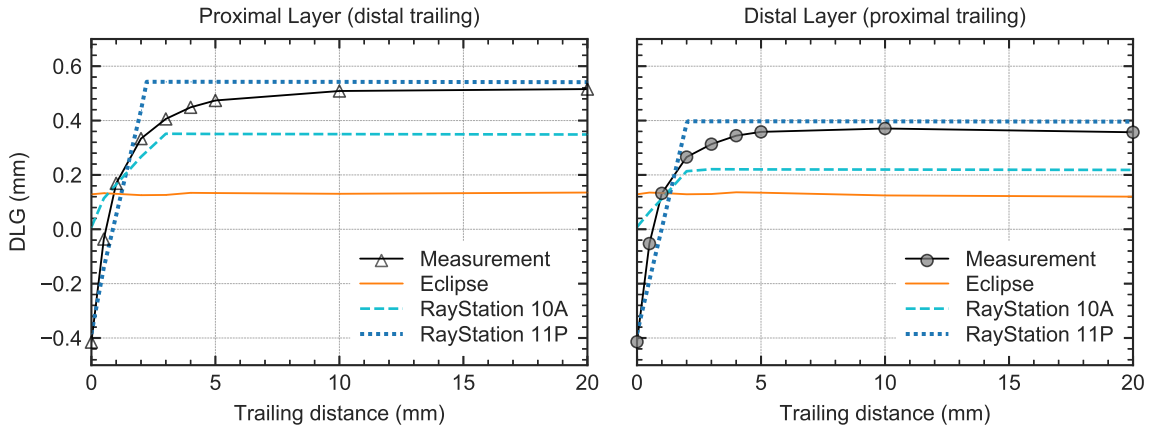

Figure 8: Dosimetric leaf gap (DLG) values obtained from measurements and calculations from the Eclipse and RayStation treatment planning systems for the proximal and distal layers, as a function of the trailing distance.