Radiation Physics and Chemistry ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

A comparison of two prompt gamma imaging techniques with collimator-based cameras for range verification in proton therapy

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HIGHLIGHTS

- Collimator-based cameras for range verification in proton therapy are compared.
- The knife-edge system achieves higher efficiency and lower influence of neutron contamination.
- The multi-slit system has sharper slope in distant falloff of PG distribution.
- Both collimator systems achieve reasonable accuracy in range prediction.

ARTICLE INFO

Article history:
Received 29 November 2015
Received in revised form
10 April 2016
Accepted 29 April 2016

Keywords:
Proton therapy
Range verification
Prompt gamma
Collimator-based camera

ABSTRACT

In vivo range verification plays an important role in proton therapy to fully utilize the benefits of the Bragg peak (BP) for delivering high radiation dose to tumor, while sparing the normal tissue. For accurately locating the position of BP, camera equipped with collimators (multi-slit and knife-edge collimator) to image prompt gamma (PG) emitted along the proton tracks in the patient have been proposed for range verification. The aim of the work is to compare the performance of multi-slit collimator and knife-edge collimator for non-invasive proton beam range verification. PG imaging was simulated by a validated GATE/GEANT4 Monte Carlo code to model the spot-scanning proton therapy and cylindrical PMMA phantom in detail. For each spot, 10^8 protons were simulated. To investigate the correlation between the acquired PG profile and the proton range, the falloff regions of PG profiles were fitted with a 3-line-segment curve function as the range estimate. Factors including the energy window setting, proton energy, phantom size, and phantom shift that may influence the accuracy of detecting range were studied. Results indicated that both collimator systems achieve reasonable accuracy and good response to the phantom shift. The accuracy of range predicted by multi-slit collimator system is less affected by the proton energy, while knife-edge collimator system can achieve higher detection efficiency that lead to a smaller deviation in predicting range. We conclude that both collimator systems have potentials for accurately range monitoring in proton therapy. It is noted that neutron contamination has a marked impact on range prediction of the two systems, especially in multi-slit system. Therefore, a neutron reduction technique for improving the accuracy of range verification of proton therapy is needed.

1. Introduction

Proton therapy uses high energy proton beam for cancer treatment and is known for its theoretically superior radiation dose benefits compared to photons due to the low entrance dose and the sharp Bragg peak (BP) at the end of the proton range (Lomax et al., 2004). However, range uncertainties in the proton beam may lead to target underdose or normal tissue overdose (Smith, 2009). As a result, additional margins are required to ensure adequate target coverage, thus reducing the superiority of protons over photons. In order to fully utilize the potential advantage of proton therapy, the range of proton beams in the patient needs to be predicted as accurately as possible in the delivering process. The range verification with in-vivo measurements would provide additional information about the treatment and could lead to a reduction of margins (Paganetti, 2012).

Prompt gamma (PG) is emitted in the decay process from an excited nucleus to its ground state following proton–nuclear

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http://dx.doi.org/10.1016/j.radphyschem.2016.04.020
0969-806X/

interaction. There is a strong correlation between the region of PG emission and dose deposition by the proton beam. Therefore, detection of the PG enabled the accurate determination of the proton range (Min et al., 2012). This is a promising method for *in vivo* range verification of proton (Min et al., 2006). PG measurements including Compton camera system (active shielding) (Peterson et al., 2010) and collimator-based camera (passive shielding) (Gueth et al., 2013; Smeets et al., 2012) have been performed over the last few years. The former uses multistage detectors for cascade photon detection and can provide three-dimensional prompt gamma image. However, due to the inefficiency in detecting the high energy PG, the Compton camera is very low in sensitivity and less effective in range verification with clinically acceptable dose rates at present. The latter shows a relatively simple design for range verification in proton therapy. Although, current collimator-based cameras merely provide one-dimensional imaging and prone to neutron contamination, the higher efficiency and more accurately retrieved information about the proton range have been verified as a quite feasible method in clinical application by several research groups (Gueth et al., 2013; Smeets et al., 2012).

In this study, we focused on prompt gamma imaging with collimator-based cameras including multi-slit collimator (Gueth et al., 2013) and knife-edge collimator (Smeets et al., 2012) for range verification. Although both PG detection systems are being studied by several groups, work comparing these two systems is limited (Cambraia Lopes et al., 2012). To this end, our goal is to evaluate the performance of the two PG detection systems as an independent tool for non-invasive proton beam range verification. This paper is organized as follows. Section 2.1 gives details on the simulation parameters used for the used Monte Carlo codes. Sections 2.2, 2.3 describe, respectively, the common set-up, and the procedure of data analysis in detection profile. Results are given in Section 3 that evaluate the dependence of the performance of the two PG cameras on different parameters including proton energy, phantom sizes, and phantom shifts. Advantages and limitations are discussed in Section 4.

