Title: Impact of varying planning parameters on proton pencil beam scanning dose distributions in four commercial treatment planning systems

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Running title: varying the PBS planning parameters for commercial TPSs

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Abstract:

Purpose: In pencil beam scanning proton therapy, target coverage is achieved by scanning the pencil beam laterally in the x- and y-directions and delivering spots of dose to positions at a given radiological depth (layer). Dose is delivered to the spots on different layers by pencil beams of different energy until the entire volume has been irradiated. The aim of this study is to investigate the implementation of proton planning parameters (spot spacing, layer spacing and margins) in four commercial proton treatment planning systems (TPSs): Eclipse, Pinnacle^3, RayStation and XiO.

Materials and Methods: Using identical beam data in each TPS, plans were created on uniform material synthetic phantoms with cubic targets. The following parameters were systematically varied in each TPS to observe their different implementations: spot spacing, layer spacing and margin. Additionally, plans were created in Eclipse to investigate the impact of these parameters on plan delivery and optimal values are suggested.

Results: It was found that all systems except Eclipse use a variable layer spacing per beam, based on the Bragg peak width of each energy layer. It is recommended that if this cannot be used, then a constant value of 5 mm will ensure good dose homogeneity. Only RayStation varies the spot spacing according to the variable spot size with depth. If a constant spot spacing is to be used, a value of 5 mm is recommended as a good compromise between dose homogeneity, plan robustness and planning time. It was found that both Pinnacle^3 and RayStation position spots outside of the defined volume (target plus margin).

Conclusions: All four systems are capable of delivering uniform dose distributions to simple targets, but their implementation of the various planning parameters is different. In this paper comparisons are made between the four systems and recommendations are made as to the values that will provide the best compromise in dose homogeneity and planning time.

Keywords: Proton therapy, particle therapy, treatment planning.
Conflict of interest: The authors have no conflicts to disclose.

1. Introduction

1.1. Proton planning definitions

Proton treatment planning systems optimise pencil beam scanning (PBS) plans using inverse planning in a process similar to IMRT.[1] There are a number of parameters which impact on the PBS dose distribution such as spot size, spot spacing size, layer spacing and margins. These definitions are illustrated in figure 1.

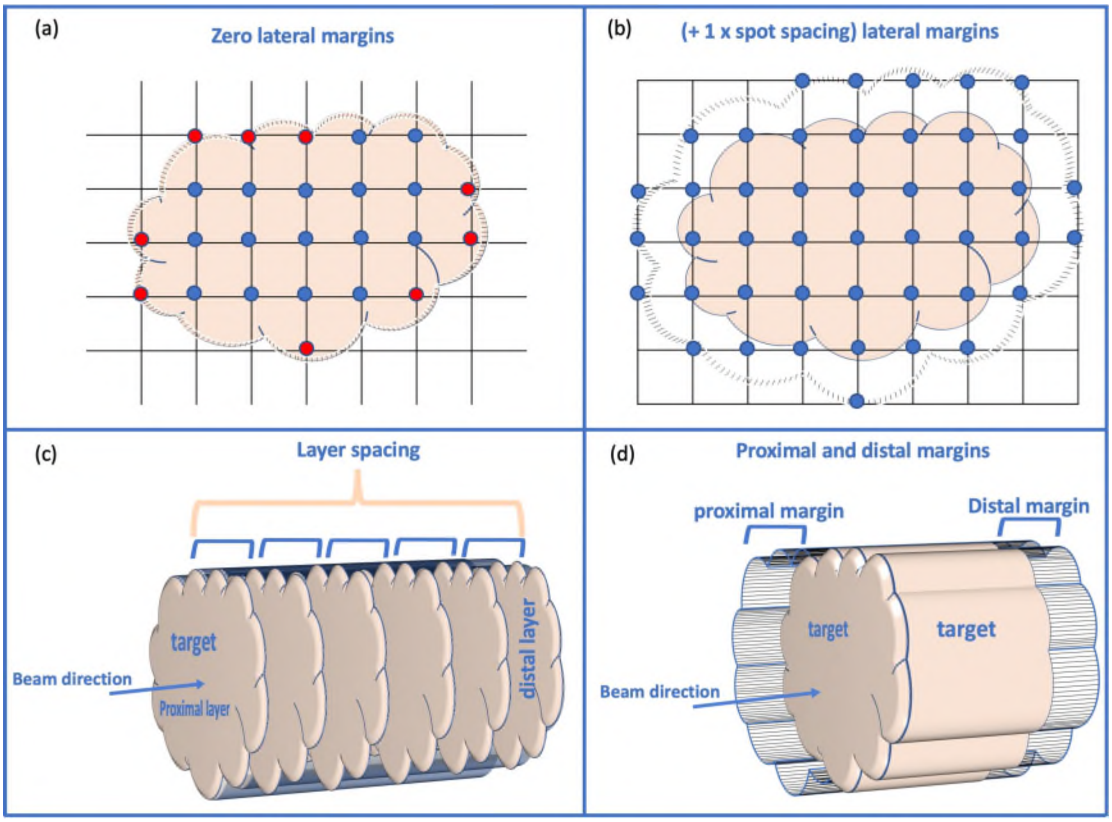

Figure 1: Illustration of the definitions of spot size, spot spacing, layer spacing and margins. Figures (a) and (b) show the spot positions at a single depth (a cross-section of the target). In this case the spots (red and blue circles) are spaced out evenly in the x- and y- directions on a square grid and all spots are the same size. In (a) the spots have been positioned in the target only (i.e. with a lateral zero margin). In (b) a lateral margin of at least 1 x the spot spacing has been applied, such that spots are positioned outside the target. Figure (c) shows the definition of layer spacing. In this case, to cover the three-dimensional target requires six layers. Each layer could have a different set of spot positions, dependent on the shape of the target at that specific depth. Figure (d) shows the definition of proximal and distal margins, which lead to additional layers being added.

As a spot of protons traverses through the patient it spreads out due to multiple Coulomb scattering. Spot sizes within the proton treatment planning system are based on measured data, with a specific spot size for each nominal energy. Each

TPS models the input data differently, leading to differences, and cannot be defined or altered by the planner.
The spot spacing, layer spacing and margins can be defined and edited during the planning process. The spot spacing is the space between spots in both lateral directions, and the layer spacing is the space between the spots in the beam direction. Reducing the spot spacing and layer spacing leads to an increase in the number of spots, improving the target coverage and the homogeneity. However, increasing the number of spots increases the delivery time. Lateral margins increase the number of spot positions for a single cross-section and proximal and distal margins increase the number of layers.

1.2. This work

The purpose of this study is to evaluate the impact of varying the PBS planning parameters defined in section 1.1, for four commercial treatment planning systems. The systems tested are: Eclipse (Varian Medical Systems, *Palo Alto, CA*) version 13.5.35; Pinnacle^3 (Philips Radiation Oncology Systems, *Fitchburg, WI*) version 16.0; RayStation (RaySearch Laboratories, *Stockholm, Sweden*) version 4.7.0.15; and XiO (Elekta CMS Software, *Maryland Heights, MO*) version 4.80.00. All the systems are commercially available for PBS planning, except Pinnacle^3 version: 16.0 which had not been released at the time of writing this manuscript.

The work is separated into two distinct parts. In the first part, phantom studies are conducted to investigate how each TPS defines the spot size, spot spacing, layer spacing and margins. It is hoped that this information will be useful for users of any of the four systems or for those considering purchasing these systems.
Following the investigation in phantoms, plans are created in Eclipse to investigate how the different parameters may impact on the delivery of the plan. After creating plans with different spot spacing and layer spacing values, the number of spots, number of layers and dose homogeneity of the plan were computed and the time to deliver the plan approximated. It is hoped that this information will be useful to current users of any of the four systems who wish to improve the efficiency of their treatment delivery.

