An Analysis of Proton Therapy: A Method to Reduce Lateral Penumbra

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Purpose

To ensure proper treatment of a target in X-ray therapy, large amounts of healthy tissue are put at risk to harmful radiation levels. In proton therapy, radiation treatments can be delivered in a conformal distribution sparing healthy tissue. However, at low energies the lateral dose spread, called lateral penumbra, can compromise the advantage of protons. A dynamic collimation system (DCS) was computationally modeled to investigate the benefit of the DCS in reducing lateral penumbra of proton therapy dose distributions delivered in a spot-scanned (SS) technique.

Introduction & Background

Delivery Techniques of Radiation Therapy:

Passive Scattering

- Broad beam delivery
- Delivered with high-energy X-rays, protons, or electrons
- Large irradiation area
- Multileaf collimator or aperture outlines target

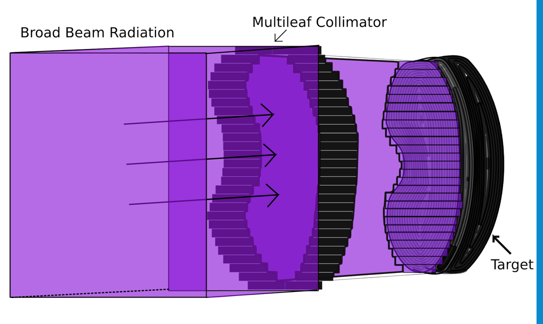

Figure 1: Passive scattering through broad beam radiation.

Active Scanning

- Spot scanning
- Mono-energetic beam of protons
- Rapid delivery by energy layer
- Lorentz force sweeps protons from a time-variant magnetic field
- Aperture and DCS collimation available

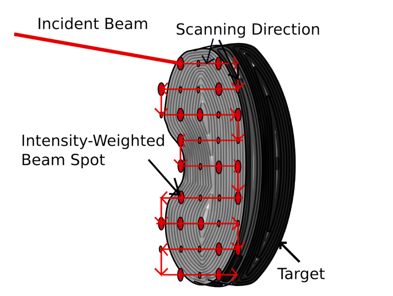

Figure 2: Active scanning with a proton beam.

Bragg Peak and Dose Fall-Off

Figure 3 shows the behavior of photons and protons as they interact with a water phantom. The maximum energy disposition of X-rays appears proximally in the phantom where as the maximum energy disposition for protons, known as the Bragg peak, is distal[3]. Since X-rays are composed of high-energy photons, they will continue to interact with matter at any depth. Due to the proton's charge and mass, they will not interact with matter past the Bragg peak thus sparing distally compared to that of the gradual decay of photon therapies[3].

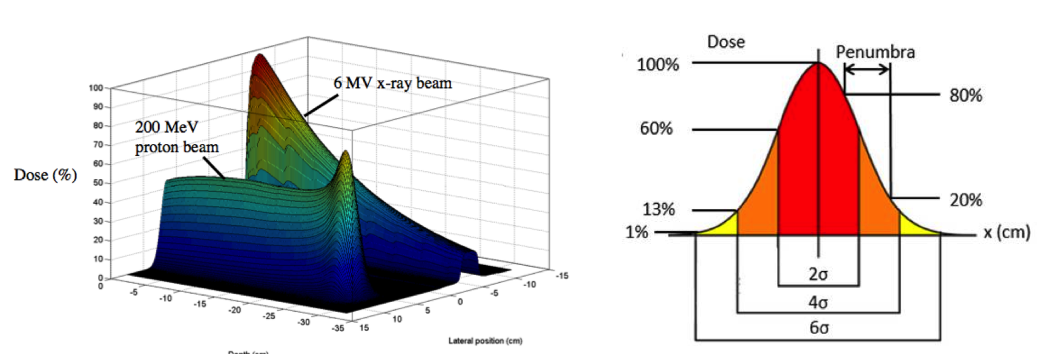

Figure 3: Distal dose distributions between X-ray and proton beams (left) and the lateral dose distribution of a beamlet (right). The Lateral penumbra is defined by from the 80% to the 20% isodose lines[3].

