Performance Evaluation of the Phase II Proton CT Scanner at CDH – Research Plan

May – August, 2015

**Background:** In 2011 the NIH/NIBIB awarded us a 4-year R01 grant to build a fast preclinical head proton CT scanner and develop methods to reconstruct the data from a head object in 10 minutes or less. With the funding provided by that grant, we have built the phase II pCT scanner, which performs as promised. Another important task within the funded R01 project was to evaluate the clinically relevant imaging performance of the pCT scanner. Whereas the original application had stated we would do this with the phase I pCT scanner, which was the predecessor of the phase II scanner, we later decided to wait with this task until the new scanner was built and technically characterized and optimized.

We are now in the position to carry out the required tests to evaluate the clinical performance of the phase II pCT scanner at the Chicago Proton Center located at the Central DuPage Hospital (CDH) (<http://www.chicagoprotoncenter.com/>). This document details the research plan for the planned beam runs and data analysis.

**Research Plan:**  The underlying hypothesis of our research is that pCT outperforms the current proton treatment planning and image guidance practice with a-high quality x-ray CT scan that is based on a stoichiometric conversion of CT Hounsfield units to relative proton stopping power (RSP) for treatment planning and a kV-cone beam CT for position and plan verification in the treatment room. The research plan outlined below aims at testing this hypothesis by performing an extensive performance evaluation of proton CT at CDH and compare the results to the standard approach with x-ray CT-based planning and cone-beam-CT based verification/image guidance in the treatment room.

Rationale of Research Approach: It is logical to test the pCT against a standard x-ray CT treatment planning scanner (CT simulator). Minimization of current proton range errors in the presence of tissue inhomogeneties is paramount for accurate proton treatment planning, and acceptable image quality at comparable doses is important for adequate target delineation and registration with other imaging modalities. Thus, we will focus on these two aspects of pCT imaging.

Approach: Three performance evaluation tasks will be completed utilizing the phase II prototype pCT system, a state-of-the-art multi-row detector CT scanner dedicated to proton treatment planning. The tests will be done at the CDH Proton Treatment Center in Warrenville, IL, which is a modern proton treatment facility with beam scanning capability and actively spread-out proton beams.

**Task 1:** Evaluate pCT image quality with phantoms and compare with x-ray CT image quality.

We will closely follow the guidelines of AAPM Task Force 2 outlined in AAPM Report No. 39, Specification and Acceptance Testing of Computed Tomography Scanners [1]. This task will evaluate

* Image noise (custom-built16-cm-diameter cylindrical water phantom)
* Field uniformity (custom-built16-cm-diameter cylindrical water phantom)
* High-contrast spatial frequency limits (Catphan, CTP528, high-resolution module)
* Modulation transfer function (MTF) (Custom-designed CIRS edge phantom)
* Low contrast detectability (Catphan, CTP515 low contrast module)
* Quantitative accuracy of RSP/CTN numbers (Catphan, CPT404 sensitometry phantom)
* Quantitative accuracy of RSP/CTN

**Task 2**: Evaluate pCT radiation dose and compare with x-ray CT dose obtained at the same image noise level.

We will closely follow the guidelines of the AAPM Report 111 of the Task Group #111: The Future of CT Dosimetry [2]. This task will evaluate the dose on the central axis and the surface of a 16 cm diameter cylindrical dose PMMA phantom. For both pCT and x-ray CT, the phantom will be exposed to uniform beam profiles of 80 mm length. The x-ray CT scan will be performed with nT = 64 x 1.25 mm and a field of view of 20 cm and using standard imaging parameters for a head scan otherwise. The pCT scan will be performed with an 8 cm x 20 cm field of 200 MeV protons and with 180 stationary projections at 2-deg increments. The total number of proton histories will be adjusted such that the central image noise of both scanning modalities will be identical to within +/-2.5%. The dose delivered by x-ray CT and pCT will be measured using a conventional thimble ionization chamber calibrated to 70-120 kV x-rays and with the chamber calibrated to measure proton doses in the 40-200 MeV energy range.

