DIAGNOSTIC PROTON COMPUTED TOMOGRAPHY USING LASER-DRIVEN ION ACCELERATION

K. Woods#, S. Boucher, RadiaBeam Technologies LLC, Santa Monica, CA 90404, U.S.A.
B.M. Hegelich, University of Texas at Austin, Austin, TX 78712, U.S.A.
V. Bashkirov, R. Schulte, Loma Linda University Medical Center, Loma Linda, CA 92354, U.S.A.

Abstract

Although the growing utilization of computed tomography (CT)-based imaging has led to major advances in diagnostic capabilities, it has also resulted in higher cumulative radiation doses to patients. In order to fully exploit the benefits of high-resolution diagnostic CT scans while minimizing the risks of radiation-induced cancer, the realization of low-dose CT is crucial. Recent research has shown that the use of protons, rather than X-rays, for CT has the potential to greatly reduce the radiation dose delivered to the patient without reducing image quality. RadiaBeam Technologies, in collaboration with the Loma Linda University Medical Center and the University of Texas at Austin, is proposing the development of a proton CT scanner utilizing laser-driven ion acceleration (LDIA) techniques. The initial design of this system is presented.

NEED FOR LOW-DOSE CT

With over 62 million scans performed each year in the United States alone, computed tomography (CT) is a crucial tool for diagnostic radiology. Over the last 15 years, there has been a large increase in the utilization of diagnostic CT imaging procedures and therefore a subsequent increase in radiation exposure. As CT scans are responsible for nearly 50% of the radiation exposure from medical imaging in the U.S., the risks associated with its relatively high radiation dose, which can be two orders of magnitude greater than corresponding X-ray radiographs, become more and more of a concern [1]. Dose reduction is especially important for pediatric diagnosis, since children are both more sensitive to radiation and have more time for developing radiation-induced secondary cancers.

PROTON CT

Recent research has shown that the use of protons, rather than X-rays, for CT has the potential to reduce the radiation dose by an order of magnitude without reducing image quality [2], [3]. Ongoing studies of proton CT (pCT) at Loma Linda University Medical Center (LLUMC) are being performed to develop this technology for improving the accuracy of treatment planning in hadron therapy.

Principles of pCT

The first requirement for pCT is the production of a proton beam with high enough energy to fully penetrate the body part to be imaged. Protons with energies 200 - 250 MeV would be necessary for performing a typical head scan, while 330 MeV protons would be able to span most human torsos (60 cm range). Position-sensitive detectors are placed on either side of the subject to track the entry and exit points of each proton. The energy loss of individual protons is then measured with an energy detector/range counter, as shown in Figure 1.

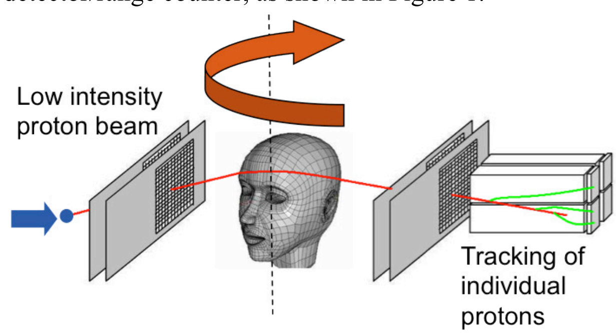

Figure 1: Conceptual design for a pCT scanner [Courtesy of R. Schulte, LLUMC].

Images can be created from the individual proton histories through the use of iterative reconstruction algorithms and path concepts such as the "most likely path" approach, as illustrated in Figure 2.

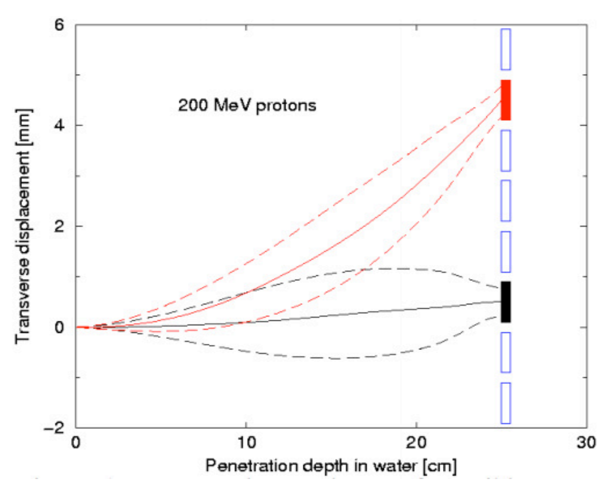

Figure 2: Monte Carlo simulation – solid lines: the most likely path of 200 MeV protons with exit displacements of 0 and 4 mm after traveling 25 cm in an object with water density; dashed lines: one sigma envelopes from Monte Carlo.

