ORIGINAL PAPER

Experimental validation of a 4D dose calculation routine for pencil beam scanning proton therapy

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Received 8 March 2017; accepted 25 July 2017

Abstract

Respiratory induced organ motion poses a major challenge for high-precision radiotherapy such as pencil beam scanning proton therapy (PBS). In order to employ PBS for target regions affected by respiratory motion, the implementation of dedicated motion mitigation techniques should be considered and residual uncertainties need to be assessed. For the latter purpose, a routine simulating the delivery of a scanned proton beam to a moving target was developed and implemented in the commercial treatment planning system RayStation. The time structure of the beam delivery was extracted from electronic irradiation protocols of the delivery system. Alternatively to electronic irradiation protocols, an empirical time model of the beam delivery was created to allow for prospective estimations of interplay effects between target motion and pencil beam scanning. The experimental validation of the routine was performed using a two-dimensional ionization chamber array and a dynamic phantom. A 4D CT data set, including 10 respiratory phases, provided the spatial temporal information about the phantom motion.

Experimentelle Validierung einer 4D-Dosisberechnungsroutine für die Pencil Beam Scanning Protonentherapie

Zusammenfassung

Atmungsbedingte Organbewegungen stellen eine große Herausforderung für hochpräzise Formen der Strahlentherapie, wie der Pencil Beam Scanning Protonentherapie (PBS), dar. Um dennoch von der dreidimensionalen konformalen Bestrahlung der PBS-Technik für bewegte Zielvolumina profitieren zu können, müssen Methoden zur Verringerung von Bewegungsunsicherheiten evaluiert und verbleibende Abweichungen von der nominellen Dosisverteilung abgeschätzt werden. Zu diesem Zweck wurde eine Routine entwickelt und innerhalb der kommerziellen Bestrahlungsplanungssoftware RayStation implementiert, die die Strahlapplikation eines magnetisch gelenkten Nadelstrahls bei gleichzeitiger Organbewegung („Interplay“) simuliert. Die zeitliche Struktur des Scanvorgangs

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Z. Med. Phys. **xxx** (2017) xxx–xxx
http://dx.doi.org/10.1016/j.zemedi.2017.07.005
www.elsevier.com/locate/zemedi

The dosimetric comparison of the measured and the calculated dose distribution yielded gamma pass rates above 96% using a 3% dose difference and a 3 mm distance to agreement criterion. Thus, a tool for the evaluation of interplay effects is available in a clinical software environment and patient-specific quality assurance can be extended to dynamic treatment scenarios.

Keywords: Proton therapy, Pencil beam scanning, Respiratory motion, Interplay effect, 4D dose calculation

wurde den elektronischen Bestrahlungsprotokollen entnommen. Alternativ zu Bestrahlungsprotokollen wurde ein empirisches Zeitmodell des Strahlverlaufs aufgestellt, um Auswirkungen des Zusammenspiels von Organ- und Strahlbewegung prospektiv untersuchen zu können. Die experimentelle Validierung der Routine erfolgte mit einer zweidimensionalen Ionisationskammer-Matrix in einem dynamischen Phantom. Ein 4D-CT-Datensatz mit zehn Atemphasen lieferte die räumlich-zeitlichen Informationen über die Phantombewegung. Der dosimetrische Vergleich der gemessenen und der berechneten Dosisverteilung ergab für alle Messungen Quoten von über 96% für das Bestehen der Gammaanalyse bei einem Akzeptanzkriterium von 3% für die relative Dosisabweichung und 3 mm für die Ortsabweichung. Somit steht ein Werkzeug zur Untersuchung von Interplay-Effekten in einer klinischen Softwareumgebung zur Verfügung und die patientenspezifische Qualitätssicherung kann auf dynamische Behandlungsszenarien ausgeweitet werden.

Schlüsselwörter: Protonentherapie, Pencil Beam Scanning, Atembewegung, Interplay-Effekt, 4D-Dosisberechnung

1 Introduction

Charged particle beams provide a localized energy deposition for the treatment of tumors owing to their characteristic absorption profile. This allows for normal-tissue sparing and a possible dose escalation in the tumor. In particle therapy, including proton therapy, a distinction is made between passive and active beam delivery techniques. Compared with passive scattering techniques, active pencil beam scanning (PBS) benefits from some considerable advantages: (1) a conformal dose distribution both at the distal and proximal edge of the target, (2) the absence of patient specific hardware and (3) the option to modulate the intensity allowing for multi-field optimization strategies. However, the high conformal dose delivery involves additional risks. Since pencil beam scanning and organ motion occur on a similar time scale, their interplay can lead to serious under- and overdosage of the target and organs at risk, an effect known as interplay effect [1–4]. Nevertheless, there is a clear trend towards PBS including treatment of moving targets [5,6]. The number of particle therapy centers equipped with active scanning systems grows and first of them recently started treating tumors in liver and lung with pencil beams (see [5] for examples). A translation from latest research results into clinical application becomes therefore an increasingly important task.

Various approaches have been made to mitigate motion induced effects, such as four-dimensional treatment planning, rescanning, gating or beam tracking (see [7–12] and references therein). The interplay effect – although reduced – persists on a low level for some of the above supplementary techniques. This also holds for localizations with moderate motion amplitude which could be treated without these supplementary techniques. Thus, modeling of the interplay effect is a key ingredient of motion management in PBS to evaluate the available options and determine residual deviations from the intended dose distribution. So far the impact of interplay effects has been subject of numerous investigations both experimental and in silico [13–17], but there are only a few approaches for the experimental validation of the 4D dose calculation itself [18–20].

The present study focuses on an end-to-end test of a customized routine simulating interplay effects in PBS proton therapy within a clinical framework. For this purpose, a dynamic technical phantom underwent 4D CT acquisition, treatment planning and irradiation, followed by a dosimetric analysis. The time structure of the fields delivered with multiple pencil beam spots was taken from electronic irradiation protocols, hereafter referred to as log files. As an alternative, a time model for the beam dynamics was established based on empirical measurements to prospectively estimate the effects of the interplay.

We followed a strategy to separate tasks for validation of PBS for moving targets, i.e. the end-to-end test does not use an anthropomorphic phantom [21] or an elastic phantom, which would enable to test the deformable registration. This study extends previous work with its beam time model and a more