Modeling and System Specifications for an Integrated 3-D Proton Treatment Delivery System*

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Abstract

Beam scanning in proton radiotherapy facilities imposes stringent requirements on the accelerator and beam transport system performance. We will report on a study of the interrelationship between the beam quality presented to the scanning system and the quality of the dose delivered to the desired target volume. The constraints on the accelerator will be quantitatively specified so the clinical specifications will be met.

I. INTRODUCTION

The use of proton accelerators for radiotherapy allows full three-dimensional conformal treatment of a tumor volume by sweeping a pencil beam transversely and longitudinally, filling the volume to the desired dose. Scanning the beam transversely by magnetic deflection and longitudinally by changing the accelerator energy allows optimal shaping of the dose distribution in the target volume and minimizing the dose outside. This can be achieved with full electronic computer control without mechanical beam modifying devices such as scattering foils, range shifters or collimators. The longitudinal dose distribution is given by the Bragg curve, which peaks at the distal end, followed by a small tail due to energy straggling. The transverse size of a single pencil beam spreads as the beam proceeds toward the distal Bragg peak, widening the transverse falloff downstream and reducing the dose along the axis for any one beamlet.

The raster scanning method chosen here uses velocity modulation instead of intensity modulation of the beam. This offers the following advantages:

- No modulation of the accelerator intensity is required.
- The good dynamic range provides the high occupation function values required at the edges of the dose volume.
- The non-periodic line scan rate minimizes the effect of periodic ripple modulation of the beam intensity from the accelerator.

Velocity modulated scanning requires that the accelerator beam intensity fluctuations and position, angular and energy modulation be within prescribed limits in order to meet the accuracy requirement of the dose prescription. A simulation was performed, filling a dose volume with beam subject to the above beam errors, and also subject to slew rate limitations of the scanner itself.

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II. DEFINING THE PROTON BEAM

The model pencil proton beam includes small-angle scattering, energy straggling and losses due to nuclear interactions. The spread out Bragg peak (SOBP) requires beams of several energies to be overlaid to produce a smooth longitudinal dose profile and to minimize the entrance dose. Scattering spreads the beam, and nuclear interactions attenuate the beam along the path (the dosage effect of nuclear interactions is not taken into account in these simulations). The Bragg peak is broadened by energy straggling, the peak is shifted upstream, direction, and a small distal tail is produced.

To facilitate the simulation calculation, the energy deposition function and rms beam width of pencil beams over the entire energy range are pre-calculated, using the usual scattering and energy straggling formulae[1]. Each beam starts with transverse betatron and energy spread parameters characteristic of the beam emerging from a realistic accelerator and beam transport system: $\pi\varepsilon_{x,y} = 4\pi$ cm-mrad, $\beta_{x,y} =$ 1 meter, $\alpha_{x,y} = 0$, and negligible energy spread.

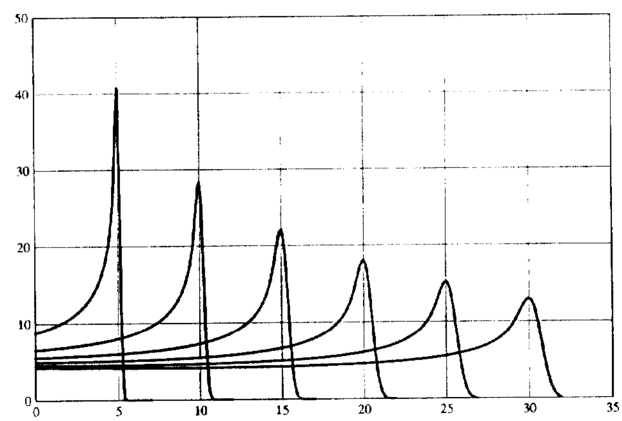

Figure 1. Energy Loss Function

Figure 1 shows the energy loss along the beam axis for ranges from 5 to 30 cm in water. The energy loss is integrated over the x and y planes transverse to the direction of motion, and attenuation due to nuclear interactions is included.

III. OPTIMIZATION PROCEDURE

The dose distribution D is a three-dimensional convolution of a density function F with the beam distribution P: $D(x,y,z) = F \otimes P$. An optimization procedure is needed to determine how the target volume is best filled by pencil beams assuming no restrictions are imposed by the scanning system or the accelerator. The procedure consists of finding the function F which delivers the required dose to the target

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volume while maximizing the lateral and distal falloffs. We have used an optimization procedure developed by Brahme[2] and by Lind[3]. The function F is approximated through an iteration process

$$F_0 = D_0$$

$$F_{n+1} = C\,[F_n + a\,(D_0 - F_n \otimes P\,)].$$

Here, D_0 is the desired dose distribution, C is a constraint operator guaranteeing non-negative occupation function amplitude, and a is a convergence speed parameter.

This method of determining the occupation function F has two advantages over other optimization methods:

- F is non-negative,
- D is never smaller than the desired dose D_0 within the treatment volume at the scanned points.
- The dose outside the treatment volume is minimized.

