University of Groningen

Proton radiography to improve proton therapy treatment

Takatsu, J.; van der Graaf, E. R.; van Goethem, Marc-Jan; van Beuzekom, M.; Klaver, T.; Visser, Jan; Brandenburg, S.; Biegun, A. K.

Published in:
Journal of Instrumentation

DOI:
[10.1088/1748-0221/11/01/C01004](https://doi.org/10.1088/1748-0221/11/01/C01004)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Takatsu, J., van der Graaf, E. R., van Goethem, M.-J., van Beuzekom, M., Klaver, T., Visser, J., Brandenburg, S., & Biegun, A. K. (2016). Proton radiography to improve proton therapy treatment. *Journal of Instrumentation*, 11, [01004]. <https://doi.org/10.1088/1748-0221/11/01/C01004>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

17TH INTERNATIONAL WORKSHOP ON RADIATION IMAGING DETECTORS
28 JUNE – 2 JULY 2015,
DESY, HAMBURG, GERMANY

Proton radiography to improve proton therapy treatment

J. Takatsu,^a E.R. van der Graaf,^b M.-J. Van Goethem,^c M. van Beuzekom,^d T. Klaver,^d
J. Visser,^d S. Brandenburg^b and A.K. Biegun^{b,1}

^a*Department of Radiation Oncology, Graduate School of Medicine, Osaka University,
2-2 D10 Yamadaoka, Suita, Osaka, 565-0871, Japan*

^b*KVI-Center for Advanced Radiation Technology, University of Groningen,
Zernikelaan 25, 9747AA Groningen, The Netherlands*

^c*Department of Radiation Oncology, University Medical Center Groningen, University of Groningen,
Hanzeplein 1, 9700 RB Groningen, The Netherlands*

^d*National Institute for Subatomic Physics (Nikhef),
Science Park 105, 1098 XG Amsterdam, The Netherlands*

E-mail: a.k.biegun@rug.nl

ABSTRACT: The quality of cancer treatment with protons critically depends on an accurate prediction of the proton stopping powers for the tissues traversed by the protons. Today, treatment planning in proton radiotherapy is based on stopping power calculations from densities of X-ray Computed Tomography (CT) images. This causes systematic uncertainties in the calculated proton range in a patient of typically 3–4%, but can become even 10% in bone regions [1–8]. This may lead to no dose in parts of the tumor and too high dose in healthy tissues [9]. A direct measurement of proton stopping powers with high-energy protons will allow reducing these uncertainties and will improve the quality of the treatment.

Several studies have shown that a sufficiently accurate radiograph can be obtained by tracking individual protons traversing a phantom (patient) [4, 6, 10]. Our studies benefit from the gas-filled time projection chambers based on GridPix technology [11], developed at Nikhef, capable of tracking a single proton. A BaF₂ crystal measuring the residual energy of protons was used. Proton radiographs of phantom consisting of different tissue-like materials were measured with a 30 × 30 mm² 150 MeV proton beam. Measurements were simulated with the Geant4 toolkit.

First experimental and simulated energy radiographs are in very good agreement [12]. In this paper we focus on simulation studies of the proton scattering angle as it affects the position resolution of the proton energy loss radiograph. By selecting protons with a small scattering angle, the image quality can be improved significantly.

KEYWORDS: Image reconstruction in medical imaging; Simulation methods and programs

¹Corresponding author.

Contents

1	Introduction	1
2	Proton radiography setup	1
2.1	Experiment and the simulation layout	1
2.2	Geant4 physics list	2
3	Proton energy loss and scattering angle	3
3.1	Energy loss radiograph	3
3.2	Proton scattering angle calculation and applied cuts	3
4	Summary and outlook	6

1 Introduction

Proton radiography is one of the novel imaging modalities, which has a potential to be widely used not only for patient positioning, but also as an alternative imaging tool in proton treatment. It delivers direct information about the stopping powers of different materials of an object through which the proton beam has passed. Currently, both 2-dimensional (2D) proton radiography and its 3D extension, proton CT (pCT), are under development in different laboratories [6, 10, 13–15]. With pCT several 2D measurements at different proton beam directions allow to determine a 3D map of proton stopping powers of imaged object. In both 2D and 3D measurements of an object under study, the image quality is reduced by the multiple Coulomb scattering and energy loss processes of protons in matter. These processes will affect the position resolution of a proton traversing different materials in the object, and will lead to blurring of the obtained images. The scattering angle distribution of protons passing through various materials was studied in order to assess the possibilities to reduce this blurring. In particular, we investigated the influence of selection of the proton scattering angle on the quality of the reconstructed energy radiograph.

