Fan-beam intensity modulated proton therapy

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Purpose: This paper presents a concept for a proton therapy system capable of delivering intensity modulated proton therapy using a fan beam of protons. This system would allow present and future gantry-based facilities to deliver state-of-the-art proton therapy with the greater normal tissue sparing made possible by intensity modulation techniques.

Methods: A method for producing a divergent fan beam of protons using a pair of electromagnetic quadrupoles is described and particle transport through the quadrupole doublet is simulated using a commercially available software package. To manipulate the fan beam of protons, a modulation device is developed. This modulator inserts or retracts acrylic leaves of varying thickness from subsections of the fan beam. Each subsection, or beam channel, creates what effectively becomes a beam spot within the fan area. Each channel is able to provide 0–255 mm of range shift for its associated beam spot, or stop the beam and act as an intensity modulator. Results of particle transport simulations through the quadrupole system are incorporated into the MCNPX Monte Carlo transport code along with a model of the range and intensity modulation device. Several design parameters were investigated and optimized, culminating in the ability to create topotherapy treatment plans using distal-edge tracking on both phantom and patient datasets.

Results: Beam transport calculations show that a pair of electromagnetic quadrupoles can be used to create a divergent fan beam of 200 MeV protons over a distance of 2.1 m. The quadrupole lengths were 30 and 48 cm, respectively, with transverse field gradients less than 20 T/m, which is within the range of water-cooled magnets for the quadrupole radii used. MCNPX simulations of topotherapy treatment plans suggest that, when using the distal edge tracking delivery method, many delivery angles are more important than insisting on narrow beam channel widths in order to obtain conformal target coverage. Overall, the sharp distal falloff of a proton depth-dose distribution was found to provide sufficient control over the dose distribution to meet objectives, even with coarse lateral resolution and channel widths as large as 2 cm. Treatment plans on both phantom and patient data show that dose conformity suffers when treatments are delivered from less than approximately ten angles. Treatment time for a sample prostate delivery is estimated to be on the order of 10 min, and neutron production is estimated to be comparable to that found for existing collimated systems.

Conclusions: Fan beam proton therapy is a method of delivering intensity modulated proton therapy which may be employed as an alternative to magnetic scanning systems. A fan beam of protons can be created by a set of quadrupole magnets and modified by a dual-purpose range and intensity modulator. This can be used to deliver inversely planned treatments, with spot intensities optimized to meet user defined dose objectives. Additionally, the ability of a fan beam delivery system to effectively treat multiple beam spots simultaneously may provide advantages as compared to spot scanning deliveries.

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Key words: proton therapy, intensity modulation, Monte Carlo, proton treatment planning, range compensator

1. INTRODUCTION

There are clear advantages often identified with magnetically scanned delivery of proton therapy as compared to more common scattered delivery techniques. Magnetic scanning does not require scattering materials to create a treatment field, and therefore does not suffer from losses of primary beam or secondary particle production due to these components. More

importantly, magnetic control over the proton beam allows dose to be delivered by individual proton beam spots. This dose may be optimized, allowing a treatment to take full advantage of the normal tissue sparing possible with intensity modulated proton therapy (IMPT). However, even with these identified advantages, IMPT deliveries remain in the minority in an otherwise quickly growing field. Over 50 proton therapy facilities are expected to be in operation worldwide by

FIG. 1. The coordinate system and general aspects of the beamline, including the quadrupole fan beam creation system and dual-purpose range and intensity modulator (not to scale).

the end of 2014, but only a subset of the total treatment rooms will deliver beams using a magnetic scanning system capable of delivering fluence-modulated IMPT.^{1,2}

We propose a concept for a new proton therapy delivery system. First, a proton fan beam is created with quadrupole magnets operating in steady state. The dose distribution is then shaped with a multielement device which modulates both the range and fluence of protons in subsections of the treatment field. The underlying system design is akin to scattering systems, yet the system may be used to deliver IMPT. It is designed such that it may be retrofit onto present proton therapy systems, enabling the technology to be widely implemented.

2. MATERIALS AND METHODS

2.A. General system overview

The fan beam proton therapy system is conceptually depicted in Fig. 1. Defined within the system geometry, for a given source position the beam axis refers to the direction traveled by the primary beam as it enters the quadrupole spreading system, which is therefore also the central axis of the fan. The lateral axis refers to an axis orthogonal to the beam axis in the transverse plane of a patient. The patient axis refers to the axis orthogonal to both the beam and lateral axes, along the superior-inferior direction of the patient. All axes are coincident at isocenter.