2. TPS parameters

In this section we systematically outline each of the parameters that can be varied during proton PBS treatment planning (detailed in section 1.1). Firstly, based on the physical interactions of protons, estimates are made as to what would be ideal values for each parameter. Then, the different implementations of the various parameters in each TPS are defined, according to their respective manuals. The manuals that were inspected were: for Eclipse[2–5]; Pinnacle[3 6,7]; RayStation[8]; and XiO[9–11]. Also, the system help tools provide a good amount of information for both beam modelling, proton planning parameters and most of the systems tools.

For this study, we compared the parameters listed in table 1. The parameter scanning order was not investigated as this is more dependent on machine delivery functionality rather than TPSs.

2.1. Spot volume and margins

In the delivery of proton PBS there is a need to define a specific volume in which spots can be positioned, known as the spot volume. Table 1 indicates how each TPS defines the spot volume.

Ideally the TPS should define the spot volume in a consistent manner, i.e. spots should only be positioned within the volume defined by the user. However, this is extremely complex in heterogeneous anatomy. If the planner has requested margins then the optimiser should utilise the additional spot positions where possible. Should margins be used, it is highly likely that different beams will require different spot volumes.

For RayStation, there are two different ways of defining the spot volume:

1. The system automatically defines the plan spot volume during the optimisation process from any optimised objective labelled as PTV during the contouring process. That PTV volume can be one or more volumes. If it is more than one volume, then the system will sum them together and that volume will be used for all beams.
2. Manually define the spot volume for each beam. It is possible to define the spot volume per beam by using the optimisation parameter.

The margins are defined differently in each TPS. For Eclipse, Pinnacle[3] and RayStation the plan can be made with or without margins. Auto margins are available in three of the four TPSs; Pinnacle[3], RayStation and XiO offer auto margin options in addition to manually defined margins; whereas in Eclipse margins must be defined manually. In Pinnacle[3] the auto margin is applied only in the proximal and distal directions (i.e. no lateral auto margin), with margins equal to 3.5% x radiological depth to target proximal/distal edge + 3 mm. In RayStation the auto margin is a 3D margin. In XiO the auto margin is automatically up to 10 mm from the spot volume in all three dimensions, with no tools to add or edit these margins, and is based on the spot spacing value.

Table 1: PBS planning parameters

<table>
<tr><th rowspan="2">Parameter</th><th colspan="4">Treatment Planning System (TPS)</th></tr>
<tr><th>Eclipse</th><th>Pinnacle[3]</th><th>RayStation</th><th>XiO</th></tr>
<tr><td rowspan="2">Spot volume and margins</td><td colspan="4">Spot volume is the volume into which spots are to be positioned. The spot volume can be equal to the target volume or can include margins that extend beyond the target. A single spot volume may be used for all beams, or each beam may use an individual spot volume.</td></tr>
<tr><td>Defined manually.</td><td>Defined manually.</td><td>Either defined manually or automatically based on optimisation parameters.</td><td>Defined manually.</td></tr>
<tr><td>Spot size</td><td colspan="4">Lateral spread as function of depth, $\sigma(z)$, defined as $\sigma(z) = \sqrt{\sigma_0^2 + \sigma_{MCS}(Z)^2}$ [1]
where:
z is radiological depth;
σ_0 is spot width in air at isocentre;
$\sigma_{MCS}(z)$ is the contribution of Multiple Coulomb Scattering.
All TPS base their calculation of lateral spread on this formulism.</td></tr>
<tr><td rowspan="2">Spot spacing</td><td colspan="4">Spot spacing is critical for reducing dose ripple across a given layer as a function of depth.</td></tr>
<tr><td>Varied as a function of FWHM, (2.35σ_0), for both x and y axes separately.
Defined at distal-most layer.</td><td>Equal to σ_0 and defined by the highest energy for both x and y axes.</td><td>Equal to $\sigma(z)$, and so varies as a function of layer for both x and y axes.</td><td>User defined spot spacing.</td></tr>
<tr><td rowspan="2">Layer spacing</td><td colspan="4">Layer spacing critical for reducing dose ripple along the depth axis, accounting for changes in pristine Bragg peak widths as a function of depth.</td></tr>
<tr><td>Defined during beam modelling using increments in any of the following: distance; energy; energy range sigma.</td><td>Default is to match distal and proximal 80% doses of Bragg peaks. Doses matched may also be varied by user.</td><td>Defined during beam modelling to match distal and proximal 80% doses of Bragg peaks.
May also be varied by user to be any distance between peaks.</td><td>Defined during beam modelling to be any value and may be varied by user.
Matching distal and proximal 80% used for this study.</td></tr>
<tr><td rowspan="2">Spot location</td><td colspan="4">Spot locations within calculation volume are dependent on spot spacing and layer spacing.</td></tr>
<tr><td>Spot spacing fixed for all layers.
3D grid used, with adjacent layers of spots aligned.</td><td>Spot spacing fixed for all layers.
2D grids for each layer used with adjacent layers of spots off-set by half a spot spacing.</td><td>Spot spacing variable or fixed for all layers.
3D grid used, unless variable spot spacing, then 2D grids for each layer with adjacent layers of spots aligned.</td><td>Spot spacing variable or fixed for all layers.
3D grid used, unless variable spot spacing, then 2D grids for each layer with adjacent layers of spots aligned.</td></tr>
<tr><td>Scanning order</td><td colspan="4">Dependent on machine delivery functionality. Scan pattern during delivery can impact the dose delivered as a function of interplay with patient motion.</td></tr>
</table>

2.2. Spot size

As a spot of protons traverses through tissue it becomes more diffuse and larger in size because of multiple Coulomb scattering (MCS). The lateral spread of the beam is defined in equation (1) in table 1. [12–14]

The formulae used to compute *σ(z)* has not been disclosed by any of the proton TPS manufacturers, but is expected to be based on equation (1).

2.3. Spot spacing

It is the task of the TPS to select a suitable spot spacing such that the target can be adequately covered, reducing ripples in dose in a given layer. If they are spaced too far apart spots will need to be weighted heavily to achieve a uniform dose, whereas if spots are positioned too close together it may not be possible to lower their weight sufficiently to prevent dose rippling due to machine constraints.

The spot spacing affects the spot positions available in the treatment plan. As the spot size increases with depth (see section 2.2), the spot spacing should also increase with depth to prevent rippling of dose. The spot spacing should therefore be different for different energy layers, within a single beam. Spot spacing should also account for any beam divergence.

The method used to select the spot spacing is different for each TPS and is described in table 1.

XiO - has no default settings and the spot spacing must be defined by the user. It can be set to be constant or can be varied on a layer by layer basis.

In addition to XiO, all three other TPSs offer the option of manually setting the spot spacing. In Eclipse, the x and y values can be different, but the spacing is the same across all layers. In both Pinnacle[3] and RayStation the manually selected value is the same for x and y and applies across all layers.

For the TPSs that defined the spot spacing based on the highest energy in the beam it should be noted that the spot size in air has the smallest value for the highest energy. Due to MCS, however, in medium the highest energy produce the largest spot size.

2.4. TPS layer spacing

In a similar manner to the spot spacing, the layer spacing is also critical in reducing ripples in dose as a function of depth. Each TPS has different methods and tools to define the layer spacing as described in table 1.

Both RayStation and XiO also offer a tool called the peak width multiplier (which can take any value), which allows the user to vary the layer spacing uniformly across the whole volume, during planning. A value of less than one reduces the layer spacing and a value of greater than one increases the layer spacing.

2.5. Spot locations

Available spot positions are defined by the spot spacing (section 2.3 above), layer spacing (section 2.4, above), target shape and any margins.

