Proton Computed Tomography – an NIU, LLUMC, UCSC Collaboration[1]

Imaging in general and medical imaging in particular, are very important scientific endeavors. Their importance has been recognized by several Nobel Prize laureates. Proton Computed Tomography (pCT) is such an example, having its roots in the works of a Nobel Prize laureate (Allan Cormack, 1979). After a period of stagnation, the revival of the pCT idea is mainly due to the proliferation of proton therapy centers. For proton treatments, pCT promises better dose accuracy and more effective outcomes. To this end, our collaboration embarked in a modeling, designing, building, and testing program that will result in the world's first pCT prototype capable of imaging head-sized objects. Some details of the project are summarized below.

Proton CT is a diagnostic imaging process analogous to conventional X-ray CT. The end result is quite similar, namely a 3D density map of the human body in the region of interest. Both techniques use a radiation source and detectors that can rotate around the patient to get enough information to allow for 3D image reconstruction. The data can be viewed in 1 to 3 mm thick, 2D slices through the body. These slices containing electron density information that are used to simulate and plan the proton therapy before treatments begin. This x-ray imaging modality is used universally for all x-ray and proton treatments today.

While x-ray CT (in the 100 keV region) is perfectly adequate for megavoltage x-ray treatments, this is not completely true for proton (or heavier ion) treatments. The reason is that, for an x-ray CT, the conversion from Hounsfeld units (i.e. photon attenuation coefficients, μ) to electron density, ρ_e, are not as precise as one would like. The electron density is what determines where the protons stop in the patient (also called the range) and what the dose is at each point. The principle problem is that the measured values of μ depend on the photon energy spectrum as well as ρ_e, by $\mu = \rho_e\ f(E\gamma)$. Furthermore, the diagnostic photon energy ($E\gamma$) spectrum changes, due to beam hardening, as the x-ray beam penetrates through the patient. In order to solve the set of equations for ρ_e, one must ascribe an average value of photon energy to the diagnostic energy spectrum to get $f(E_\gamma)$ and thus solve for ρ_e at each point in the anatomy. This is an approximation that leads to errors in the resulting electron density map. A medical physicist Uwe Scheider at PSI in Switzerland applied standard x-ray CT imaging to a sheep's head. He then placed the sheep's head in the proton beam to measure the range errors for protons that passed through the sheep's head. He found that roughly 5% of the protons had range errors exceeding 5 mm due to inaccuracies in the electron density map. This was a very sobering result since x-ray CT is used universally in proton therapy. In general, proton treatment planners ascribe a range error equal to 3% of the proton range in the body. So for a 10 cm range proton beam (energy about equal to 120 MeV) the range error will be about 3 mm while for a 30 cm range proton beam (energy 220 MeV), the range error will be about 9 mm. This means, that in most cases, the proton beam energy must be increased to make sure the tumor is getting the full dose. This in turn means that there will, in many cases, be a higher dose delivered to healthy tissue downstream or behind the target. In order to reduce these dose errors, proton CT has been suggested as a solution: a technique first proposed by Allan Cormack in the 1960s and discussed in his Nobel Prize

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[1] This project was supported in part by a Department of Defense Contract (W81XW-08-1-0205) to Northern Illinois University.

acceptance speech in 1979. With proton CT, we believe it should be possible to reduce these range errors below one or two mm. We expect that images can be taken using less dose to the patient than an x-ray CT and that streaking artifacts from metal rod and dental implants will be eliminated or minimized thereby giving higher quality images.

An equipment setup similar to what is being assembled in Loma Linda this month is shown in Fig. 1. The basic idea is to measure proton trajectories and energy loss through the patient over 360 degrees of beam entry directions in order to determine energy loss, or dE/dx, in each 1mm voxel in the patient. Approximately 1,000,000 tracks will be acquired for each gantry (or rotation) angle with a minimum of 72 gantry angles. This requires new deconvolution techniques similar to finding μ in each voxel for x-ray CT. A central part of this project is finding reconstruction algorithms and computers that are fast enough to reconstruct images from 70,000,000 proton tracks within clinically meaningful time scales (e.g., a few minutes).

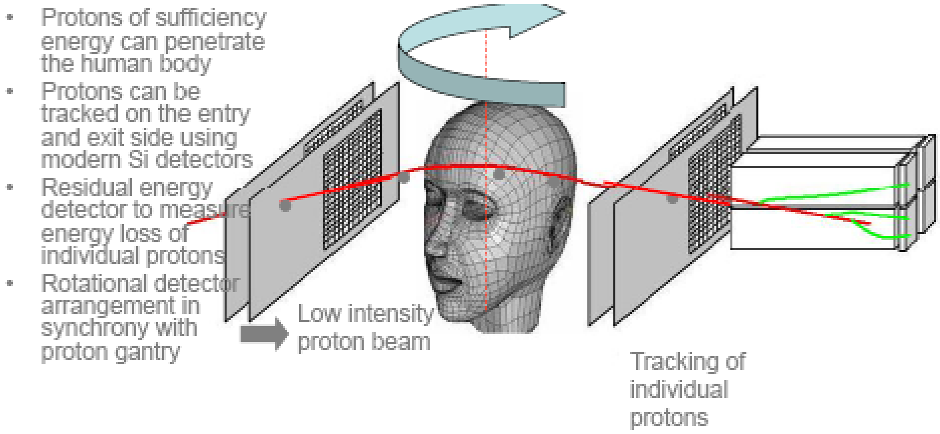

Fig. 1 Schematic of the proton CT setup for Loma Linda proton beam tests starting March 2010.

