Monte Carlo Studies of a Proton Computed Tomography System

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Abstract—**Proton therapy is a precise forms of radiation therapy that makes use of high energy proton compared to the conventional, more commonly used and less precise x-ray and electron beams. On the other hand, to fully exploit the proton therapy advantages, very accurate quality controls of the treatments are required. These are mainly related to the dose calculations and treatment planning. Actually dose calculations are routinely performed on the basis of X-Ray computed tomography while a big improvement could be obtained with the direct use of protons as the imaging system.**

In this work we report the results of Monte Carlo simulations for the study of an imaging system based on the use of high energy protons: the proton Computed Tomography (pCT). The main limitation of the pCT and the current adopted technical solutions, based on the use of the Most Likely Path (MLP) approximation are illustrated. Simulation results are compared with experimental data obtained with a first prototype of pCT system tested with 200 MeV proton beams available at the Loma Linda University Medical Center (LLUMC) (CA).

Index Terms—**Computed tomography, GEANT4, Monte Carlo, proton.**

I. Introduction

PROTON beams have important advantages compared to other radiation treatment options. Thanks to their specific depth dose curve, when they penetrate inside matter (a relatively low entrance dose followed by a high-dose peak) they can deliver the prescribed dose precisely to the tumor mass, leaving surrounding healthy tissues almost undamaged.

On the other hand, a precise radiation modality requires very accurate Quality Assurance (QA) of the treatment procedures. In proton therapy QAs are mainly related to the patient positioning and to the dose calculations with a treatment planning software.

In existing proton treatment centers, positioning and dose calculations are currently based on x-ray radiographs and x-ray computed tomography (xCT), respectively. A new challenge, in the next years, will be the direct use of the proton beam for the tomographic imaging of the patient body developing a proton Computed Tomography (pCT) system. This will make the proton radiation procedure more precise by defining the position of the Bragg peak more accurately (enabling the verification of patient and tumor position with respect to the proton beam) and by permitting a direct measurements of the electron densities (and hence of the stopping powers values) of the involved tissues [1]. Stopping powers, today, are in fact indirectly derived from the conversion of the linear attenuation coefficients, measured with a conventional x-tomography of the patient. This conversion is not error free and can produce, in many cases, an uncertainty in the stopping power values and, consequently, in the calculated dose deposition [2].

Proton computed tomography is currently been investigated by several groups in the world. At present three scientific Institutes are involved in different pCT projects: the Paul Scherrer Institute (Switzerland) [2] the Loma Linda University Medical Center (LLUMC) in collaboration with the Santa Cruz Institute for Particle Physics (SCIPP) in US [1], [3] and a group composed of researchers by the National Institute for Nuclear Physics (section of Catania, Firenze and Laboratori Nazionali del Sud) and of University of Firenze.

The main task for any imaging system, especially if devoted to critical applications, like medical diagnostic or dose calculation in a radiation treatment, is to obtain images with sufficient contrast ($\leq 1\%$) and spatial (1 mm) resolutions. Recent works [1], [3] based on analytical methods and Monte Carlo simulations, demonstrated the possibility to obtain proton tomographies of good contrast resolution that could be manufactured as a working pCT prototype. On the other hand many limitations must be yet investigated. In this work we investigated the possibility to overcome pCT's most severe limitation: a poor spatial resolution due to the intrinsic presence of Multiple Coulomb Scattering (MCS). One possible solution for spatial resolution

Manuscript received October 26, 2006; revised February 12, 2007.

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Digital Object Identifier 10.1109/TNS.2007.906988

improvement, is the use of the so-called 'single tracking technique', whose principle is tracking each single proton as it enters and exits the imaged object [4]. In this paper we present a study aimed at verifying the single tracking approach, using the Monte Carlo method (with the GEANT4 [6] simulations toolkit). The results are compared to those obtained in an experimental measurement with a first prototype of a pCT system and with a semi-analytical approach [7]. The basic physic principles of a proton Computed Tomography system and its principal limitations are illustrated in Section I. The experimental prototype we tested and the Monte Carlo approach for the investigation of the single tracking is reported in Section II. Finally simulation results and their comparison with the experiment and the semi-analytical approach are shown and discussed in Sections III and IV.