Ideally the spot locations should reflect the user's selections in spot spacing, layer spacing and target margins, and spots should not be positioned anywhere outside of these limits. Typically, the spots are organised on a three-dimensional square grid (see below), but some systems offer spots positions that are offset either within a single layer (offset rows) or between rows. It may be that such a solution provides the optimiser with greater flexibility to deliver the dose as required, but this is to be investigated.

For both Eclipse and Pinnacle the spot spacing can only be a fixed value for all layers, whereas for both RayStation and XiO the spot spacing can be either variable or fixed for all layers (see section 2.3).

- With fixed spot spacing the spot locations for all systems, except Pinnacle, are defined by a 3D grid passing through the isocentre within the spot volume, such that every layer is identical and exactly overlaid. On a given layer, Eclipse and XiO use square grids, whereas RayStation offsets adjacent rows by half the spot spacing. In Pinnacle[3] the spot locations are defined by 2D square grids for each energy layer, from the left hand side of the target, such that energy layers are not exactly overlaid. It has been shown that the spot locations impact the dose coverage and organ at risk (OAR) sparing in Eclipse, Pinnacle[3] and XiO.[15]

- With variable spot spacing in both RayStation and XiO, the spot locations are defined by a 2D grid passing through the isocentre within the spot volume for each energy layer.

2.6. Dose calculation and optimization algorithms

The accuracy of each dose calculation and performance of each optimization algorithm was not investigated in this work. However, information that may prove useful to readers is provided below.

The dose calculation algorithms of each system are as follows: 'Proton convolution superposition' algorithm for Eclipse; 'Proton PBS' for Pinnacle^3; and 'Pencil beam' algorithm for RayStation and XiO.

Pinnacle^3, RayStation and XiO use sub-spots to compute the dose more accurately, particularly in cases where there are lateral heterogeneities. The sub-pencil beams (SubPB) parameter divides each single spot and recalculates it for different numbers of sub-pencil beams (SubPBs). In both Pinnacle^3 and RayStation the SubPB values are constants and cannot be changed or edited by the user. The number of SubPBs in Pinnacle^3 is dependent on the size of the in-air fluence of the spot and spot spacing, with no fewer than 4 sub-pencils per 3 sigma lateral distance of the in-air fluence. As Pinnacle^3 computes laterally 4 sigma for the primary fluence, at least 134 SubPBs are computed per spot in the dose computation.[16] For RayStation the number of SubPBs is fixed to 19 per spot.[8] In XiO the number of SubPBs per spot is defined as: $(2n+1)^2$ pencil beams calculated per spot, in which the value of n is defined by the user and can be between 0-5. For further details about sub-spots the reader should refer to Soukup et al (2005).[17]

2.7. Scanning order

The scanning order of spots during planning (if it starts from the left or right or top or bottom) does not make any difference to the on-screen plan. The order of delivery is dependent on the machine, but the spot locations and weights remain constant. The scanning order may impact on the delivery of dose as it will be dependent on patient motion factors such as breathing, but that will not be investigated in this work.

3. Material and Methods

This work is separated into two parts. In the first, investigations were made into the four TPSs to verify that they perform as predicted from their respective manuals. These tests were carried out using homogenous and heterogeneous phantoms, by creating plans in which the spot spacing, layer spacing and margins were systematically varied.

In the second part of this work investigations were made into the delivery implications of different plans with one TPS, Eclipse. Plans were created with different spot and layer spacing values, and parameters that impact on the delivery were evaluated. The number of layers, number of spots, dose homogeneity and approximate delivery time were computed.

3.1 TPS commissioning and dose calculation settings

Prior to commencement of the comparison and plan delivery studies, it was necessary to input the same machine data into each TPS. PBS beam data from the IBA system at the University of Pennsylvania (UPenn) was entered into all four TPSs and the modelling was then benchmarked against UPenn measured data. A minimum spot weight of 0.021 MU was implemented as this is the lowest dose that could be reliably measured.

The Hounsfield unit (HU) to proton relative stopping power (RSP) calibration curve was based on a stoichiometric calibration[18] and made consistent between all systems. In RayStation and XiO the mass density calibration curve must be defined. The mass density is then converted to RSP, but this conversion cannot be controlled. In Eclipse and Pinnacle[3], the HU-RSP calibration curves are entered directly.

Doses were calculated in all systems with a grid size of 2.5 mm, using each system's dose calculation algorithm. In this study the precision parameter in XiO was switched off (resulting in no sub-spots) and the nuclear interaction was switched on (for an improved dose calculation). For homogeneous media there is of course no need for a sub-spot division in XiO. This would be inappropriate for clinical use. In the case where heterogeneities are present the plan would benefit from a larger number of sub-spots.[17]

The plans on Eclipse were optimized using the Simultaneous Spot Optimization (SSO) algorithm, while for Pinnacle[3], RayStation and XiO the full intensity modulated proton therapy optimization algorithm was used.

For the dose optimisation objectives, the cube targets were optimised in all the plans with the same objectives and same priority/weights for both higher and lower doses, to ensure a fair comparison. Objectives were set to deliver a minimum of 100% and a maximum of 102% across the target volume in all the phantoms studies.

3.2 Phantom studies

The aim of the phantom studies is to investigate and understand the implementation of the planning parameters of each TPS (spot size, spot spacing, layer spacing and margin).

In each TPS, three homogeneous water cubic phantoms were created (40 x 40 x 40 cm^3 in size), with 10 x 10 x 10 cm^3 cubic targets at different depths. Targets are required to position the spots within the plan. Phantom 1 included the cubic target with its surface at a depth of 3 cm; as this is shorter than the 7.6 cm range in water for the lowest energy (100 MeV) in this case it necessitated the use of the range shifter. Phantom 2 consisted of a cubic target at the middle of the phantom. Phantom 3 consisted of a cubic target at a depth such that its distal side plus a 1 cm margin corresponded to the range of the highest available energy from the cyclotron (range of 226 MeV beam of 32.3 cm). For RayStation, an additional 3D rectangular target 10 x 10 x 20 cm^3 (phantom 4) was created and used for RayStation variable spot spacing.

3.2.1 Layer spacing

Plans in Eclipse, RayStation and XiO were made with a constant layer spacing value and with default layer spacing values. The constant layer spacing for each phantom was defined as the mean of the proximal and distal peak widths (80-80%). In phantom 1, close to the phantom surface, this resulted in a constant layer spacing of 5.5 mm. For phantom 2, in the centre, the layer spacing was 6.8 mm. The layer spacing for phantom 3, with the deepest target, was 7.5 mm.

The default layer spacing values in Eclipse were chosen to be '*Variable distance equal to four times the range sigma of the next highest energy*'. This makes it comparable to the default values of the three other systems; because from figure 2 four times the range sigma is closer to peak widths (80-80%). Figure 2 shows: the peak widths (80-80%) and (90-90%) of the measured in water integral depth dose (IDD) curves for 27 nominal energies, ranging from 100 to 226.7 MeV and the calculated range sigma, which were calculated using equation 2 [19,20]:

$$\text{range sigma} = 0.012R_0^{0.935} \qquad (2)$$

Where:

$$R_0[cm] = 0.0022 \times E[MeV]^{1.77} \qquad (3)$$

As Pinnacle[3] did not have an option of constant layer spacing, plans were made with the default variable layer spacing only, which was selected to be the peak width between 80–80% for each nominal energy layer.