Current Status of the Proton CT Project

The detector shown above consists of 8 planes of position sensing Silicon strip detectors covering an area of 9 x 18 cm with two measurements of X and Y before the patient (shown here as a head phantom) and two measurements of X and Y after the patient. The detector has been built at the Santa Cruz Institute of Particle Physics (SCIPP) at Univ. of California in Santa Cruz (UCSC) headed by Hartmut Sadrozinski and assisted with a large staff including NIU physicist Victor Rykalin who is in charge of the calorimeter design and construction. SCIPP was able to leverage a decade of R and D applied to Si track detectors at CERN and the GLAST space detector. The most expensive part, the VLSI electronics chips for signal amplification and digitization, was accomplished at a fraction of the cost by using electronic components from these other projects. The calorimeter consists of 18 CsI crystals mounted in a 3 x 6 array and allows higher data rate capability than using a single crystal. The pitch of the Si strip detectors is 240 microns and thickness along the beam direction is 400 microns. These measurements allow for an entry trajectory to the head as well as an exit trajectory. One can then determine the most likely path through the patient as well as the integrated energy loss though the patient. This integrated energy loss will be given by

$$\Delta E\ (\text{patient}) = E(\text{incident}) - E\ (\text{calorimeter}) - \Delta E(\text{4 Si strip detectors})$$

The incident energy is well defined to better than 0.2% and the calorimeter design measures residual energy after the patient to within 1%. This detector system will be fully assembled and ready for preliminary beam testing by the end of February 2010. A rotational stage that attaches to an anthropomorphic head phantom was purchased by NIU and is now installed in Loma Linda. Given the limited beam time at any clinical facility like Loma Linda's and the complexity of the hardware with 1000's of readout channels, there will likely be many months (6 or 8) before sufficient data is available for reconstructing the first 3D images in proton CT. As we discuss below, this may allow sufficient time for much needed software development.

Software and Hardware for Image Reconstruction

A large amount of progress has already been made towards 3D image reconstruction. In 2007, a plastic cylindrical phantom with several high-density materials inserted in the phantom was imaged at LLUMC using software originally developed at Brookhaven National Laboratory, State University of New York, and further developed by Scott Penfold, a graduate student in medical physics from University of Wollengong in Australia. This demonstrated a proof a principal for image reconstruction for a 2D slice through the cylinder using standard CPU on a PC. Going to 3D will be much harder and new techniques are required. Recently, Keith Schubert from Cal State San Bernardino and one of his graduate students used Monte Carlo simulated data for a similar phantom to show that certain components of the image reconstruction algorithm could be sped up by up to a factor of 500 through a new approach that makes use of special hardware called a graphic processing unit (or GPU). These are the same computers used in the video gaming industry (like X Box and PlayStation) and are well suited to the proton CT problem that requires solving for the electron density at each voxel (10^7 voxels) from a system of approximately 10^8 equations, one for each proton track .

Last year, Bela Erdelyi (from the NIU physics department), Nicholas Karonis, and Kirk Duffin (both from the NIU computer science department) began working on this problem. In addition to developing new software and algorithms, they realized the potential of a high-performance GPU cluster at Argonne National Laboratory that uses 24 interconnected GPUs to allow parallel processing of proton track data. This computing cluster was purchased from an MRI grant through NSF and the University of Chicago (UC). We are in contact with UC medical physicists to develop a collaborative effort on the project. The computer science staff at Argonne has shown strong interest in the project, and we believe that with their expertise in GPUs and access to their GPU hardware, we can put this development on a fast track and be ready for imaging using beam data from LLUMC in the fall of 2010. The goal is to achieve image reconstruction time less than 5 minutes.

What are the Next Steps?

Once we have images, we can begin investigating image quality and accuracy. For example, how good are the measured electron densities when compared with known values? How much have the proton range errors been reduced? Can we actually deliver lower dose than an x-ray CT? We also plan to do imaging studies with anesthetized mice and rats. Proton radiography can be done on small animals to verify the correct range of protons similar to Schneider's sheep head experiment. These questions and more will be answered as data analysis gets into full swing.

Software Developments

At the present time NIU is in the process of acquiring their own GPU hardware with existing university funds. Once we have successfully demonstrated image reconstruction on the Argonne GPU cluster, we can use the code that was developed on the Argonne computer on the NIU computer to do further developments in image reconstruction with the eventual goal of using the computer for image reconstruction at NIPTRC.

Hardware Developments

After initial testing of the prototype detector at LLUMC, efforts will be underway to speed up the data acquisition rate of the detector from 200 kHz to 2MHz with the goal of acquiring 70 million tracks in less than 3 minutes. Detector data acquisition boards will need to be modified and a new calorimeter design has been started which uses stacks of scintillator plates to measure the range of the protons. A new Si tracker with larger area, 18 x 36 cm, will be started some time this year, and the new scintillator calorimeter will also be 18 x 36 cm. For NIPTRC as well as Loma Linda, the final goal will be to build and install a duplicate detector on a treatment room gantry. This will require us to work with the proton therapy equipment vendor to make a mechanical support system that will insure compatibility with their equipment and allow the pCT do be retracted from the beam during treatments. We anticipate that a medical physicist will need to be trained in the use of the pCT equipment to be able to acquire images and to transfer them to a treatment planning station. Daily and weekly QA procedures will also need to be established.