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Efficient double-scattering proton therapy with a patient-specific bolus

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ABSTRACT

Purpose: Passive scattering proton radiotherapy utilizes beam-specific compensators to shape the dose to the distal end of the tumor target. These compensators typically require therapists to enter the treatment room to mount between beams. This study investigates a novel approach that utilizes a single patient-specific bolus to accomplish the role of multi-field compensators to improve the efficiency of the treatment delivery.
Methods: Ray-tracing from the proton virtual source was used to convert the beam-specific compensators (mounted on the gantry nozzle) into an equivalent bolus thickness on the patient surface. The field bolus contours were combined to create a single bolus. A 3D acrylic bolus was milled for a head phantom. The dose distribution of the compensator plan was compared to the bolus plan using 3D Gamma analysis and film measurements. Boluses for two clinical patients were also designed.
Results: The calculated phantom dose distribution of the original proton compensator plan was shown to be equivalent to the plan with the surface bolus. Film irradiations with the proton bolus also confirmed the dosimetric equivalence of the two techniques. The dose distribution equivalency of the bolus plans for the clinical patients were demonstrated.
Conclusions: We presented a novel approach that uses a single patient-specific bolus to replace patient compensators during passive scattering proton delivery. This approach has the potential to reduce the treatment time, the compensator manufacturing costs, the risk of potential collision between the compensator and the patient/couch, and the waste of compensator material.

1. Introduction

The use and availability of proton radiotherapy has accelerated in recent years [1]. Compared to the photon radiotherapy, proton therapy has the distinct advantage of delivering a finite range of dose in the body and sparing healthy tissue beyond tumor. Proton therapy treatments typically have two or more treatment fields from different angles to direct radiation to the target. In the double scattering (DS) proton delivery technique, each treatment field requires beam shaping in both the lateral and depth directions. The lateral shaping ensures the beam covers the tumor laterally and is usually achieved by a field aperture, such as brass plates or multi-leaf collimators (MLC). In the depth direction, the beam can only be designed to conform to the distal edge of the tumor. The distal shaping is achieved by first tracing along discrete voxel path in the beam's eye view (BEV) to determine the water-equivalent thickness (WET) to the tumor distal edge. A field-specific compensator (Fig. 1) is formed to create a uniform WET along the distal edge for a given beam energy by placing compensating material in the discrete ray paths [1–3]. The compensators are usually milled out of a block of water-equivalent material such as acrylic or paraffin wax. The blocks have a pre-defined size to allow for convenient milling and mounting to the treatment machine. Therefore, a large amount of extra material is included in the finished compensator although only the portion of active region with varying depth is useful in shaping the dose (Fig. 1). These patient- and field-specific apertures and compensators are mounted on the end of the treatment nozzle. During treatment, before each beam is delivered, therapists must re-enter the treatment room and move the gantry to the mounting angle to exchange the compensators and apertures. This is a laborious process and results in prolonged patient treatment time and low but measurable radiation exposure to staff from the activated devices. The application of automatic MLC movement to provide lateral beam shaping has greatly reduced such issue but the change of the compensator for distal shaping is still needed for each field. In each compensator, the large amount of

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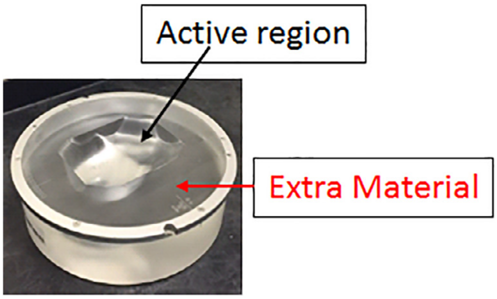

Fig. 1. A traditional field-specific compensator for double scattering proton therapy.

extra acrylic material that is not in the active beam region can potentially result in collision between the compensator and the patient/couch. The acrylic material used in the compensator is not recyclable and the extra portion of the compensator results in waste and is not environmentally friendly.

We propose the use of a patient-specific bolus as a substitute for the multiple proton field compensators during proton treatment delivery. Similar techniques previously explored for electron therapy [4–6] along with increased applications of patient-specific devices in radiation oncology [7–14] were the motivation for this work. In our proton center that uses MLC to shape the field apertures, using such a bolus reduces the need for the therapists to enter the treatment room when changing treatment fields. As the compensator manufacturer charges the machining cost per compensator, combining multiple field compensators into one specific bolus could potentially save cost and reduce waste.

