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Using Collimator Rotation to Retain Conformal Dose Distributions with Thicker MLC Leaves

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Abstract

The multi-leaf collimator (MLC) is a critical component of modern X-ray radiotherapy systems which allows for the delivery of a conformal dose distribution to the tumour. However, MLCs are one of the most sensitive components in a linac since they contain several components that are prone to failure. The current trend in design is to produce MLCs with ever-increasing numbers of leaves to improve their ability to shape the beam, but this further reduces their robustness. This robustness has shown to be an important factor in low- and middle-income countries (LMICs) where there are currently limited numbers of available linacs per person and that linac downtime has a much greater impact on treatment capacity than in high-income countries. Investigating the design of a more robust MLC system that would decrease the linac downtime and thus increase the availability of radiotherapy at single unit facilities. We assess a new method to deliver a similar conformal tumour dose distribution using a significantly simplified MLC with thicker leaves whilst utilising multiple collimator angles for each delivery to attempt to retain excellent conformity of the dose. The open-source treatment planning software, matRad, was used to generate representative treatment plans to compare the conformity index, homogeneity index and mean dose delivered to circular and crescent-shaped targets for a range of MLC leaf thicknesses and collimator angles. Using MLCs with a leaf thickness of up to 1.5 cm thickness, it was possible to increase the dose conformity by using between 2 to 6 different collimators angles to deliver multiple x-ray beams and generate a conformal treatment plan for a crescent-shaped target (CI > 0.6) with a single dose distribution. Using this technique of delivering the beam from multiple collimator angles, linacs with more robust, thicker and fewer-leaved MLCs can still achieve excellent conformal dose distributions. Such a technique likely can achieve even greater conformity in step-and-shoot intensity modulated radiotherapy (IMRT).

Introduction

In 2019, the World Health Organisation estimated that cancer is one of the leading causes of premature deaths in 112 countries [1]. Worldwide, in 2020 alone, 19.3 million cases were diagnosed, with 9.96 million deaths recorded [2]. Current projections anticipate the yearly number of new cancer cases worldwide to exceed 27 million by 2040, resulting in cancer becoming the leading cause of death [3]. However, around 70% of these new cases will be in low- or middle-income countries (LMICs) which currently lack the healthcare programmes required to treat this increasing cancer burden [4,5]. Radiotherapy, one of the main components of modern cancer care and used for both curative and palliative treatments, is estimated to be beneficial for half of all cancer cases. Unfortunately, access to radiotherapy is limited and insufficient in most LMICs, with only 10% of patients in low-income and 40% in middle-

income countries who need radiotherapy having access to it [5]. 25 out of 57 African countries have no radiotherapy facilities [4,5]. Within the remaining African countries, the ratio of medical linacs to people varies massively from 1 machine per 423,000 people in Mauritius to 1 machine per over 100 million people in Ethiopia (shown in Figure 1). This compares to 1 machine per 187,000 people in the UK [4,5]. This disparity in radiotherapy access is contextualised by the International Atomic Energy Agency's definition of the ideal ratio being approximately 5 radiotherapy machines per 1 million inhabitants. Currently, there are around 400 radiotherapy machines in Africa, serving a population of over 1.2 billion people; contrasting this with the almost 4000 linacs serving the US population of 331 million illustrates clearly the global inequality in access to radiotherapy [4-7].

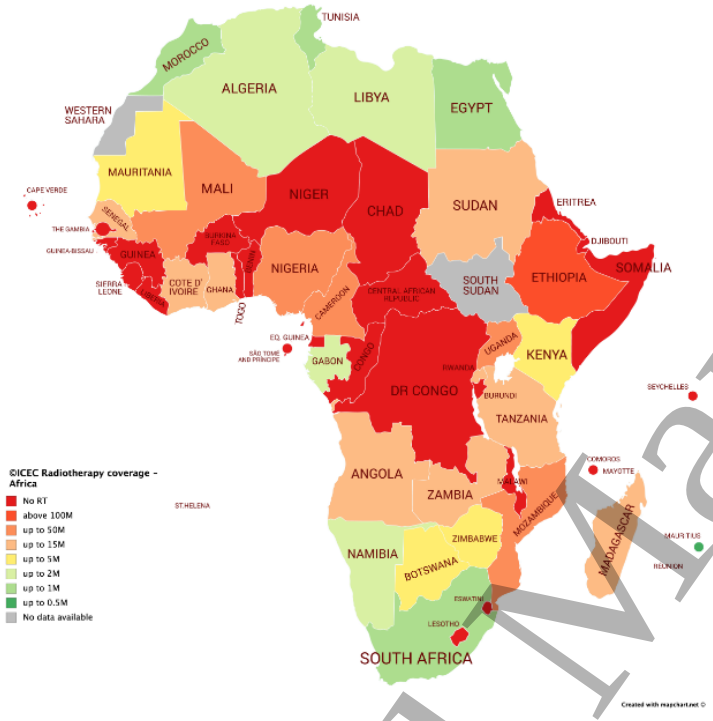

Figure 1: A map of Africa showing the number of people per radiotherapy facility in each country, showing the lack of radiotherapy in most of the continent [4].

