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Proton radiography for clinical applications

C. Talamonti [a,b,c,*], V. Reggioli [a], M. Bruzzi [b,d], M. Bucciolini [a,b,c], C. Civinini [b], L. Marrazzo [c], D. Menichelli [b,d], S. Pallotta [a,b,c], N. Randazzo [e], V. Sipala [e,f], G.A.P. Cirrone [g], M. Petterson [h], N. Blumenkrantz [h], J. Feldt [h], J. Heimann [h], D. Lucia [h], A. Seiden [h], D.C. Williams [h], H.F.-W. Sadrozinski [h], V. Bashkirov [i], R. Schulte [i]

[a] *Dipartimento di Fisiopatologia Clinica, Università degli Studi di Firenze, v.le Morgagni 85, I-50134 Firenze, Italy*
[b] *INFN, sezione di Firenze, via G. Sansone 1, I-50019 Sesto Fiorentino (FI), Italy*
[c] *Azienda Ospedaliero-Universitaria Careggi, v.le Morgagni 85, I-50134 Firenze, Italy*
[d] *Dipartimento di Energetica, Università degli Studi di Firenze, via S. Marta 3, I-50139 Firenze, Italy*
[e] *INFN, sezione di Catania, via S. Sofia 64, I-95123 Catania, Italy*
[f] *Dipartimento di Fisica, Università degli Studi di Catania, via S. Sofia 64, I-95123 Catania, Italy*
[g] *Laboratori Nazionali del Sud-INFN, via S. Sofia 62, I-95123 Catania, Italy*
[h] *SCIPP, UC Santa Cruz, CA 95064, USA*
[i] *Loma Linda University Medical Center, CA 92354, USA*

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ABSTRACT

Proton imaging is not yet applied as a clinical routine, although its advantages have been demonstrated. In the context of quality assurance in proton therapy, proton images can be used to verify the correct positioning of the patient and to control the range of protons. Proton computed tomography (pCT) is a 3D imaging method appropriate for planning and verification of proton radiation treatments, because it allows evaluating the distributions of proton stopping power within the tissues and can be directly utilized when the patient is in the actual treatment position. The aim of the PRoton IMAging experiment, supported by INFN, and the PRIN 2006 project, supported by MIUR, is to realize a proton computed radiography (pCR) prototype for reconstruction of proton images from a single projection in order to validate the technique with pre-clinical studies and, eventually, to conceive the configuration of a complete pCT system. A preliminary experiment performed at the 250 MeV proton synchrotron of Loma Linda University Medical Center (LLUMC) allowed acquisition of experimental data before the completion of PRIMA project's prototype. In this paper, the results of the LLUMC experiment are reported and the reconstruction of proton images of two phantoms is discussed.

1. Introduction

Proton radiation therapy is a high-precision form of cancer therapy, and may be considered as the most promising improvement since the introduction of photon and electron radiation therapy. There has been a steadily increasing interest in proton therapy over the past 10 years. Proton beams can achieve highly localized dose distributions, which should result in higher probabilities for local tumour control and disease-free survival and lower probabilities for normal tissue damage for many different tumour sites. In radiation therapy, the more precise a treatment the more important is its technical quality. Therefore, to fully harness the power of proton radiation therapy, accurate and precise methods of dose calculation, proton range prediction, and verification of the patient position at the time of treatment are mandatory.

Several techniques have been proposed for proton planning and verification like those based on in-beam PET, prompt photons [1–3] and proton computed tomography; this paper is focused on the last technique.

At present, proton treatment centres utilize X-ray radiography or cone-beam CT to verify the position of the patient, and dose calculations rely on the patient morphology and electron densities obtained by X-ray CT. The CT Hounsfield numbers are then converted to proton stopping power relative to water using a calibration curve. This conversion can lead to errors in the calculation of proton range in patients of approximately of 5% [4]. For this reason, the advantage of using protons can be reduced in many clinical situations.

* Corresponding author. Dipartimento di Fisiopatologia Clinica, Università degli Studi di Firenze, v.le Morgagni 85, I-50134 Firenze, Italy. Tel.: +39 055 4360616; fax: +39 055 4379930.
E-mail address: cinzia.talamonti@unifi.it (C. Talamonti).

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A proton imaging device can improve the accuracy in proton radiation therapy treatment planning and in the alignment of the patient with the proton beam, since it can provide images with exactly the same geometrical conditions encountered during the treatment. The idea to use protons for imaging was investigated at the end of the 1960s [5,6], but was abandoned due to the development of X-ray CT and the limiting factors in the quality of the proton images, mostly the inferior spatial resolution. The poor spatial resolution, compared to X-ray images, is due to multiple scattering of protons in the patient, which makes reconstruction along straight lines inaccurate. Moreover, uncertainties in stopping power or electron density arise from energy loss straggling due to the momentum spread of the beam entering the patient, and from proton range straggling in the patient. However, proton-by-proton track reconstruction techniques based on the most likely path concept promise to improve the spatial resolution of pCR and pCT images. In addition, the measurement of the energy of each proton provides the best possible density resolution.

The first step to develop a pCT device is to construct a proton computed radiography (pCR) apparatus, capable to measure a single projection. The full tomography apparatus requires the rotation of the pCR device and suitable reconstruction algorithms.

