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Dosimetric characterization of carbon fiber stabilization devices for post-operative particle therapy

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ABSTRACT

Purpose: The aim of this study was to evaluate the dosimetric impact caused by recently introduced carbon fiber reinforced polyetheretherketone (CF/PEEK) stabilization devices, in comparison with conventional titanium (Ti) implants, for post-operative particle therapy (PT).

Methods: As a first step, protons and carbon ions Spread-Out Bragg Peaks (SOBPs) were delivered to CF/PEEK and Ti screws. Transversal dose profiles were acquired with EBT3 films to evaluate beam perturbation. Effects on image quality and reconstruction artifacts were then investigated. CT scans of CF/PEEK and Ti implants were acquired according to our clinical protocol and Hounsfield Unit (HU) mean values were evaluated in three regions of interest. Implants and artifacts were then contoured in the sample CT scans, together with a target volume to simulate a spine tumor. Dose calculation accuracy was assessed by comparing optimized dose distributions with Monte Carlo simulations. In the end, the treatment plans of nine real patients (seven with CF/PEEK and two with Ti stabilization devices) were retrospectively analyzed to evaluate the dosimetric impact potentially occurring if improper management of the spine implant was carried out.

Results: As expected, CF/PEEK screw caused a very slight beam perturbation in comparison with Ti ones, leading to a lower degree of dose degradation in case of contouring and/or set-up uncertainties. Furthermore, CF/PEEK devices did not determine appreciable HU artifacts on CT images thus improving image quality and, as a final result, dose calculation accuracy.

Conclusions: CF/PEEK spinal fixation devices resulted dosimetrically more suitable than commonly-used Ti implants for post-operative PT.

1. Introduction

Spine fixation is a surgical procedure often performed within spinal tumor treatment. If surgery alone is not oncologically appropriate, patients are eligible for post-operative adjuvant particle therapy (PT). Pencil-beam scanning (PBS) PT can offer a significant dosimetric advantage over photon beam radiation therapy (RT), due to the potential improvement in normal tissue sparing without compromising target dose coverage, even when compared to the most advanced techniques, e.g. intensity modulated RT (IMRT), volumetric modulated arc therapy (VMAT) or Tomotherapy [1]. On the other hand, range uncertainties unique for PT, if not properly mitigated, can severely compromise treatment quality. Traditional metal (high-Z) implants significantly differ from normal tissues in terms of density and composition, leading to high perturbation effects on radiation beams [2–9] and metal-related artifacts in both magnetic resonance imaging (MRI) and X-ray computed tomography (CT) [4,10,11]. In principle, the irradiation through metal implants should be avoided [2,4], especially for PT, where distortion of dose distributions and range uncertainties may compromise both disease local control and normal tissue sparing. However, this recommendation cannot always be followed when defining plan geometry, if beam direction selection is limited by dose constraints to the

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organs at risk (OARs) or by lack of a gantry (i.e. for fixed beam lines) [12]. Imaging artifacts can compromise proper visualization and delineation of target and normal structures, also decreasing dose calculation accuracy. Indeed, CT number assignment to tissues within the irradiation volume is a highly critical issue in PT, where dose calculation is based on Hounsfield Unit (HU) to water equivalent path length (WEPL) calibration curve [13,14]. Various techniques have been proposed to reduce metal artifacts and improve dose calculation accuracy, such as the use of dual energy (DE) CT [15–17] and megavoltage (MV) CT [18] imaging, iterative reconstruction methods [19] or commercial orthopedic metal artifact reduction algorithms (O-MAR) [20,21]. Verburg and Seco [22] and Dietlicher et al. [23] underlined the need of using multiple fields in PT to improve dosimetric accuracy, especially in the presence of metal implants in the patients. Moreover, several strategies have been further investigated to improve treatment plan robustness, e.g. robust optimization or probabilistic treatment planning [24,25]. Recently, a carbon fiber reinforced-polyetheretherketone (CF/PEEK) fixation device (fully metal-free) has become available on the market [26]. These carbonaceous (low-Z) implants have been specifically designed for Oncology and are therefore generally recommended for patients which are eligible for RT [27,28]. The reduction of image artifacts [29], and consequent decrease of contouring uncertainties, together with significantly less dose perturbation effects can improve treatment plan dosimetric accuracy and robustness. From September 2011 to August 2017, the National Centre for Oncological Hadron Therapy (CNAO Foundation, Pavia, Italy) has treated head-and-neck, spinal and para-spinal, abdominal and pelvic tumors in more than 1400 patients with proton and carbon ion beams with PBS modality [30]. Among all treated patients, seven had a previously implanted CF/PEEK stabilization device. The aim of the present study was therefore to investigate and characterize the use of CF/PEEK implants, in comparison with titanium (Ti) ones, in terms of their impact on image quality, reconstruction artifacts, contouring and dose calculation accuracy, for both proton and carbon ion beams.

