Published in final edited form as:

Phys Med Biol. 2012 June 21; 57(12): 3785–3792. doi:10.1088/0031-9155/57/12/3785.

Monte Carlo study of radial energy deposition from primary and secondary particles for narrow and large proton beamlet source models

Christopher R. Peeler^{1,2} and Uwe Titt²

¹The University of Texas Graduate School of Biomedical Sciences at Houston, 6767 Bertner Avenue, S3.8344, Houston, TX 77030, USA

²Department of Radiation Physics, Unit 94, The University of Texas MD Anderson Cancer Center, 1515 Holcombe Boulevard, Houston, TX 77030, USA

Abstract

In spot-scanning intensity-modulated proton therapy, numerous unmodulated proton beam spots are delivered over a target volume to produce a prescribed dose distribution. To accurately model field size-dependent output factors for beam spots, the energy deposition at positions radial to the central axis of the beam must be characterized. In this study, we determined the difference in the central axis dose for spot-scanned fields that results from secondary particle doses by investigating energy deposition radial to the proton beam central axis resulting from primary protons and secondary particles for mathematical point source and distributed source models. The largest difference in the central axis dose from secondary particles resulting from the use of a mathematical point source and a distributed source model was approximately 0.43%. Thus, we conclude that the central axis dose for a spot-scanned field is effectively independent of the source model used to calculate the secondary particle dose.

Keywords

IMPT; spot scanning; secondary particles; proton therapy

1. Background

Proton therapy has traditionally been performed using passive scattering or uniform scanning techniques to produce uniform proton fields (Koehler *et al* 1977). These systems also use range-modulation techniques, including rotating range-modulator wheels, to create a spread-out Bragg peak, which can be used to deliver a dose that conforms to the shape of a tumor (Koehler *et al* 1975). Active beamlet scanning techniques, particularly intensity-modulated proton therapy (IMPT), improve on this method by using numerous individual beamlets so that the sum of all beam spot doses results in the prescribed target dose (Soukup *et al* 2005). These techniques are intended to improve dose distribution in the target while maximally sparing normal tissues.

To accurately and efficiently calculate IMPT dose, the dose distribution from individual beamlets must be specifically characterized, and much work has been done to develop accurate dose calculation models for the primary proton component of dose (Hong *et al*

2006, Kirmstrand *et al* 2007, Petti 1992, Pedroni *et al* 2005, Russell *et al* 2000, Schaffner 2008, Syzmanowski and Oelfke 2002). Because of long-range (on the order of 2–12 cm radial distance) dose depositions from secondary particles, the dose at any location is field size dependent. The dose deposition of individual beam spots in scanned beamlet systems has previously been experimentally characterized, and the presence of a low-dose envelope was shown to affect proton beam output up to field sizes of $20 \times 20 \text{ cm}^2$ (Sawakuchi *et al* 2010c, Pedroni *et al* 2005). The major contributor to this low dose envelope is secondary nuclear particles created in the target medium, particularly for higher primary proton energies (Sawakuchi *et al* 2010b). Accurate proton dose computation algorithms clearly need to distinguish between dose contributions from primary and secondary particles.

The geometric distribution of primary protons is significantly affected by many parameters, including the source-to-surface distance (SSD) and the media that the protons traverse before reaching the target, which influences the width of the proton beamlet spot at the target. To accurately account for primary proton dose in semi-empirical dose calculations, many characteristics, including the SSD, must be incorporated into the calculation.

The dose distributions from secondary particles are similarly affected. However, it is not clear how much these changes affect the total dose. An analysis of secondary particle energy deposition would help determine whether such treatment is also necessary to properly incorporate this dose into new and improved dose calculation algorithms. The tool with which this study may best be accomplished is Monte Carlo (MC) simulations.

In this study, we determined the characteristic shape of radial dose deposition from primary and secondary particles in individual proton beamlets. Furthermore, we quantified possible variations in central axis (CAX) doses of two-dimensional proton fields on the basis of changes in dose distributions from secondary particles caused by variations in the full width at half-maximum (FWHM) of the proton beamlet incident on a water phantom. This two source approach was applied to the full model for the purposes of our calculations.