The lateral fall-off from any beam of radiation is known as the lateral penumbra. As the penumbra increases, more of the healthy tissue is put at risk of secondary cancer development.

IsoTrim Prototype

Proposed by Hyer *et al*[1], the DCS is a new technology that can improve the lateral penumbra for low energy SS proton therapy. The lateral dose distribution is defined by rapidly traveling trimmer blades which track the edge of the target as a narrow proton beam scans across the target. The main components of the DCS are shown in Figure 4 and include:

- Two pairs of rectangular, orthogonal nickel rods
- Four high-precision, independently driven linear motors
- Insertable range shifter
- Maximum acceleration of a trimmer: $19.6 \frac{m}{s^2}$
- Maximum velocity of a trimmer: $2.5 \frac{m}{s}$

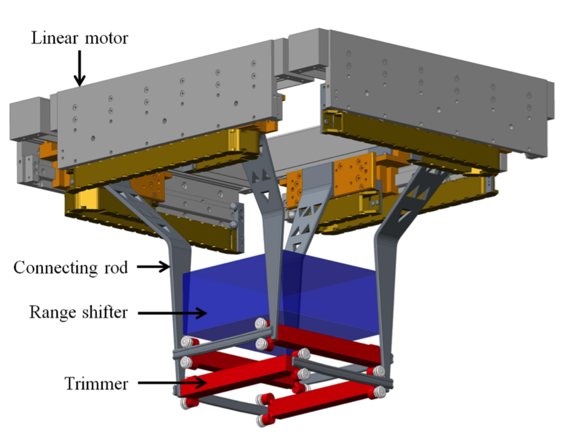

Figure 4: Illustration of the IsoTrim DCS prototype[1].

Trimmed Beamlet Model

Spot scanned proton therapy is delivered by a series of beamlets where a beamlet is a finite exposure to a proton beam. Each beamlet is defined by a depth dose and a lateral dose distribution at a particular range within the beam. By taking a 2D slice of the beamlet at any point, one can view the lateral distribution as shown below.

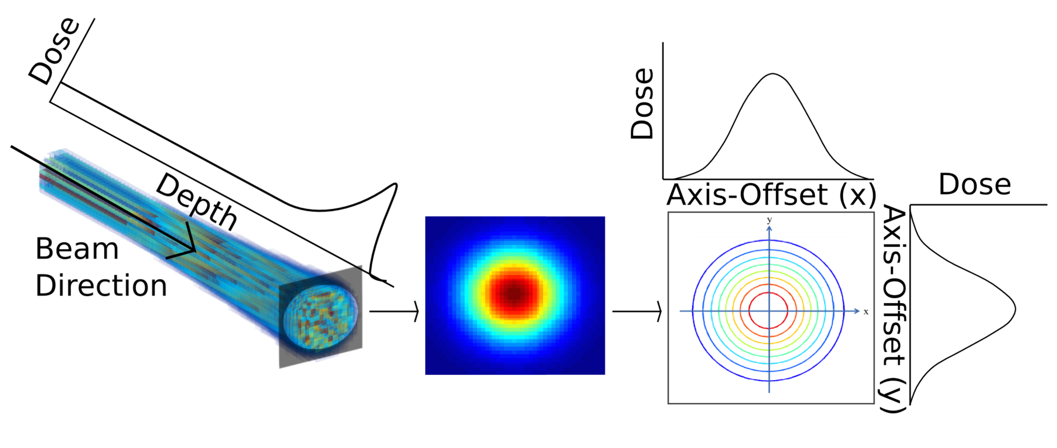

Figure 5: Schematic of an untrimmed beamlet. The distal distribution is shown on the far left. A lateral cut section is taken in the middle and the lateral distribution is mapped to a Gaussian (right).

Although the distal distribution is advantageous for treating targets at a depth, the lateral penumbra can hinder the plan quality at low therapeutic energies. However, we can alter the lateral distribution of a low-energy proton beamlet by partially blocking the beamlet with a pair of nickel rods.