2 Proton radiography setup

2.1 Experiment and the simulation layout

At the KVI-Center for Advanced Radiation Technology (KVI-CART) we performed an experiment with two GridPix-based gas-filled time projection chambers (TPCs), placed before and after a cylindrical phantom and measuring trajectories of individual protons. As a residual energy detector a BaF₂ crystal was used, which was placed behind the second position detector. The phantom was irradiated with a scattered proton beam with a size of $30 \times 30 \text{ mm}^2$ and the energy of 150 MeV. Details about the data collection, the experimental data analysis, together with comparison of the

Figure 1. (Left) Schematic view of the experimental setup in Geant4 simulation software with two position detectors before and after the phantom (red squares) and the residual energy detector (yellow cylinder). A cylindrical phantom with three solid inserts was placed between two position detectors. The track of a single proton is also shown. (Right) Sizes of the proton source, detectors and the cylindrical phantom together with distances between all elements in the simulated setup. A cross section of the phantom with all three inserts is sketched as well.

experimental proton energy loss radiograph to the simulated one are described elsewhere [12]. The experiment was simulated with the Geant4 simulation toolkit [16], where the beam size and the energy used in the simulations were the same as in the experiment. Also the implemented sizes of the detectors were also the same, except for the second position detector, for which the size in the simulations was increased from $30 \times 30 \text{ mm}^2$ (used in the experiment) to $100 \times 100 \text{ mm}^2$. With the bigger second position detector it was possible to cover essentially the full scattering angle range after the phantom (limited in the experiment). The scheme of the setup is shown in figure 1. Two red squares represent the position detectors, with sizes in x and y directions of $30 \times 30 \text{ mm}^2$ and $100 \times 100 \text{ mm}^2$ for the first and the second detector, respectively. In the simulations both position detectors have been considered as ideal detectors with 100% efficiency. The yellow cylinder in figure 1 represents the residual energy detector, for which BaF_2 was used, as in the experiment. The position detectors measured the x and y positions of a single proton before and after passing through the phantom, while the BaF_2 determined the residual energy of the proton. A cylindrical phantom (made in-house) was placed with its axis along the beam direction between the two position detectors (figure 1, left). The phantom with a diameter of 2.5 cm and a length of 2.5 cm was made of the CT solid water (Gammex 457, $\rho = 1.015 \text{ g/cm}^3$) and contained three cylindrical inserts, each with the same dimension of 0.8 cm diameter and the length of 2.5 cm. The inserts were made from PMMA ($\rho = 1.18 \text{ g/cm}^3$) and two tissue equivalent Gammex materials: adipose (Gammex 453, $\rho = 0.92 \text{ g/cm}^3$) and cortical bone (Gammex 450, $\rho = 1.82 \text{ g/cm}^3$) [17].

2.2 Geant4 physics list

In the simulations we used the Geant4.9.6p03 version with the standardized *QGSP_BIC_EMY* physics list, which is the combination of electromagnetic and hadronic physics, as suggested by Cirrone et al. [18] for medical physics applications. The *QGSP* (*Quark Gluon String Precompound*)

defines the hadronic models for nucleons, *BIC* (*Binary Ion Cascade*) defines the inelastic models for ions, and *EMY* (*ElectroMagnetic Y*) defines the electromagnetic models used by all the particles (Y indicates an EM physics particularly tailored for the use in medical physics). The *QGSP_BIC* physics uses a binary cascade for primary protons and neutrons with energies below 10 GeV. The standard electromagnetic physics in the *G4EmStandardPhysics_option3()* class changes the default value of the *finalRange* parameter, which describes the range for final step and is used in computation of the step limit by the ionization process. The *finalRange* parameter is reduced for e- and e+ to 0.1 mm and for protons to 0.05 mm, with respect to the default value of 1 mm [19].

The model that Geant4 uses for multiple scattering does not use the Molière formalism, but it is based on the more complete Lewis theory [20]. The model simulates the scattering of a particle after a given step, and also computes the path length correction and the lateral displacement. The angular and spatial distributions after each step are determined.

Any energy loss process in Geant4 must calculate the continuous and discrete energy loss in a material. Below a given energy threshold, which for secondary electrons varies between 331 keV and 492 keV (in materials of the studied phantom), the energy loss is continuous and above it the energy loss is simulated by the explicit production of secondary particles (gammas, e- and e+). After the *mean energy* loss has been calculated, the process computes the *actual* energy loss, including energy fluctuations, which are computed from a model described in section 7.2 of [20].

3 Proton energy loss and scattering angle

3.1 Energy loss radiograph

A proton from the beam passing through the different materials of the cylindrical phantom (PMMA, CT solid water, adipose and cortical bone) loses energy. The energy loss of each of the $50 \cdot 10^6$ generated protons was calculated as a difference between the proton beam energy of 150 MeV and the residual energy of proton recorded in the energy detector. The energy loss radiograph was created, as shown in figure 2. The size of each bin was $0.3 \times 0.3 \text{ mm}^2$.