II. pCT: Physical Principles and Main Limitations

The principle of pCT is based on the experimental determination of the weighted electron density η_e and stopping power path length making use of the single tracking method. For protons, in the energy range of interest in proton therapy (10 MeV–250 MeV), the stopping power S is well described by the Bethe and Bloch expression that may be written in the following form:

$$-\frac{dE(\vec{r})}{dx} = \eta_e(\vec{r}) S\left(I(\vec{r}), E(\vec{r})\right). \tag{1}$$

Here η_e is the relative electron density with respect to water, x indicates the position inside the medium, $I(\vec{r})$ the mean excitation potential of the material, which is considered constant in the following discussion ($I(\vec{r}) = \mathrm{I} = 75\,\mathrm{eV}$ for water [8]), $E(\vec{r})$ the proton energy and S the proton stopping power in water.

Starting from (1) a relation between the reciprocal of the stopping power and the electron density can be derived:

$$\int_{E_{in}}^{E_{out}} \frac{dE}{S(I_{mat}, E)} = \int_L \rho_e(r) dl. \tag{2}$$

The left side integral of (2) can be calculated if the incident and outgoing energies, of each proton traversing the medium, are known. The result is the projection of the weighted electron density along the proton path L (right side integral). The (2) is in the same format of the Radon transform in the straight line approximation. It, calculated for many different angles, will constitute the principal information for the tomographic reconstruction. Equation (2) will hence be the basis for the mathematical reconstruction of a proton imaging system. For the application of the single tracking methods, input and output energies and path of each proton traversing should be known in order to obtain the exact resolution of integral (2). In such a way, a real pCT system must be able to detect the position and the direction of each proton, before $(\vec{R}_i)$ and after $(\vec{R}_f)$ it traverses the object. Moreover a calorimeter should be used to measure the residual energy of protons (E_f).

Such a system, of course, cannot exactly predict the paths of the particles inside objects as they are affected by MCS. In order to overcome this obstacle and to derive the proton path with the best approximation, some analytical methods need to be developed. D.C. Williams [7], starting on the assumption of a completely gaussian distribution of scattering proton angles traversing a medium, proposed a semi-analytical approach able to predict the medium proton path (or Most Likely Path MLP) L_i if R_i, R_f and E_f are known. Once L_i is calculated, the integrals in the (2) can be simply solved and a pCT device realized in practice.

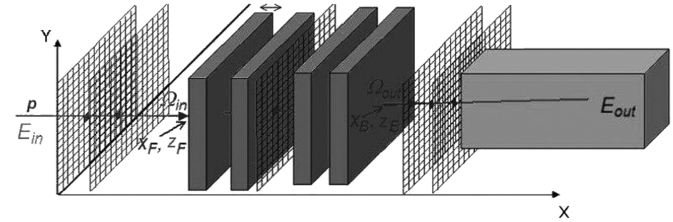

Fig. 1. The prototype of the proton CT tracking system tested at LLUMC.

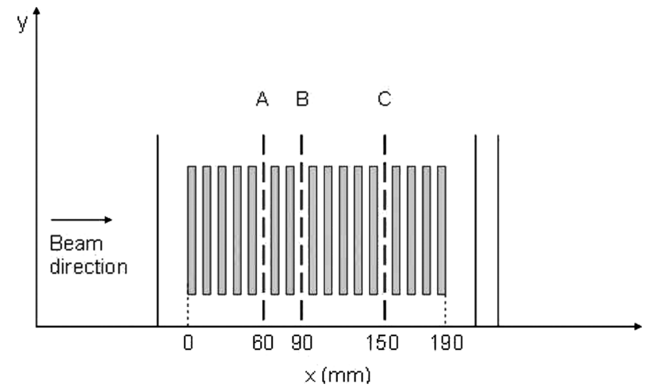

Fig. 2. A roving module is placed in three different position (set-up A, B and C) to measure the y coordinate and derive the MLP. Experimentally three beam run were carried out for each position of the roving module.

III. Approach of Study

A. Experimental Proton Tracking System

A beam experiment employing 200 MeV protons was performed at the LLUMC synchrotron. The proton beam exits in air through a titanium window 0.2 mm thick and reaches the first module of our tracking system after traversing 3.5 meters of air. Protons were tracked with silicon strip detectors used in the 1997 GLAST beam test [5]. In addition, a CsI calorimeter crystal provided energy measurement and a trigger for readout of the Si detector system. The set-up consisted of y-z silicon modules used as entrance and exit telescope, and a CsI calorimeter (Fig. 1).

