### Title

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# Dosimetric Evaluation of Proton CT using a Prototype Proton CT Scanner

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***Abstract*–These instructions provide guidelines for preparing manuscripts for submission to the Conference Record (CR) of the 2016 IEEE Nuclear Science Symposium and Medical Imaging Conference. If you are using Microsoft Word to prepare your manuscript, you should use this document as a template. Define all symbols used in the abstract. Do not cite references in the abstract. Do not delete the blank line immediately above the abstract; it sets the footnote at the bottom of this column. Proton computed tomography has been suggested as an imaging technique alternative to x-ray CT for proton therapy treatment planning and image guidance. Dose, image quality, and range prediction accuracy are closely related and the calculation of the dose delivered during a proton CT scan is crucial for characterizing a proton CT scanner. Here we report on the dosimetric evaluation of proton CT scanner using a prototype built by the pCT collaboration between Loma Linda University, the University of California Santa Cruz, and Baylor University. The Catphan CTP554 16 cm acrylic dose phantom, representing a human head, was used to measure the dose to water during a typical proton CT scan at the Northwestern Medicine Chicago Proton Center in Warrenville, Illinois. A Farmer ionization chamber was installed in two locations (centre and periphery of the phantom) and the accumulated charge was measured with the 35040 Advanced Therapy Dosimeter (Fluke Biomedical). The proton CT scanner was exposed to a uniform beam profile of 200 MeV protons on the uniform scanning clinical proton beam line. At a rate of 1 M protons sec it takes 7 minutes in order collect about 400 M protons during a continuous 360 deg rotation. The proton fluence at the level of upstream inner tracker planes during the 7 minutes of exposure was estimated to be 1.4 M protons/cm$^2$. The dose to water was 1.46 mGy in the peripheral location and 1.48 mGy in the central location, demonstrating that it is practically uniform across the phantom. According to these results, we can conclude that, based on an initial dosimetric characterization of a prototype pCT scanner conducted on a clinical proton beam line, proton CT is a promising modality for low-dose image guidance and adaptive proton therapy.**

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## I. Introduction

Proton therapy (PT) is increasingly used, because of distinct dosimetric advantages of proton beams, including no exit dose, reduced low-dose exposure to normal tissues, and high target conformality [1]. It is preferred especially for pediatric tumors and for those cancers where conventional x-ray radiotherapy may pose a higher risk to the patient [2].

Technical challenges of PT require continued development of this radiation therapy technology. At present, the potential of proton therapy cannot be fully exploited because of prevailing range uncertainties in proton treatment planning and delivery; one reason for this is that volumetric imaging for planning and pre-treatment verification is based on the conversion of x-ray computed tomography (CT) Hounsfield units (HU) to relative stopping power (RSP). The conversion of HU to RSP is inherently inaccurate, leading to a systematic range error of 3-5% [3], and the quality of x-ray cone beam CT (CBCT) is not sufficient for accurate estimation of range errors at the time of treatment [4]. Additional range errors are introduced by beam hardening and high-density artifacts in CT. Proton computed tomography (pCT) is an imaging technique that provides RSP directly which should lead to reduced proton range uncertainty in treatment planning and verification than currently possible with standard x-ray CT technology [5].

An additional aspect to be considered in modern image-guided PT is the relatively high dose to PT associated with CBCT, especially when it is performed for every treatment faction. Here, pCT also potentially offers an advantage, especially when the pCT technology is based on single-proton registration [5], [6].

The dose required for pCT depends on the underlying technology of the scanner. Testa et al [7] described a prototype proton radiography and pCT system using a two-dimensional, diode-array detector capable of fast dose rate measurements; they recorded the time dependence of the dose distribution delivered by a proton beam traversing a range modulator wheel in passive scattering proton therapy systems. By

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measuring the time dose pattern at the point of interest, the WEPL to this point can be decoded and a WEPL radiograph or RSP pCT image can be reconstructed. The authors reported that the technique requires a dose of about 7 mGy to the patient.