Dose distributions are delivered by a fan beam of protons created using a quadrupole doublet, an approach not yet applied to ion radiotherapy. The resulting dose distribution can be selectively modified within subsections of the fan beam using a specialized modulator. The fan field is limited in extent on the lateral and patient axes by a graphite field collimator. The latter is out of plane in Fig. 1, and it may be designed such that slices of a user-selectable thickness along the patient axis may be exposed by the fan beam.

A composite volumetric dose distribution is achieved by the superposition of dose distributions from multiple source positions around a patient, achieved by the combination of angular rotation and patient translation. Depending on the beam source trajectory relative to the patient, the geometry is sim-

ilar to the concepts of either tomotherapy or topotherapy.³⁻⁵ In a tomotherapy-based approach, the beam source rotates about the patient axis with concurrent translation of the patient along the patient axis. In a topotherapy-based approach, the beam source is held fixed in space while the patient is translated along the patient axis. The beam source is then repositioned through a rotation about the patient axis, and the translation is repeated. The rotation-translation sequence is repeated until the treatment plan has been delivered. As yet, both the tomotherapy and topotherapy concepts have only been applied to x-ray based intensity modulated therapies. The system geometry and depth-dose characteristics of protons make distal-edge tracking (DET) the treatment planning method of choice, though the system could also be operated in a mode similar to spot scanning.⁶ The system could be mounted on a fixed beamline; however, it is best paired with a rotating gantry.

Two pieces of equipment are studied herein to assure that the proposed system for fan beam proton therapy is indeed feasible rather than only conceptually plausible. The first is a fan beam creation system, capable of spreading a narrow and nearly monoenergetic proton beam created from an accelerator into a fan. The second is a range and intensity modulation device that can be used to alter the proton energies and intensities across the radiation field, such that protons deliver dose to specified locations within a target.

2.B. Creating a proton fan beam

The spatial distribution of a proton beam emerging from either a cyclotron or a synchrotron is not immediately useful for therapeutic purposes. To transform such a beam, one typically employs scattering foils to broaden the beam. Alternatively, magnetic dipoles can be used to steer the beam to different locations in the target in a scanned beam approach. In this work, we seek to create a beam of protons with a large aspect ratio, that is, the beam is broad in the lateral dimension and relatively narrow in the dimension parallel to the patient axis. While this could readily be achieved using scattering foils in combination with thick collimators, this approach is undesirable since it is an inefficient use of the beam and would result in unwanted activation and neutron production. In this work, we propose an alternative method using a pair of magnetic quadrupoles to shape the proton beam exiting the accelerator.

2.B.1. The quadrupole doublet

When charged particles pass through a quadrupole field, they are deflected in a manner similar to a ray of light being deflected by an optical lens. As such, when referring to the use of quadrupoles in the context of charged particles, they are often described as quadrupole lenses. A distinguishing feature of the quadrupole is that it acts as both a convergent and divergent lens simultaneously, focusing the charged particle beam in one direction while defocusing it in the orthogonal direction.

Pairs of quadrupoles, known as doublets, are commonly found in accelerator beamlines. They are arranged sequentially with their pole configurations rotationally offset from each other by 90° to produce a net focusing of the beam in both dimensions. In this work, we wish to achieve a net divergence of the beam in one dimension, thus creating a fan. To accomplish this, the second quadrupole seen by the beam is oriented with its pole configuration identical to that of the first, amplifying the defocusing effect of the first lens in one plane while maintaining a near parallel beam in the orthogonal plane.

2.B.2. Beam dynamics and field specification

Magnetic quadrupole fields and proton transport through these fields were modeled in SIMION version 8.0 (Scientific Instrument Services, Inc., Ringoes, NJ). For magnetostatics, SIMION uses a scalar magnetic potential specified at the location of the magnetic poles as boundary conditions in the iterative solution of Laplace's equation. Particle transport is computed using a standard fourth order Runge-Kutta method to numerically integrate the particles acceleration as determined via the Lorentz force equation. Relativistic effects are accounted for in the calculations. For more information on the theory used in these models, the reader is referred to various resources available in the literature.⁷⁻¹²