The challenge to keep up with current and future demand for access to radiotherapy for cancer treatment in LMICs can be addressed in large part by developing more reliable and robust linacs. A recent study found that the linac component with the highest fault rate in both Botswana and Nigeria was the multi-leaf collimator (MLC) [8]. This component is responsible for shaping the radiation beam to match the shape of the tumour target, which is essential in modern precision radiotherapy. Another recent study in Indonesia also found that the MLC was responsible for almost 60% of both mechanical faults in linacs and faults requiring a replacement component [9]. These studies clearly show that the MLC is a mechanically sensitive component.

The impact of MLC failures is particularly severe in LMICs. In Indonesia, MLC faults corresponded to 25% of total linac downtime and 27% of faults by number, compared to only 17% of downtime and 21% of faults in high-income countries [9]. Another recent study involving a survey of 59 linacs across 28 African countries found that 41% of facilities experienced frequent MLC failures, with MLC downtime ranging from 2-18% depending on local repair capability and spare parts availability [10]. These studies emphasise the greater importance of improved robustness of linacs in LMICs, particularly since in HICs most RT centres have readily available spare parts and easily accessible full technical support

from the manufacturer; this is rarely the case in LMICs. This impacts on the quality of radiotherapy that is delivered in Africa. Studies have also demonstrated that African centres with MLC equipped machines minimise the load on the MLC by using them for 3D conformal radiotherapy, where the MLC does not move during treatment. Whilst this limits plan precision and treatment quality, it reduces the risk of MLC failure [11-14].

The current trend among MLC manufacturers, however, is to continue reducing the thickness of the leaves, thereby increasing the number of leaves per MLC [15,16]. While narrower leaves have demonstrated dosimetric advantages in conformal radiotherapy and stereotactic techniques [17, 18, 19], recent evidence suggests that treatment plan quality may not be significantly compromised by wider MLC leaves when using modern delivery techniques. A systematic review and meta-analysis found that the difference in conformity index between 2.5 mm and 5.0 mm leaf widths was negligible when using IMRT techniques [20]. Studies comparing 4 mm versus 10 mm MLC leaf widths found that narrower leaves improved only target conformity in IMRT, with no significant improvements in homogeneity, OAR sparing, or treatment efficiency [21]. Similarly, while 4 mm leaves showed significant advantages over 10 mm for 3D conformal radiotherapy, no significant differences were observed between the same leaf widths when using IMRT [22]. More recently, a study comparing VMAT treatment plans with MLC leaf widths between 2.5 mm, 5 mm, and 10 m found there was little difference between treatment plan quality and that all widths produced clinically acceptable plans [23].

Furthermore, as one continues to continue to increase the number of leaves, there are diminishing returns on resolution improvement below approximately 1.5–1.8 mm leaf width [24]. However, this increase in resolution comes at a significant cost in terms of the complexity and fragility of the component as each leaf requires its own motor and optical positioning system, introducing more potential points of failure. As such, one study discovered that the MLC with narrower, and hence more, leaves experienced more failures and faults than standard width MLC [25]. These findings suggest that for modern delivery techniques such as IMRT and VMAT, the dosimetric benefits of narrower leaves may not justify the increased mechanical complexity and reduced robustness, particularly in LMIC settings where linac uptime is paramount.

Therefore, this study investigates the extent to which the MLC can be simplified whilst retaining the ability to deliver conformal dose distributions using basic representative static intensity modulated radiotherapy treatment plans generated with matRad. We explore whether introducing fields from multiple collimator angles can compensate for the reduced lateral resolution of thicker MLC leaves while maintaining treatment conformity. This two-dimensional analysis was deliberately chosen to isolate the fundamental relationship between MLC leaf thickness and lateral conformity without the additional degrees of freedom inherent in full 3D optimisation, which would complicate like-for-like comparison. This work aims to establish whether reducing MLC complexity could decrease component-related downtime, particularly within radiotherapy centres in LMICs, without sacrificing treatment quality.

Materials and Methods

For this work, we developed 2D simulations of static IMRT treatment, where an equally spaced set of co-planar beams are used to treat the tumour, and the MLC leaves move during treatment. We evaluated this configuration rather than full volumetric modulated arc therapy (where the beam rotates continuously round the patient) as it represents the next logical increment from 3D conformal radiotherapy, which is the prevalent technique used in many African centres [11-14].