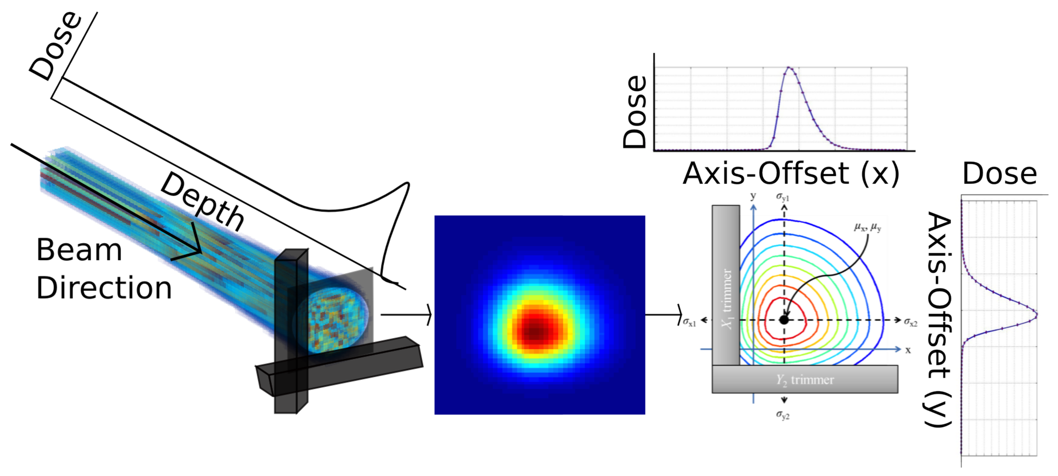

Figure 6: Schematic of a trimmed beamlet. The distal distribution in relation to a set of trimmer blades is shown on the far left. A lateral cut section is taken in the middle and the lateral distribution is mapped to a set of four Gaussian distributions along each primary half axis[2] (right).

The benefit of beamlet trimming is demonstrated in Figure 7 below. In the first case, an untrimmed beamlet is placed outside the target to ensure full target (outlined in green) coverage. In the second case, the beamlet is trimmed as to provide adequate target coverage but reduce the lateral penumbra to the normal tissue.

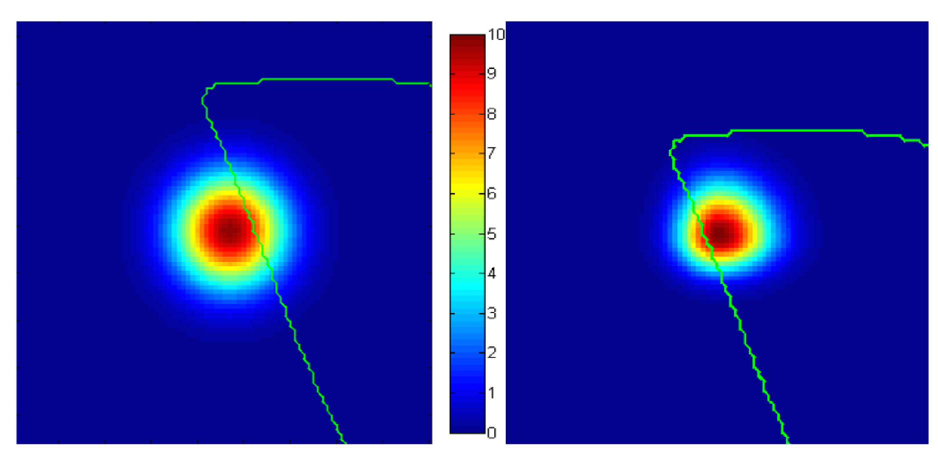

Figure 7: Comparison between beamlets in an untrimmed beamlet plan (left) and a trimmed beamlet plan (right). The relative dose intensities of the beamlets are shown by the color scale.

It now becomes a question of how to select trimmer orientations for each beamlet as to maximize the dose conformity inside the target and reduce the dose to normal tissue. There must also be a balance between the amount of trimming and the time penalty associated with the respective degree of trimming performed.

