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Sensitivity of a prompt-gamma slit-camera to detect range shifts for proton treatment verification

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ABSTRACT

Background and purpose: A prompt-gamma imaging (PGI) slit-camera was recently applied successfully in clinical proton treatments using pencil beam scanning (PBS) and double scattering (DS). However, its full capability under clinical conditions has still to be systematically evaluated. Here, the performance of the slit-camera is systematically assessed in well-defined error scenarios using realistic treatment deliveries to an anthropomorphic head phantom.

Materials and methods: The sensitivity and accuracy to detect introduced global and local range shifts with the slit-camera was investigated in PBS and DS irradiations. For PBS, measured PGI information of shifted geometries were compared spot-wise with un-shifted PGI information derived from either a reference measurement or a treatment-plan-based simulation. Furthermore, for DS and PBS the integral PGI signal of the whole field was evaluated.

Results: Deviations from the treatment plan were detected with an accuracy better than 2 mm in PBS. The PGI simulation accuracy was well below 1 mm. Interfractional comparisons are more affected by measurement noise. The field-integral PGI sum signal allows the detection of global shifts in DS.

Conclusions: Detection of global and local range shifts under close-to-clinical conditions is possible with the PGI slit-camera. Especially for PBS, high sensitivity and high accuracy in shift detection were found.

The high sensitivity of proton range to uncertainties and changes of the material in the beam path limits the precision of proton therapy [1–7]. The reduction of these uncertainties would translate into margin reductions and reduce dose delivered to healthy tissue, which would likely increase the clinical benefit of proton therapy. Verification of the proton range in patients has been pursued as important to reduce range uncertainties. Along the trajectory of high-energy protons, secondary prompt-gamma radiation [8] is instantaneously emitted and can be used for non-invasive in-vivo range verification without additional dose exposure [1,2]. Different detection approaches resolve either energetic, temporal or spatial distribution of prompt-gamma emission, namely prompt-gamma spectroscopy [9], prompt-gamma timing [10–12] and prompt-gamma imaging (PGI) [13–17], respectively.

So far, only one prompt-gamma-based system has been applied clinically [18], the so-called PGI slit-camera [16,19]. In a proof-of-principle application, we monitored several fractions in double scattering (DS) for two patients and the PGI sum-signal, averaged over the entire treatment field, was compared with dose recalculation on control CTs. Whereas in one patient there was a good agreement [18], for the other, the dose recalculation revealed mild under- and over-ranges in different parts of the treatment field, but no relevant shift was detected in the PGI sum-signal. In DS mode, the possibility of partial or full compensation of different local range shifts within one treatment field is a general limitation of PGI range verification. Very recently, the slit-camera was applied during a pencil beam scanning (PBS) patient treatment [20].

Previous proof-of-principle phantom studies demonstrated the general applicability of the slit-camera [16,18,19,21–23]. However,

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several simplifications were used, e.g. one-spot pencil beam plans with non-clinical spot doses used in one-dimensional heterogeneous phantoms [21] or DS investigations in an anthropomorphic phantom were limited to global range shifts [21,23]. Furthermore, no comparison between PGI measurement and simulation was performed. Therefore, this study aims for the first comprehensive evaluation of the sensitivity to detect range shifts of different type and magnitude in close-to-clinical scenarios – using a realistic three-dimensional anthropomorphic geometry, clinical dose rate, spot doses and positioning systems. Moreover, the same experimental settings in DS and PBS allow the direct comparison of the slit-camera sensitivity in both modes. Altogether, the aim of this systematic study with known ground truth is a better understanding and interpretation of future clinical PGI applications.

Material and methods

PGI slit-camera

The slit-camera projects the prompt-gamma distribution through a knife-edge slit-collimator on a segmented detector, resulting in a one-dimensional spatially resolved prompt-gamma distribution. Although the slit-camera was originally developed for application in PBS, it can also be applied in DS [18,21]. Technical details are given in [16,21,23]. Range monitoring parameters were chosen as in clinical application [18,21]. The slit-camera is positioned next to the phantom, with the collimator opening parallel to the beam. The field of view (FOV) is approximately 10 cm along the beam axis and focused on the distal part of the target volume [16,19,22]. The experimental setup is presented in Fig. 1.

