Monte Carlo Simulations for the Development a Clinical Proton CT Scanner

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Abstract– **In support of developing the next phase of a proton computed tomography (pCT) scanner with features making it applicable to clinical situations, much insight can be gained through Monte Carlo simulation using Geant4. Careful simulation of energy/range detectors, as well as silicon strip detectors (SSDs), has offered insights into the physical limitations placed on a pCT scanner. Simulation also offers the opportunity to evaluate different detector design schemes and regimes for reconstructing CT images using protons.**

I. Introduction

PROTON computed tomography (pCT) aims to provide improved treatment planning for hadron therapy. Current methods for generating treatment plans rely on X-ray CT and a conversion from Hounsfield units to proton stopping power. pCT takes advantage of the same physics as treatment and avoids the uncertainty inherent to converting from X-ray attenuation to proton stopping power.

To design a system that generates a clinically viable estimation of proton range, the water-equivalent path length (WEPL) and proton track through the patient must be derived. By accurately measuring a proton's direction before and after the patient a path can be reconstructed, and residual proton energy or range provides the amount of material a proton encountered. Careful simulation of energy/range detectors, as well as silicon strip detectors (SSDs), has offered insights into the physical limitations placed on a pCT scanner that will allow these single proton events to be measured. Simulation also offers the opportunity to evaluate different detector design schemes and regimes for reconstructing CT images using protons.

In this paper four separate simulation schemes and their purposes are described:

1. Simulation of inelastic nuclear interactions to determine their importance for selecting useful events for pCT reconstruction.
2. Simulation of energy deposition in a model silicon strip detector (SSD) to determine charge deposition characteristics.
3. Simulations to compare two viable range detector concepts in regards to their water equivalent path length (WEPL) resolution.
4. Simulation of pCT scans of a digital human head phantom to provide insight into the influence of system parameters on the quality of pCT reconstruction.

Simulations for this paper were carried out using Geant4.9.4p02 [11].

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II. Nuclear Interactions

Most protons in the 200 MeV energy range lose energy through Coulomb interactions (Fig. 1, left). However, a significant percentage of protons will interact with other nuclei in an inelastic collision. Protons that undergo a nuclear interaction can lose a relative large amount of energy, scatter at a large angle, and/or may create secondary neutral or charged particles that may or may not deposit energy in the system (Fig. 1, right). In the pCT scanner concept, realized in our current and planned prototypes, we require information from individual events that underwent the most common process of energy loss by electronic interactions; inelastic nuclear interactions and their products can, therefore, mislead the reconstruction process.

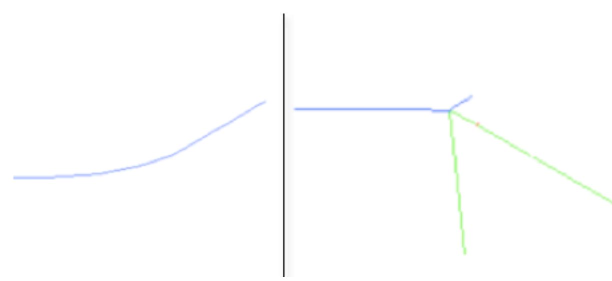


Fig. 1. Two separate proton events. On the left, the proton (shown in blue) is gradually stopped through electronic Coulomb interactions. On the right, the proton undergoes an inelastic collision releasing secondary particles in green.

Two protons may follow similar paths through the phantom. One undergoes multiple Coulomb scattering (MCS) only, while the other undergoes MCS only to collide later with a carbon nucleus in the range detector. Although we measure similar paths through the phantom for the two events, the measured range will be dramatically different. To limit these misleading data statistical cuts are made during pCT reconstruction. Previous work has shown that removing energy outliers improves pCT reconstruction quality [1].

An experiment designed to mimic closely a prototype pCT scanner was modeled and 10,000 events were simulated. This system consisted of a 200 MeV pencil beam passed through a lead scatterer, 8 silicon strip detectors 0.4mm thick, a variable thickness water degrader, and lastly a multi-stage scintillator (MSS) shown in Fig. 2 [4]. Only events that deposited energy in the MSS were recorded. For each event, energy deposited in each stage of the range detector, particle position in the tracker, and particles involved in the event were recorded.

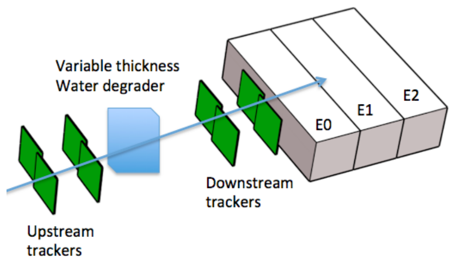


Fig. 2. Simulation of the multi-stage scintillator proposed in Bashkirov[4]. The variable water degrader allows the entirety of the range to be studied. The trackers are silicon strip detectors providing direction vectors before and after the degrader. The water degrader can be varied to select areas of interest in the proton's range. The multi-stage scintillator measures light intensity in the stage where the proton stops.