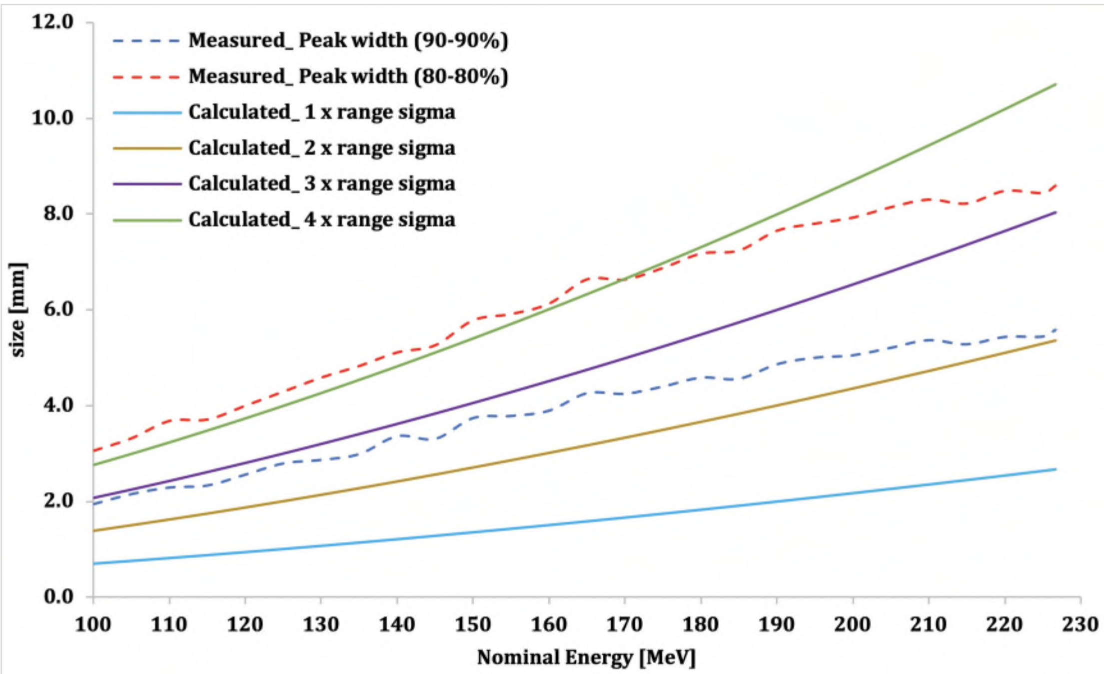

Figure 2: Measured peak widths and calculated range sigma widths for 27 energies between 100 and 226.7 MeV.

3.2.2 Spot spacing

For Eclipse, Pinnacle[3], and RayStation, the implementation of default spot spacing was investigated for the three different energies 100, 170 and 226 MeV. All plans were created with an individual energy and calculated with a 10 x 10 cm^2 water phantom, such that each plan contained only one layer. For RayStation, another plan was calculated with a 3D rectangular target 10 x 10 x 20 cm^3, such that multiple layers would be required and the variable spot spacing with depth could be investigated.

These were compared to the computed spot spacing sizes (σ_z) in the water phantom at maximum range, in the Eclipse, Pinnacle[3] and RayStation TPSs.

3.2.3 Margins

For each of the three phantoms, six plans were made with: no margin, a 3D margin equal to 1 x spot spacing; a 3D margin of 2 x spot spacing; a 3D margin of 3 x spot spacing; a 3D margin of 4 x spot spacing; and an auto margin (as defined by each TPS). For both RayStation and XiO the auto margins were investigated with different spot spacing values. These were calculated with both fixed and variable spot spacing.

3.2.4 Data analysis

The plans were assessed by visual inspection of the dose distribution; extraction of the percentage depth dose (PDD) along the central axis; and extraction of lateral profiles at the centre of each of the three targets. The distribution of spots for each beam were analysed using 2D spot maps, in which all the spots in 3D were overlaid.

3.3 Plan delivery

Following the phantom studies, additional plans were created in Eclipse investigating the delivery of the plan. The delivery time, numbers of layers, number of spots and dose homogeneity were computed for plans with different layer spacing and different spot spacing values.

It has been estimated that for an IBA machine the delivery for a spot with weight around 4.7 MU is approximately 1 to 5 milliseconds (depending on the dose rate). Across all energy layers, the delivery of the spots to a single layer requires on average 2 ms. With a maximum beam current in the nozzle of 5 nA, capable of delivering 1 Gy to a spot in about 3 milliseconds, a plan with one single beam will take around 40 seconds to cover a cubic target 10 x 10 x 10 cm^3 in size. Most of the time is spent switching between layers, which for the UPenn IBA machine is about 1.4 s (averaged across all energies). The irradiation time t_i can be approximated (within ±10%) by multiplying the number of times the energy is switched (i.e. the number of layers n_l minus 1) by the machine layer switching time t_E and adding the time taken to irradiate each layer (multiplication of the number of spots n_s and the time it takes to deliver a single spot t_s) [21]; expressed as:

$$t_i = (n_l - 1) \times t_E + n_s \times t_s. \quad (4)$$

In this part of the work plans were created in Eclipse with different layer and spot spacing values. The layer spacing was varied between 3.7 mm (the Bragg peak width 90-90% of the most proximal part of the target) and 10 mm. In these plans the lateral spot spacing was set to 5 mm. For the spot spacing study the spot spacing was varied between 3 and 10 mm, with constant layer spacing. Phantom 2, with a 10 x 10 x 10 cm^3 target at its centre, was used with 10 mm 3D margins.

All plans were optimised with the same dose prescription and the same objectives (see section 3.1). In evaluating the plans, the numbers of layers, number of spots and dose homogeneity were computed and equation 4 was used to approximate the delivery time.

The number of spots and layers for each plan was extracted from the DICOM plan file, using a Matlab script. The plan dose homogeneity was evaluated as the dose difference between D_1-D_{99}, D_2-D_{98} and D_5-D_{95} of the plan target, in a method proposed by Dowdell et al (2013).[22] In addition to the estimation of the plan delivery time using equation 4, the time required for the whole planning process (dose calculation and optimization) was recorded.

4. Results

4.1 Phantom studies

In the phantom studies the layer spacing, spot spacing and margins were systematically varied in three phantoms with targets at three different depths.

4.1.1 Layer spacing

When using the default layer spacing for each system, this study found that if the variable distance layer spacing is chosen for Eclipse it will be constant for all layers within one beam but can differ for each individual beam within a plan. Whereas the default layer spacing for RayStation, Pinnacle and XiO are variable.

When using the same constant layer for Eclipse, XiO and RayStation it was found that both RayStation and XiO define the first distal layer based on distal range 80% R_{80}, whereas Eclipse TPS defines the first distal layer based on the range 90% R_{90}.

4.1.2 Spot spacing

The default spot spacing options in Eclipse, Pinnacle[3], and RayStation were investigated in each of the three phantoms. According to the method of section (3.2.2). The resultant spot positions for each TPS and each phantom are shown in figure 3.