Here, we report on the initial dosimetric evaluation of a pCT scanner prototype utilizing a tracking telescope and a multistage energy detector. The prototype was built by the pCT collaboration between Loma Linda University, the University of California Santa Cruz, and Baylor University [8], [9] and is based on individual proton registration.

## II. Materials and Methods

### A. pCT scanner prototype

The prototype pCT scanner (Fig. 1), which is based on single proton registration, was developed based on the original design concept presented in [5]. Protons are tracked individually before entering and after exiting the phantom or patient with 2D-sensitive silicon trackers. The entry and exit telescopes consist of four planes of paired, single-sided silicon strip sensors with orthogonally arranged strip orientation. A multistage scintillator detector measures the residual energy of the protons traversing the scanned object and is calibrated in terms of water equivalent path length (WEPL) [10], [11]. The detector signal of the stage in which the proton stops is converted by a PMT attached to each stage. The data acquisition has been described elsewhere [8].

Image reconstruction software utilizing the WEPL and coordinate measurements of individual protons has been developed and generates 3D images of RSP [12]. When performing a full pCT scan, the phantom is rotated on the vertical axis of the rotation platform of the scanner either in discrete angular steps (4 degrees) or continuously.

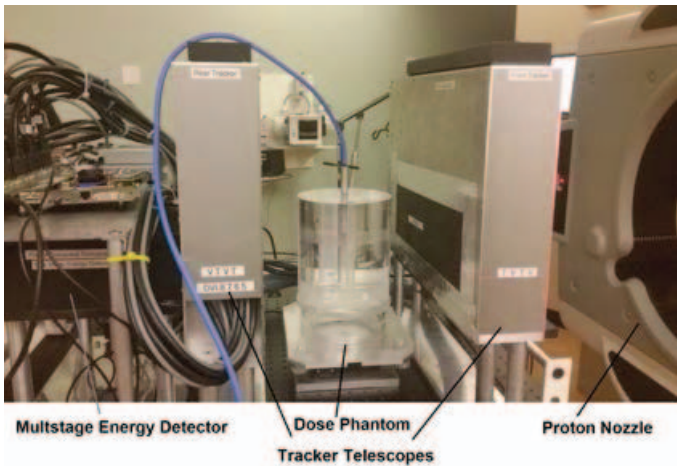


Fig. 1. Prototype pCT scanner with dose phantom and ion chamber mounted on the fixed-beam clinical proton beam line at the Northwester Medicine Chicago Proton Center.

### B. Experimental Setup

The Catphan CTP554 16 cm acrylic dose phantom (The Phantom Laboratory, Greenwich, NY), representing a human head, was used to measure the dose to water during a typical pCT scan at the Northwestern Medicine Chicago Proton Center in Warrenville, Illinois (Fig. 1).

A proton energy of 200 MeV at nozzle exit (range in water 26 cm) was used and the initial beam was spread out using the internal nozzle scattering system to a symmetric Gaussian spot of 40 mm FWHM. The beam spot was then uniformly spread by horizontal and vertical wobbler magnets. The pCT scanner was centered on the beam line with the upstream surface of the front tracker placed at the isocenter. The CPT554 dose phantom was installed on the rotation platform as shown in Fig. 1.

A Farmer ionization chamber (model 30013, PTW, Freiburg, Germany) was placed in either the central hole (Fig. 1) or one of the four peripheral holes of the dose phantom. For the central location, which coincides with the axis of rotation, the phantom was kept still during the proton CT exposure, while for the peripheral location, the phantom was continuously rotated at a speed of 1 rpm.

The accumulated charge was measured with the 35040 Advanced Therapy Dosimeter (Fluke Biomedical, Solon, OH, USA). For both ion chamber locations, the phantom was exposed for a time of 7 minutes in order to collect total number of about 360 M protons triggering the system, typical for a planning pCT scan with low noise (<1%).