Treatment planning and irradiation

A clinical target volume (CTV = 142 cm^3), representing a brain tumor (e.g. glioblastoma) in the temporal lobe, was defined in an anthropomorphic head phantom (CIRS, Norfolk, USA) [24] by an experienced oncologist. The phantom consists of tissue-equivalent material with known stopping-power-ratio (SPR) used for phantom-specific CT-number-to-SPR conversion [25]. A pseudo-monoenergetic CT dataset (79 keV), calculated from a dual-energy CT scan (80/140 kVp, SOMATOM Definition AS, Siemens Healthineers, Forchheim, Germany), was used for treatment planning [26].

The DS treatment was planned with XiO5 (Elekta AB, Stockholm, Sweden). According to the clinical protocol, the dose was prescribed to the CTV, the beam was extended with a lateral margin of 3 mm and a range uncertainty margin of ±(3.5% + 2 mm) was applied.

Table 1
Introduced global and local shifts in water and brain tissue surrogate.

Acronym	Type	Shift in water/mm	Shift in brain/mm
G-10	Global	10.3	9.9
G-7	Global	7.2	6.9
G-5	Global	5.2	5.0
L-10	Local	10.4	10.0
L-7	Local	7.4	7.1
L-4	Local	4.0	4.0

In PBS, an isotropic CTV extension of 3 mm was used to account for setup uncertainty, while range uncertainty of ±3.5% was considered in robust optimization with respect to CTV. A single-field uniform dose (SFUD) and an intensity-modulated proton therapy (IMPT) treatment were calculated with RayStation4.7 (RaySearch Laboratories AB, Stockholm, Sweden).

For all three plans (IMPT, SFUD, DS) consisting of two equally-weighted fields, a total photon-equivalent dose of 60 Gy (assuming a constant relative biological effectiveness of 1.1) with 2 Gy/fraction was prescribed to the target volume, resulting in ≈1 Gy/field. To distinguish the influence of statistical noise, for each modality an additional high-dose plan (5 Gy/field) was calculated. For all cases, only one of the two fields (gantry angle: 270°) was monitored with the slit-camera.

The experiments were performed at the clinical proton facility at OncoRay (Dresden, Germany) applying clinical dose-rates (nominally 2 Gy/min in DS; protons-per-spot histograms for IMPT and SFUD are presented in Supplement A). Range shifts of known magnitude were introduced (Table 1). For global shifts, water-equivalent material (RW3, PTW, Freiburg, Germany) covering the complete beam exit was used. For local shifts cylindrical slabs (Ø = 5 cm) of Gammex tissue substitutes (Sun Nuclear GmbH, Neu-Isenburg, Germany) were positioned at the center of the snout.

Data evaluation

Three application scenarios were evaluated: (a) Spot-wise analysis of absolute deviations from the treatment plan in PBS (comparing PGI measurements with simulations based on the treatment plan); (b) Spot-wise analysis of interfractional shifts in PBS (comparing two measurements with and without shift); and (c) Analysis of PGI information integrated over the entire treatment field, the so-called PGI sum-signal, for DS and PBS.

Range differences between a measured PGI profile and a (measured or simulated) reference profile were determined using

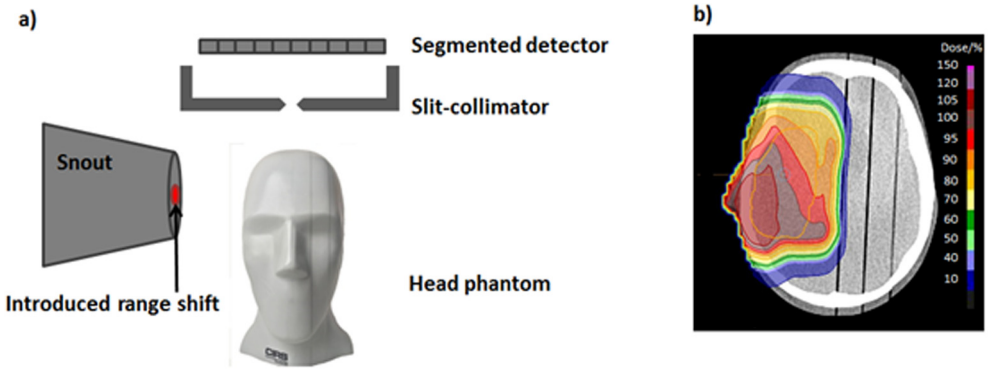

Fig. 1. (a) Experimental setup. (b) IMPT plan for the monitored beam only; CTV in orange.

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