Events that generated secondary particles fell outside the normal energy straggling spectrum. We found that 33.5% of 200 MeV protons underwent nuclear interactions across their entire range. This effect was observed in prior range counter simulations [5]. Resulting secondary particles were analyzed to determine how the resulting MSS energy spectra would be affected (Fig. 3).

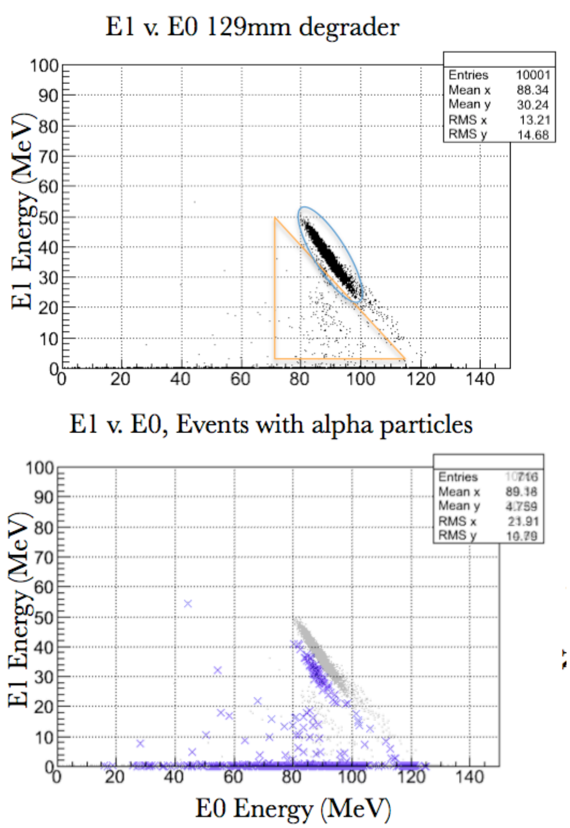


Fig. 3. Correlating energy deposition in the first (E0) and second (E1) stages of the MSS. (a) In the blue ellipse are protons that exhibit expected energy straggling. In the orange triangle are events with total energy less than expected with only Coulomb interactions. (b) Events creating alpha particles, highlighted blue, totaled ~7% of events in this simulation, all of which were outside the usable energy spectrum.

Proton CT reconstruction finds a volumetric representation from the proton's path in the phantom and it's WEPL. As a fraction of the protons lie outside the useable WEPL distribution, some cuts may be applied. Careful statistical treatment of events that travelled along similar paths will allow us to avoid introducing misleading data into the reconstruction process.

III. Energy Deposition in Silicon

To perform effective pCT reconstructions we measure the proton's trajectory before it enters a phantom and after it has exited. To perform this fast data acquisition we have chosen to use silicon strip detectors (SSD), similar to those in use in the Fermi Gamma-ray Space Telescope [10]. These SSDs provide good spatial resolution and favorable signal to noise characteristics. In our clinical scanner we expect near 2 MHz proton rate, which requires a brief time window (100ns) in order to ensure most protons will be measured.

A simulation was carried out to measure the energy deposited in an SSD by a 200 MeV proton. Protons with higher energy deposit less energy in the material they pass through according to the Bethe-Bloch equation. By investigating 200 MeV protons we expect to find the minimum energy deposited in a single 0.4 mm silicon plane in the pCT system. The simulation consisted of a 200 MeV pencil beam passing through air and a 0.4 mm rectangular prism of silicon. 10,000 events were simulated, and events that deposited energy in the simplified SSD were recorded. In Fig. 4 the energy deposition in the simulated SSD is shown.

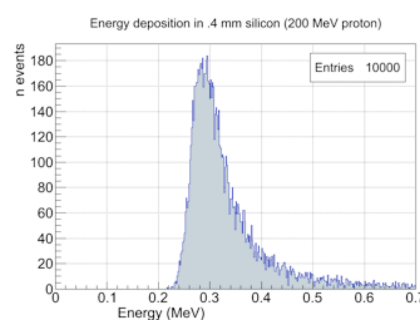


Fig. 4. Histogram of the energy depositions of 10,000 200 MeV protons in 0.4 mm of silicon (representing a SSD). The minimum energy deposited was 0.217 MeV. This provides an ample signal to achieve the performance required for a clinical pCT tracker.

We found the minimum energy deposited in 0.4 mm silicon to be 0.217 MeV. With 3.6 eV[7] per electron-hole pair we expect a minimum of ~60,000 electrons. Our amplifier's shaping signal peaks at about 200 ns, which approaches the 100 ns time window of the accelerator. To reduce time walk within the interval a proper threshold must be selected for the discriminator. Events with minimum energy deposited could pass the threshold later than high energy events if this threshold is set too high.