In this study, we outline the clinical implementation of an efficient patient-specific bolus for double scattering proton therapy. The method maintains the same dose-shaping capabilities of field-specific proton compensators while simultaneously reducing the amount of material usage by combining multiple field compensators into one and improving efficiency by eliminating the need to exchange compensators between treatment fields. This will especially benefit proton centers equipped with MLCs for lateral field shaping.

2. Methods

2.1. Patient specific bolus design

A double scattering proton plan with traditional field-specific compensators was designed and calculated using the Eclipse treatment planning system (TPS) (Varian Medical Systems, Palo Alto, CA). The traditional compensator design accounts for organ/tumor motion through smearing and sharp edges through border smoothing [15]. The proton plan and structure files in DICOM RT format were input to an in-house program written in MATLAB® (MathWorks, Natick, MA) V2014a software to design the patient-specific bolus.

The MATLAB program uses a ray-tracing technique, projecting the compensator thickness pattern from the virtual source position onto the patient surface along a given ray. The projected bolus thicknesses on the patient surface from the compensator were connected into a continuous virtual surface to form a solid bolus that conforms to the patient body. Fig. 2 illustrates the process of ray-tracing projections.

The boundary points of the designed bolus surface were rewritten into an RT structure file and imported into Eclipse. Dose calculations were performed for each individual field to compare the dose distribution of the new bolus plan with the original compensator plan.

2.2. Bolus fabrication

After the bolus for each field was designed, the individual boluses were stitched together into one continuous 3D structure. A shoulder

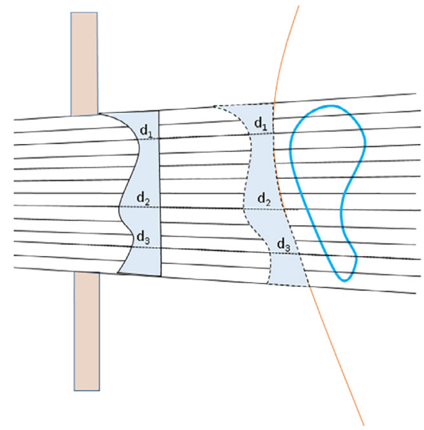

Fig. 2. Projection of traditional compensator (solid outline) onto patient surface to generate a patient specific surface bolus (dotted outline): along each ray, the WET in the compensator is the same as in the bolus that conforms to the patient contour.

was added in the superior/inferior or lateral directions of the bolus for securing the bolus to the patient surface. The MATLAB program meshes all the surfaces of this 3D bolus following the process illustrated by Zou et al. [16] to generate an STL file. The bolus was manufactured by .decimal® (Sanford, FL), a company specializing in the construction of patient-specific devices for proton radiotherapy, from the generated STL file. The bolus was milled using a tissue-equivalent acrylic material, the same material previously used in proton compensator fabrication. This ensures that introduction of the bolus material in the beam path would produce the same proton interactions as a compensator.

2.3. Phantom study design and implementation

An anthropomorphic head phantom was used to evaluate the dose distribution of a three-field DS plan delivered using the proton bolus compared to using the three traditional beam-specific compensators. The head phantom was chosen for the study as it provided a challenging topographical surface and inhomogeneous structure to assess the accuracy of the bolus design [17]. A CT of the head phantom was first acquired without any treatment devices to develop the traditional compensator-based DS plan. The custom bolus for the head phantom was then generated and manufactured. A second CT scan was acquired with the manufactured custom bolus in place.

Verification of the bolus design was performed in two ways. First, the original DS plan without the compensators was forward-calculated on the head phantom scan with the custom bolus in place. The bolus structure was overridden with the proper Hounsfield units or proton stopping power ratio (SPR) of the bolus material (acrylic), which has SPR = 1.161. The DVHs and the planned dose distribution of the bolus plan were compared with the compensator plan.

Secondly, the custom bolus accuracy was confirmed using film measurements of the 2D dose distribution at the target. EBT2 Gafchromic film (ISP, Wayne, NJ) was used to measure the two-dimensional proton dose distribution of the delivered bolus plan in the anthropomorphic phantom. Calibration of the EBT2 Gafchromic film to the proton beam dose followed the methods developed in previous studies [18–22]. In our clinic, the film was calibrated under the proton beam of 0–800 cGy at the middle of spread-out Bragg peak (SOBP) and scanned 24 h after irradiation using the EPSON Expression 10000XL flatbed scanner (Epson, Long Beach, CA) at 300 dpi. The calibration curve was generated from fitting a third-order polynomial function of the dose to the red channel of the scanned film .tiff file. A film from the same batch was then positioned between the slices of the head phantom where the target volume resides, similar to a previous study [17]. The DS plan was delivered with the custom bolus in place. The film

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