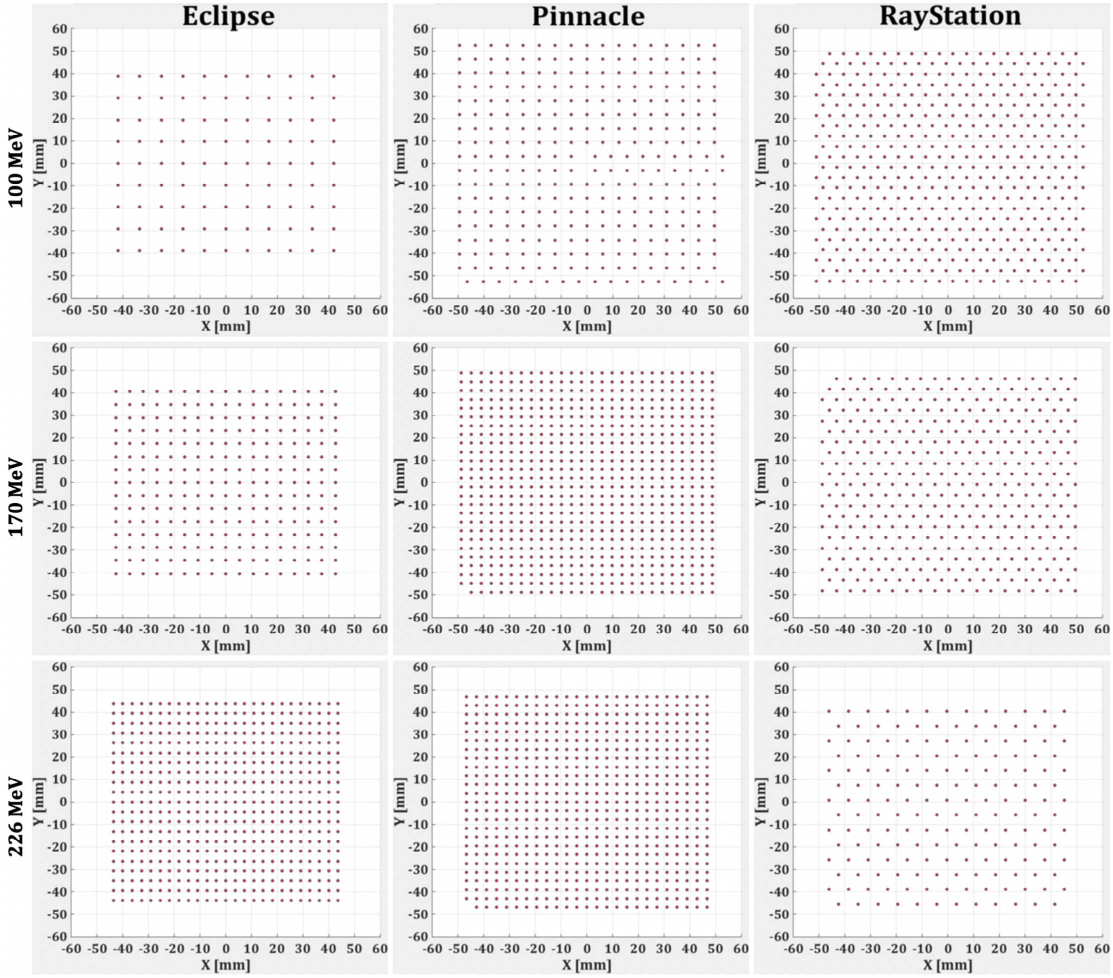

Figure 3: Spot maps, as viewed from the beam direction, for the three phantom plans (phantom 1 = top row; phantom 2 = middle row; phantom 3 = bottom row) and for each TPS (left = Eclipse; centre = Pinnacle[3]; right = RayStation). The target extent is between -50 mm and +50 mm in both lateral directions for all plans.

To investigate the variable spot spacing with depth option in RayStation, plans were made for a 3D rectangular target 10 x 10 x 20 cm^3. These results are shown in figure 4. It can be seen that the spot maps at different depths within a single plan in RayStation (figure 4) look very similar to those for the plans on the different phantoms with targets at different depths (figure 3, right).

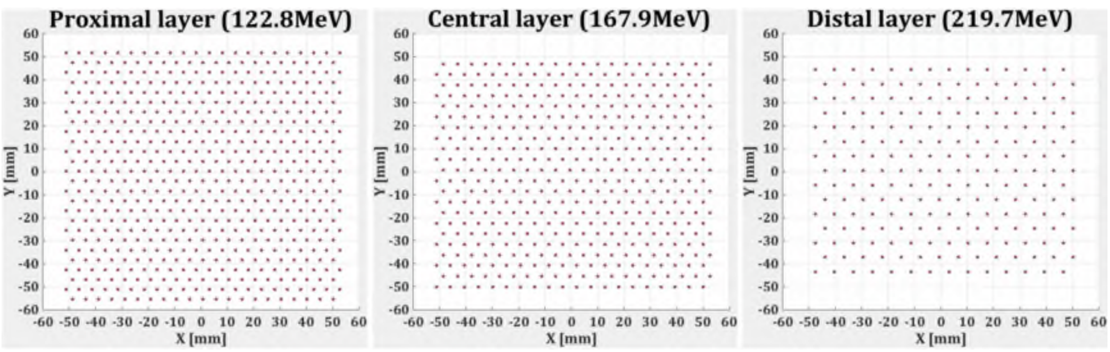

Figure 4: Spot maps, as viewed from the beam direction, at different depths within a single RayStation plan, when using default variable spot spacing option.

4.1.3 Margins

Figure 5 shows a set of dose-volume histograms (DVHs) for the target for plans with different margins, demonstrating the need for target margins. It can be seen that the target coverage improves significantly if a margin of one times the spot spacing is added and it improves slightly further if the margin is increased up to two times the spot spacing. It was found that increasing the spot spacing by more than two times the spot spacing did not improve the dose coverage (figure 5). It was also found that Eclipse automatically removes spots further away than one times the spot spacing, so dummy target volumes had to be created to test wider margins.

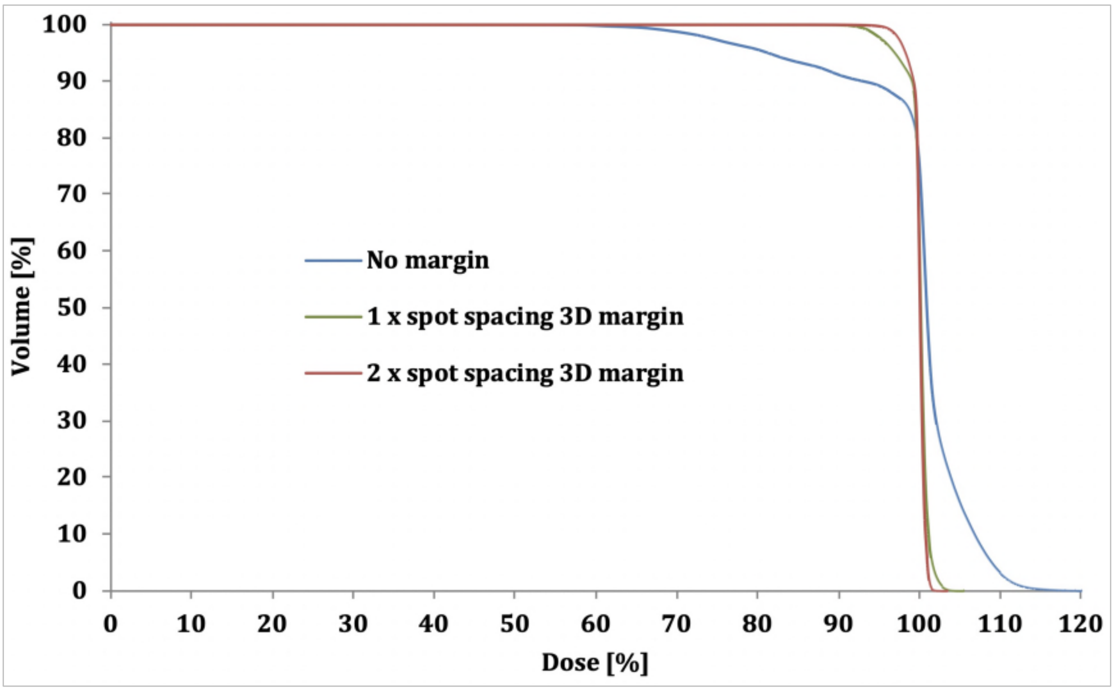

Figure 5: DVHs for the target for plans created with different target margins in Eclipse (blue = no margin; green = 1 times the spot spacing; red = 2 times the spot spacing). The results with margins for 3 and 4 times the spot spacing are not shown but they were identical to the 2 times spot spacing result.

Figure 6 shows the SOBPs and the lateral profiles at the central axis with zero margin for Eclipse, Pinnacle^3 and RayStation (XiO does not allow zero margin plans); and with a 10 mm 3D margin for Eclipse, Pinnacle^3, RayStation and XiO. All plans were created from plans with the default layer spacing of each TPS and a 5 mm spot spacing size.

