Physica Medica xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

Original paper

Visualization of air and metal inhomogeneities in phantoms irradiated by carbon ion beams using prompt secondary ions

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A R T I C L E I N F O

Article history:
Received 17 August 2016
Received in Revised form 19 April 2017
Accepted 9 May 2017
Available online xxxx

The results presented in this publication are part of Gaa, Tanja: Visualization of inhomogeneities in a phantom irradiated by carbon ion beams using prompt secondary ions, Master thesis, University of Heidelberg, 2014.

Keywords:
Carbon ion beam radiotherapy
Non-invasive beam monitoring
Secondary ions
Pixelized detector Timepix

A B S T R A C T

Purpose: Non-invasive methods for monitoring of the therapeutic ion beam extension in the patient are desired in order to handle deteriorations of the dose distribution related to changes of the patient geometry. In carbon ion radiotherapy, secondary light ions represent one of potential sources of information about the dose distribution in the irradiated target. The capability to detect range-changing inhomogeneities inside of an otherwise homogeneous phantom, based on single track measurements, is addressed in this paper.
Methods: Air and stainless steel inhomogeneities, with PMMA equivalent thickness of 10 mm and 4.8 mm respectively, were inserted into a PMMA-phantom at different positions in depth. Irradiations of the phantom with therapeutic carbon ion pencil beams were performed at the Heidelberg Ion Beam Therapy Center. Tracks of single secondary ions escaping the phantom under irradiation were detected with a pixelized semiconductor detector Timepix. The statistical relevance of the found differences between the track distributions with and without inhomogeneities was evaluated.
Results: Measured shifts of the distal edge and changes in the fragmentation probability make the presence of inhomogeneities inserted into the traversed medium detectable for both, 10 mm air cavities and 1 mm thick stainless steel. Moreover, the method was shown to be sensitive also on their position in the observed body, even when localized behind the Bragg-peak.
Conclusions: The presented results demonstrate experimentally, that the method using distributions of single secondary ion tracks is sensitive to the changes of homogeneity of the traversed material for the studied geometries of the target.

1. Introduction

The aim of radiation therapy is to treat cancer cells with radiation dose sufficient to stop their growth and simultaneously to spare the surrounding healthy tissue. To avoid side effects, a high dose conformation to the target volume is desirable. The sharp distal fall-off of the dose deposition behind the Bragg peak makes particle irradiation suitable for tumors close to critical structures. The beam range can be adapted according to the distal end of the tumor volume. A three dimensional target volume can be covered with a Spread out Bragg peak (SOBP), produced by superimposing beams with different energies, which are weighted in terms of number of particles per pencil beam, in order to obtain the required dose distribution.

Delivering highly conformed dose to the target demands high accuracy in the treatment planning and beam delivery systems. In ion beam radiotherapy, the final dose distribution in the patient exhibits strong susceptibility to patient alignment and inter- and intrafractional displacements. Possible misalignments of the patient position, anatomical changes within the patient body, or organ motion during the treatment course can influence the stopping power in the patient and thus the final dose distribution.

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http://dx.doi.org/10.1016/j.ejmp.2017.05.055
1120-1797/

Therefore, in addition to quality assurance of the ion beam as delivered by the machine, monitoring the dose deposition within the patient during irradiation is desired.

Due to the complete stopping of the primary ion beam in the patient, investigations focus mainly on exploiting information carried by secondary radiation, which may leave the patient. Evaluation of the quality of the beam delivery within the patient has been shown to be feasible by measurement of activity distribution of positron-emitting isotopes created in nuclear interactions of the therapeutic beam with patient tissue [1,2]. Positron emission tomography (PET) scanners are used as radiation detectors. However, this method suffers from physiological washout of the signal caused by blood flow and other physiological processes, its smearing and the rapid decay with time [3,4]. If the measurements are performed offline, prolonged data acquisition times are required [5,6]. Therefore, alternative monitoring methods are of interest.

Another potential source of information, which could be used for treatment monitoring, is the prompt radiation produced in nuclear interactions of the beam with tissue. Prompt photons [7–9] and prompt secondary ions [10,11] are currently under investigation. Due to the emission time scales of less than 10^{-9} s, impairment of the signal by physiological processes is excluded. In contrast to the PET based monitoring techniques, for both types of prompt radiation there are currently no dedicated detection techniques to measure the directions of single particles. In case of prompt photons their high energies in the MeV range make the radiation highly penetrating, what makes its detection and separation from the neutron background challenging. On the contrary, secondary ions, which are investigated also in this contribution, are heavy charged particles and thus exhibit denser ionization leading to a relatively high signal. However, they require detectors which were up to now not used for medical purposes. Therefore, the development and evaluation of this technique needs a considerable amount of further research, in order to be able to test its potential in clinical applications [12].