For the simulations in this work, quadrupole pole shapes were modeled as truncated hyperbolae with the ratio of maximum to minimum pole radii (measured from the quadrupole center) equal to 2.66. Magnetic potentials (positive and negative for North and South poles, respectively) were applied uniformly to each pole and adjusted to obtain the desired field strengths. In all cases, the simulation boundary used in solving for the magnetic field was extended 25 cm from the entrance and exit planes of each quadrupole in order to accurately model the fringe field that results in these regions due to the finite extent of the poles. Particle trajectories through the quadrupole system were calculated for an incident beam of monoenergetic 200 MeV protons. The beam's initial spatial distribution before entering the quadrupole doublet was determined via random sampling of a two-dimensional Gaussian function with full-width at half maximum (FWHM) equal to 1.5 cm in each transverse dimension. Beam emittance was simulated by uniformly sampling a cone with half angle equal to 0.143° to determine each particles velocity vector. The particle source plane was located 30 cm upstream of the first quadrupole, outside of the fringe-field region. All simulations were performed over a distance of 2.5 m measured along the beam's central axis from the source plane. Quadrupole field strength, separation distance, and length were all parameters that could be varied, and were optimized through a process of trial and error to create a broad, divergent beam of protons. In addition to mapping particle trajectories, 2D intensity distributions were also recorded at the source plane and after exiting the quadrupole doublet at a distance of 2.1 m from the source plane as measured along the beam's central axis.

FIG. 2. A conceptual diagram for the delivery of beam through a single channel of the modulator (not to scale).

2.C. Range and intensity modulator

After a fan beam of protons is created, the ranges and intensities of the protons in the field must be manipulated to match those required by the treatment plan. In general, range and intensity modulation could be achieved in separate devices which vary in design and material composition, such as range shifting plates followed by a multileaf collimator. However, if the range shifter can present the beam with enough material to stop the protons in the range shifter itself, a proper mix of beam pulses with and without full blocking may also be used to modulate intensity. This is the approach used to create the dual-purpose range and intensity modulator presented here.

2.C.1. Design

One design for a fan beam modulation device has been previously proposed, using wedges of tissue-equivalent material inserted or retracted from the beam with variable positioning to achieve range and intensity modulation.¹³ Instead we develop an alternative device to achieve the same effect. In this design, discrete leaves of material are inserted or retracted from the fan beam by a system of linear actuators in a fashion similar to a binary collimator used to temporally modulate photon beams.¹⁴

The leaves are arranged into channels, shown in Fig. 2, and each channel affects the depth of what effectively becomes a beam spot attributable to that subsection of the fan beam. Insertion of the correct leaves for one channel achieves user-selectable range shifting. Insertion of all the leaves of a single channel concurrently causes the beam to stop in the modulator, therefore providing user-selectable intensity levels for that beam spot. Proton intensity may be selected in discrete levels between zero intensity, where the primary beam is stopped in the modulator device, and full intensity, where all pulses deliver dose to a beam spot. Therefore, in this context, the term “intensity” refers to the number of protons stopping in a given subvolume within the patient, which in turn is proportional to the dose delivered by that beam spot.

Leaf thickness is defined as the nominal water-equivalent thickness (WET) of material traversed by a proton going through the leaf. The channel width is defined as the arc length illuminated by a beam channel on a circle centered on the effective beam source and passing through isocenter.

FIG. 3. A scale representation of one modulator beam channel (left) and the modulator assembly in a perspective view (right). In this case, a proton beam traverses an individual beam channel from left to right. The leaf thicknesses increase from 1 mm to 128 mm with proximity to the patient. Individual channels are divergent in width to follow the divergence of a fan, and may be stacked alongside one another into the assembly. The assembly would intersect a fan beam originating from a point to the lower left of the assembly. Note that the fan beam, field collimation, and patient are not explicitly shown.

Acrylic was chosen for the leaf material because it is commonly used in proton therapy for tissue compensators, it is low cost, easily machined, radiologically similar to tissue, and possesses a favorable neutron production cross section.

The leaf thicknesses for a channel are selected in a base-2 system with the smallest leaf presenting 1 mm of material to the beam. The remaining leaves therefore have thicknesses ranging from 2 mm up to 128 mm, as shown in Fig. 3. The largest 128 mm leaf is located furthest downstream in the modulator in order to minimize the relative contribution to the beam broadening that this leaf will create between the modulator and the patient. With all of the leaves engaged into the beam, the 255 mm of acrylic in a beam channel can provide up to approximately 300 mm of water-equivalent range shift, selectable in approximately 1 mm increments. A design with leaves of base-2 thicknesses is advantageous in that the device requires the fewest number of moving parts to provide this spectrum of shifts at this resolution. As long as the range of source protons is less than 255 mm in acrylic, true for protons less than approximately 215 MeV, a modulator channel will contain enough material to stop the beam. In order to modulate a fan beam of protons, a multichannel range and intensity modulator is created by stacking single channel assemblies alongside each other along the lateral dimension of the modulator apparatus, also shown in Fig. 3.