The software, matRad v2.10.1, was used to generate simplified representative radiotherapy treatment plans [26]. It is an open-source radiation treatment planning toolkit entirely written in MATLAB. In matRad, photon dose calculations use a singular value decomposed pencil beam algorithm [27] with base data derived from the clinically approved PDC++ dose calculation engine [28] for a 6 MV linear accelerator. matRad software works by approximating the target volume as a set of voxels of a

resolution specified by the user. The fluence distribution of the beam hitting the target is approximated as a set of pixels at the same resolution. The software calculates the dose delivered to each voxel by each pixel of the x-ray beam, then optimises the fluence of each pixel, using the Interior Point Optimizer (IPOPT) [29], to a set of objectives and constraints defined by the user. From this, the optimised beam fluence, the dose distribution across the entire treated volume and the total dose that is delivered to volumes that have been defined during the treatment plan, such as the target can be outputted.

Currently, matRad can simulate MLCs with a leaf thickness equal to the pixel width. Modifying the pixel width of the simulation has the effective of modelling different MLC leaf widths, as it decreases the number of voxels used to approximate the target, thus reducing the ability to simulate fine structures. Additionally, increasing the pixel size also reduces the precision of the position of the MLC leaves which should be equally accurate for all leaf thicknesses. Therefore, modifications were made to the matRad source code so that the fluence output of the MLC was approximated as thin rectangles of equal fluence. These rectangles are one pixel tall and have a thickness specified by the user. The rectangles have their fluences equal to the mean of the fluences of their constituent pixels. This represents a reasonable approximation for the fluences that can be generated by an MLC. Furthermore, since the MLC was modelled using matRad's aperture-based approach without explicit modelling of transmission, leakage or scatter contributions. This simplification was appropriate for the present study as the focus was on geometric conformity rather than absolute dose accuracy.

To reduce the time taken for a dose calculation, matRad only calculates the beam fluence for pixels that will pass through the target volume. However, to measure the conformity of the dose to the target and the dose delivered outside the target, a buffer zone surrounding the target volume was created such that the beam also is being simulated outside of the target volume.

While it is not possible to define the collimator angle in matRad, the user is able to specify the angle of the beam and the angle of the couch for each shot. A simple way of simulating a rotation of the MLC is by rotating the couch an equal amount in the opposite direction. This method is only correct if the direction of the beam is the same as the axis of rotation of the target, i.e., directly above the target. Therefore, the use of thin 2D targets, and couch rotation to emulate collimator rotation can be considered an acceptable alternative to a simulation of rotating the collimator itself. This is because radiation fields delivered from multiple angles are required to generate 3D conformal dose distributions, which removes the ability to simulate the rotation of the MLC. As such, the work presented in this paper is representative of the dose delivered for a single gantry angle, but can be assumed to be repeatable for all gantry angles.

The angles investigated were spaced equally between 0° and 180°. Collimator angles ≥ 180° were not included due to the twofold rotational symmetry of the MLC, and 0 degrees was used in all cases. For example, the 4 collimator angles scenario utilised the angles of 0°, 45°, 90°, and 130°. In total, 30 parameter combinations were chosen, 5 collimator distributions and 6 leaf thicknesses.
Two target volumes were produced for this investigation. The first volume is composed of a thin cylindrical target of radius 67 mm and depth of 10 mm surrounded by a buffer of radius 100 mm. This was located 8 mm below the upper surface of a larger cylinder of 20 mm depth and of radius 182 mm which represents the surrounding healthy tissue. The geometry of this target was chosen to evaluate how well the MLC can conform to a constant radius of curvature. The second volume differs from the first only by the target which has been modified to form a crescent shape. The outer radius was unchanged, and the inner radius was set at 33 mm. This geometry was chosen to be reflective of a challenging and small target, particularly since concave targets are harder for an MLC to conform to due to the increased complexity of the shape.

The simulations were repeated over a range of virtual leaf thicknesses from 2 mm to 20 mm. The leaf thickness as defined in this study is defined by its projection to the isocentre, which was 100 cm from the target. The physical thickness of the MLC systems is therefore approximately half of the values stated herein. For reference, the physical leaf thicknesses of commercial linacs varies from 2.5 mm to 10 mm.

An easy way of visualising the dose distributions is with a two-dimensional contour plot. Ideally, a tight grouping of contours associated with a large change in the dose should conform to the target's edge. In addition, there should be no bunching of contours within the target as a uniform dose distribution across the target is desired.

To quantify the quality of the dose distribution achieved in each of the exemplary treatment plans, three quantities were evaluated. Two of these are the conformity and homogeneity indices. These quantities are used clinically and throughout the literature to evaluate radiotherapy treatment plans [30]. The third quantity was the mean dose delivered to the target as the previous two quantities do not measure the magnitude of the dose delivered.

To measure the conformity of the dose distributions, the conformity index (CI) was used:

$$CI = \frac{\frac{TV_T}{TV} * TV_T}{V_T} \quad (1)$$

Where TV is defined as the treated volume (the entire volume that received dose), TV_T is the treated volume within the target volume i.e., the first part is the volume of healthy tissue receiving a dose greater than the reference dose, and V_T is the volume of the target, i.e., the second part is a measure of the quality of the target coverage. CI values can range from zero (target receives less than reference dose) to one (perfect conformity to target). For this investigation, the reference dose was set as 9.5 Gy, 95% of the targeted dose of 10 Gy. The chosen definition of CI for this work, coined as the conformity number, states that a CI greater than 0.6 is conformal [31].