2. Materials and methods

2.1. CF/PEEK implant

In this study we analyzed a completely metal-free CF/PEEK stabilization device (CarboFix Orthopedics Ltd., Herzeliya, Israel), designed for Oncology. The biocompatibility [31] and biomechanical properties of CF/PEEK Orthopedic implants were previously reported [32] and were beyond the scope of this work.

One single pedicle screw (diameter = 6.5 mm) was used for the first test in water, while the CF/PEEK implant adopted in the second and third phases of this study was primarily composed by 8 pedicle screws and 2 longitudinal rods as shown in Fig. 1. This lightweight device has a density of 1.55 g/cm^3. The main characteristics of the CF/PEEK implant are summarized in Table 1.

Table 1
Main characteristics of the CF/PEEK implant investigated in this study.

	Diameter [mm]	Length [mm]	Mass [gr]	Volume [cm^3]	Total Density [gr/cm^3]
Carbon Screw (8 units)	6.5	45	1.49	0.96	1.55
Locking Element (ring + collar, 8 units)	x	x	2.95	1.90	1.55
Longitudinal rods (2 units)	6.0	220	8.10	1.22	1.55

A 6 by 6 cm^2 slab of 5 mm thickness of the same material, provided by the manufacturer, was used to measure the material specific WEPL with the Peakfinder (PTW Freiburg, Germany) water column. The relative WEPL was determined as the shift of the position of the Bragg peak measured in water, when the beam is passing through the material sample, as described in Mirandola et al. [33].

The same implant configuration and vertebral sample, described in Fig. 1, were adopted for the Ti screws analysis.

2.2. Beam perturbation: Transversal dose profiles

As a first step, protons and carbon ions Spread-Out Bragg Peaks (SOBPs) were delivered to a CF/PEEK and a Ti screw of the same diameter. The SOBPs, previously calculated for homogenous dose distribution in water phantom, consisted of a dose cube of 6 × 6 × 6 cm^3 of 31 isoenergetic slices (IES). The modulation region of the SOBPs ranged from 6 to 12 cm water-equivalent depth (89.2– 30.6 MeV and 169.4–250.5 MeV/u for protons and carbon ions, respectively). Screws were positioned at the isocenter behind 7 cm of water-equivalent solid slabs (RW3, PTW Freiburg, Germany, ρ = 1.045 g/cm^3) reaching a depth of 1 cm in the SOBPs. Three gafchromic EBT3 films (Ashland Inc., Bridgewater, NJ, USA) were placed orthogonally to the beam direction at several depths of the SOBP: behind the screw, 2 and 4 cm far from it (i.e. at a depth of about 1, 3 and 5 cm in the SOBPs), respectively. The schematic representation of the experimental set-up is shown in Fig. 2.

Transversal dose profiles were acquired to experimentally evaluate beam perturbation in an homogenous dose distributions, as shown in Fig. 3 (red lines). EBT3 films were scanned in transmission mode using an Expression 10000XL-Photo flatbed A-3 scanner (Epson Corp., Nagano, Japan), using the landscape orientation, as recommended by the manufacturer, positioned in the central region of the scanner. RGB film images were collected at 48 bits (16 bits per color channel) with a spatial resolution of 72 dpi (~0.35 mm/pixel). From the resulting RGB images, the red channel was extracted to calculate the dose matrix using the commercial software MEPHYSTO mc^2 (PTW Freiburg, Germany). Pre-established dose calibration curves specific for each particle type were used [33].

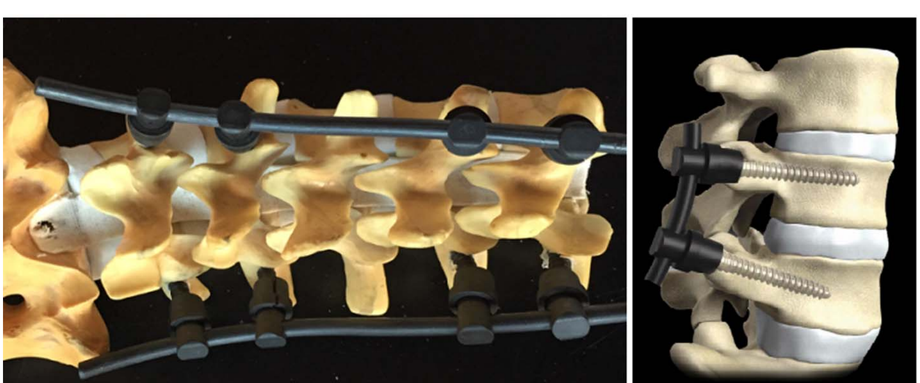

Fig. 1. Overview of a CF/PEEK implant for spine fixation. In this example, the construct is composed by 8 pedicle screws and 2 longitudinal rods.