The function F is the irradiation or Bragg peak density defined throughout the volume and describes the amount of beam deposited in the volume with the center of the Bragg peak at a particular location. F can also be viewed as a beam occupation distribution which can be directly used to control a voxel scanning system.

As an illustration, a one-dimensional example is given. A gaussian beam irradiates a line segment to give a uniform dose for $0 \le x \le 50$ and no dose for $50 < x \le 100$. Figure 2 shows the beam half-profile (dashed) and the occupation function (solid line), the time spent along the line segment by the beam, the inverse of the scanning velocity, as it sweeps. Note that the occupation function has a peak at the edge and oscillates within the dose area. This occupation function assures that full dose (dot-dash) is given inside the required dose volume, and the width of the fall-off is minimized.

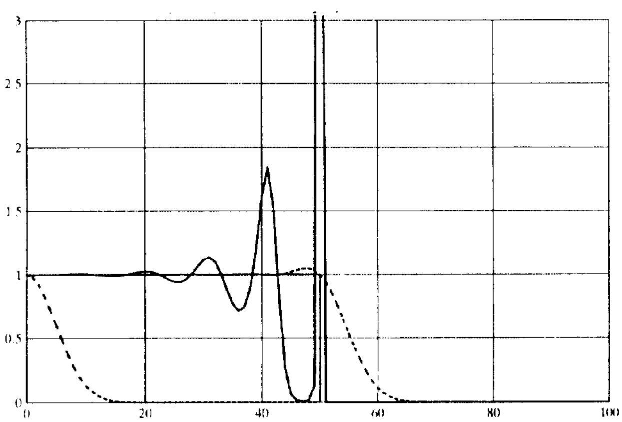

Figure 2. Dose, Occupation Function

We have simulated a raster scanner scanner system in which each layer of target volume is transversely scanned as shown in Figure 3.

The idealized dose distribution without imperfections was first determined for a fixed raster scanning pattern consisting of zig-zag pattern with a 10 mm separation at the turn-around points. The accelerator and beam transport system energy is changed for each layer. Typically, layers are separated in range by 5 mm and as many as 60 layers may be used.

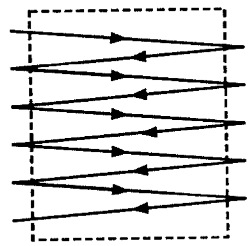

Figure 3.

The sweep velocity is modulated to vary the pixel dose. The raster pattern is conserved by keeping the ratio of the horizontal and vertical sweep velocities constant. This pattern requires the smallest slew rate to cover the dose area. The maximum slew rate requirement of the scanning magnets is specified at 10 times the average, with no lower limit to provide high dose capability to selected pixels, particularly at the edges.

For simulation of the raster scan the density function F is defined along the zig-zag scan lines only and is determined by an iteration procedure as described above. The linear sweep velocity is the inverse of the occupation function F for each voxel on the scan line. The calculations were done on a 1 mm transverse grid with a 5 mm longitudinal spacing. About 20 iterations are necessary for F to converge.

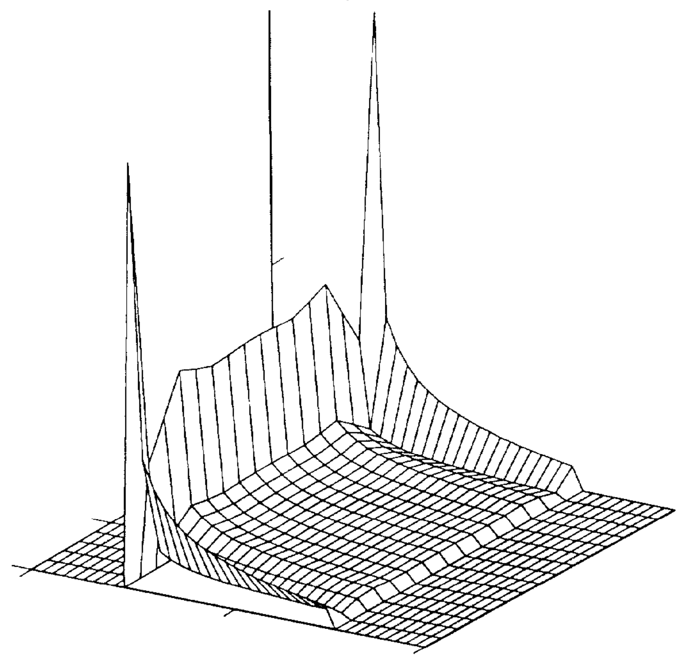

Figure 4. Bragg Peak Density Function F

Figure 4 shows the optimized Bragg peak density function on a plane perpendicular to the scan plane and through the central axis of the radiation field.

IV. SENSITIVITY TO FLUCTUATIONS

The goal of this study is to evaluate the dose distribution subject to imperfections in the scanned beam such as intensity fluctuations and scanning system limitations.