Initially, no cut for proton scattering angle was applied, which results in a rather poor quality of the image. From the three insert materials (PMMA, adipose, cortical bone) only the highest density, cortical bone can be distinguished. The PMMA and adipose inserts, of which the densities are similar to each other and also similar to the surrounding material, CT solid water, are not recognizable in the energy loss image (figure 2). Therefore, a selection of protons is needed to enhance the contrast between materials in the phantom.

3.2 Proton scattering angle calculation and applied cuts

The scattering angle ϕ of a proton that passed through the phantom was calculated using the momentum vectors generated in the source ($\vec{p}_0$), before the phantom, and in the energy detector ($\vec{p}_3$), after the phantom, according to the following formula:

$$\phi(\text{rad}) = \arccos\left(\frac{\vec{p}_0 \vec{p}_3}{|\vec{p}_0| |\vec{p}_3|}\right) \quad (3.1)$$

where $(\vec{p}_0) = (p_{0x}, p_{0y}, p_{0z})$ and $(\vec{p}_3) = (p_{3x}, p_{3y}, p_{3z})$.

Figure 2. Proton energy loss radiograph of the cylindrical phantom obtained from Geant4 simulations for proton beam energy of 150 MeV. All protons were accepted (no cut for proton scattering angle). The phantom cylinder was made of CT solid water and filled with three cylindrical solid inserts of PMMA, adipose and the cortical bone.

The scattering angle distribution of the protons is shown in figure 3 (left). For most protons the angle between the in-going and out-going momentum was between 0 and 6 mrad. However, protons that passed the highest density material scattered more, with the largest scattering angle in the cortical bone material being 35 mrad. The approach to improve the quality of the energy radiograph was to select protons that passed through the phantom with various maximum scattering angles: 17.4, 8.7, 5.2 and 1.7 mrad, as marked in figure 3 (left) by blue dashed lines. Only protons with angles smaller than the maximum scattering angles were considered to build energy radiographs presented in figure 4.

The cuts on the proton scattering angle clearly improve the quality of the energy radiograph image. Considering protons with small scattering angles (5.2 mrad and even 1.7 mrad), which

Figure 3. (Left) Scattering angle distribution of protons calculated from momentum vectors according to the formula (3.1). No additional conditions were applied. Blue dashed lines show the applied scattering angle cuts. (Right) Proton scattering angle radiograph of the cylindrical phantom, with no cut for proton scattering angle.

Figure 4. Proton energy radiographs of the phantom for different scattering angle cuts as marked in figure 3 (left): 17.4 mrad (top-left), 8.7 mrad (top-right), 5.2 mrad (bottom-left) and 1.7 mrad (bottom-right).

correspond to protons travelling along almost straight paths, the blurring of the energy radiograph image decreases significantly. This allows distinguishing different insert materials in the phantom with similar densities, which is not possible when all protons were considered. The inserts are clearly visible and the edges between materials are sharp. The sharpness of the material boundaries is measured by so-called *Delta* parameter (figure 5), which is calculated as a difference in position

Figure 5. *Delta* parameter representing the sharpness of material boundaries for different proton maximum scattering angles: 17.4, 8.7, 5.2 and 1.7 mrad. Different symbols represent *Delta* between two different materials in the phantom.

taken at 90% and 10% of the slope between two materials (CT solid water and cortical bone, CT solid water and PMMA, and CT solid water and adipose). A decrease of the *Delta* parameter means that the edge between two materials is sharper, improving the image quality. For protons that scattered less than 5.2 mrad *Delta* is smaller than or equal to 1.5 mm.

The sharpness of the material boundaries is obtained at the cost of the number of events that had to be rejected. From $50 \cdot 10^6$ generated protons almost all of them (99.98%) passed the first condition of being registered by all three detectors. Applying the cut for maximum proton scattering angle it decreased the number of protons that were used to create the energy radiograph image, as demonstrated in table 1.

Table 1. Accepted protons (in %) after different maximum scattering angles cuts used to create the energy radiography images.

Scattering angle cut (mrad)	Number of accepted protons (%)
No selection	100.0
17.4	82.1
8.7	58.1
5.2	42.3
1.7	9.3

The highest quality of the proton radiography image was obtained for the scattering angle cuts of 5.2 and 1.7 mrad (figure 4, lower panel). In case of the proton maximum scattering angle cut of 5.2 mrad, the percentage of accepted protons to create the energy radiograph was 42.3%. Most of the considered protons are located in the peak shown in figure 3 (left). The edges between materials are the sharpest for the case of the maximum scattering angle cut of 1.7 mrad, but only a very small fraction of the generated protons (9.3%) are taken into account, which makes the use of such angular cut very inefficient. Thus, the maximum proton scattering angle cut of 5.2 mrad gives the best trade-off between image quality and efficiency.