The distance between the Si planes and the calorimeter was fixed during the runs. The set-up was flexible and allowed for insertion of 10 absorber plates (1.25 cm PMMA each) and a "roving" module whose position can be varied between the telescopes. For the experimental determination of MLPs it is necessary the determination of the y and z coordinate of each proton while it traverses the absorber (Fig. 2). The following basic configuration was used: one entrance y-z plane, a "roving plane" in

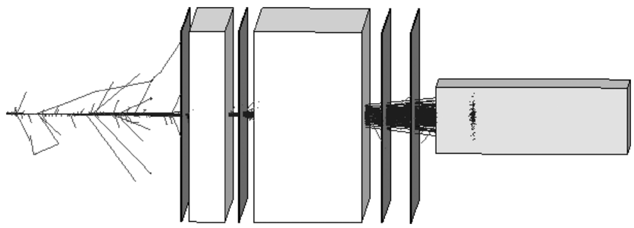

Fig. 3. The proton CT system as simulated with GEANT4.

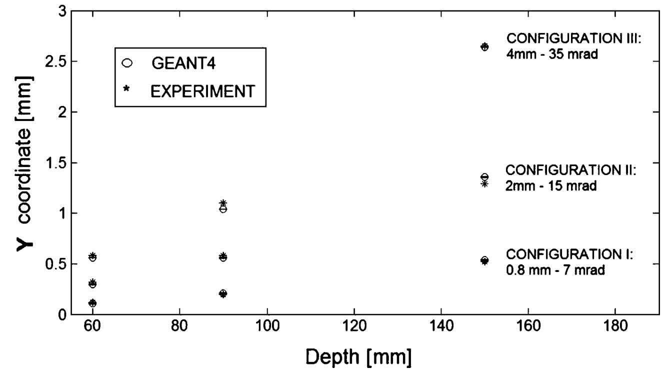

Fig. 4. Three most likely paths experimentally measured with the Loma Linda proton beam and derived from the GEANT4 simulations under the same conditions. Each point is affected by an error less than 0.45 mm.

the middle and two exit Si planes. In the latter configuration, data were taken both without absorber (to check the alignment), and with absorber to map out the MLP at different depths within the PMMA stack with the roving module. The roving module was moved in three different positions (60 mm, 90 mm and 150 mm depth of PMMA) corresponding to the set-up A, B and C. Fig. 2 shows the layout of the three set-ups.

Each set-up corresponds to a point of the measured MLP. The experimental system for the MLP determination permitted measuring only the entrance location but not the entrance angle of the proton. Since the MCS angle turned out to be much larger than the beam spread, this was, not a serious limitation [9].

B. Simulation of the Tracking System

The exact reconstruction of the final tract of the beam line and of the proton tracking system (Fig. 3) was carried out exploiting the capabilities of the GEANT4 Monte Carlo toolkit [6], [10]. A specific GEANT4 application was developed for this purpose starting from the Hadrontherapy [11], [12] example, developed by some of us and now freely available as advanced example inside the official GEANT4 release.

The LLUMC proton beam was simulated with a square spot with 2.5 mm. Its energy distribution is described with a gaussian centered on the 200 MeV nominal value and with FWHM of 35 keV. The three positions of the roving module (set-ups A, B and C) were simulated as was including the air gaps between the modules and the PMMA slices. The microstrips detectors (two per each module) are simulated as 4.5 $\times$ 4.5 cm silicon slices 0.5 mm in thickness. In order to reconstruct the medium proton path (MLP) the position and direction of each proton traversing the microstrips detectors are registered. In such a way the MLP can be reconstructed exactly in the same way as in the experiment. Fig. 3 represents a typical set-up used in the experiment as simulated by GEANT4. Protons and secondaries tracks traverse the five microstrips modules (dark gray) and the PMMA phantom (light gray). Finally the protons stop inside the calorimeter (on the right side of the whole system).

The physics models implemented are the ones already tested [11] in the Hadrontherapy example. Regarding the electromagnetic processes the LowEnergy package [14] and the MCS GEANT4 non-gaussian Multiple scattering model [15] were used. The hadronic processes as nucleon-nucleon elastic scattering and non-elastic interactions are also considered making use of the proton precompound Hadronic model associated with the GEM evaporation model [16], [17].