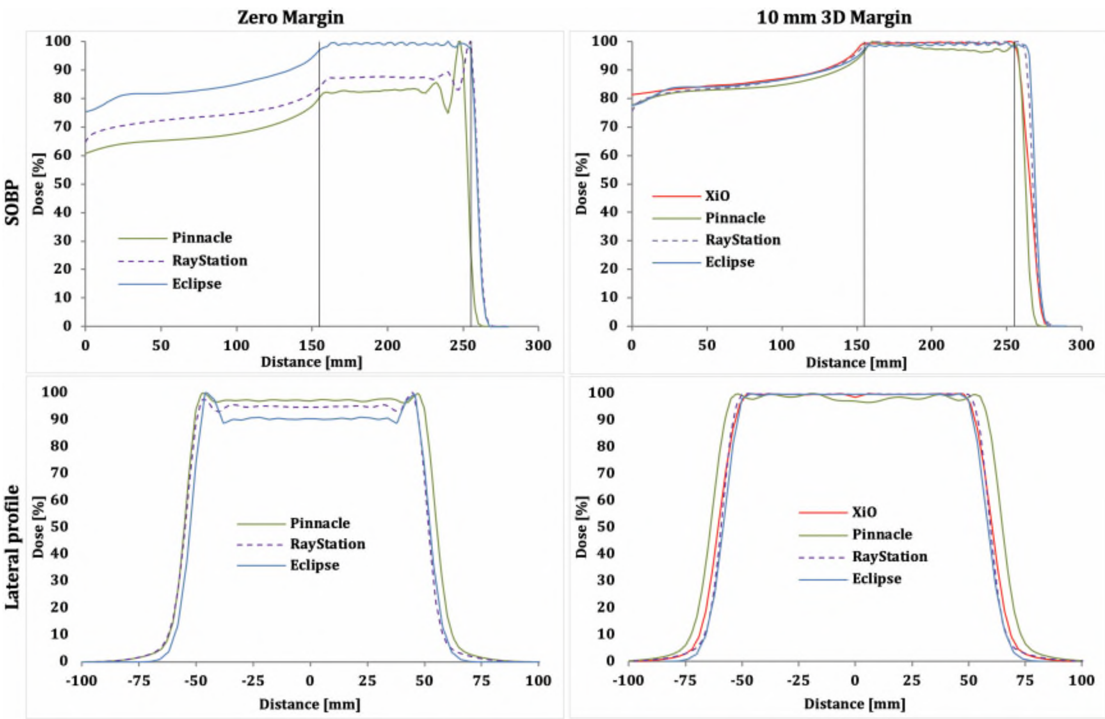

Figure 6: SOBPs and lateral profiles with zero and 10 mm 3D margins.

It can be seen that, without a margin, Pinnacle³ and RayStation are unable to deliver a uniform dose in the depth direction (inspection of the SOBP depth dose profiles) and Eclipse is unable to deliver a uniform dose in plane (from inspection of the lateral profiles). All TPSs except Pinnacle³ are able to deliver a uniform dose to the target when a margin is used.

Figure 7 shows the spot positions and weight distributions in 2D, with the spots in all layers overlaid for all the TPSs. The results for zero margins are shown for Eclipse, Pinnacle³ and RayStation and the results with a 10 mm 3D margin are shown for all TPSs. The spot weight for each TPS plan has been normalized to its own maximum.

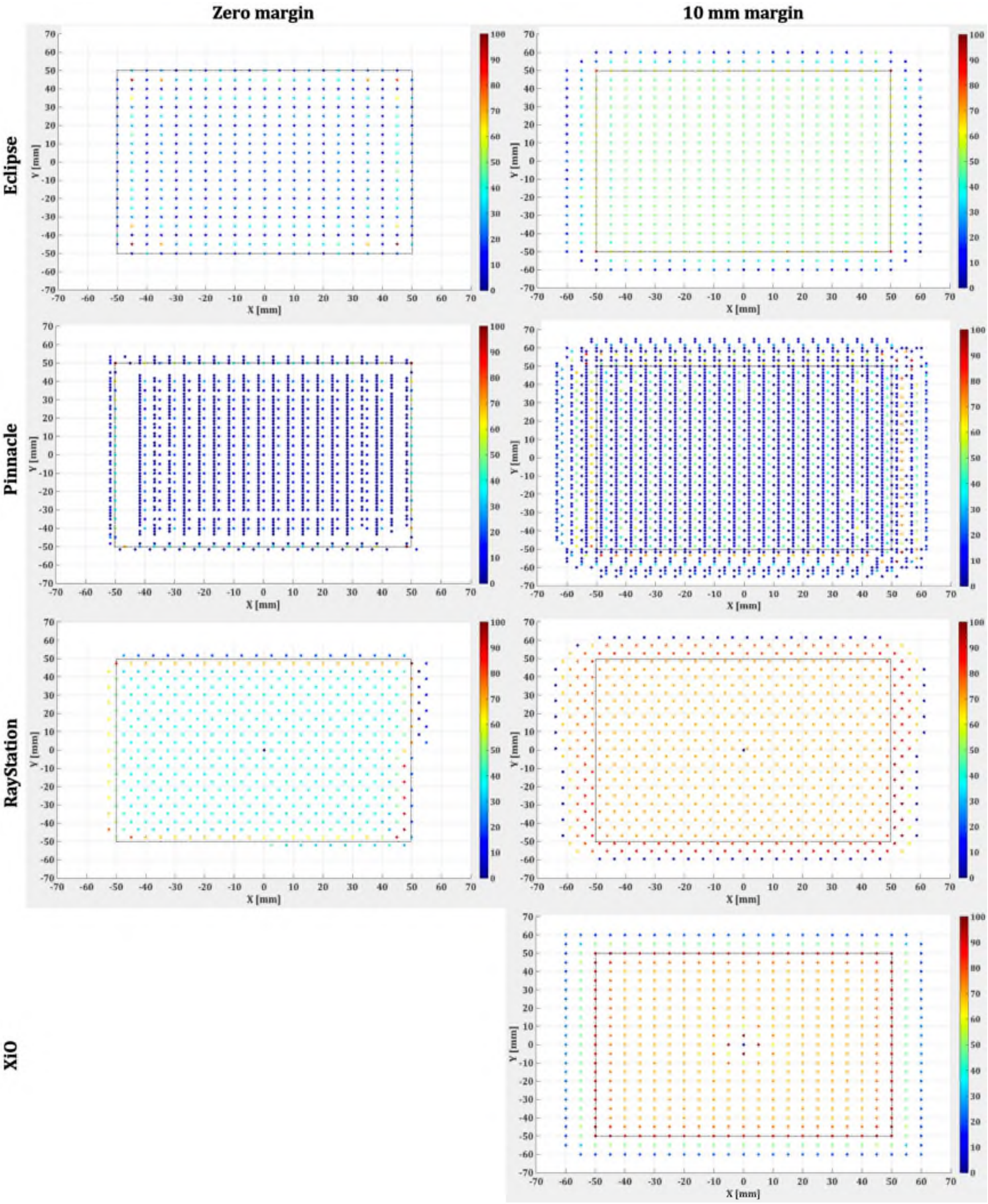

Figure 7: Beam's eye views of the spot positions and weight distributions in 2D spot maps, with the spots in all layers overlaid for (Eclipse, Pinnacle[3], RayStation and XiO). The target boundaries are shown by the solid lines.

