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A beam model for focused proton pencil beams

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ABSTRACT

Introduction: We present a beam model for Monte Carlo simulations of the IBA pencil beam scanning dedicated nozzle installed at the Skandion Clinic. Within the nozzle, apart from entrance and exit windows and the two ion chambers, the beam traverses vacuum, allowing for a beam that is convergent downstream of the nozzle exit.
Materials and methods: We model the angular, spatial and energy distributions of the beam phase space at the nozzle exit with single Gaussians, controlled by seven energy dependent parameters. The parameters were determined from measured profiles and depth dose distributions. Verification of the beam model was done by comparing measured and GATE acquired relative dose distributions, using plan specific log files from the machine to specify beam spot positions and energy.
Results: GATE-based simulations with the acquired beam model could accurately reproduce the measured data. The gamma index analysis comparing simulated and measured dose distributions resulted in > 95% global gamma index pass rates (3%/2 mm) for all depths.
Conclusion: The developed beam model was found to be sufficiently accurate for use with GATE e.g. for applications in quality assurance (QA) or patient motion studies with the IBA pencil beam scanning dedicated nozzles.

1. Introduction

A current trend in proton therapy is to use pencil beam scanning (PBS) technology; data collected by the Particle Therapy Co-Operative Group (PTCOG) indicate that the majority of proton therapy sites constructed after 2010 are either PBS capable only, or both PBS and passive scattering capable[1]. The PBS technique relies on magnets to scan the beam laterally in order to “paint” the desired dose distribution. Depth modulation is performed by changing the protons’ kinetic energy. Treatment beam specifications are transferred to the treatment machine as a list of spots, each spot having a position, weight in terms of monitor units (MU), and kinetic energy. The weight of each spot in a treatment plan is optimized, allowing for greater target conformality than what is possible with the passive scattering technique [2,3].

The Swedish national proton therapy facility, the Skandion Clinic, became clinically operational in 2015. It uses an IBA PBS dedicated nozzle with vacuum separating its two monitoring ionization chambers (see Fig. 1). The overall water equivalent thickness (WET) of the nozzle is on the order of 2 mm. The protons are accelerated in a cyclotron to a fixed energy and then modulated by an energy selection system (ESS). The ESS includes an absorber, known as a degrader, to reduce the proton kinetic energy to the specified kinetic energy. The resultant mean kinetic energy in air at isocenter can then be varied from 60 to 226 MeV. Due to energy straggling in the degrader, the emergent protons will have a distribution of energies, the variance of which is reduced by means of dipole magnets with narrow momentum selection slits.

This paper describes the design and validation of a beam model for use with Monte Carlo (MC) simulations. The MC method is a powerful tool to study many aspects of proton dose delivery, e.g. for quality assurance [4] and for studying the effects of patient motion [5]. To effectively deploy MC for these applications, a beam model is necessary. Our primary use case for the proposed beam model is dose calculations in water phantoms and patients.

At the Skandion Clinic, the proton pencil beam is convergent, i.e. its spot size initially decreases with propagation after the nozzle exit. The position of the beam waist, or the effective extended source, is located downstream of the nozzle exit but upstream of the isocenter plane for most energies at the Skandion Clinic.

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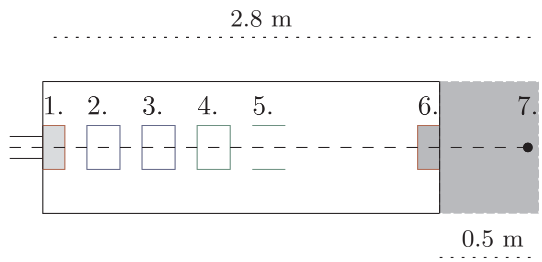

Fig. 1. Schematic layout (not to scale) of the IBA PBS dedicated nozzle at Skandion. At the nozzle entrance is IC1, an ionization chamber (**1**). Some distance downstream are two quadrupole magnets (**2** and **3**). These are followed by the two scanning dipole magnets (**4** and **5**). Just before the nozzle exit is IC2/3 (**6**), housing the primary and secondary monitor chambers. Fifty centimeters downstream of the nozzle exit is the isocenter (**7**). The white background indicates regions where the beam passes through vacuum, and the shaded areas where it passes through matter (air, water phantom, patient).

2. Material and methods

In line with earlier work by [6], the proton phase space at the nozzle exit is specified using seven energy-dependent parameters: spot size, angular spread and emittance for the lateral dimensions x and y, and energy spread. The spot size, angular spread and energy spread parameters are defined as single standard deviations of Gaussian distributions. This effectively means that the halo generated by occasional large angle scattering events in the nozzle is neglected and assumed not to reach the patient/phantom in any significant amount. This has proven successful for a similar beam line [6,7]. Any large angle scattering events downstream of the nozzle will be included in the MC transport for patient/phantom dose calculations.

For all simulations for this paper, we used the GATE code, which uses Geant4 for particle transport. GATE has tools for medical imaging and radiotherapy [8]. Geant4 is a general purpose simulation library for particle physics simulations [9]. GATE version 8.0 was used, compiled with Geant4.10.3.