pCT Research at LLUMC

Over the last ten years, researchers at LLUMC have been developing pCT technology for improving the accuracy of treatment planning for hadron therapy. Currently, planning for proton therapy is done using X-ray CT, from which the relative stopping power of protons is reconstructed. However, there is a significant degree of error associated with this conversion that results in a range uncertainty between 3 and 5% for soft tissues [4]. This often causes conflict between the physician's desire to completely cover the tumor volume and the need to spare healthy surrounding tissue. When protons are used for treatment planning rather than X-rays, this conversion is bypassed and the stopping power can be reconstructed directly.

Between 2008 and 2010, LLUMC and their collaborators developed a Phase I scanner to prove the feasibility of pCT [5]. Rather than develop custom detectors for this prototype, they used the silicon strip detectors and data readout from the Fermi Space Telescope, which was a NASA GLAST Mission. They also used a multi-segmented crystal calorimeter for residual energy measurements, an FPGA-based data acquisition (DAQ) system, and a GPU-based reconstruction system. The scanner was then tested with different phantoms to demonstrate density resolution; the radiographs are shown in Figure 3.

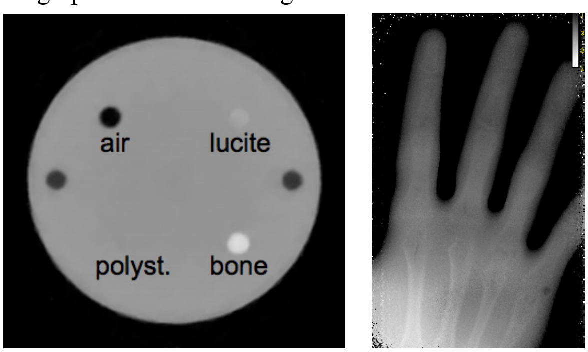

Figure 3: Left: Radiograph of a polystyrene head phantom with inserts of various densities (bone, polystyrene, Lucite, and air); right: radiograph of a hand phantom demonstrating high contrast between bone and soft tissue [Courtesy of R. Schulte, LLUMC].

In 2011, the group began the development of a Phase II pCT scanner featuring several major improvements. This scanner will have improved detectors with twice the active area (9 cm x 36 cm) and slim edges for reducing the dead space from overlapping silicon strips. It will also feature a simplified energy detector consisting of a 5-stage scintillator with a photomultiplier tube (PMT) readout scheme. The total scan time will be reduced to around five minutes through the development of a dedicated application-specific integrated readout (ASIC), and a GPU cluster will enable reconstruction in under ten minutes. This scanner is currently in the final stages of development.

DIAGNOSTIC PROTON CT

Although the research at LLUMC has clearly demonstrated the feasibility of pCT for improved treatment planning, the need for massive therapeutic proton accelerators and expensive proton gantries makes this development impractical for diagnostic applications. It can cost up to $150 million to build a proton therapy facility [6] (with an additional $21 million in yearly operational costs), compared to about $5 million for a conventional CT system.

In order for the diagnostic utilization of pCT to be possible, lighter, more compact accelerators that can be more easily rotated around the patient must be developed.

Advantages

The main advantage of diagnostic pCT is the major dose reduction from conventional X-ray CT. The estimated dose from a pCT scan is between 0.03 and 0.3 mGy, which is a potential reduction of about two orders of magnitude. This would justify the use of CT for a much broader range of diagnostic applications where the potential benefits were previously outweighed by the risks of excessive radiation exposure, such as pediatric diagnosis and patients with conditions requiring frequent imaging.

Another advantage of pCT over X-ray CT is its potential for quantitative imaging and its superior representation of electron density [4]. pCT has the potential to detect very small changes in density, which could make it useful for applications such as lung cancer screening. It could also provide better bone density measurements for patients with osteoporosis and improve detection of kidney or urinary stones, which are sometimes difficult to see on an X-ray image.

Collaboration

To meet this need, an international collaboration of scientists, doctors, and engineers has been established. The ultimate goal of this collaboration is the development of a compact diagnostic CT system for low-dose (sub-mSv) imaging. The institutions involved and their roles in the project are given in Table 1.