The source models selected for the study were a mathematical point source and a distributed source that was based on the specific characteristics of the spot-scanning system beamlets used at our institution. Both sources were located about 324 cm from the upstream surface of a water phantom. Radial energy deposition profiles at multiple depths in a water phantom were evaluated for two initial proton beam energies, 148.8 MeV and 221.8 MeV. Note that the energy deposition per cm^3 per particle in water corresponds to the dose in water per particle, assuming a water mass density of 1 g cm^{-3} .

2. Materials and Methods

2.1 Monte Carlo model and parameters

We used the MC model of the MD Anderson Cancer Center (Houston, Texas) spot-scanning proton beam nozzle developed by Sawakuchi *et al* (Sawakuchi *et al* 2010a). It contains a beam profile monitor, which consists of an ionization chamber with thin wires to record the spatial distribution of ionization around the beams path, followed by a long helium chamber at atmospheric pressure to minimize scattering. Subsequently a set of ionization chambers used as monitor chambers are found, followed by another wire chamber, acting as a spot position monitor. The exact specifications of the equipment cannot be disclosed as they are the property of Hitachi, Ltd., Tokyo, Japan. Proton beam simulations were conducted using MCNPX (Waters *et al* 2005) version 2.6, which incorporates the multiple coulomb scattering model (Moliere 1948) implemented by Stankovskiy *et al.*, with previously determined parameters (Kuhn and Dodge 1992). Basic input parameters that characterize individual Proton Therapy Center-Houston (PTCH) spot-scanning beams were determined

during commissioning of the system (Gillin *et al* 2009) and have been implemented in the MC model. For all simulations, protons, neutrons, photons, deuterons, and alphas were transported with cut-off energies set to the minimum values, which were 0 MeV for neutrons and 0.001 MeV for other particles. The default MCNPX physics model that uses Bertini's intranuclear cascade treatment (Bertini 1963, 1969) was used for particle transport.

Two source definition types were used for this study: a mathematical (i.e., zero-dimensional) pencil beam source and a distributed source. The proton beam phase space for the distributed source at the nozzle entrance was approximated in the simulations using Gaussian profiles in the X and Y dimensions with a mean FWHM value of in-plane and cross-plane distributions.

Proton beam sources were simulated for energies of 148.8 and 221.8 MeV, corresponding to maximum ranges in water of 15.2 cm and 30.6 cm, respectively. The sources were defined at a Z -axis position of +324.1 cm, with protons directed in the negative Z direction through the spot-scanning nozzle model. The parameters for the definition of the distributed source with a mean energy of 148.8 MeV were as follows:

- Gaussian energy spectrum with FWHM = 0.223 MeV and mean energy = 148.8 MeV.
- Gaussian distribution (at the source location) of position coordinates in X and Y with FWHM = 0.93 cm and mean value = 0.

This source specification results in a FWHM of 1.72 cm at the surface of a water phantom at the isocenter. The parameters for the definition of the distributed source with a mean energy of 221.8 MeV were as follows:

- Gaussian energy spectrum with FWHM = 0.333 MeV and mean energy = 221.8 MeV.
- Gaussian distribution (at the source location) of position coordinates in X and Y with FWHM = 0.675 cm and mean value = 0.

This source definition results in a FWHM of 1.18 cm at the surface of a water phantom at the isocenter. The mathematical zero-dimensional source was defined with X and Y position coordinates of 0. The source protons were defined as having Gaussian energy spectra with the same parameters as the distributed sources. The mathematical zero-dimensional source definition resulted in FWHMs of 1.40 cm and 0.96 cm at the surface of a water phantom at the isocenter for 148.8 MeV and 221.8 MeV source protons, respectively.

2.2 Calculation of Energy Deposition from Primary and Secondary Particles

Data for each simulation were collected using a cylindrical mesh tally in which energy deposition was scored starting at the upstream surface of a water phantom, located at the isocenter, to a depth of 35.0 cm, with a resolution of 0.1 cm in the beam direction. The tally radius was defined as 20 cm with 0.1-cm bins, with the Z -axis (the central beam axis) as the central axis of the tally. The angular definition was set to 360 degrees. This type of tally was possible because of the use of a symmetric source definition, as energy would be deposited symmetrically in the water phantom and energy deposition data could be collected in the concentric, cylindrical bins of the tally. This resulted in shorter calculation time than that required to collect data in a rectangular mesh grid tally, which has many more bins. It also allowed for the extraction of radial energy deposition data at specific depths from completed simulations.