The homogeneity index (HI) was used to quantify the uniformity of the dose delivered. It is defined as follows:

$$HI = \frac{D5 - D95}{referencedose} \quad (2)$$

Here, D5 and D95 are the dosages delivered to 5% and 95% of the target volume respectively. The reference dose was chosen as the dose aimed to be delivered to the entire target, which was 10 Gy. This definition of HI is a measure of the difference between the highest 5% and the lowest 5% dose delivered to the target as a proportion of the ideal dose. A lesser value corresponds to a more uniform dose distribution. These dose metrics are similar to clinical practice following the International Committee on Radiological Units (ICRU) report 62 guidance on prescribing, where the tumour target volume should be covered by the 95% isodose, and dose levels lower than 5% are low dose from a target conformation perspective.

Results

The matRad radiotherapy treatment plans for this investigation aim to deliver a dose of 10 Gy to the target whilst minimising the dose delivered to the remaining non-target volume. Firstly, contour plots of the dose distribution on the thin circular target and the surrounding region at a depth of 10 mm were generated for different MLC leaf thicknesses. The resolution of this simulation is only 2 mm. However, there is a visible difference in the conformity achieved by the 2 mm leaves and the 20 mm leaves shown in Figure 3. This difference is expected as the larger leaves are unable to produce the shallow curves of the circular target at high and low y-values. Additional fields from different MLC angles were added to attempt to retain the conformity achievable with thinner leaves. For the 20 mm virtual thickness leaves, the dose distribution from the delivery using multiple MLC angles conforms to the circular target significantly closer than that using a single angle. However, even with the extra MLC angles, the dose drop-off at the edge of the target is not as sharp as that for the 2 mm leaf distribution. Nevertheless, Figure 3 shows how using as few as two different MLC angles can significantly improve the conformity

of the dose distribution. It is also apparent from Figure 3 that the multiple collimator angle approach results in more extensive low-dose regions beyond the target boundary, as seen by the broader spread of the lower dose contours in the 6-angle case compared to the single-angle 2 mm leaf distribution. While the conformity index accounts for high-dose spillage outside the target, the clinical acceptability of this low-dose bath would depend on the dose tolerance of adjacent organs at risk.