Treatment Delivery Algorithms and Techniques

DCS Raster-Style Scanning Delivery

To treat targets in both an effective and timely manner, a technique known as raster-style scanning was adopted. It was found that the method detailed below gave the best compromise between healthy tissue sparing and the time penalty associated during treatment.

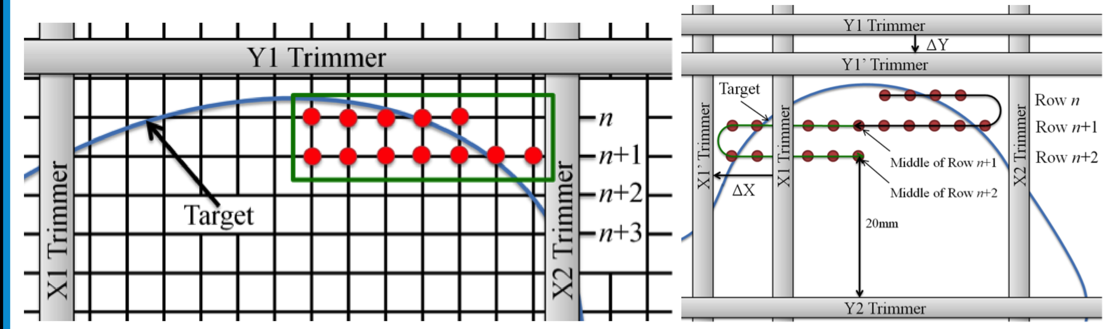

Figure 8: An illustration of raster-style scanning with the DCS[1]. A single orientation of trimmer blades is chosen for the beam spots within the green box (left). As soon as the trimmers are placed, the proton beam scans through all positions in the double-half row and stops (right). Thus the process is repeated for each double-half row sequence.

Dose Delivery

- A full treatment of a target is done in discrete energy layers
- The highest (deepest reaching) energy is delivered first
- Subsequent lower energies are then delivered
- There can be thousands of individual beamlets that must be delivered rapidly in a single treatment
- A single orientation of trimmer blades allow for raster scanning in a double-half row beamlet group pattern
- Beam scans from the middle of row n to middle of row $n+1$
- Trimmers move into position for next double-half row and the process repeats

Collimation Method	Spot Spacing (mm)	Time Penalty (s)
Beamlet-Unique Trimming	5	479.88
Raster Scanning	5	58.27

Figure 9: Time penalties associated with various trimming and scanning techniques. The spot spacing denotes the lateral distance between each beamspot.

Test Plan

The figure below shows the optimal plans to treat a cubical target with the DCS. The plans were generated by altering the distance the trimmer blades were from the edge of the target.

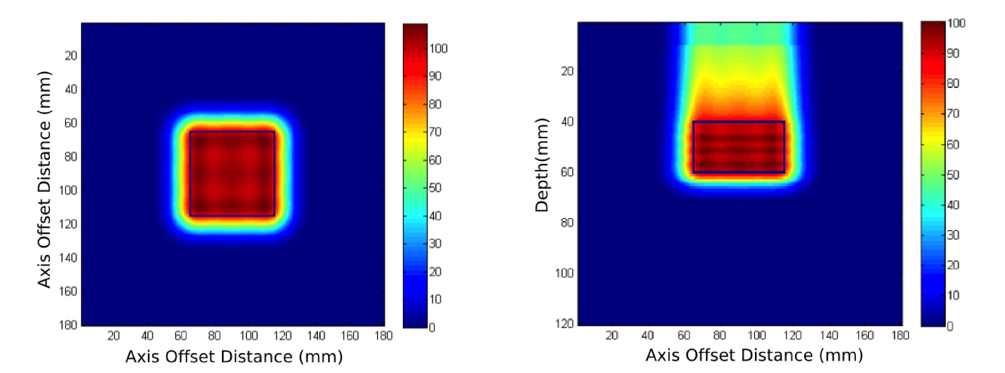

Figure 10: Dose distribution in beam's eye view (left) and in depth (right).

Although the majority of dose is distributed at the Bragg peak, there is residual dose in depth and transversally as shown below.