Table 1: Collaborating Institutions and Project Roles

Institution	Project role
RadiaBeam Technologies	Accelerator diagnostics and components
Loma Linda University, Dept. of Radiation Medicine	pCT expertise and medical input
University of Texas at Austin, Dept. of Physics	Acceleration scheme
Univ. of California, Santa Cruz, Institute of Particle Physics	Detector system
Baylor University, Dept. of Electrical and Computer Engineering	Computational scheme
Ludwig-Maximilians-Universität München, Dept. of Experimental Medical Physics	International collaborator
University of Haifa, Dept. of Mathematics	Reconstruction algorithms

ISBN 978-3-95450-138-0

Approach

The crucial reduction in system size and cost for diagnostic pCT may be feasible with the implementation of innovative Laser-Driven Ion Acceleration (LDIA) technology. LDIA of highly energetic ion beams is a cutting-edge area in advanced accelerator research. Electrostatic fields in excess of 10^{12} V/m, produced via charge separation within a small area of several micrometers defined by the laser beam's focus, are theoretically capable of accelerating protons or heavier ions to energies suitable for imaging.

Dr. Manuel Hegelich, the main collaborator at UT Austin, is an expert in LDIA and will be leading the research efforts for the acceleration scheme. Dr. Hegelich was previously at Los Alamos National Laboratory, where his group demonstrated laser-driven protons with record-breaking energies of over 160 MeV [7]. Although this is still not quite high enough for imaging, this project will be utilizing a much more powerful laser. With the Texas Petawatt Laser at UT Austin, the most powerful laser in the world, energies of over 300 MeV should be achievable.

There are several requirements that must be met in order to develop a useful, accurate, and commercially relevant system. These specifications are outlined in Table 2.

Table 2: Requirements for a Diagnostic pCT System

Specifications	
Energy	330 MeV
Intensity	10^6 protons/second
Detection rate	1 MHz
Size	Single room
Scan time	~5 minutes
Cost	Comparable to X-ray CT (~$5 million)

POTENTIAL CHALLENGES

Although previous research strongly suggests the feasibility of the proposed system, there are several aspects of this project that may present challenges. The biggest challenge will be the development of a novel acceleration scheme to achieve the necessary beam specifications for imaging. Current LDIA techniques can produce a high-energy beam, but with very high intensity (~10^9 protons/pulse) and extremely low repetition rate. This is essentially the opposite of an ideal beam for pCT, which would be a rapid stream of individual protons to simplify detection and reconstruction. There are several acceleration techniques currently being explored to overcome this problem, but if the intensity cannot be sufficiently reduced, there is also the option of improving the spatial resolution of the detectors. In other words, it may be possible to compensate for the inability to temporally resolve each proton history by instead resolving them better spatially.

The system must also be sufficiently fast to acquire the scan quickly enough to ensure patient comfort and perform the image reconstruction in a relatively short amount of time. To achieve this level of speed, a DAQ and reconstruction system similar to LLUMC's Phase II scanner will have to be developed, with a dedicated ASIC and GPU cluster.

Although the development of diagnostic pCT will require many years of research, development, and testing, the success of such a system would have a major impact on diagnostic imaging and patient safety. While there are some challenges in the implementation of this technology, as previously mentioned, this strong collaboration of institutions should have the necessary expertise and experience to overcome such hurdles.

REFERENCES

[1] D. J. Brenner and E. J. Hall, "Computed Tomography — An Increasing Source of Radiation Exposure," *New England Journal of Medicine*, vol. 357, no. 22, pp. 2277–2284, 2007.

[2] R.H. Huesman, A.H. Rosenfeld, and F.T. Solmitz, "Comparison of Heavy Charged Particles and X-Rays for Axial Tomograpic Scanning," California Univ., Davis (USA). Dept. of Engineering, LBL--3040, Sep. 1975.

[3] A.M. Cormack and A.M. Koehler, "Quantitative proton tomography: preliminary experiments," *Phys. Med. Biol.*, vol. 21, no. 4, p. 560, 1976.

[4] V. A. Bashkirov, R. W. Schulte, S. N. Penfold, and A. B. Rosenfeld, "Proton computed tomography: Update on current status," in *IEEE Nuclear Science Symposium Conference Record, 2007. NSS '07*, 2007, vol. 6, pp. 4685–4688.

[5] H.F.-W. Sadrozinski, et al., Nuclear Instruments & Methods In Physics Research A (2012), http://dx.doi.org/ 10.1016/j.nima.2012.04.029.

[6] "Advancements in proton therapy cause for celebration | symmetry magazine."; http://www.symmetrymagazine.org/breaking/2011/10/21/advancements-in-proton-therapy-cause-for-celebration.

[7] D. Jung, "Ion acceleration from relativistic laser nano-target interaction," Ph.D. Dissertation, LMU München: Fakultät für Physik, Munich, Germany, 2012.