We quantify the radial extent of a pencil beam in terms of a Gaussian standard deviation, referred to as the spot size. The spot size for pencil beams may thus be determined by fitting a 2D-Gaussian to measured beam profiles. Supposing a Cartesian (x, y, z) coordinate system where the x and y axes define the lateral plane and the z axis is along the proton central beam axis, a 2D Gaussian may be expressed as

$$G(x, y) = Ae^{-\frac{\frac{(x-x_0)^2}{2\sigma_x^2}+\frac{(y-y_0)^2}{2\sigma_y^2}-\frac{\rho(x-x_0)(y-y_0)}{\sigma_x\sigma_y}}{1-\rho^2}} \quad (1)$$

where A is the amplitude of the Gaussian at its center coordinate (x_0, y_0), σ_x and σ_y are the standard deviations in x and y respectively, and ρ is the correlation coefficient. If $\rho \neq 0$, the principal axes of an isocontour of Eq. (1) will not coincide with the x and y axes. To keep the model simple, we assumed $\rho = 0$, by which Eq. (1) reduces to

$$G(x, y) = Ae^{-\frac{(x-x_0)^2}{2\sigma_x^2}-\frac{(y-y_0)^2}{2\sigma_y^2}} \quad (2)$$

All spot sizes in this paper are thus the resultant σ_x and σ_y from beam profile fits to Eq. (2). Due to differing angular and spatial distributions in x and y, in general $\sigma_x \neq \sigma_y$ at any z. We define $z = 0$ as the nozzle exit.

2.1. Measurements

Lateral beam profile data were measured with the Lynx (IBA Dosimetry), which consists of a fluorescent screen, a CCD camera and a mirror. The Lynx produces images with 600 × 600 pixels of size 0.5 mm in both directions. Beam profiles were recorded in air at (−19, −10, 0, +10, +20) cm from the isocenter (negative sign means upstream of the isocenter), for 18 energies ranging from 60 to 226 MeV. In addition the spot size data recorded by IC2/3 (see Fig. 1) were extracted from the delivery system's log files. Following [6], the uncertainty for the spot sizes based on Lynx measurements were estimated to be within 0.1 mm for all energies, with the uncertainty for IC2/3 was estimated to be within 0.5 mm.

To obtain the energy parameters, measured depth dose distributions in water served as a basis. Measurements were carried out for 34 energies in the 60–226 MeV interval with the plane parallel PTW 34070 ionization chamber that has a diameter of 8.2 cm.

2.2. Modeling the energy parameters

Unless otherwise stated, by range we mean projected range, defined as the mean distance from a proton's starting point until it comes to a stop, having only undergone electromagnetic interactions and projected along beam central axis. A measurable surrogate for the mean projected range is the distal 80% dose point of a depth dose curve [10]. To obtain a sense of the error made by using the surrogate, relative depth fluence distributions were generated in Geant4. The resultant distributions were multiplied with collisional stopping power, yielding depth dose curves with deviations of at most 0.11 mm between the distal 80% and the corresponding mean projected range for 34 energies in the 60–226 MeV interval. An example is shown in Fig. 2.

Since we intend to use a phase space specification at the nozzle exit as the starting point for our MC simulations, it is necessary to find the mean beam energy at this point. We did this by generating depth dose curves in GATE, starting particle transport 54 cm upstream of the scoring volume. The initial mean beam energy was varied to find the mean energy that minimizes the difference between the obtained simulated distal 80% range and the measured equivalent. This was done assuming the distal 80% range is insensitive to the energy distribution. Since the log files only provide nominal ranges at the nozzle entrance, it is necessary to convert these to energies at the nozzle exit. This was solved by not-a-knot cubic spline interpolation (see e.g. [11]) of the determined energy at the nozzle exit as a function of the ranges in the log files.

We obtained the energy spread from the distal 80% range, the relative range deviation between the measured and simulated proximal 50%, 60% and 70% depths were used. We also computed an average relative deviation in the plateau region, defined as the region of the depth dose distribution up until the proximal 30%. The absolute values of the deviations were used as an objective function for optimization of the energy spread.

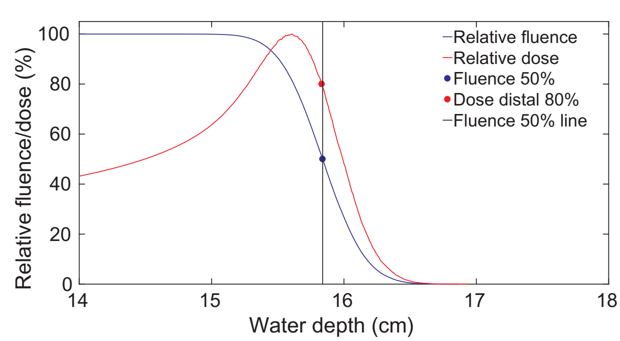

Fig. 2. (Red) A 150 MeV proton dose depth curve, with an energy spread calculated using the method described in Section 2.2. (Blue) A relative depth fluence distribution of a proton beam with the same incident energy spread as the depth dose curve. The projected range can be seen to correspond closely to the distal 80% dose point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)