2. Materials and methods

2.1. Monte-Carlo simulations

The GATE platform, based on GEANT4 toolkit, is an MC simulation application enabling modeling of emission tomography, transmission tomography and extending to radiation therapy recently (Jan et al., 2011). The GATE platform can provide both features of radiotherapy application and modeling of complex collimator/detector, making it easy to meet our anticipated needs for studying prompt gamma imaging during proton therapy within the same framework. GATE version 6.1, based on GEANT4 version 9.4 p01, was used. We used the physics list proposed by (Grevillot et al., 2011), which considered both electromagnetic process and hadronic process. For electromagnetic process, the Opt3 electromagnetic standard package parameters were selected. G4UHadronElasticProcess combined with the G4HadronElastic model was used for elastic hadronic (HAD) interactions and Binary Cascade (BC) model for inelastic HAD interactions. The BC model was used for energies higher than 14 MeV, and high precision neutron package (Neutron HP) was used to transport neutrons down to thermal energies for neutrons. The range cut-off for gamma, electrons and positrons was set to be 0.1 mm.

Although this work focuses on the comparison of collimator-based PG systems under the same MC simulation environment, the hadronic models used by this study needed to be benchmarked. Such validation was performed by comparing GATE simulations with the yields and energy distributions of secondary particles reported by (Robert et al., 2013). We reproduced the experimental set up used by Robert et al., which is performed by using a perfect line beam of 10^7 protons irradiating a PMMA phantom ($C_5H_8O_2$, $10 \times 10 \times 60$ cm^3). The comparison of yields of secondary particles exiting from the target obtained by Robert et al. and the current model was listed in Table 1. The current MC model underestimated the yields of secondary particles (up to ~8%) as obtained by Robert et al., but the photon-to-neutron ratio between the two is found quite close. The shapes of the energy distributions are similar to those of Robert et al., (Fig. 1); All the major gamma lines are reliably reproduced by our MC model, despite the slight discrepancies in the magnitude of each gamma line.

Table 1
Comparison of yields of outgoing particles per primary particle obtained by Robert et al. and the current model for a 134 MeV proton beam irradiating a homogeneous PMMA phantom.

Particles	Current model	Robert et al.
Photon (> 1 MeV)	0.086895	0.094496
Neutron	0.082304	0.087136
Proton	0.001200	0.001292

2.2. Simulation setup for the prompt gamma imaging

Fig. 2 illustrates the configurations for the multi-slit system (Gueth et al., 2013) and the knife-edge system (Smeets et al., 2012). For both systems, the volume of detector was $360 \times 400 \times 50$ mm^3 (transaxial, axial and depth directions) with each LYSO crystal of size $2 \times 2 \times 50$ mm^3. The detector was located at 600 mm from the phantom perpendicular to the beam direction. Both collimators were placed halfway between the phantom and detector to create a 1:1 projected image of the PG. The collimator in the multi-slit system consisted of 100 lead septa each with size of $2 \times 400 \times 200$ mm^3 (Min et al., 2012) and space of 2 mm. The knife-edge collimator was similar to a slit collimator with thickness of 60 mm, height 400 mm, and a total volume of $400 \times 400 \times 60$ mm^3. The slit width was 6 mm with slit angle of 63° (Smeets et al., 2012).

We simulated a mono-energetic Gaussian proton pencil beam (FWHM = 11.775 mm) directly incident onto the center of a 200 mm long cylindrical PMMA phantom. A single spot of 10^8 protons was considered for each simulation run. Five realizations

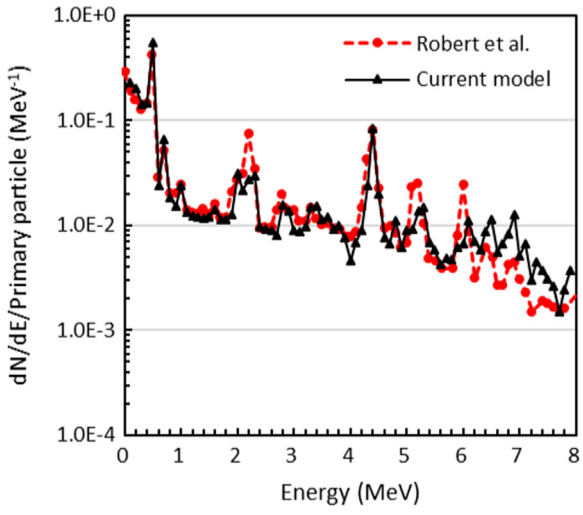

Fig. 1. Outgoing photon energy distributions per primary particle exiting from the PMMA target obtained by the current model and Robert et al.

Please cite this article as: Lin, H.-H., et al., A comparison of two prompt gamma imaging techniques with collimator-based cameras for range verification in proton therapy. Radiat. Phys. Chem. (2016), http://dx.doi.org/10.1016/j.radphyschem.2016.04.020