In other work we have shown our amplifiers have noise of around 1100 electrons [6]. In order to minimize time walk we will set the threshold near 1.0 fC, or ~6000 electrons to give sufficient noise rejection. Given the results of this simulation and measured performance of our amplifier we expect to have minimal time jitter in the threshold crossing.

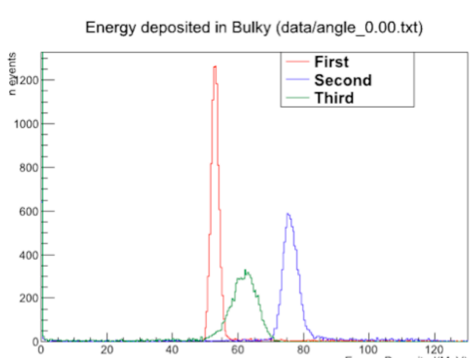
IV. WEPL Resolution

Several methods have been devised to measure the water equivalent path length (WEPL) a proton has travelled through the phantom. The prototype pCT system employs a segmented crystal calorimeter for WEPL measurements [9]. The measured light intensity released when the proton comes to rest in the calorimeter is calibrated to known degrader thicknesses. These responses are fit, and the resulting function provides a transformation from light intensity to WEPL.

A range counter employs a direct measurement of the proton's residual range. An array of light-isolated organic scintillator plates with individual light readout allows one to measure the depth at which the proton comes to rest. By setting a threshold well above noise the range counter makes a digital measurement of the proton's range.

A third method proposed by Bashkirov[4] (see Fig. 2) uses a multi-stage scintillator with fewer and thicker stages. The height of the signal is measured in the scintillator where the proton comes to rest allowing better control over the dynamic range required for the amplifiers, as well as higher WEPL sensitivity of the scintillator in which the calibrated WEPL measurement takes place.

To investigate the performance of methods of range detection for pCT, the figure of merit is the WEPL resolution. In simulation we are able to investigate how a range counter or MSS will behave in the absence of noisy electronics. In these simulations a simplified pCT scanner was modeled with 4 0.4 mm SSDs upstream and downstream from a variable thickness water degrader, followed by the range detector under test. A 200 MeV pencil beam was scattered through 0.9 mm of lead foil before entering the tracking telescope.



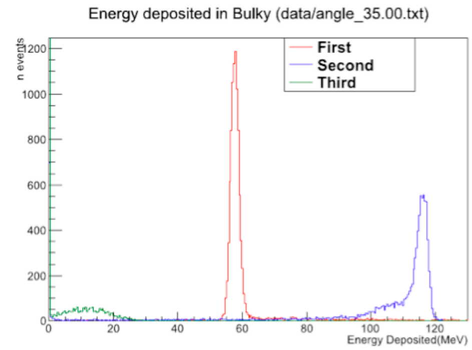


Fig. 5. Energy spectra of a 3-stage MSS. (a) With no water degrader the majority of protons stop in the third (furthest downstream) scintillator. (b) With 35 mm protons stop either in the second or the third scintillator.

By simulating the performance of a polystyrene range counter and a 3-stage MSS across a range of known degrader thicknesses, we obtain the WEPL resolution. For a MSS, the calibration method is synonymous to the WEPL calibration of a calorimeter for each of the scintillator stages. For a range counter, measuring the WEPL calibration is performed by finding the last plane wherein a proton stops for a known degrader thickness. Using these calibrations, simulated events were converted to WEPL values and the resulting distribution gives the WEPL uncertainty. In Fig. 7, simulated data are presented alongside experimental results found by Zatserklyaniy [3] and Bashkirov [4].

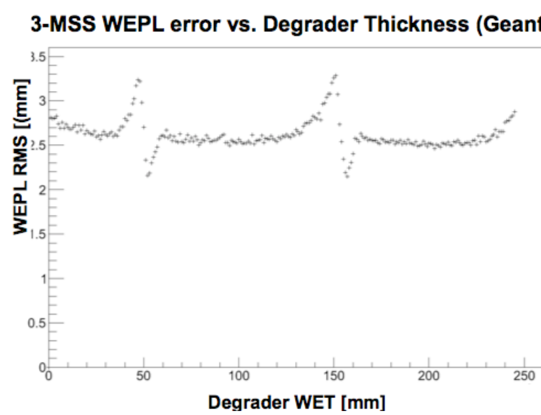


Fig. 6. Results of simulation of a 3-stage MSS show resolution varies with depth remaining under 3 mm for the majority of the range.