The leaves are moved by an array of linear actuators connected to the leaves by steel cables integrated into the base of each leaf. This array may be located within a reasonable distance of the modulator, allowing it to be placed at a convenient location near, but not necessarily adjacent, to the modulator assembly. When energized, an actuator provides a pulling force on the leaf, removing the leaf from the beam. Typical specifications for linear actuators suitable for this application include approximately 2 cm of piston travel and can move a leaf to a retracted position within tens of milliseconds. The use of linear actuators, rather than other motion devices such as linear motors or pistons, significantly reduces the overall weight, complexity, and cost of the system. The predictable

throw length of the solenoid pistons make the system highly reproducible, such that optical or other low-cost sensors can be used to verify the position of each leaf rather than motion indexers. Finally, since the leaves have default positions inserted into the beam, power loss to the actuator system will return all leaves to inserted positions and safely stop the beam prior to reaching the patient.

2.C.2. MCNPX simulation of beam channel dose

A research treatment planning system was developed in MATLAB for the purpose of simulating system performance and optimizing design parameters. Treatment plans are created assuming a tomotherapy delivery, namely, that dose is delivered with a fixed gantry angle to sequential slices of a target via patient translation. This process is repeated for any additional gantry angles requested in the treatment plan. The tomotherapy method was chosen because it is the most likely initial clinical implementation, as opposed to the more complex, tomotherapy-like helical delivery.

In order to perform an optimization on the beam spot weights, the dose distribution due to each beam channel must be known. The user first defines the set of source positions to be used for the treatment plan, which are stored as unique combinations of gantry angle and position along the patient (longitudinal) axis. At each source position, the modulator is configured to deliver dose spots to the target distal edge. Using a set of patient data and target contours, a ray-tracing calculation determines the water-equivalent depth between an effective source point and the distal edge of the target contour for each beam channel. The amount of range shift required for the channel is the difference between the range of the source particles and this water-equivalent depth. The leaf positions are then sequenced to be in or out of the fan as necessary to provide the correct amount of water-equivalent range shift for each beam channel.

Monte Carlo methods were chosen for the dose calculations due to the highly variable arrangements of acrylic and

air interfaces which result in complex scattering conditions within the modulator. After determining the modulator configurations for each source position, MATLAB functions generate an MCNPX input file for each beam channel at each source position. The previously determined modulator configurations are interpreted by these functions, and the modulator leaves are placed in their properly inserted or retracted positions relative to the proton fan beam. Particle transport through the modulator included the relevant effects of multiple scattering and energy straggling, producing realistic dose distributions. Dose is delivered primarily from protons stopping in the patient, and therefore neutrons were not tracked for the beam channel simulations. This provided the benefit of significantly reduced calculation times.

Because MCNPX 2.5 does not support particle transport in external magnetic fields, a fan beam source was approximated by a cylindrical surface source with particles emerging normal to the surface and located directly behind the modulator. The proton intensity was sampled from intensity distributions determined by the magnetic field particle transport simulations described in Sec. 2.B. In the lateral dimension, the source intensity was limited precisely to the beam channel being simulated. This was fundamentally important, allowing the dose distribution calculated by each input file to be attributed uniquely to each beam channel, lending itself for intensity optimization. If the source particle distributions from all the beam channels were summed together, the original intensity distribution from the entire fan beam would be recreated.

Dose for each beam channel is calculated on a three-dimensional grid. For phantom treatment plans, a cubic water phantom was defined using simple surfaces. However, for treatment plans using clinical data and contours, patient computed tomography (CT) scan data were integrated into the simulation using a method of “voxel-universe” specification.¹⁵ Physical densities of these voxels were determined by correlation with the CT scanner image value to density table, and materials were chosen using a physical density thresholding scheme and ICRU material compositions.¹⁶ Computations were performed on a large 500+ node grid computing network capable of computing a single beam channel in approximately 1 CPU-hour.¹⁷

2.C.3. Optimization and treatment planning

A true optimization of all the available modulator configurations would require an impractical number of $m \cdot 256^n$ input files, assuming m source positions, n beam channels in the modulator, and 256 possible beam ranges available from each beam channel. In a more practical situation, this number may be reduced by limiting beam channels and spots to those which intersect the target region of interest. However, even under conditions where three beam channels are projected across a small 3 cm target with 30 potential spot treatment depths, the system would still require 30^3 simulations per source position. This is computationally impractical, and in practice treatment time will increase as a function of the total number of modulator configurations required. Therefore,

an attempt should be made to minimize the total number of modulator configurations required for a treatment plan.