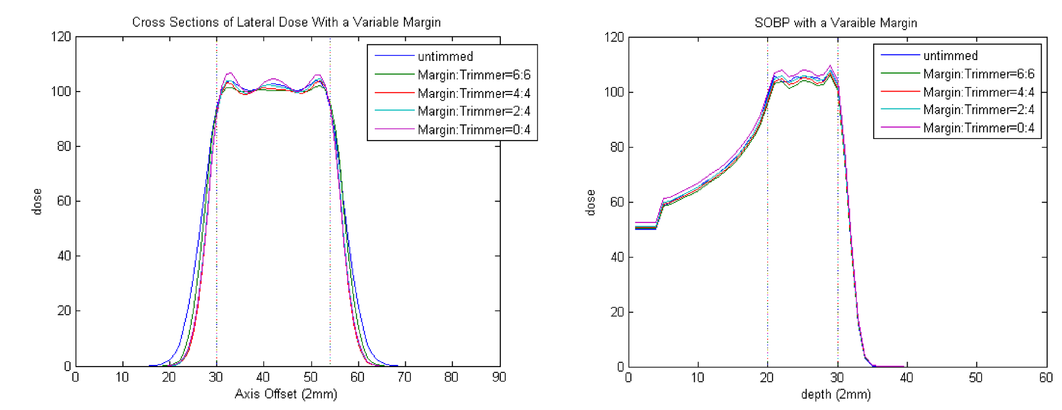

Figure 11: The dose as a function of depth across the target (left) complimented by the lateral dose cross-sectional profile (right) respectively to the distributions shown in Figure 10.

The DCS test plans reveal a reduction in penumbra as compared to the untrimmed technique as outlined in blue. However, dose inhomogeneity, as outlined by the magenta dose lines, may occur under too much collimation.

Clinical Data Set Investigation: Results and Analysis

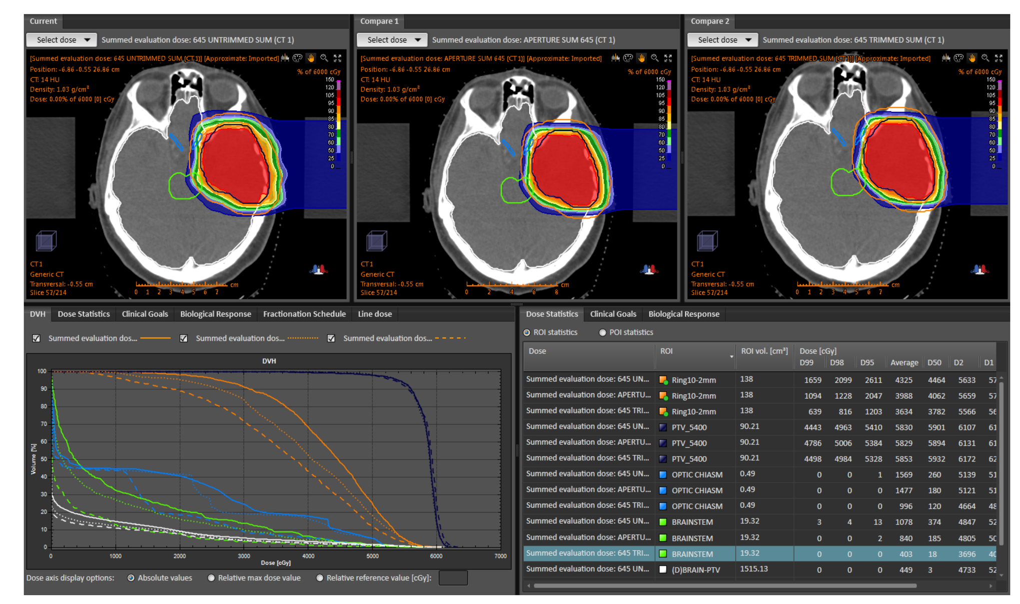

Figure 12: Three simulated plans produced from our in-house treatment planning system. The plans for the untrimmed plan (top left), aperture plan (top middle), and the DCS trimmed plan (top right) are compared with a DVH of critical structures (bottom).