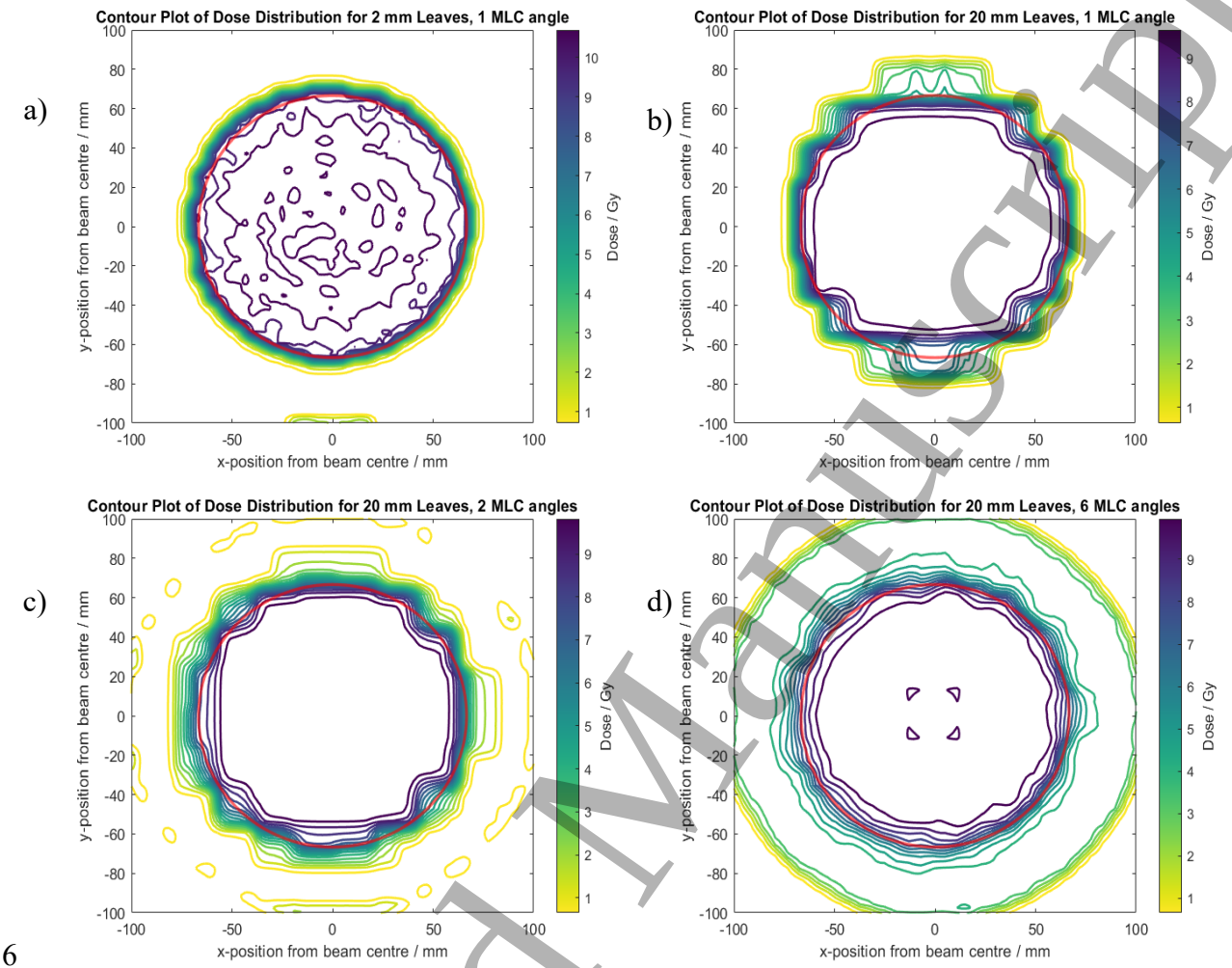

Figure 2: Contour plots of the dose distribution delivered to the circular target at a depth of 10 mm for (a) single angle delivery of 2 mm of leaf thickness, and with 20 mm thick leaves delivered with (b) one angle, (c) 2 angles and (d) 6 angles. The outline of the target is shown in red.

Consequently, the next set of simulations investigated whether thicker MLC leaves can conform to a more complex concave target. The resulting contour plots are shown in Figure 3. Here, the difference in conformity between the 2 mm leaves and 20 mm leaves is more apparent. The dose distribution generated from a single MLC angle with 20 mm leaves appears unable to achieve sufficient conformity around the inner radius of the target to a good approximation. However, once again, by using fields from different MLC angles, a dose distribution that conforms to the target far closer than when only one angle is used was obtained. This was as expected since the increased number of angles gives more opportunities for the faces of the MLC leaves to align with the structure of the target. Although the conformity is improved by using multiple MLC angles, it was found that the dose at the edges of the target decreases more slowly when using thicker leaves. This occurrence was only reduced slightly by the introduction of more angles. The increased low dose spread to surrounding tissue is also evident in Figure 3c. To quantify this observed increase in conformity with more MLC angles, the behaviour of the conformity index, from equation (1) by varying the leaf thickness and the number of collimator angles was investigated. The results of this are shown in Figure 4.