Two simulations were performed for each combination of energy and source model. One simulation was conducted to collect total energy deposition data. For the second simulation,

secondary particle biasing was used to “turn off” the tracking of all secondary nuclear species. This simulation provided data for energy deposition resulting from primary protons only and could be subtracted from the total energy deposition data set to determine the energy deposition resulting from secondary particles only. Each simulation was terminated after 1×10^7 protons had been transported. This number was chosen to provide a maximum local relative uncertainty in energy deposition of less than 3% in the radial bins of the mesh tally at a radial distance of 20 cm. Geometric particle splitting, a variance reduction technique, was used inside the water phantom (Hendricks and Booth, 1985). MC simulations were carried out on 80 quad-core CPUs with 2.3 GHz processor speed of a Linux computing cluster and required approximately 57,000 minutes of total CPU time for the highest energy simulated, 221.8 MeV.

2.3 Calculation of Integral Depth Dose for Primary and Secondary Particles

To determine the depth in the water phantom where the influence of secondary particles was highest, we determined the integral depth doses (IDDs) of the secondary particle doses by summation over the radial dose distributions for each depth. This was carried out using a cylindrical mesh tally in which energy deposition was scored from the surface of the water phantom to a depth of 50 cm, with one bin of radius 20.0 cm. IDD_s were obtained for total energy deposition and energy deposition from primary protons only; this was then subtracted from the total to obtain the IDD_s for only the secondary particles.

2.4 Calculation of CAX Dose for Various Field Sizes

To estimate the variations in CAX dose when the secondary dose contribution was taken from the distributed source or the point source, we computed the total CAX dose. Dose was calculated at a depth of 6.5 cm for 148.8 MeV protons and 14.5 cm for 221.8 MeV protons. For a set of rectangular field sizes (2×2 , 5×5 , 10×10 , and 20×20 cm²) organized such that the centers of adjacent beam spots formed a cross pattern, the contribution of each spot to the CAX dose was computed from the primary dose profiles and respective secondary dose profiles. A summation was performed over all spots in the field, assuming a center-to-center spot distance of 0.5 cm.

3. Results

IDD profiles calculated for distributed sources for both source proton energies are shown in Figure 1. The IDD profiles were analyzed to determine the appropriate depth for radial dose profile analysis. In keeping with performing a “worst-case scenario” calculation of differences in CAX dose resulting from the use of different source models, we extracted radial dose profiles at the depth with the largest secondary particle contribution to the total dose for each respective energy. Figure 2a and Figure 2c show plots of absolute radial energy deposition for the mathematical pencil beam source and distributed beam proton source models, with 148.8 MeV source protons at a depth of 6.5 cm and 221.8 MeV source protons at a depth of 14.5 cm in a water phantom, respectively. Radial energy deposition from secondary particles is shown, in addition to total energy deposition and primary particle contribution.

Figure 2b and Figure 2d show the differences in secondary particle radial energy deposition between the point source and distributed source models for the respective simulated proton energies. The largest differences between the two models were found near the CAX of the simulated beamlets and decreased rapidly for increasing radial distances. Beyond a radial distance of 1 cm, the differences between the two models fell below 10^{-3} MeV cm⁻³ h⁻¹.

Table 1 illustrates the contribution of secondary particle energy deposition, calculated with the point source and distributed source models, to the CAX distributed source energy deposition for simulated spot-scanned fields. This analysis was performed for data at a depth of 6.5 cm for 148.8 MeV source protons and 14.5 cm for 221.8 MeV source protons. Values are presented as a percentage of the total energy deposition on the CAX. The largest difference in CAX dose between the two source models occurred for 221.8 MeV source protons for the smallest field size, $2 \times 2 \text{ cm}^2$, where the difference was approximately 0.43%.