Firstly, when inspecting the plans with a zero margin, it can be seen that spots at the edges of the target have a high weight (as expected to deliver a uniform dose to the target). Considering the spots within the target, all TPSs position spots evenly throughout the target except for Pinnacle[3]. In Pinnacle[3], the spots just inside the edge of the target are removed in a post-processing step as they do not exceed the minimum spot MU. These spots have a low weight as the adjacent spots on the edge of the target have a very high weight (see the non-uniformities of figure 7). Regarding the application of the margin, only Eclipse adheres to the user's instructions of applying no margin, with both Pinnacle[3] and RayStation positioning spots outside of the target. For Pinnacle[3], the spots were positioned up to 1.7 mm outside the volume in the x-direction and up to 3.3 mm in the y-direction. In RayStation spots were positioned up to 5 mm outside in the volume in the x-direction and up to 2.1 mm outside the volume in the y-direction.

For the plans with a 10 mm 3D margin, all TPSs position spots evenly throughout the target. Eclipse and XiO adhere to the 10 mm margin definition, not positioning any spots outside of this distance. Again, Pinnacle[3] (up to 3.3/5 mm in the x- and y-directions, respectively) and RayStation (up to 3.8/1.3 mm in the x- and y-directions, respectively) position spots outside of the user-defined boundaries.

Figure 7 shows that the spot positions in Eclipse and XiO are symmetrical in both lateral directions, but they are not in Pinnacle[3] or RayStation. It can also be seen that Eclipse, RayStation and XiO position spots according to a 3D rectangular grid passing through the isocentre, whereas Pinnacle[3] uses spot positions defined in 2D square grids for each energy layer (as expected from each manual, section 2.5). Also, as predicted from the manual, RayStation positions spots from a different point for each row (adjacent rows of spots are off-set by half the spot spacing).

We investigated the use of auto 3D margins in both RayStation and XiO. For RayStation the plan can be calculated with zero margin, fixed 3D margin or variable auto 3D margins for each energy layer. For XiO it was found that the plan cannot be made with zero margin; it adds an auto 3D margin to the plan spot volume. The auto margin for both systems is affected by the spot spacing value. For XiO the auto margin with the fixed spot spacing is between 4 – 6 mm for 2 to 9 mm spot spacing, jumping to 10 mm at 10 mm spot spacing. Whereas for RayStation the auto 3D margin was up to 17.4 mm with 5 mm fixed spot spacing and up to 20.4 mm with auto variable spot spacing.

4.2 Plan delivery

Following the phantom studies, investigations were made into the implications of different spot spacing and layer spacing on the plan delivery. Spot weights were optimised to deliver a uniform dose to a target of 122 mm in depth. For each plan, the number of spots and layers, planning time, estimated delivery time (based on equation 4) and dose homogeneity (D_1-D_{99}, D_2-D_{98} and D_5-D_{95}) were computed.

4.2.1 Layer spacing

Table 2 shows results for different layer spacing (3.7-10 mm), for a constant spot spacing of 5 mm. Reducing the layer spacing improves the dose homogeneity.

Table 2: Statistics for plans with different layer spacing.

Plan	Layer spacing [mm]	Number of layers	Removed layers post optimising	Number of spots	Number of spots after post-processing	Proximal energy layer [MeV]	Post Proximal energy layer [MeV]	Distal energy layer [MeV]	Times (sec)		Dose Homogeneity		
									Planning	Delivery ±10%	D_1-D_{99}	D_2-D_{98}	D_5-D_{95}
1	10	13	1	6716	6603	148.6	154.3	207.4	324.0	28.6	0.65	0.53	0.37
2	9	14	1	7317	7181	150.4	155.4	207.4	345.0	31.2	0.51	0.43	0.30
3	8	16	1	8443	8277	148.6	153.2	207.4	372.0	36.2	0.48	0.40	0.27
4	Default (7.6)	16	1	8375	8276	150.6	154.6	207.4	376.0	36.2	0.48	0.40	0.27
5	7	18	1	9578	9391	149.2	153.2	207.4	419.0	41.2	0.47	0.39	0.26
6	6	21	1	11158	10736	148.7	152.1	207.4	484.0	48.1	0.45	0.36	0.23
7	90-90% of distal range ≈ 5.3	24	2	12333	12122	147.6	153.7	207.4	500.0	53.6	0.43	0.34	0.22
8	5	25	1	13184	12589	148.7	151.6	207.4	550.0	57.4	0.43	0.34	0.22
9	4	31	2	16214	15887	148.8	153.5	207.4	710.0	71.0	0.44	0.35	0.23
10	90-90% of Proximal range ≈ 3.7	33	1	17785	17081	149.8	152.0	207.4	731.0	77.6	0.43	0.34	0.22

Figure 8 shows the impact on the dose distribution in the depth direction when altering the number of layers in the plan. Above 5 mm layer spacing, or if too few layers are used, the dose distribution to the target is not uniform.

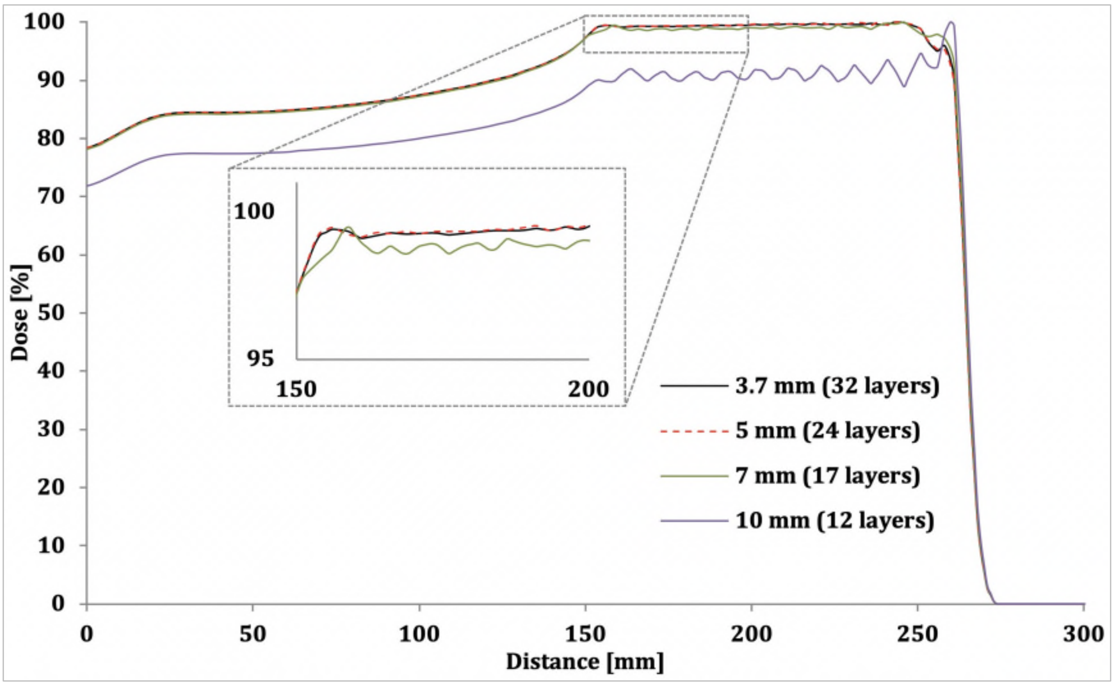

Figure 8: Depth dose profiles for plans created with different layer spacing.

4.2.2 Spot spacing

Table 3 shows results with different spot spacing (3-10 mm) and a constant layer spacing (4 x sigma of the next highest energy ~7.6 mm). It can be seen clearly that reducing the spot spacing improves the dose homogeneity.

Table 3: Statistics for plans with different spot spacing.