**Task 3**: Evaluate uncertainty of proton range determined with pCT and x-ray CT

The final test will be to evaluate the improved range estimation of pCT over conventional x-ray CT in proton therapy. To complete this, an anatomically detailed head phantom containing human tissue-equivalent soft tissue, brain, trabecular and compact bone, and sinus-air material (lung-equivalent) will be scanned with both imaging modalities using the setting of Task 2 that gives equivalent dose at the center of the phantom (to be verified by Geant4 Monte Carlo simulation). The water equivalent range of a pre-determined set of circular proton pencil beams (2 cm diameter) will be predicted for both planning modalities using a standard proton treatment planning system as well as by the TOPAS Monte Carlo simulation package. The head phantom contains a dosimetry insert in the posterior fossa that contains a stack of radiochromic film, which will allow us to measure the actual range of the delivered proton pencil beams to within better than +/- 0.1 mm.

**Timeline:** Three beam tests, further detailed below will be scheduled at the CDH proton facility during the months of May and June, 2015. The first run will take place on May 16, 2015.

Detailed Plan for the CDH Beam Test on May 16, 2015

Phantoms (Abbrev.)

* Calibration Phantom (Calib/0) mounted on platform
* 4 additional polystyrene plates (100 x 400 x 50.8 mm each)
* Alignment (rod) phantom (Rod)
* Water Phantom (Water)
* CTP528 High Resolution Line Pair Phantom (Linepair)
* CTP404 Sensitometry Phantom (Sensitom)
* CTP515 Low Contrast Module (LowCon)
* CIRS Edge Phantom (CIRSEP)
* HN715 CIRS Pediatric Head Phantom (CIRSPHP\_0)

Experimental Setup

The phase II pCT scanner will be mounted on a bread board, which will be placed on a platform mounted to the robotic positioner in the uniform scanning room at CDH.

The pCT system center will be placed at room isocenter user room alignment lasers. Lateral alignment will be done approximately by eye (for now).

We will run with a 200 MeV proton beam of 4 cm (FWHM) spot size, uniformly scanned using wobbler magnets to the field sizes specified below (at 50% isodose).

The beam intensity will be adjusted the night before the proper runs to approximately 1M protons per sec and spot. Time variations of +/-10% are acceptable.

Run Plan

1. Stepped Scans (stop beam after each projection, transfer data, restart beam for new projection)

* Empty run: 4-5 M histories, field size 12 cm x 36 cm
* Calibration run: 4-5 million histories per brick (0, 1, 2, 3, 4 bricks), field size 12 cm x 36 cm
* Water phantom: one projection, 4-5 M histories, field size 4 cm x 16 cm
* CIRS Edge phantom (CIRSEP): 90 projections, 4 deg intervals, 4-5 M histories per projection, field size 8 cm x 24 cm
* CIRS head phantom: superior and inferior run, each run 90 projections, 4 deg intervals, 4-5 M histories per projection, field size 12 cm x 24 cm
* Water Phantom (Water): 90 projections, 4 deg intervals, 4-5 M histories per projection, field size 4 cm x 16 cm
* CTP404 Sensitometry Phantom (Sensitom): 90 projections, 4 deg intervals, 4-5 M histories per projection, field size 4 cm x 20 cm
* CTP528 High Resolution Line Pair Phantom (Linepair): 90 projections, 4 deg intervals, 4-5 M histories per projection, field size 8 cm x 20 cm
* CTP515 Low Contrast Module (LowCon): 90 projections, 4 deg intervals, 4-5 M histories per projection, field size 8 cm x 20 cm
* Alignment (rod) phantom (Rod): 90 projections, 4 deg intervals, 4-5 M histories per projection, field size 4 cm x 20 cm

1. Radiography Scans:

Data will be acquired in two projections at orthogonal angles (0 deg, 90 deg) to allow for reconstruction of radiographs

* CIRS head phantom: superior and inferior projection, each 2 projections, 90 deg intervals, 8-10 M histories per projection, field size 12 cm x 24 cm
* CIRS Edge phantom (CIRSEP2): 2 projections, 90 deg intervals, 8-10 M histories per projection, field size 8 cm x 24 cm

1. Continuous Scan

This will be done to obtain first experience with a continuous run mode.

* CTP404 Sensitometry Phantom (Sensitom): 90 projections, 4 deg intervals, 4-5 M histories per projection, field size 4 cm x 20 cm