4. Discussion and Conclusions

The results of our analysis of MC simulations demonstrate that the shapes of radial energy deposition profiles for secondary particles do not differ substantially between the mathematical point source and distributed source models. Most importantly, the calculation of CAX energy deposition for varying spot-scanned field sizes revealed that the end result differed by a fraction of a percent when the more simplistic mathematical point source model was used to calculate the secondary particle energy deposition.

The largest difference between the two models occurred for 221.8 MeV protons in a $2 \times 2 \text{ cm}^2$ field size, but this can be readily explained by the nature of the secondary particle energy deposition for that energy. Because the differences in secondary particle energy deposition between the two models were largest near the CAX of the beamlets, the total CAX doses for the two models exhibited the largest discrepancy in the smallest field size because many of the beamlets distant to the CAX for a $2 \times 2 \text{ cm}^2$ field are within 1 cm of the CAX. This difference was further compounded by the secondary particle energy deposition contributing a larger percentage of the total energy deposition for 221.8 MeV source protons than for 148.8 MeV source protons. The results indicate that secondary particles' contribution to dose is not dependent on the FWHM of the simulated beamlet and, therefore, independent of the source model employed.

A limitation that can be indicated for this study is the lack of analysis of CAX dose for a wide spectrum of energies, as the energies of the PTCH system span from 72.5 MeV to 221.8 MeV; however, secondary nuclear species contribute little to dose distributions for energies in the lower end of this spectrum and would thus have little effect on CAX dose for spot-scanned fields. It is also important to note that data collected in the bins used in Monte Carlo calculations represent integral values as the bins have a finite size. The energy deposition information presented, therefore, does not represent exact energy deposition at a point. Strengths of the study include the accuracy of the calculated data, which was made possible by the defined geometry, and the use of the PTCH spot-scanning nozzle model, which allows the results to be easily translated to future studies of the dose distributions produced by the system.

Our results demonstrate that the secondary particle dose resulting from IMPT beamlets need only be calculated once with a simple mathematical point source model for each of the available energies to properly incorporate the secondary particle contribution into the dose calculation for simple phantoms. In our future studies, we will focus on investigating the contribution of secondary particles to dose for more complicated geometries and integrating this information into a numerical algorithm that can be used to more accurately and efficiently determine doses for IMPT.

Acknowledgments

This research is supported in part by NCI grant P01CA021239 and in part by The University of Texas Graduate School of Biomedical Sciences at Houston, UT Health Science Center.