Plan	Spot spacing [mm]	Number of spots	Number of spots post-processing	Time (sec)		Dose Homogeneity		
				Planning	Delivery ±10%	D_1-D_{99}	D_2-D_{98}	D_5-D_{95}
1	10	2193	1897	133.0	24.8	1.39	1.13	0.80
2	9	2580	2450	134.0	25.9	0.70	0.55	0.37
3	8	3291	3260	135.0	26.1	0.50	0.42	0.28
4	7	4239	4184	240.0	28.0	0.49	0.41	0.28
5	6	5778	5580	308.0	30.8	0.48	0.40	0.28
6	5	8375	8276	376.0	36.2	0.48	0.40	0.27
7	Default: column≈4.8, row≈4.3	9848	9733	430.0	39.1	0.47	0.39	0.27
8	4	13056	12701	508.0	45.0	0.46	0.38	0.26
9	3	23249	22542	790.0	64.7	0.44	0.37	0.26

4.2.3 Planning and delivery times

Figure 9 shows the planning and estimated delivery times with different layer spacing and with different spot spacing. It can be seen clearly that the required time to produce a plan increases significantly if the layer spacing or spot spacing are reduced, while the delivery time only increases slightly.

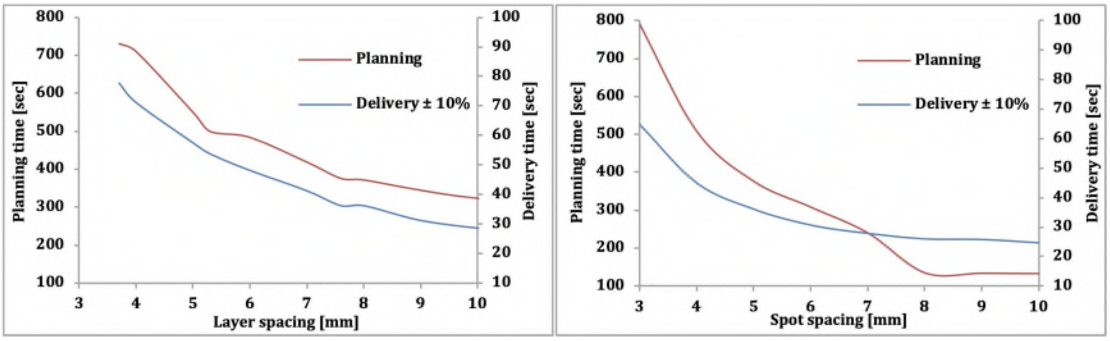

Figure 9: Planning and estimated delivery times for plans with different layer spacing (left) and spot spacing (right).

5. Discussion

The overall aim of this study was to investigate the performance of four proton TPSs, Eclipse, Pinnacle[3], RayStation and XiO, providing information that will be useful to potential purchasers of each system and for current users. The work was separated into two parts. In the first, the implementation of different proton planning parameters was determined for each TPS. Using three water phantoms with targets at different depths, investigations were made into how each TPS positions spots when plans are made with different layer spacing, different spot spacing and different margins. In the second part the impact of varying the layer spacing and spot spacing on the plan delivery was investigated within Eclipse.

5.1 Layer spacing

All the TPSs, except Eclipse, use variable layer spacing based on the Bragg peak width between the proximal 80% and distal 80% of each layer. As detailed in section 2.4 and table 1, variable layer spacing is desirable as it allows the variable Bragg peak width with energy (caused by energy and range straggling) to be accounted for and a homogeneous dose to be more easily delivered. In Eclipse layers can only be positioned with a constant value per beam.

In Eclipse, tests were made with different layer spacing values. If the layer spacing was too large, the dose homogeneity was affected (table 2 and figure 8). This agrees with previous works by Hillbrand and Georg (2010) and van de Water et al (2013, 2015).[23–25] However, if the layer spacing was less than 5 mm, layers were removed after the optimization process and the dose homogeneity worsens.

Acting against the improvement in dose homogeneity (down to 5 mm) is the increased delivery time for additional layers when using smaller spacing. The energy switching time is significantly longer than the layer scanning time (switching time 1.8 s, scanning time 0.02 msec) and it is the major component of the delivery time.[23,26] The actual beam delivery time within the clinical setting is dependent on machine specific performance characteristics. In this work we demonstrate that it is the planning time (caused by longer optimisation times with more layers and more spots), rather than the delivery time, that is impacted with more layers (figure 9).

Also, it was found whether using a constant or a variable layer spacing, that if the distal range is defined by the R_{90} then the layers are unnecessarily close; a definition according to R_{80} is sufficient.

5.2 Spot spacing

In order to deliver a uniform dose to the treatment volume, the spot spacing as defined by the TPSs should be dependent on the spot size. In a study by Lee (2015)[27] , it was found that, provided the spot spacing was equal to or smaller than two thirds of the spot size (FWHM), a plan with 100% uniformity could be achieved. It has been shown previously that spot spacing has an impact on the field sizes [28]. This was not found in our work, with the extent of spot positions remaining within the field sizes as expected, however, an optimal spot spacing should be found to balance dose homogeneity with output factor for a given field size [28].

It was found that reducing the spot spacing improves the dose homogeneity (table 3), but not for values less than 4 mm. Although our work was based on uniform material phantoms and simple cubic targets, it has been shown that similar values are suitable for patient geometries. Cao et al (2013)[29] planned four prostate cases with spot spacing between 3-7 mm. They found that reducing the spot spacing below 4 mm did not improve the plan dosimetry and they recommended a value of at least 6 mm. Robertson et al (2009)[30] also planned a selection of prostate cases with spot spacing between 2.5-10 mm. They found that while decreasing the spot spacing increases the target dose homogeneity and lowers rectal dose, it also results in a large number of low-intensity spots. It was suggested that this would decrease the plan robustness and increase the planning time. A value of 5 mm was recommended as a compromise. Based on our results and other works within patient geometries, we believe 5 mm to be a suitable value for spot spacing. The spot spacing of 5 mm not only gives good homogeneity, but improves the calculation and beam delivery time.

5.3 Margins

In PBS delivery a spot volume must be defined in which spots could be positioned. To ensure that the spots on the edges of the target do not have too high weighting an optimisation volume is typically formed from the target volume to include a margin. It was shown in this work that this margin should be at least two times the spot spacing to ensure the best dose coverage (increasing it by more than this does not improve the plan).

Users should be aware that Pinnacle^3 and RayStation position spots outside of the defined volume (target plus margin), whereas both Eclipse and XiO adhere to the planner's requests.

5.4 Spot positions

The available spot volume is defined by the layer spacing, spot spacing and margins defined by the user. Each TPS arranges the spots slightly differently within this volume. Eclipse, RayStation and XiO arrange the spots on a 3D grid passing through the isocentre, whereas in Pinnacle^3 the spot locations are defined by 2D square grids for each energy layer. It has been suggested that this flexibility may allow for improved OAR sparing compared to systems that use fixed 3D grids [15]. Additionally, RayStation offsets adjacent rows by half the spot spacing, which may help to give the optimiser further flexibility, and improve robustness by reducing the risk of systematic interplay with patient anatomical motion. This could be evaluated through further investigation.

6. Conclusions

This study compared four proton TPSs: Eclipse, Pinnacle³, RayStation and XiO. An investigation was made into the implementation and optimal selection of different proton planning parameters by each system.

All TPSs, except Eclipse, are able to offer variable layer spacing based on the Bragg peak width between the proximal 80% and distal 80% of each layer, which is ideal if a homogeneous dose in the depth direction is required. If constant layer spacing must be used, a value of not less than 5 mm was recommended to ensure good dose homogeneity.

Eclipse, Pinnacle³ and RayStation offer options for variable spot spacing with depth, which is ideal due to the depth dependency of spot size (due to MCS). RayStation adheres to this as expected, with increasing spot spacing for increasing spot sizes, but Eclipse and Pinnacle³ define the spot spacing in the opposite way. If constant spot spacing must be used, a value of 5 mm was recommended as a good compromise between dose homogeneity, plan robustness and planning time.

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