4 Summary and outlook

In this paper we discuss the analysis of proton energy loss radiography images and studies of the influence of the proton scattering angle cuts on the quality of the energy loss image. In our approach a cut on the maximum scattering angle of the proton was applied. The results in figure 4 show that the selection giving the best quality of the energy loss radiograph is for a maximum proton scattering angle of 1.7 mrad (figure 4, bottom-right image). The drawback of this selection is a very high percentage of rejected protons (90.7 %), which makes it highly inefficient. For a maximum scattering angle of 5.2 mrad nearly 50% of the protons were used, while the image quality is almost not affected.

Further study with the selection of the proton scattering angle is being performed. A more complex phantom with more tissue-equivalent materials has been built and implemented in the Geant4 code. More materials are inserted on the beam path simulating in more realistic way a patient geometry.

Acknowledgments

We would like to thank the staff of the Millipede cluster (www.rug.nl/cit/hpcv/faciliteiten/HPCCluster) of the University of Groningen (The Netherlands), where the Monte Carlo simulations were performed. This work was partially supported by the Japan Society for Promotion of Science Core-to-Core Program (number 23003).

References

- [1] U. Schneider and E. Pedroni, *Proton radiography as a tool for quality control in proton therapy*, *Med. Phys.* **22** (1995) 353.
- [2] U. Schneider, E. Pedroni and A. Lomax, *The calibration of CT Hounsfield units for radiotherapy treatment planning*, *Phys. Med. Biol.* **41** (1996) 111.
- [3] W. Schneider, T. Bortfeld and W. Schlegel, *Correlation between CT numbers and tissue parameters needed for Monte Carlo simulations of clinical dose distributions*, *Phys. Med. Biol.* **45** (2000) 459.
- [4] G. Cirrone et al., *The Italian project for a proton imaging device*, *Nucl. Instrum. Meth. A* **576** (2007) 194.
- [5] H. Paganetti, *Range uncertainties in proton therapy and the role of Monte Carlo simulations*, *Phys. Med. Biol.* **57** (2012) R99.
- [6] T. Plautz et al., *200 MeV Proton Radiography Studies with a Hand Phantom Using a Prototype Proton CT Scanner*, *IEEE Trans. Med. Imag.* **33** (2014) 875.
- [7] G. Landry et al., *Deriving concentrations of oxygen and carbon in human tissues using single- and dual-energy CT for ion therapy applications*, *Phys. Med. Biol.* **58** (2013) 5029.
- [8] J. Schuemann et al., *Site-specific range uncertainties caused by dose calculation algorithms for proton therapy*, *Phys. Med. Biol.* **59** (2014) 4007.
- [9] A.-C. Knopf and A. Lomax, *In vivo proton range verification: a review*, *Phys. Med. Biol.* **58** (2013) R131.
- [10] V. Sipala et al., *A proton Computed Tomography system for medical applications*, in proceedings of the 14th International Workshop on Radiation Imaging Detectors (IWORID2012), Figueira da Fox, Portugal, 1-5 July 2012, [2013 JINST 8 C02021](#).
- [11] H. van der Graaf, *GridPix: An integrated readout system for gaseous detectors with a pixel chip as anode*, *Nucl. Instrum. Meth. A* **580** (2007) 1023.
- [12] A.K. Biegun et al., *Proton Radiography with Timepix based Time Projection Chambers*, accepted to *IEEE Trans. Med. Imag.* (2015).
- [13] H. Ryu et al., *Density and spatial resolutions of proton radiography using a range modulation technique*, *Phys. Med. Biol.* **53** (2008) 5461.
- [14] U. Schneider and E. Pedroni, *Multiple Coulomb scattering and spatial resolution in proton radiography*, *Med. Phys.* **21** (1994) 1657.
- [15] G. Poludniowski, N.M. Allinson and P.M. Evans, *Proton radiography and tomography with application to proton therapy*, *Brit. J. Radiol.* **88** (2015) 20150134.
- [16] S. Agostinelli et al., *Geant4—a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250.
- [17] <http://www.gammex.com/>.

- [18] G.A. Pablo Cirrone et al., *Hadrontherapy: A Geant4-Based Tool for Proton/Ion-Therapy Studies*, *Prog. Nucl. Sci. Technol.* **2** (2011) 207.
- [19] http://geant4.web.cern.ch/geant4/collaboration/working_groups/electromagnetic/physlist9.6.shtml#opt3.
- [20] <http://geant4.web.cern.ch/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/>.