IV. RESULTS AND DISCUSSION

In this work our attention was concentrated on the analysis of three different MLPs, each calculated in correspondence of a defined entrance and exit proton direction and position. We set an unique entrance position and direction, 0 mm and 0 rad. We have chosen three different exit point 0.8 mm and 7 mrad (configuration I), 2 mm and 15 mrad (configuration II) and 4 mm and 35 mrad (configuration III). The uncertainties on positions and angles, taking into consideration the experimental set-up, are respectively $\pm$0.2 mm and $\pm$2.5 mrad. The angles we chosen are those measured with our experimental set-up at the corresponding exit points. The three proton paths were experimentally measured and derived both from analytical calculations (following the Williams' theory [7]) and from Monte Carlo simulations. A comparison between these approach was carried out. After a check of cylindrical symmetry of the MLP distribution, we decided to focus our attention to the y coordinates of proton path.

Conceptually our work was divided in two steps. The first was the check of GEANT4 simulated paths versus the experimental ones. Then, once the MC application resulted fully validated, we proceeded with the test of the Williams' paths considering the Monte Carlo paths as reference data. The main goal was to verify the accuracy of the Williams calculations and, eventually, to point out its limitations.

A. Simulated MLPs Versus Experiment

For each of the chosen configurations a comparison between the experimental and simulated MLPs, for the three positions of the roving module (A, B and C), was carried out. Results are shown in Fig. 4. In order to perform a consistent comparison between the two data set, exactly the same number of protons were considered in the experimental and in the Monte Carlo MLP reconstruction.

The Student test (or t-test) [13] was used to statistically verify the agreement between the single data points of Fig. 4. Table I reports the values of the Y coordinates for MLPs obtained from simulations (Y_{G4}) and experiment (Y_{Exp}) in each set-up. For each comparison the t-test variable is shown. In our case, fixing the significant level at 5%, the value of the calculated t variable must be lower than the tabulated [13] threshold of 1.96. The

TABLE I
G4 AND EXPERIMENTAL MLP COORDINATES FOR CONFIGURATION I

	$Y_{G4}[mm]$	$Y_{Exp}[mm]$	t
SET-UP A (x = 60 mm)	0.11 ± 0.30	0.12 ± 0.34	0.71
SET-UP B (x = 90 mm)	0.21 ± 0.37	0.20 ± 0.44	0.57
SET-UP C (x = 150 mm)	0.54 ± 0.29	0.52 ± 0.43	1.22

TABLE II
G4 AND EXPERIMENTAL MLP COORDINATES (mm) FOR CONFIGURATION II

	$Y_{G4}[mm]$	$Y_{Exp}[mm]$	t
SET-UP A (x = 60 mm)	0.30 ± 0.30	0.32 ± 0.33	0.64
SET-UP B (x = 90 mm)	0.54 ± 0.36	0.58 ± 0.45	1.03
SET-UP C (x = 150 mm)	1.34 ± 0.27	1.29 ± 0.36	1.49

TABLE III
G4 AND EXPERIMENTAL MLP COORDINATES (mm) FOR CONFIGURATION III

	$Y_{G4}[mm]$	$Y_{Exp}[mm]$	t
SET-UP A (x = 60 mm)	0.56 ± 0.33	0.58 ± 0.37	0.90
SET-UP B (x = 90 mm)	1.04 ± 0.39	1.1 ± 0.41	2.35
SET-UP C (x = 150 mm)	2.65 ± 0.31	2.65 ± 0.35	0.00

analogous results for the configurations II and III are summarized in Tables II and III, respectively.

The reported results show a good agreement between simulated and measured data.

The Kolmogorov-Smirnov (K-S) test was also performed for the comparison of the entire paths. The K-S test is applicable if two samples are derived from the same population or from population with the same distribution [18]. If the two sample have been drawn from the same population distributions, then the cumulative distribution of both samples may be expected to be fairly close to each other. The test focuses on the largest value of the difference D_{max}, between the cumulative curves of two samples. From D_{max} it is possible to determine the value of the K-S statistical variable KSstat. If the observed value, for a fixed level of significance, results lower than a given tabulated threshold [18], one can affirm that the two samples are drown from the same distribution. In our case, fixing the significance level at 5%, the threshold is 20 [18]. For all the studied configurations (I II and III) KSstat resulted 0.02, far below the threshold. This evidences an optimal agreement between the simulated and experimental data.