As a result, we implement an optimization approach which exclusively uses distal edge beam spots for optimization. The primary assumption made is that a beam channel will either be configured to deliver a distal beam spot to the target, or be fully closed to remove and provide intensity modulation for that spot. While the aforementioned presence of modulator scatter prevents any spot from being treated as completely independent and therefore cannot be turned “off” without affecting neighboring beam channels, the approximation is used to find the optimal intensity weighting for the spots. A least-squares optimizer was implemented in MATLAB, which minimized an objective function based on user-defined absolute dose and dose-volume constraints to targets and critical structures.

After the beam spot weights were determined, a final dose calculation must be performed. This occurs after optimization in order to properly account for the effects of “crosstalk” on the dose distribution as the modulator configuration changes and leaves are fully inserted in beam channels in order to achieve intensity modulation. This is accomplished again by MCNPX simulation, using a new set of automatically generated MCNPX input files. The final result then represents the “deliverable” dose distribution which has fully accounted for scatter in the changing modulator configurations.

2.C.4. Evaluation of dose delivery and performance

A defining characteristic of the fan beam modulator is the beam channel width, which relates to the ability of the system to shape a dose distribution along the distal edge of a target. Determining the minimum beam channel width that produces acceptable dose distributions is important, as it minimizes the number of channels treating the target within a given treatment field. In turn, this reduces dose calculation time, simplifies quality assurance by requiring fewer moving parts which might fail, and also simplifies the design of leaves so that they may be manufactured without being excessively thin in the lateral dimension.

Using a fixed number of 29 gantry angles, treatment plans were created for several different beam channel widths. The large number of angles ensures that any dose coverage deficiencies that arise are dominated by the size of the dose spots delivered at a given beam channel width. Channel width was increased from 5 to 21 mm in 4 mm increments for treatment plans of a cylindrical target in a water phantom, an avoidance target in a water phantom, and a clinical prostate target. Target dose distributions were then evaluated to determine the maximum beam channel width which produced reasonably conformal dose distributions in the transverse plane.

After determining an acceptable beam channel width, this value was used for the remainder of the investigations. Additional treatment plans were then generated using the prostate target, this time reducing the number of delivery angles incrementally from 26 to 5. The dose conformity was again evaluated to determine the point at which decreasing the number of

FIG. 4. Scale drawing showing calculated trajectories of 200 MeV protons traversing quadrupoles Q1 and Q2. Fifty thousand particle tracks are shown. Also shown are the locations of the source and exit planes where particle intensities were recorded. Orthogonal profiles taken in the exit plane are shown in Figs. 5(a) and 5(b).

treatment angles caused significant degradation of the target dose distribution.

To observe the effects that the assumption of beam channel independence made during optimization has on the composite dose distribution, treatment plans on the prostate target were compared before and after the final dose calculation. For each gantry angle, the fan beam was limited by the field collimator to the target edges in the lateral dimension and exposed slices which project to a 1.0 cm thickness in the patient (longitudinal) dimension at isocenter. The topotherapy delivery method was utilized, with longitudinal patient translation steps of 2.5 mm. Treatment times were also estimated from the MCNPX -determined doses using nominal values of beam current, gantry rotation speed, and patient translation speed. Finally, neutron contributions to patient dose in the treatment field were estimated with separate MCNPX simulations on the prostate patient.

3. RESULTS

3.A. Fan beam properties

The results from particle transport simulations through the quadrupole doublet are presented in Fig. 4. As shown, using a pair of electromagnetic quadrupoles, it is possible to broaden a 1.5 cm FWHM beam of energetic protons to a lateral width of approximately 22 cm FWHM over a distance of 2.1 m. In the orthogonal dimension, the width of the beam exiting the calculation grid is only 2.0 cm FWHM and characterized by a much smaller divergence. For the simulation results shown, quadrupoles Q1 and Q2 were modeled with lengths of 30 cm and 48 cm, respectively, with transverse gradients of 17.5 and 8.75 T/m. These gradients correspond to magnetic field strengths at each pole tip of 0.7 T and quadrupole bore diameters of 8 cm and 16 cm for Q1 and Q2, respectively. These parameters were chosen because they fit our design goals of producing a divergent fan beam of protons over a relatively short distance, while staying within the range of