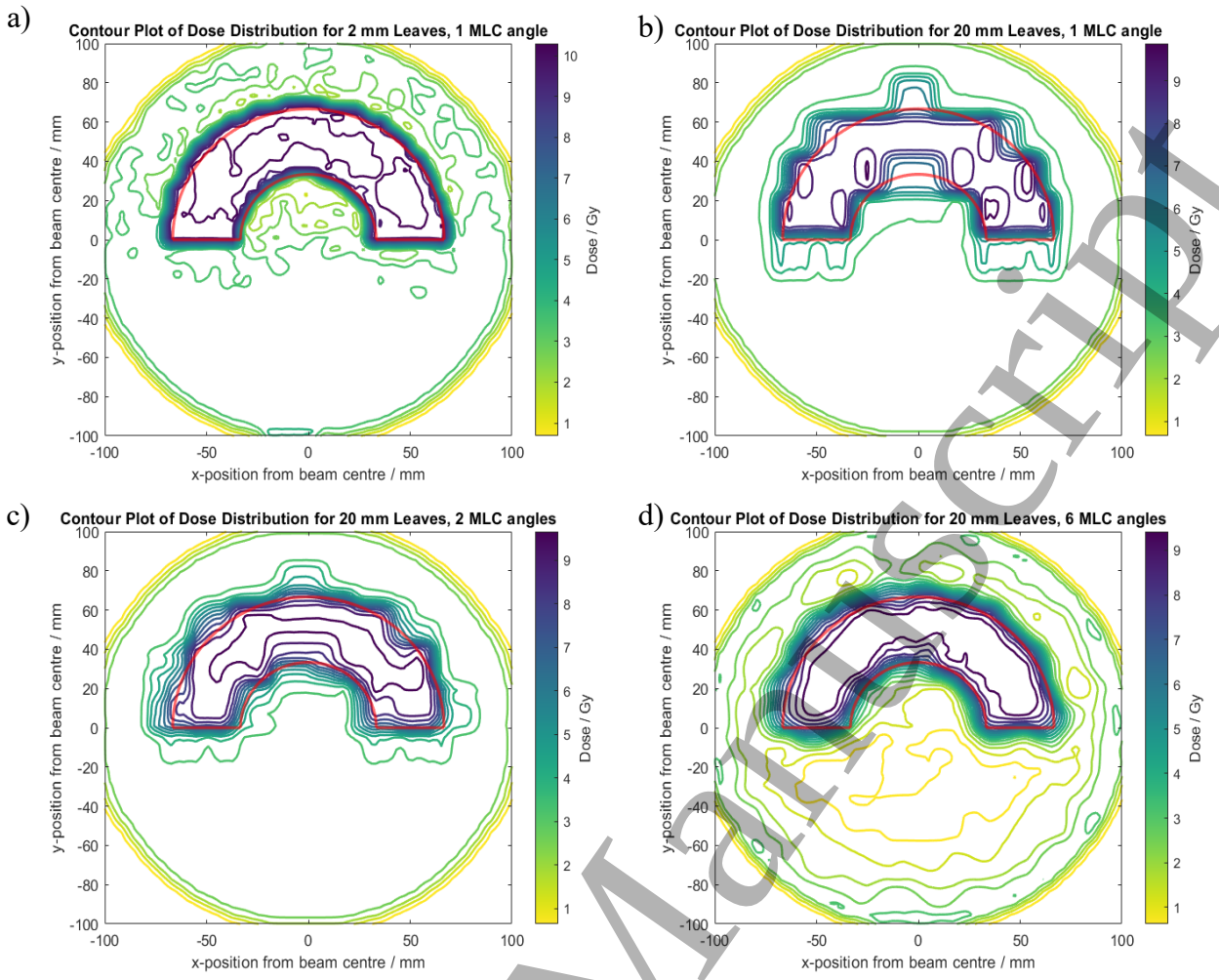

Figure 3: Contour plots of the dose distribution delivered to the concave target at a depth of 10 mm for (a) single angle delivery of 2 mm of leaf thickness, and with 20 mm thick leaves delivered with (b) one angle, (c) 2 angles and (d) 6 angles. The outline of the target is shown in red.

The treatment plan for the concave target with only one angle showed that the conformity index decreased rapidly for leaves with thicknesses greater than 4 mm, as seen in Figure 4a. However, the addition of fields from multiple collimator angles dramatically increased the conformity of the dose distribution. This is evidenced by the 351% increase in the conformity index of dose delivered by the 16 mm virtual leaves when employing two collimator angles instead of one. A similar, but less sizable, increase in CI occurs upon increasing the number of angles for leaves of all thicknesses greater than 4 mm. The dose distribution delivered by the 16 mm virtual leaves using 6 collimator angles has a CI = 0.58, just under the requirement of CI > 0.6 for a dose distribution to be conformal. This dose distribution was delivered by using leaves that are over 6 times the thickness of MLC leaves used in current linacs such as the Varian TrueBeam, which uses 2.5 - 5 mm leaves [32]. The dose distributions using virtual leaves of thickness of 4 mm or less increases the CI by less than 2% from using 1 angle to 6 angles. This comparatively small increase indicates that the collimator rotations are unnecessary for treating this concave target if the collimator leaves are 4 mm thick or less. In Figure 4b, the small increase in CI from 4 mm leaves to 2 mm leaves shows that continuing to decrease the thickness of MLC leaves leads to diminishing returns for the quality of treatment while significantly impacting the complexity of the collimator.