B. Williams' Analytical Paths Versus Monte Carlo

Considering simulations as reference we proceeded with the second step of our work: the check of the agreement between the GEANT4—Williams MLPs. In this case the Kolmogorov-Smirnov (K-S) test was adopted as statistical tool and applied to the paths as a whole. In the previous section we demonstrated the use Monte Carlo simulations to determine the MLP. Numerical simulations with GEANT4 code were adopted as a reference to test the quality of the William's approach in the calculation of the same MLPs. We derived the analytical MLPs for the three configurations investigated Using the William's equations [7]. In Fig. 5 the comparison between the two analytical and Monte Carlo derived MLPs (configuration I and III) is reported. For the simulated MC curve we report also the uncertainty defined as 1σ around the MLP curves, evidencing the characteristic 'banana shape' of the MLP. The maximum difference between the two curves is 0.029 mm for configuration I and 0.106 mm for configuration III. In the same Figure an inset is reported representing the zoom of the MLPs for configuration I in the region for depths between 80 mm and 120 mm. One can note the difference of 29 μm between the curves. The vertical dashed line placed at $\mathrm{x} = 191$ mm indicates the end of the PMMA phantom.

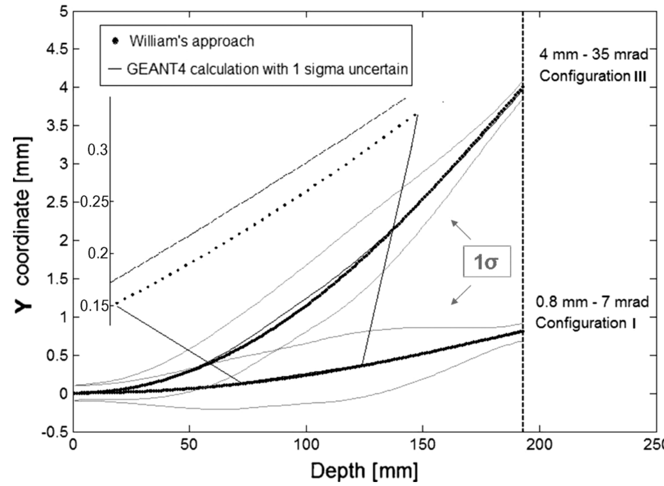

Fig. 5. The most likely paths from theory and GEANT4 simulations relative to the congiguration I and III. Dots represent the proton paths derived via the Williams approach while lines represent the GEANT4 output. For the simulated curves a statistical uncertain region is reported as 1σ around the MLP. The insert represents a zoom of the MLP for the configuration I.

TABLE IV
RESULT OF THE KOLMOGOROV-SMIRNOV TEST FOR THE COMPARISON BETWEEN SIMULATED AND ANALYTICAL MLPS

	Config. I	Config. II	Config. III
KSstat	0.047	0.041	0.047
MLP max distance [mm]	0.029	0.042	0.106
GEANT4 MLP max std [mm]	0.429	0.441	0.473
Analytical MLP max std [mm]	0.549	0.549	0.549

Also in the case of GEANT4—Williams MLPs comparisons, the K-S test was performed fixing the significant level at 5%. Table IV summarizes, for the tested configurations, the results of the K-S test. The values of the statistic variables (KSstat) is reported, the critical tabulated [18] threshold resulting 0.14 for this case. Moreover, the value of the maximum distance between the considered curves (MLP max distance) and the maximum values of the standard deviation (GEANT4 and Analytical MLP max std) of both are shown (maximum width of the bananas in Fig. 5). The agreement between Monte Carlo and analytical calculation results are better for the case I and show a slight worsening while the MLP moves towards more extreme configuration, i.e. bigger angles and exit points.

V. CONCLUSION

Proton computed tomography may provide additional information for proton treatment planning. On the other hand it actually requires more studies and investigations. Many aspects, as those related to the image quality and reconstruction algorithms, must be yet improved while others, related to the amount of deposited dose, deeper discussed and understood. In our work we investigated one of the possible approach to proton image reconstruction using the Most Likely Path, via the Monte Carlo method. A specific application was developed using the GEANT4 libraries. The application was firstly validated against experimental results acquired at the LLUMC center with a 200 MeV proton beams. Secondarily the simulation outputs were used to verify a specific analytical approach to the MLP problem [7].

The obtained results demonstrated the usefulness of the Monte Carlo GEANT4 toolkit approach in the pCT studies. Simulated results have shown excellent agreement with the measured data. Numerical simulation with the GEANT4 code also agreed within 100 $\mu\mathrm{m}$ with the same order of magnitude of the spatial resolution of our experimental set-up.The possibility to use a Monte Carlo application, validated versus experiment, can also represent the basis of further studies in the imaging reconstruction with proton beams being a quite realistic tool for the imaging and dose quality assurance, also in the case of non homogeneous phantoms.

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