The Proton Therapy Nozzles at Samsung Medical Center:  
A Monte Carlo Simulation Study using TOPAS

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Abstract

To expedite the commissioning process of the proton therapy system at Samsung Medical Center (SMC), we have developed a Monte Carlo simulation model of the proton therapy nozzles using TOPAS. At SMC proton therapy center, we have two gantry rooms with different types of nozzles; a multi-purpose nozzle and a dedicated scanning nozzle. Each nozzle has been modeled in detail following the geometry information provided by the manufacturer, Sumitomo Heavy Industries, Ltd. For this purpose, novel features of TOPAS, such as the time feature or the ridge filter class, have been used. And the appropriate physics models for proton nozzle simulation were defined. Dosimetric properties, like percent depth dose curve, spread-out Bragg peak (SOBP), beam spot size, have been simulated and verified against measured beam data.

Beyond the Monte Carlo nozzle modeling, we have developed an interface between TOPAS and the treatment planning system (TPS), RayStation. An exported RT plan data from the TPS has been interpreted by the interface and then translated into the TOPAS input text.

The developed Monte Carlo nozzle model can be used to estimate non-beam performance of the nozzles such as the neutron background. Furthermore, the nozzle model can be used to study mechanical optimization in the design of the nozzle.

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I. INTRODUCTION

The ultimate goal of radiation therapy is to deliver high tumor dose while minimizing dose to the surrounding healthy tissue. Since the first insight of using fast protons in radiotherapy by R. Wilson in 1946 [1], the physical characteristics of the Bragg curve have been well studied as distinct dosimetric advantages of protons; reduced integral dose and improved target volume coverage. The reduced integral dose can be achieved due to the fact that there is no exit dose and the highly conformal target volume coverage can be achieved by the improved geometric control of distal fall-off. At the same time, the sharp dose fall-off demands higher accuracy, and thus the accurate patient set-up, imaging, dose calculation and quality assurance procedures are required in proton therapy.

In general, Monte Carlo dose calculations are more accurate than analytical dose computation methods. Therefore, the Monte Carlo methods become important in proton therapy to achieve the most accurate dose calculation. And Monte Carlo methods can be used in the study of particle fluence as well. The verification of analytical dose calculation models, estimation of relative biological effectiveness (RBE) in-patient, neutron dose estimation, and calculation of neutron shielding would be the typical Monte Carlo application in proton therapy.

At the Proton Therapy Center at SMC, two different types of nozzles have been installed: the multi-purpose nozzle and the dedicated scanning nozzle. The multi-purpose nozzle can deliver proton beams either in passive scattering mode or pencil beam scanning mode. The other treatment nozzle is dedicated to pencil beam scanning only with an extended vacuum pipe in the downstream of the nozzle. The commissioning of the treatment nozzles will demand numerous sets of measurements. Especially for the wobbling mode, there are various options with different combinations of nozzle elements to generate SOBPs. Thus the measurements will consume extensive resources.

Although measurements are the solid basis of commissioning, Monte Carlo simulations can play an important role. The main purpose of this project is to build a Monte Carlo model of the treatment nozzles to expedite the commissioning process, which requires substantial amount of resources, and to support technical developments and clinical operation.
II. EXPERIMENTS AND DISCUSSION

A. Monte Carlo simulation

We have used TOPAS to build Monte Carlo model of the treatment nozzles. TOPAS, which stands for TOol for PArticle Simulation [2], is a Geant4 application mainly developed for the Monte Carlo simulation of particle therapy nozzles including proton therapy nozzles. Geant4 is a framework for simulating the fundamental physical process along the passage of particles through matter [3]. It is a well-proven toolkit and it has not only flexibility but also includes a complete range of functionality, like tracking, geometry, physics models and hits. Especially the provided physics processes cover a comprehensive range. Furthermore, it is the result of a worldwide collaboration of physicists and software engineers.

TOPAS basically inherits all these merits of Geant4 with extended features like time feature [4] and user-friendly interface. We have used g4em-standard_opt3 with high-precision hadronic process physics models to include low energy neutron contribution more precisely.

B. The treatment nozzles at SMC

Two different types of nozzles have been installed at SMC, a multi-purpose nozzle (MPN) and a dedicated pencil beam-scanning nozzle (PBS). Both nozzles share most of the upstream nozzle elements, like, quadrupole magnets, scanning/wobbling magnets, and beam profile monitors as shown in Figure 1.

In the downstream, MPN has its own elements for passive scattering of proton beams; scatterers, ridge filters, and range compensators. On the other hand, PBS has an extended vacuum pipe to preserve the emittance of proton beams.

MPN has two different operation modes; a wobbling mode and a scanning mode. In wobbling mode, the two dipole magnets are used with a 90° phase shift to make a circular trajectory (wobbling) on scatterers which is perpendicular to the beam propagation. After then, in order to generate SOBP, proton beams pass through the ridge filter after passing scatterers. Finally, the multi-leaf collimator (MLC) or the aperture, and compensator shape the lateral and distal edges of the proton beams. For scanning mode, the two dipole magnets are used to control proton beams in x and y direction, and scatterers and ridge filters are withdrawn from the proton beam path. One of the special features in MPN is the MLC.
FIG. 1: (Color online) The diagram of the proton therapy nozzles at SMC: the multi-purpose nozzle (top) and the dedicated scanning nozzle (bottom). From the upstream, there is a pair of quadrupole magnets for focusing and a pair of scanning magnets for wobbling or scanning. Note that the beam modulation components of the multi-purpose nozzle have been replaced by an extended vacuum pipe in the dedicated scanning nozzle.