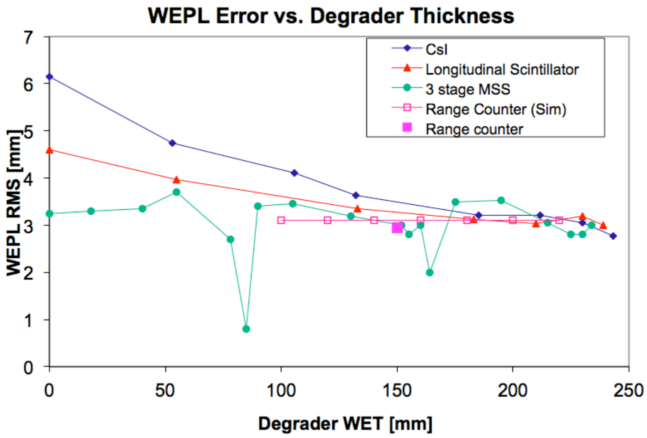


Fig. 7. WEPL resolution for various experimental and simulated range detectors. CsI is a segmented crystal calorimeter used in the current pCT prototype. The longitudinal scintillator is a single stage of doped polystyrene. Also shown are experimental results for a 3-stage polystyrene MSS and range counter. A simulated direct range counter was found to have near 3 mm WEPL error for the entirety of the range analyzed.

V. Simulated Reconstructions

Reconstructed images from simulated pCT scans provide insight into relevant detector geometries. In the current and planned pCT scanners, the phantom is located between two pairs of silicon trackers. The distance between the inner trackers should be large enough to fit the desired object to be scanned. The distance of the inner trackers is important because scattering in the tracker planes leads to inaccuracies of the entry and exit locations of the proton track at the surface of the object. These are larger when the inner trackers are further away from the object.

This simulation includes a calorimeter and two pairs of SSDs with 0.1 mm strip pitch for measuring proton direction before and after the phantom. The phantom studied is a simplified model of the human head designed by Gabor Herman [12]. It is an elliptical cylinder containing brain, bone, and other small features designed to study two dimensional reconstruction. In this simulation a 200 MeV parallel beam was passed through the system. Only events that deposited energy in the calorimeter were recorded.

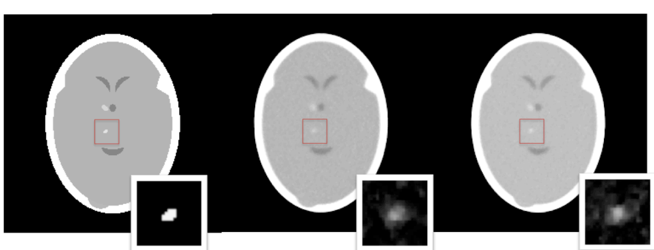


Fig. 8. Left, a digitized version of the Herman head used for comparison. The zoomed region represents a carcinoma roughly 3 mm in diameter. Right, a reconstructed image using simulated pCT data with 50 cm between tracking telescopes. A reconstructed image using simulated pCT data with 30cm between tracking telescopes.

By transmitting around ~20k protons in each of 180 angular projections every 2 degrees around the volume, a simulated pCT scan was performed. Tracked positions protons in SSD and energy deposition in the calorimeter were simulated witha a parallel beam of 200 MeV protons. The simulated data were then reconstructed using a total variation superiorization (TVS) diagonally relaxed orthogonal project method (DROP) as described previously [1,2]. The reconstructions achieved by pCT are maps of relative stopping power (RSP). Fig. 8 shows the results of simulated systems with 30cm and 50 cm spacing between the tracking telescopes.

We were able to successfully reconstruct the Herman head with both a 50 cm and 30 cm distance between the tracking telescopes. We found both reconstructed images to be quite similar and that increasing the distance between the tracking telescopes would not have an immediate deleterious effect on image quality.

VI. Conclusions

In this paper four separate simulation schemes to study a clinical pCT scanner were carried out. We observed that nuclear interactions present a challenge when identifying useable events for reconstruction. Most nuclear interactions lie outside of the energy straggling distribution. With sufficient statistics for a given path through the phantom, effective cuts on WEPL can be made. Provided adequate statistics nuclear interactions do not provide a challenge to single-particle detection based pCT.

We have verified that the signal to noise characteristics for SSDs in our clinical pCT scanner will be favorable. Secondly, we have ensured that the minimum energy deposited in a 0.4 mm SSD is well above the desired threshold, leading to minimum threshold crossing time jitter.

The performance of two different WEPL detector designs for pCT (MSS and range counter) was simulated. We found that the simulated range counter provided a practically constant WEPL resolution of about 3mm. The simulated MSS design achieved a WEPL resolution that varied bewteen 2.6 mm and 3.3 mm. Thus, both designs give similar WEPL resolution.

We have demonstrated that increasing the inner telescope distance from 30 cm to 50 cm had no major effect on the image quality (spatial resolution) of the reconstructed images.

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