References

- Bertini HW. Low-energy intranuclear cascade calculation. *Physical Review*. 1963; 131:1801–1821.
- Bertini HW. Intranuclear-cascade calculation of the secondary nucleon spectra from nucleon-nucleus interactions in the energy range 340 to 2900 MeV and comparisons with experiment. *Physical Review*. 1969; 188:1711–1730.
- Gillin MT, Sahoo N, Bues M, Ciangaru G, Sawakuchi G, Poenisch F, Arjomandy B, Martin C, Titt U, Suzuki K, Smith AR, Zhu XR. Commissioning of the discrete spot scanning proton beam delivery system at the University of Texas M.D. Anderson Cancer Center, Proton Therapy Center, Houston. *Med. Phys.* 37:154–163. [PubMed: 20175477]
- Hendricks, JS.; Booth, TE. Monte-Carlo Methods and Applications in Neutronics, Photonics and Statistical Physics. Berlin: Springer; 1985.
- Hong L, Goitein M, Buccolini M, Comiskey R, Gottschalk B, Rosenthal S, serago C, Urie M. A pencil beam algorithm for proton dose calculations. *Phys. Med. Biol.* 1996; 41:1305–1330. [PubMed: 8858722]
- Kirmstrand P, Traneus E, Ahnesjo A, Grusell E, Glimelius B, Tilly N. A beam source model for scanned proton beams. *Phys. Med. Biol.* 2007; 52:3151–3168. [PubMed: 17505095]
- Koehler AM, Schneider RJ, Sisterson JM. Range modulators for protons and heavy ions. *Nuclear Instruments and Methods*. 1975; 131:437–440.
- Koehler AM, Schneider RJ, Sisterson JM. Flattening of proton dose distributions for large field radiotherapy. *Med. Phys.* 1977; 4:297–301. [PubMed: 407436]
- Kuhn SE, Dodge GE. A fast algorithm for Monte Carlo simulations of multiple Coulomb scattering. *Nuclear Inst. and Methods in Physics Research, A*. 1992; 322:88–92.
- Moliere G. Theorie der Streuung schneller geladener Teilchen II. Mehrfach und Vierfachstreuung. *Z. Naturforsch.* 1948; 3a:78–97.
- Pedroni E, Scheib S, Bohringer T, Coray A, Grossmann M, Lin S, Lomax A. Experimental characterization and physical modelling of the dose distribution of scanned proton pencil beams. *Phys. Med. Biol.* 2005; 50:541–561. [PubMed: 15773729]
- Petti P. Differential-pencil-beam dose calculations for charged particles. *Med. Phys.* 1992; 19:137–149. [PubMed: 1320182]
- Russell KR, Isacson U, Saxner M, Ahesjoe A, Montelius A, Grusell E, Dahlgren CV, Lorin S, Glimelius B. Implementation of pencil kernel and depth penetration algorithms for treatment planning of proton beams. *Phys. Med. Biol.* 2000; 45:9–27. [PubMed: 10661580]
- Sawakuchi GO, Mirkovic D, Perles LA, Sahoo N, Zhu XR, Ciangaru G, Suzuki K, Gillin MT, Mohan R, Titt U. An MCNPX Monte Carlo model of a discrete spot scanning proton beam therapy nozzle. *Med. Phys.* 2010a; 37:4960–4970. [PubMed: 20964215]
- Sawakuchi GO, Titt U, Mirkovic D, Ciangaru G, Zhu XR, Sahoo N, Gillin MT, Mohan R. Monte Carlo investigation of the low-dose envelope from scanned proton pencil beams. *Phys. Med. Biol.* 2010b; 55:711–721. [PubMed: 20071752]
- Sawakuchi GO, Zhu XR, Poenisch F, Suzuki K, Ciangaru G, Titt U, Anand A, Mohan R, Gillin MT, Sahoo N. Experimental characterization of the low-dose envelope of spot scanning proton beams. *Phys. Med. Biol.* 2010c; 55:3467–3478. [PubMed: 20508318]
- Schaffner B. Proton dose calculation based on in-air fluence measurements. *Phys. Med. Biol.* 2008; 53:1545–1562. [PubMed: 18367787]
- Soukup M, Fippel M, Alber M. A pencil beam algorithm for intensity modulated proton therapy derived from Monte Carlo simulations. *Phys. Med. Biol.* 2005; 50:5089–5104. [PubMed: 16237243]
- Szymanowski H, Oelfke U. Two-dimensional pencil beam scaling: an improved proton dose algorithm for heterogeneous media. *Phys. Med. Biol.* 2002; 47:3313–3330. [PubMed: 12375823]
- Waters, LS.; Hendricks, J.; McKinney, G. MCNPX. Los Alamos, NM: Los Alamos National Laboratory; 2005.

Figure 1.

Plots of integral depth doses from primary and secondary particles for 148.8 and 221.8 MeV source protons for a distributed source model. Energy deposition is in units of MeV per cubic centimeter per source proton.

Figure 2.

Plots of radial energy deposition from primary and secondary particles for a mathematical point source and distributed beam source for primary proton energies of 148.8 MeV (a) at a depth of 6.5 cm and 221.8 MeV (c) at a depth of 14.5 cm. Plots of differences between the secondary particle energy deposition for point and distributed sources (b) and (d) for the respective primary proton energies. Energy deposition is in units of MeV per cubic centimeter per source proton.

Contribution of secondary particle doses from point and distributed sources from all beam spots in a spread out field to the total central axis dose calculated with the distributed source primary particle dose (%) at the depth of maximum impact

Table 1

Field Size (cm ²)	E _p = 148.8 MeV			E _p = 221.8 MeV		
	Pt. Src. Sec.	Distr. Src. Sec.	Difference	Pt. Src. Sec.	Distr. Src. Sec.	Difference
2 × 2	2.544	2.210	0.334	6.980	6.546	0.434
5 × 5	2.858	2.782	0.077	10.527	10.411	0.116
10 × 10	2.971	2.963	0.007	14.291	14.243	0.048
20 × 20	3.075	3.071	0.003	16.290	16.277	0.013