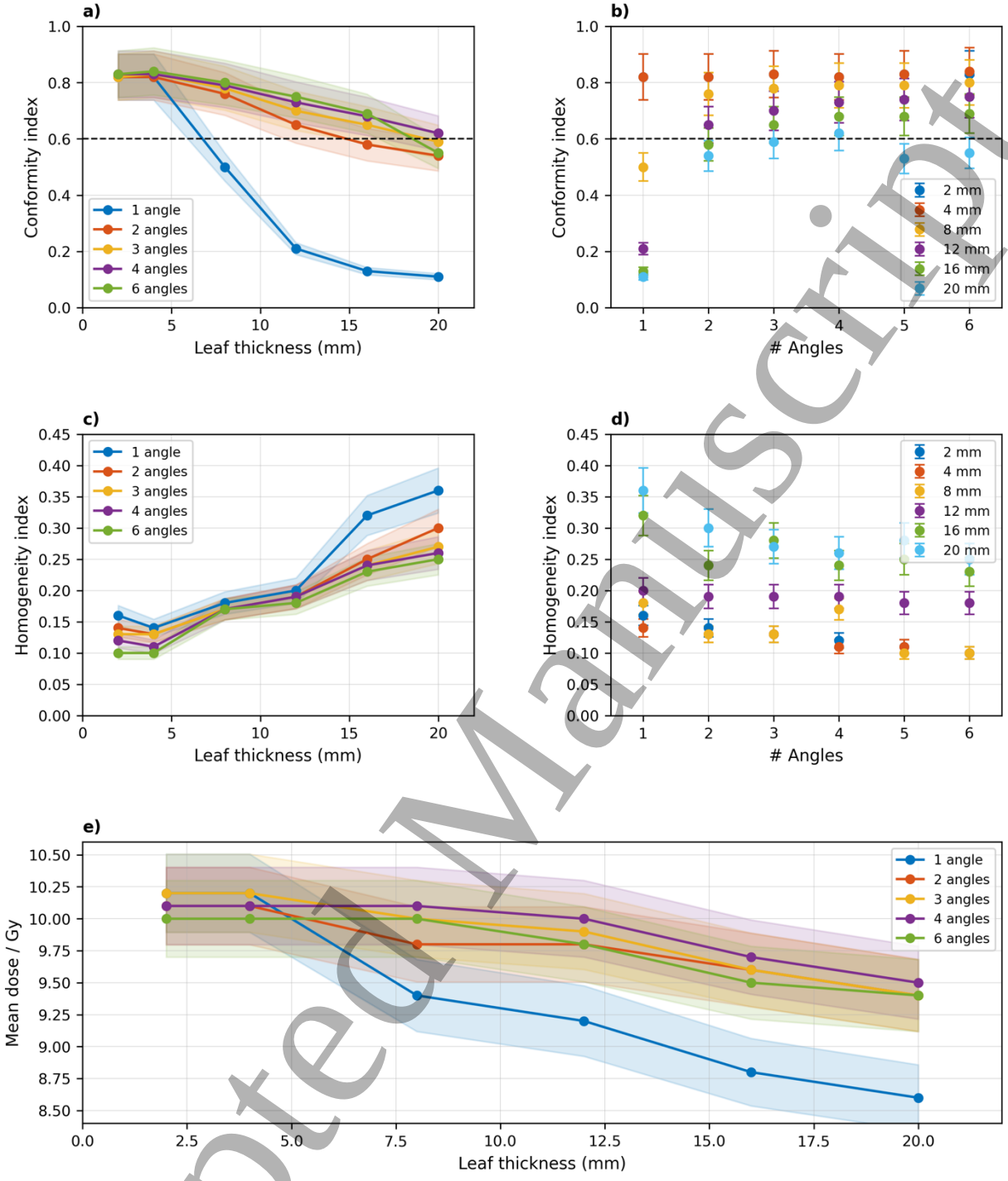

Figure 4: Plots comparing the conformity index of treatment plans on the concave target as a function of (a) the thickness of the MLC leaves, and for (b) the number of collimator angles used to deliver the field, the same is shown for the homogeneity index in (c) and (d) respectively; (e) shows a plot of the mean dose (Gy) to the target as a function of leaf thickness.

To evaluate the uniformity of the delivered dose distribution, the homogeneity index for each of the treatment plans was calculated using equation (2). Figure 4c shows that the HI increases with increased leaf thickness for the concave target. For any given number of collimator angles, the HI remains constant for 2 mm – 4 mm leaves before increasing at an increasing rate thereafter. This plateau in HI for the thinnest leaves provides evidence for diminishing returns when decreasing the thickness of MLC leaves. This effect is more pronounced when thinking about the inverse proportionality between the

number of leaves and the thickness of the leaves. A halving in thickness results in a doubling in the number of leaves, effectively doubling the number of components and points of failure of the device.

However, if instead the effect of the number of collimator angles on the HI is investigated, it is observed that apart from leaves of thickness 8 mm and 12 mm the addition of angles results in a 30±10% decrease in HI, as shown in Figure 4d. This shows that the use of multiple collimator angles can dramatically increase the uniformity of the dose delivered. The HI for the 8 mm and 12 mm leaves remain almost constant, decreasing 5% and 0.8% respectively as the number of angles is increased from 1 to 6.

The reason for these thicknesses being less impacted by the number of angles is likely due to the definition of the HI which defines a specific threshold precision which relates to the size of the leaves and target. However, further investigation is needed to determine if this is the case.

Figure 4e shows that, with increasing leaf thickness, the mean dose delivered decreases at a much greater rate when only one collimator angle is used. This demonstrates the need for thinner leaves when treating tumours of complex shape for single field treatments. However, if the same treatment with multiple fields can be performed by rotating the MLC, a similar mean dose can be delivered with fewer leaves. This effect is shown in Figure 4e where the combination of 8 mm leaves and 4 or 6 collimator angles achieves a mean delivered dose within 3% of that delivered by 2 mm leaves.

Uncertainties in the calculated values of CI, HI, and mean dose are dominated by partial-volume effects arising from the 2×2 mm dose grid sampling the target boundary. The perimeter of the crescent-shaped target is approximately 380 mm, which gives rise to sampling uncertainties of approximately 10% in CI and HI volumetric parameters, shown as shaded bands in Figures 4a, 4c and 4e. Uncertainties arising from the dose calculation algorithm and variations in the optimisation convergence are expected to be better than 3%, shown as error bars in Figures 4b and 4d. These uncertainties are systematic and uniform across all simulated conditions; the dose grid and phantom geometry are fixed throughout and therefore do not affect the relative trends presented in Figure 4.