FIG. 5. Normalized intensity profiles taken in a plane perpendicular to the beam's central axis after exiting the quadrupole doublet and located 2.1 m from the source plane. (a) Lateral beam profile taken along the divergent dimension of the fan beam showing a FWHM of 22 cm without beam collimation. (b) Longitudinal beam profiles taken along the narrow dimension of the fan beam in the same plane showing the relative intensity and width of the beam both on axis and at two distances off axis, also without beam collimation. Normalization for all profiles is to the intensity at the beam's central axis.

water-cooled magnets. The center to center separation of the magnets was 89 cm. Figures 5(a) and 5(b) show normalized intensity profiles taken perpendicular to the beam axis at a distance of 2.1 m from the source plane. Normalization in both cases was to the intensity recorded at the position of the beam's central axis. These distributions were sampled in subsequent MCNPX simulations to determine the correct intensity of particles within a beam channel.

3.B. Dose dependence on channel width and delivery angles

For a given number of delivery angles, the ability of the system to deliver a conformal dose distribution to a phantom with a centrally located cylindrical target does not change significantly as a function of beam channel width within the range of 5 to 21 mm. This was also true for a target which encloses an avoidance region over a range of approximately 270° , shown in Fig. 6. The insensitivity to beam channel width indicates that the large number of delivery angles provided sufficient options for the optimizer with regard to deliverable beam spot locations, compensating for the size of dose spots delivered from large channel widths.

Figure 7 presents dose profiles through the clinical prostate target for varying beam channel widths between 5 and 21 mm. In general, little variation in the dose profiles is observed for all beam channel widths, suggesting that a modulator with beam channel widths in this range will have the ability to produce acceptable dose distributions. For this profile, the largest 21 mm beam channel width does exhibit slightly higher dose outside the target, most likely due to the large spot size. The asymmetry apparent in the profile is primarily a result of the optimization constraints, and could be changed by choosing different optimization parameters and values. The similarity of profiles indicates that conformity is not a strong function of beam channel width, especially for beam channel widths of approximately 20 mm and narrower. In addition to this weak dependence on beam channel width, optimized dose distributions were similar over a wide range of 9 to 26 total

FIG. 6. Transverse dose distributions for treatments using beam channel widths of 13, 17, and 21 mm. The targeted region measures 10 cm on each side and includes an avoidance region 5 cm on each side (indicated by a black line).

delivery angles. Dose conformity was found to become unacceptably coarse on the edge of the target only when treatment angles were reduced below approximately nine angles equally spaced around the target.

3.C. Optimized and deliverable dose distributions

Significant differences were observed between the optimized dose distribution and sequenced “deliverable” dose distribution for a prostate target, readily seen in the dose-volume histogram presented in Fig. 8. Sequencing has little effect on the dose to structures outside the treatment target. However, the dose homogeneity suffers in the deliverable dose distribution, which includes the effects of changing modulator configurations to achieve intensity modulation. This is attributable to a breakdown of the fundamental assumption of beam spot independence used during optimization. Fully simulating the changes of the modulator reveals a reduction of the overall dose in the delivered beam spots, due primarily to greater attenuation of scattered protons. This does not necessarily mean the system is incapable of delivering clinically acceptable dose distributions, but does suggest that the optimization process may be improved by more explicitly including the effects of changing modulator configurations in a manner similar to direct aperture optimization of photon IMRT. Alter-

natively, the reduction of dose to normal tissues obtained using IMPT may allow the prescription dose to cover the target volume without unacceptably increasing the dose delivered to relevant sensitive structures, even with the level of target dose heterogeneity observed in the deliverable distribution.

3.D. Estimated treatment time and neutron considerations

For the prostate example, beam-on time is estimated to be approximately 50 s to deliver 2 Gy to the target volume target assuming a beam current of 10 nA entering the quadrupole doublet. For this target with a length of 4.75 cm in the direction of couch translation, the total treatment time from first beam-on to last beam-off is estimated to be approximately 5 min using 26 delivery angles and a tomotherapy delivery approach. This estimate assumes a gantry rotation speed at the IEC limit of 360 deg/min and couch translation speed of 0.5 cm/s, but neglects time required for setup and imaging as well as second-order effects such as time for gantry acceleration and deceleration. Nevertheless, it indicates that the fan beam delivery, even for a large number of angles, can be accomplished using current accelerator technology within a clinically acceptable timeframe. Overall treatment time is

FIG. 7. Dose distribution and profile relative to isocenter proceeding from the posterior to anterior direction for prostate target treatment plans delivered from 29 angles using varying beam channel widths. The delivered dose distribution is similar for all channel widths in this range.