Even though MLC is an essential part of modern photon radiotherapy, there are only a few proton centers having MLC equipped in their proton therapy nozzles. In MPN at SMC, MLC is made of brass and the leaf thickness of MLC was designed to be thick enough to stop 230 MeV proton beam.

PBS nozzle is dedicated to pencil beam-scanning mode and provide a larger radiation field size (up to 30 cm x 40 cm). In the downstream, an extended vacuum pipe is equipped to maintain a sharp penumbra by suppressing in-air-scattering of proton beam.

Both in MPN and PBS, the scanning beam is delivered via continuous line scanning with an optional use of patient collimators.
FIG. 2: (Color online) The OpenGL visualization of the TOPAS model of proton therapy nozzles at SMC; the multi-purpose nozzle (left) and the dedicated scanning nozzle (right).

C. Simulation of the nozzles

Each nozzle element in both nozzles was modeled with sub millimeter accuracy following the detailed information from Sumitomo Heavy Industries, Ltd. as shown in Figure 2.

The MC modules of the common proton nozzle elements, like quadrupole magnets, dipole magnets have been provided by TOPAS. For the site-specific elements such as ridge filters and MLC, SMC has developed corresponding module classes and made contribution to TOPAS. In order to simulate wobbling motion, the magnetic field strength of two dipole magnets (wobbling magnets) has been varied during the simulation using the time feature of TOPAS. The magnetic field strength of each dipole has been varied and the proton beam center deviation at the isocenter plane has been determined. The linear fit result is used to simulate an arbitrary wobbling radius as shown in Figure 3.

The combinations of scatterer thickness and wobbling radius need to be determined to generate a uniform proton radiation field. The beam size should also be a parameter to determine the condition. Using TOPAS, we could make possible combinations of parameters with reasonably uniform radiation field. Total scatterer thickness is variable with resolution of 0.1 mm by the combination of 7 scatterers. The beam spot size with different thickness of scatterer has been simulated.

The simulated spot size has been used to determine wobbling radius as shown in Figure 4.
FIG. 3: (Color online) The relation between magnetic field strength of dipole magnets and the displacement at the isocenter plane.

FIG. 4: (Color online) The flat region around the center (left) is used to make a flat dose distribution. When the wobbling radius is too large (right), the dose distribution around the center is distorted.

By assuming a single Gaussian distribution, the wobbling radius can be easily estimated analytically. It is known that there is non-negligible contribution of long-range scattering protons in a medium and thus a single Gaussian function might fail to describe the exact dose profiles in a certain case [6], a single Gaussian function was enough for the purpose of
determining radii. When the wobbling radius is optimized, a possible flat central region will limit the maximum field size.

Even though the thicker scatterer would provide a larger flat region, at the same time, proton beam will lose more energy and thus end up with a shorter range. Therefore, there is always a trade-off between proton range and field size. The optimal combination of these parameters can be decided in Monte Carlo simulation. And we actually performed basic analysis using TOPAS as mentioned above.

As shown in Figure 5, the range-energy relations from the measured integrated depth dose curve of MPN have been compared with continuous slowing down approximation (CSDA) range [5]. They agree well and the data points are almost on top of each other except in the low energy region. From the difference between CSDA range and the measured range for a given nominal proton beam energy, the water equivalent thickness (WET) of the scanning nozzle can be decided.

D. RayStation-TOPAS interface

At SMC, RayStation (RaySearch Medical Laboratories AB, Stockholm, Sweden) is chosen as the treatment planning system (TPS) for proton therapy. RayStation provide a python based scripting function, in which users can not only simplify and customize the planning workflow but also directly interact with core algorithms. This opens a possibility of exporting the plan parameters in DICOM [7] RT plan in TPS and translate into TOPAS input text.
Ideally, one click of button on TPS screen would generate Monte Carlo simulation data using the plan parameters and patient CT images. At this moment, we have developed a Matlab GUI application, which reads in DICOM RT plan files and interprets plan parameters, like proton beam energy, gantry angle, spot position, etc., then the application generates TOPAS input text file based on the plan parameters.

We are currently working on a python GUI version of RayStation-TOPAS interface on RayStation python scripting environment. And we believe that a successful implementation will bring an one-click Monte Carlo simulation era.

III. CONCLUSIONS

We have modeled and simulated the two proton therapy nozzles at SMC using TOPAS. Each nozzle elements has been modeled in detail and various combinations of elements have been studied by examining dosimetric properties, like integrated depth dose curves and dose profiles. Using the modeled proton therapy nozzles, we will expand our study not only to dosimetric properties but also to design improvement, e.g., ridge filters, MLCs, etc. We will perform a validation with measured data and then use the MC simulation to interpolate/extrapolate the measured data. We believe the commissioning process of the proton therapy nozzles at SMC will be expedited by MC simulation. Furthermore, the RayStation-TOPAS interface will be a valuable tool to validate clinical cases via Monte Carlo simulation.

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