For the design of the dedicated detection techniques, properties of the secondary ions and their distribution have to be taken into account. In general, the velocity of secondary ions is close to that of the primary ones [13], and their lower charge compared to those of the primary ions results in lower stopping power. Thus, the nuclear fragments have in general a longer range than the primary particles. This leads to the characteristic dose tail behind the Bragg peak in the depth dose distribution of heavy ions in matter. Secondary ions with sufficient energy to leave the irradiated body can be in principle detected. Although their directions are strongly peaked in the direction of the primary carbon ion beam (see e.g. [14]) a hydrogen dominated component can be detected at angles of 30° [15], or even 60° up to 90° [16] with respect to the direction of the primary carbon ion beam. The geometric accuracy of the determination of the point of its origin in depth increases with the increasing angle of the secondary particle with respect to the beam direction. At the same time, the number of secondary particles decreases rapidly, as well as does the amount of information about the particle production in the direction perpendicular to the beam direction. Therefore studies focus on both, high particle angles (60°–90°) and low particle angles (around 30°), which is used also in this contribution. For an overview of the published studies see [12].

The correlation between the delivered dose distribution and the spatial distribution of the emitted secondary ions is not trivial. Longitudinal profiles of the secondary ion abundance exhibit a maximum close to the entrance of the beam in the phantom, which is followed by a steady decrease [16–18]. The number of detected ions is dependent on the cross section for their production, while the therapeutic energy range is particularly difficult to model [12]. As mentioned above, the secondary ion distribution is highly anisotropic. Therefore also the shape of the longitudinal profile of the ion emission is highly dependent on the detector angle with respect to the beam axis. The attenuation of the secondary ion fluence in the patient depends on the energies and spatial distribution of the produced secondary ions. Their direction is further influenced by the multiple scattering, mainly in the patient. In order to obtain accurate models describing all these miscellaneous effects, a large amount of experimental data is needed for benchmarking. This amount is currently limited [12].

For measurement of the particle tracks employ the experimental studies gaseous detectors [16,19], semiconductor based trackers [18,20] and scintillating fibers [21]. Research in our group concentrates on pixelated silicon based detection system based on the Timepix detection technology [22]. In previous work, this detector was shown to be suitable for registration of single ions from secondary ion spectra produced in carbon ion therapy [23,24,31]. Recent results demonstrate that a 2D image of a carbon ion pencil beam in a homogeneous head-sized PMMA phantom can be reconstructed using single measured tracks of secondary ions leaving the phantom [18]. With this approach, changes of both lateral beam position and width, could be determined with an uncertainty below 1 mm. The method was found to be sensitive to variations of the beam range down to at least 2.8 mm in the analyzed setup within typical clinical conditions.

When in the beam path, changes in tissue homogeneity might seriously deteriorate the beam distribution in the patient. Therefore, in this work the capability of the above described method to detect inhomogeneities of the tissue during irradiation, as they might occur in the human body, was studied.

2. Materials & methods

To address extreme cases, for this study we selected materials for inhomogeneities representing extreme material differences to soft tissue: air cavities and metal inserts. The influence of the created inhomogeneities on the distribution of nuclear fragment tracks was studied for different sizes and positions of the inhomogeneities with respect to the Bragg peak. In particular the sensitivity of the method to detect inhomogeneities in an otherwise homogeneous phantom was examined.

The experiments were performed at the Heidelberg Ion-Beam Therapy Center (HIT), Germany. To establish reference conditions, a homogeneous phantom was constructed. The experimental setup is depicted in Fig. 1. The block phantom consisted of 14 PMMA (polymethyl methacrylate) slabs placed perpendicular to the beam. The size of each 10 mm thick slab was 300×300 mm^2. The pencil beam hits the frontal slab in the center. The phantom was positioned to fit the isocenter at the border between the 10th and 11th slab (100 mm in depth). The carbon ion beam energy of 241.84 MeV/u was chosen in order to position the Bragg peak in 100 mm depth. This energy is typical for patient treatments. The width of the pencil beam was 4.6 mm (FWHM) at the isocenter. For each measurement, the phantom was irradiated with 7×10^9 -ions. A typical number of primary ions delivered per a single pencil beam in the distal layer in case of a head & neck fractionated therapy is of the order of 10^5 ions. In order to relate both numbers, we corrected the number of applied ions for the size of the sensitive area of 2 cm^2 and the dead time, which was in this case a factor of 200 longer than the active measurement time of the detector. This results into 15×10^5 ions which would be needed to be applied for the same quality of the results, when a deadtime-free detector consisting of a 1.4 cm wide full ring of detectors would be used. In reality a thicker detector ring would be used, which makes the applied number of ions a realistic approximation of single therapeutic pencil beams.

Please cite this article in press as: Gaa T et al. Visualization of air and metal inhomogeneities in phantoms irradiated by carbon ion beams using prompt secondary ions. Phys. Med. (2017), http://dx.doi.org/10.1016/j.ejmp.2017.05.055