FIG. 8. Dose-volume histogram showing the optimized dose distribution, which ignores the effects of changing modulator configurations, and a deliverable (sequenced) dose distribution. Thoroughly accounting for scatter in neighboring beam channels after modulator sequencing shows a significant reduction in target dose homogeneity.

affected most by the number of delivery angles due to the toposurgery delivery, as the couch must translate through the treatment field a number of times equal to the number of delivery angles.

Neutron dose from this system if physically constructed would be heavily influenced by the components used in the beamline and radiation head as well as the geometry of the treatment room. Basic neutron level estimates in the prostate patient, at a point centrally located in the treatment field and using a quality factor of $Q = 20$, are on the order of 10 mSv/Gy. This value is comparable to those found in literature sources for existing scattered delivery systems.^{18,19} This comparable level occurs even though a significant fraction of the beam is stopped in the modulator and collimator during the treatment, and is likely a result of using acrylic and graphite as beam shaping materials.

4. DISCUSSION

The fan beam delivery system combines different advantages of both scattering and magnetic scanning systems, having the straightforward beam transport approach of scattering systems but targeting and dose delivery abilities more representative of magnetic scanning. Since the modulator system dynamically affects individual subsections of the fan, the fan beam system effectively delivers multiple dose spots from each accelerator beam pulse. Depending on the beam source current, this may reduce the total delivery time at a given angle up to a maximum factor linearly proportional to the number of fan beam channels involved in treating the target from that angle. Furthermore, the increased number of spots per pulse and use of multiple delivery angles may result in treatments that are more robust with respect to target motion or range uncertainties, as any given subvolume in the target will receive dose from multiple beams and angles throughout the treatment.

It is important to design the system to achieve an acceptable dose distribution while maximizing delivery efficiency. With respect to individual modulator channel design, there is very little dependence on beam channel width on both target coverage and critical structure avoidance across a large range of channel sizes. The large number of delivery angles employed likely plays a role in allowing for similar target coverage with different dose spot sizes. Assuming sufficient beam delivery angles, significant degradation of the dose distribution would be expected only for beam channel widths which approach the size of the target. The distal falloff of the dose spots provides sufficient spatial control over the dose distribution from individual spots to deliver an intensity modulated dose distribution, even in the presence of relatively coarse control over the lateral distribution of dose from one spot.

Treatment planning combining MATLAB and MCNPX is certainly achievable, but is not without complexity. The assumption that beam channel dose distributions are independent of one another creates a significant discrepancy between optimized and deliverable dose distributions. As a result, optimization should explicitly include some method of accounting for scatter arising due to changing modulator configura-

tions. This could be achieved by incorporating the effects of leaf sequencing back into the optimizer, allowing the deliverable dose distribution to influence the iterative changes to beam spot weights. The deliverable dose distribution arising from such an optimization would more closely resemble the optimized plan and more easily match the treatment objectives and constraints.

Delivery uncertainties due to patient setup and proton range are a constant concern for all ion therapies, due in particular to the high dose gradients achieved with the Bragg peak. This system is no exception, and a work is underway to characterize the effects of range and setup uncertainties as they apply in particular to the fan beam delivery. To first order, these uncertainties are not expected to be any greater for this system as compared to others, as the proton fan beam and range modulator can be well-characterized relative to the uncertainties introduced by daily setup and patient composition. However, this system may exhibit some unique properties in the presence of these uncertainties. Scattered protons emerging from the modulator are subject to setup and range uncertainties, and therefore may have an impact on the delivered dose distribution spatially separated from the beam channel where they arise. Additionally, the large number of delivery angles may also change the way these uncertainties manifest in the delivered dose distribution, perhaps as a blurring of the dose gradient along the target edge rather than the stark underdose or overdose that is observed with delivery using only a few fields.

5. CONCLUSIONS

Simulations have shown that it is possible to create a therapeutically viable fan beam of protons with dimensions of 22 cm $\times$ 2 cm FWHM using a quadrupole doublet over a distance of 2.1 m, and modulate this fan beam using a binary acrylic leaf range modulator. The use of the base-2 system for modulator leaf thicknesses requires the fewest number of moving parts while providing approximately 1 mm resolution for spot placement in depth. For the phantoms and patient data sets presented here, beam channel widths in the range of 10 to 15 mm produce acceptable dose distributions when delivered from approximately nine angles or more around a patient, though it is best to use the fewest number of angles necessary to create an acceptable dose distribution in order to minimize the treatment time. The potential to produce a relatively inexpensive system which can deliver the enticing dose distributions achievable with intensity modulated proton therapy, especially as an upgrade to costly existing systems which otherwise deliver treatments without intensity modulation, warrants further consideration.