Dose-Volume Histograms (DVH)

- A DVH shows the percent (volume) of a structure that receives a specific dose of radiation measured in Gray (Gy)
- All the plans were optimized for same target coverage (95% of target receives 55 Gy)

Analysis of Figure 12

- Coloring System: Purple: Target, Orange: 10mm around the Target, Blue: Optic Chiasm, Green: Brainstem, White: Bone/Skull
- Solid Line: Untrimmed Plan, Dotted Line: Collimation with an Aperture, Dashed Line: Collimation with the DCS
- Uncollimated plans served as a bases for comparison
- The DCS greatly reduces excess dose delivered to all vital structures but maintains target coverage

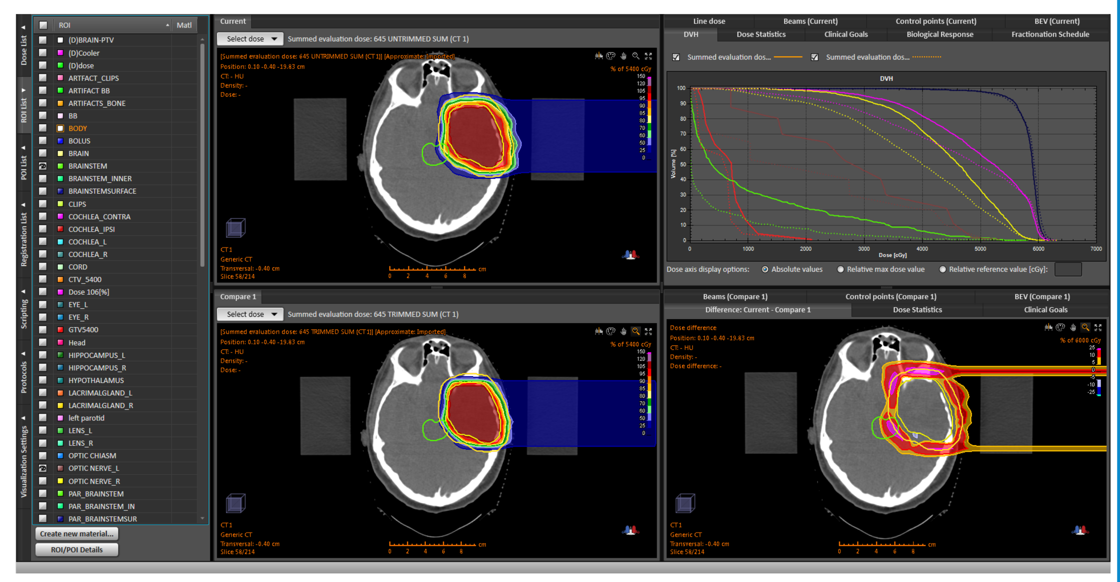

Figure 13: Comparison of the untrimmed plan (top left), a DCS trimmed plan (bottom left), and the difference between the untrimmed and the DCS trimmed plans (bottom right). The DVH of all three plans is provided for reference (top right).

Analysis of Figure 13

- Reduction in dose to normal tissue from the DCS shown in the bottom right
- Critical structures such as the brainstem, the optic nerves, and cochlea are spared with the DCS
- Due to the reduced dose to healthy tissue, patient tolerance of the treatment increases
- Reduction in excess dose greatly reduces secondary cancer rate induced by treatment

Conclusion

The DCS's ability to collimate each energy layer yields better conformity and reduces the dose delivered to normal tissue adjacent to the target region. Furthermore, the device can be integrated with current or future proton therapy equipment and may serve as a useful tool to further improve the next generation of proton therapy[1].

References

1. Hyer D, Hill P, Wang D, Smith B, Flynn R. A dynamic collimation system for penumbra reduction in spot-scanning proton therapy: Proof of concept. Med Phys. 2014 September. 41(9):091701.
2. Gelover E, Wang D, Hill P, Flynn R, Hyer D. A method for modeling laterally asymmetric proton beamlets resulting from collimation. Med Phys. 2015 March. 42(3):1321-1334.
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