We have simulated the actual dose distribution with limited maximum slew rate of the sweep magnets and with realistic fluctuations in the accelerator beam intensity. The maximum sweep rate capability is specified at 10 times the average sweep rate, which satisfies the requirement of the occupation function calculated in the treatment planning process.

The perturbed dose distribution using F was then calculated by imposing maximum slew rates on the scan velocity and introducing beam intensity fluctuations.

The accelerator beam intensity fluctuation is defined within a moving time window[4]. Ripple, intensity spikes and random variations are averaged within a moving time window. This reflects the integrating effect of a finite beam width as it moves along its path. In our example, a beam with an rms size of 3–8 mm moves over a 1300 mm path in one second. The maximum fluctuations within the window are:

Window	Fluctuation
200 μsec	≤±20%
100 μsec	≤±100%
<25 μsec	$<5\times10^6$ in 25 μsec

For a moving time window shorter than 25 μsecond, the number of particles permitted in an intensity spike is limited as shown. Full r.f. modulation of the beam is permitted, as it will occur at a megaHertz rate, and r.f.-on spill simplifies the synchrotron beam spill monitoring function.

Figure 5 shows the dose distribution for a ±20% intensity fluctuation within a 200 μsecond traveling window, a scanner slew rate limitation of 10 times the average rate, and with an additional 180 Hz ripple modulating the intensity by 30%. This distribution differs by no more than 3% from a dose distribution with no perturbations and unlimited scanner slew rate.

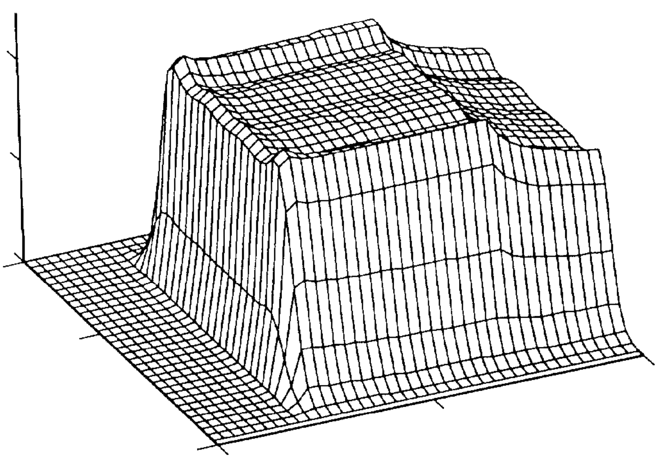

Figure 5. Dose Distribution with Nominal Perturbations

Additional perturbations were applied to the beam and limitations applied to the maximum scanning rate. The table lists the effect on the dose distribution in each of these cases. The fluctuation σ defines the random intensity variations within a 25 μsecond window. When σ = 0.35, the ±20% variation integrated in a 200 μsecond window is achieved.

The error indicated is the maximum deviation at any one point of the achieved dose distribution with the added fluctuations or scanner slew rate limitation from the distribution with no fluctuations.

Simulation Parameter	Error
Max sweep velocity = 2 × average	2%
Max Sweep velocity = 1.2 × average	40%
Fluctuation σ = 0.35 and 30% 180 Hz ripple	3%
Fluctuation σ = 1.05 and no a.c. ripple	4%
Fluctuation σ = 0.35 and 100% 180 Hz ripple	7%
Fluctuation σ = 0.35 and 30% 60 Hz ripple	7%
Fluctuation σ = 0.35 and 100% 60 Hz ripple	19%

V. CONCLUSIONS

This simulation study shows that a 3-D dose distribution can be delivered by a velocity modulated raster scanning system without the use of an intensity modulator or collimator. Velocity modulation serves well for distributing a pencil beam as required by the occupation function which peaks at the outside edges. A maximum sweep velocity of several times the average seems to be sufficient. Depending on the beam diameter, target volume size and sweep velocity, effects of beam intensity fluctuations and ripple are washed out to a large degree due to the large overlap of beam between different scan lines and layers and the non-periodic line scan rate.

Acknowledgements

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VI. REFERENCES

[1]. For example, Section 16.07D in *A Physicist's Desk Reference,* AIP (1989)

[2]. A. Brahme, P. Källman and B. K. Lind, *Optimization of Proton and Heavy Ion Therapy Using an Adaptive Inversion Algorithm,* **Radiotherapy and Oncology, 15:** 189-197 (1990)

[3]. B. K. Lind, *Properties of an Algorithm for Solving the Inverse Problem in Radiation Therapy,* **Inverse Problem 6:** 415-426 (1990)

[4]. W. T. Chu, J. W. Staples, B. A. Ludewigt, T. R. Renner, R. P. Singh, M. A. Nyman, J. M. Collier, I. K. Daftari, H. Kubo, P. L. Petti, L. J. Verhey, J. R. Castro and J. R. Alonso, *Performance Specifications for Proton Medical Facility,* LBL Report LBL-33749, March 1993