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¹Particle Therapy Cooperative Group [PTCOG], Particle therapy facilities in operation (incl. patient statistics) [homepage on the internet], 2012 [updated May 06, 2012; cited May 25, 2012] (available URL: <http://ptcog.web.psi.ch/ptcentres.html>).

²Particle Therapy Cooperative Group [PTCOG], Particle therapy facilities in a planning stage or under construction [homepage on the internet], 2012 [updated May 04, 2012; cited May 25, 2012] (available URL: <http://ptcog.web.psi.ch/newptcentres.html>).

³T. R. Mackie, T. Holmes, S. Swerdloff, P. Reckwerdt, J. Deasy, J. Yang, B. Paliwal, and T. Kinsella, "Tomotherapy: A new concept for the delivery of dynamic conformal radiotherapy," *Med. Phys.* **20**, 1709–1719 (1993).

⁴Timothy W. Holmes, "A model for the physical optimization of external beam radiotherapy," Ph.D. dissertation, University of Wisconsin – Madison, 1993.

⁵G. Olivera, K. Ruchala, W. Lu, J. Haimeri, E. Schnarr, T. Mackie, K. Langen, P. Kupelian, and S. Meeks, "Dynamic tangents and tomotherapy: New delivery capabilities for helical tomotherapy," *Med. Phys.* **32**, 2034 (2005).

⁶J. Deasy, D. Shepard, and T. Mackie, "Distal edge tracking: A proposed delivery method for conformal proton therapy using intensity modulation," in *ICCR 1997: Proceedings of the XIIth International Conference on the use of Computers in Radiation Therapy*, edited by D. D. Leavitt and G. Starkschall (Medical Physics Publishing, Madison, WI, 1997), pp. 406–409.

⁷D. Griffiths, *Introduction to Electrodynamics* (Prentice Hall, Upper Saddle River, NJ, 1999).

⁸G. Grime and F. Watt, *Beam Optics of Quadrupole Probe-Forming Systems* (Adam Hilger Ltd., Bristol, UK, 1984).

⁹L. Shampine, "Some practical Runge-Kutta formulas," *Math. Comput.* **46**, 135–150 (1984).

¹⁰W. Press, *Numerical Recipes in C* (Cambridge University Press, New York, 1992).

¹¹G. Forsythe, *Computer Methods for Mathematical Computation* (Prentice Hall, Upper Saddle River, NJ, 1977).

¹²D. J. Manura and D. A. Dahl, *SIMION 8.0 User Manual – Document Revision 4* (Scientific Instrument Services, Inc., Ringoes, NJ, 2008).

¹³J. Deasy, T. R. Mackie, and P. M. DeLuca, Jr., U. S. patent 5,668,371 A (1 October 1996).

¹⁴P. Hill and T. R. Mackie, "Range and intensity modulators for an ion fan beam," in *Proceedings of the XVth International Conference on the use of Computers in Radiotherapy*, edited by J. P. Bissonnette (Department of Radiation Oncology, University of Toronto, Toronto, ON, 2007), Vol. 2, pp. 546–550.

¹⁵V. Taranenko, M. Zankl, and H. Schlattl, "Voxel phantom setup in MC-NPX," in *The Monte Carlo Method: Versatility Unbounded in a Dynamic Computing World* (American Nuclear Society, LaGrange Park, IL, 2005).

¹⁶International Commission on Radiation Units and Measurements, "Stopping powers and ranges for protons and alpha particles," ICRU Report 49 (International Commission on Radiation Units and Measurements, Bethesda, MD, 1993).

¹⁷Facilities – Grid Laboratory – Medical Physics Department – University of Wisconsin – Madison [homepage on the internet], The Board of Regents of the University of Wisconsin System [updated March 24, 2011; cited August 4, 2011] (available URL: <http://www.medphysics.wisc.edu/facilities/glow/>).

¹⁸J. C. Polf and W. D. Newhauser, "Calculations of neutron dose equivalent exposures from range-modulated proton therapy beams," *Phys. Med. Biol.* **50**, 3859–3873 (2005).

¹⁹Y. Zheng, W. Newhauser, J. Fontenot, P. Taddei, and R. Mohan, "Monte Carlo study of neutron dose equivalent during passive scattering proton therapy," *Phys. Med. Biol.* **52**, 4481–4496 (2007).