Unlike images based on photon detection, proton radiographic images contain information on the range of protons passing through the patient. The energy loss is characterized by the proton stopping powers, which depend on the proprieties of the traversed materials. Their precise knowledge is essential for radiotherapy treatment planning. Therefore, proton radiographs can be used for imaging purposes and treatment verification.

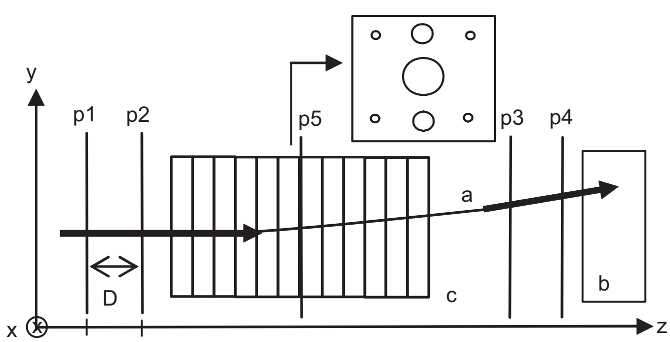

Fig. 1. Sketch of pCR system, in the test configuration A. The telescope (planes p1 to p4), the calorimeter (b) and a phantom (c) are shown. The phantom is composed of 12 PMMA homogeneous slabs, except one as indicated by the gray one. The plane p5 is sandwiched between the drilled slab and the subsequent one. A possible proton trajectory (a) is indicated as an illustration.

In literature, two different pCR approaches based on single particle tracking can be found. The group at Paul Scherrer Institute (PSI, Villigen, CH) proposed an apparatus made of two scintillating fiber hodoscopes, used to measure the entrance and exit coordinates, and a range telescope consisting of a stack of scintillator tiles [7,8] to determine the residual range. The "Fondazione TERA" (Novara, I), instead, is developing a similar system with gas electron multipliers as tracking detector [9].

The pCT apparatus originally proposed by the groups at the Santa Cruz Institute of Particle Physics (SCIPP, USA) and Loma Linda University Medical Center (LLUMC, USA), consists of a tracker made of silicon microstrip detectors used to measure the entrance and exit proton coordinates and angles [10,11]. In addition, a CsI calorimeter provides an independent measurement of proton residual energy [12]. After initial experiments with existing detector hardware, a pCT prototype for imaging head-size objects is now being developed in a collaboration between several US institutions, including SCIPP, LLUMC, Northern Illinois University (NIU), and the Centre of Medical Radiation Physics (CMRP) at the University of Wollongong, Australia [13].

The PRIMA collaboration, (INFN, University of Florence and University of Catania), is developing a pCR prototype based on single proton tracking and calorimetric energy measurement, capable of acquiring proton events at a 1 MHz rate. Similar to the design suggested by SCIPP and LLUMC, this device consists of a silicon microstrip tracker and a calorimeter to detect the residual energy [14]. The development of data analysis and reconstruction algorithms has been initiated using data from previous experiments. In particular, the data from a SCIPP-supported beam test at LLUMC have been considered [15]. The proton images of two phantoms obtained during this beam test are presented and discussed in detail in this paper.

2. Materials and methods

The beam test was performed at one of LLUMC's proton synchrotron research beam lines with 200 MeV protons. The protons had a negligible energy spread (<0.2 MeV) and were tracked with silicon strip detectors (SSDs) developed for the 1997 GLAST beam test [16]. A single CsI crystal calorimeter provided residual energy measurements and a trigger for the Si detector system readout.

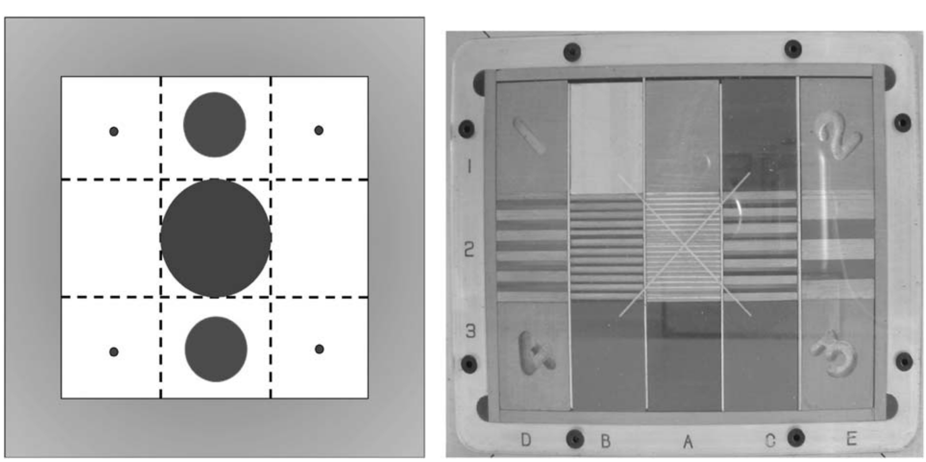

Fig. 2. Left: details of the drilled slab of the phantom used in the test configuration A. Right: QC3 phantom realized assembling material of different density. The red square indicates the area covered by the x–y plane.