### C. Dose Measurement

A run without beam, before and after the exposure, was performed for background-dose subtraction. The background dose was assumed to be the arithmetic mean of both measurements. At the time of the measurement, atmospheric temperature and pressure were recorded to correct the conversion of charge to dose. The following standard formula for converting measured charge to dose was used:

$$D = (q - bkgr) \times K_{T,P} \times CF$$

where $q$ is charge, $bkgr$ is the background dose accumulated when the proton beam was turned off, and $CF$ is the chamber factor ($5.391\times10^7$ Gy/C +/- 1.1% according to the chamber certificate). $K_{T,P}$ is the correction factor for temperature and pressure defined as:

$$K_{T,P} = \frac{T(Kelvin)}{295} \times \frac{P(mmHg)}{760}$$

## III. Results

The conditions at the time of the measurements were T = 296.6 K and P = 739.94 mmHg, resulting in $K_{T,P}$ = 0.979. The average background charge accumulated during the measurement was 1.52 pC for the central run and 1.87 pC for the peripheral run, respectively.

The central proton fluence at the level of upstream inner tracker planes during the 7 minutes of exposure was estimated to be 1.4 M protons/cm$^2$ taking into account the trigger rate, tracker plane efficiency, and loss due to nuclear interactions in the object. The resulting dose to water, after the background correction, was 1.46 mGy in the peripheral location and 1.48 mGy in the central location, respectively. Thus, the dose per 1 M protons protons/cm$^2$ at the entry to the phantom is about 1 mGy.

## IV. Discussion

We have provided first measurements of the dose delivered during a high-quality pCT scan with a (preclinical) prototype pCT scanner utilizing single proton registration. The dose was found to be of the order of 1 mGy for a scan with of the order of $10^6$ protons per $cm^2$ at the entry to the phantom. The dose was within 0.2 mGy the same at the central and peripheral locations of the Catphan dose phantom, demonstrating that pCT delivers a uniform dose for a 360-degree scan. The measured dose was for a high-RSP resolution planning pCT with low noise content (<1%). For a verification and replanning scan, the dose required may be up to 10 times lower, thus of the order of 0.1 mGy. High energy protons are low-LET-type radiation. There will be a small high-LET component from neutrons and recoil nuclei produced in inelastic nuclear interactions. A detailed cytoxic and nanodosimetric study of pCT vs. standard kV x-ray CT should be performed to demonstrate that the equivalent dose is not more than 10-20% higher than the physical dose.

The correlation of dose measurements with entry proton fluence at the center of the scanner, as registered by the inner upstream tracker planes, will allow an estimation of the dose to phantom objects and human anatomy of similar size than the Catphan dose phantom (16-cm diameter). Some variation can be expected, however, due to different atomic composition and size of the scanned object. For example, the dose to an acrylic phantom per unit fluence may be higher than to a human head due to the higher carbon content in the phantom. For a more accurate dose estimation we are planning to use a software simulation platform of the pCT scanner prototype [13], that allows to directly simulation the dose distribution in any phantom or anatomical region of choice. The platform can also be adapted to estimate doses delivered with CBCT by modeling the effective source spectrum and full bow-tie filter attenuation of a typical CBCT scanner used in radiation therapy [14]. We can then compare doses and dose distributions for a similar level of image noise of the two imaging modalities in realistic anthropomorphic phantoms. This is work in progress. From preliminary results, we expect the dose with pCT to be at least 5 times lower than with CBCT (unpublished simulation results).

## V. Conclusions

An initial dosimetric characterization of a prototype pCT scanner was conducted on a clinical proton beam line. Our results demonstrate that pCT based on single proton registration is a low-dose (< 1.5 mGy) imaging modality that would be useful for range verification and dose replanning at the time of treatment, applications that have yet to be explored. Validating the dose calculation of a pCT software platform for simulation of pCT scans will allow realistic dose estimates for arbitrary objects, including patients in which the geometry is available from CT scans.

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