Discussion

Whilst the focus of this study was on increasing the conformity of the radiation dose distribution with thicker MLC leaves by using multiple fixed collimator angles, the natural progression would be to consider its applicability to IMRT and volumetric arc-mode therapy (VMAT) treatments with fewer MLC leaves. Although our analysis was conducted in two dimensions, this methodology remains directly relevant to clinical practice. The 2D approach examines in-plane conformity with the MLC, which determines beam shaping in each transverse slice of a 3D treatment. The results are therefore directly applicable to step-and-shoot IMRT techniques such as field-in-field radiotherapy, where optimising collimator angle for lateral beam conformity is already a standard component of treatment planning for sites including breast.

Our results demonstrate that collimator rotation can significantly compensate for increased MLC leaf thickness. The uniformity of dose delivered by 8 mm leaves using 6 collimator angles surpassed the uniformity achieved with the delivery from a single angle with MLC leaves with a virtual thickness of 2 mm by 1%, whilst the conformity index was only 5% worse. This suggests that comparable treatment quality can be achieved using an MLC with much fewer leaves, which has important implications for machine robustness. We successfully achieved conformal dose distributions using virtual MLC leaves up to 12 mm thickness.

The concept of using different collimator angles during radiotherapy treatment has been shown before by Sun et al. whereby it was demonstrated that dual-arc VMAT plans using different collimator angles for each arc (rather than rotating the collimator during arc delivery) significantly improved plan quality for whole-brain radiotherapy [33]. This suggests that the multiple collimator angle strategy investigated in this work could translate effectively to more advanced delivery techniques. For full 3D

VMAT optimisation, incorporating collimator angle as an additional degree of freedom alongside gantry rotation could potentially offset further increases in MLC thickness; however, demonstrating this rigorously would require studies with realistic patient geometries, which is beyond the scope of this proof-of-principle investigation. VMAT implementation also remains challenging for many centres, particularly in LMIC settings where resources and expertise may be limited, and employing continuous collimator rotation could introduce additional complexities. Static-field IMRT may therefore provide a more accessible pathway for implementing multiple-collimator-angle techniques with thicker MLC leaves, as this approach could be readily incorporated into conventional inverse planning systems. Given the evidence that modern optimisation techniques can mitigate the dosimetric disadvantages of wider leaves, the combination of increased MLC leaf thickness for improved mechanical robustness with multiple-angle collimator compensation represents a promising strategy for delivering high-quality treatment plans in resource-limited settings.

We acknowledge that our simulations are simplistic in nature compared to modern 3D treatment paradigms. This study employed simplified MLC aperture modelling without accounting for transmission, leakage and scatter contributions, as the focus was on geometric conformity rather than absolute dose accuracy; future clinical implementation would require validation with more comprehensive MLC models. However, our 2D simulations are representative of typical radiotherapy planning target volumes in the thorax and pelvis. Radiotherapy treatment protocols typically add margins to the gross tumour target to allow for microscopic spread into adjacent tissues and for residual uncertainty in positional setup. These margins typically have the effect of adding a 1-2 cm geometric expansion around the tumour, resulting in more spherical target volumes.

The present work establishes that utilising beam delivery from multiple collimator angles can indeed compensate for thicker MLC leaves in the transverse plane, providing the foundation for future 3D validation studies. Further investigation is needed to explore optimal distribution of collimator rotations for a given treatment, the minimum number of collimator angles required to achieve sufficient IMRT treatment quality, comparison of static IMRT with multiple beam directions to volumetric modulated arc therapy with the same leaf profiles, how the effectiveness of collimator rotations is affected by target geometry, and whether the potential benefits of more robust MLCs with thicker leaves are counteracted by increased treatment time and planning complexity associated with multiple collimator rotations.

Conclusions

This study demonstrates that delivering radiation from multiple collimator angles can significantly compensate for increased MLC leaf thickness, greatly improving conformity and uniformity of dose distributions. The benefits are most pronounced for MLCs with virtual leaf widths ≥8mm. Notably, virtual leaf widths of 8 mm with 6 collimator angles achieved comparable or superior plan quality to 2 mm leaves at a single collimator angle, suggesting that high-quality treatments can be delivered with substantially fewer leaves.

This approach offers a novel strategy for improving the robustness of linear accelerators through minimising the complexity MLC design using thicker leaves, whilst maintaining treatment quality through the use of multiple collimator angles. The technique is particularly relevant for resource-limited settings, such as in LMICs, whereby reducing MLC related faults can hopefully significantly decrease maintenance requirements and hence machine downtime. Further work with full 3D patient geometries and comprehensive MLC modelling is needed to translate these findings into clinical practice.

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