



# Comprehensive Evaluation of Carbon-Fiber-Reinforced Polyetheretherketone (CFR-PEEK) Spinal Hardware for Proton and Photon Planning

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## Abstract

**Purpose:** To evaluate a novel spine implant, carbon-fiber-reinforced polyetheretherketone (CFR-PEEK), for proton and photon treatment planning. **Materials and Methods:** We compared target coverage and sparing of organs-at-risk (OARs) for a spinal phantom with 4 different spine configurations: (a) normal (no implant); (b) Titanium; (c) CFR-PEEK; and (d) hybrid (CFR-PEEK with Titanium tulip head). The spinal phantom was imaged via computed tomography (CT) scan, and the iterative Metal Artifact Reduction (iMAR) CT set was used for planning. A representative spinal chordoma target and associated OARs were contoured. The prescription dose was 50 Gy to the initial target volume, followed by a 24 Gy boost, for which multi-field optimization (MFO) proton plans were developed with a 3 mm setup and 3.5% range uncertainties. For photon planning, volumetric modulated arc therapy (VMAT) plans were developed for the initial and boost plans. OAR dose constraints were set according to our institutional guidelines. **Results:** For the 4 spine configurations, the proton plans achieved similar nominal target coverage and OARs sparing. While evaluating coverage and OAR dose under uncertainty scenario analysis for initial clinical target volume (CTV) 50 Gy 95% and 90% coverage, higher means and the narrower band of doses variations were achieved for the normal and CFR-PEEK plans. Similarly, uncertainty analysis of spinal cord  $D_{max}$  showed tighter distribution for normal and CFR-PEEK plans. Overall plan quality showed no significant difference for photon planning when compared to normal spine versus other inserts. However, for proton planning, there is a larger difference for the normal spine insert scenario versus the Titanium insert scenario. For each insert scenario comparison between photon and proton plans, there was a larger difference for OARs: heart and spinal cord. **Conclusion:** The CFR-PEEK implant has similar clinical properties to a normal spine for proton planning, allowing us to pass protons through the material and achieve superior target coverage and OAR sparing under nominal and uncertainty conditions.

## Keywords

CFR-PEEK, proton, spine, hardware

## Abbreviations

cc, cubic centimeters; CT, computed tomography; CTV, clinical target volume; CBCT, cone-beam CT; CFR-PEEK, carbon-fiber-reinforced polyetheretherketone; EF, effective volume; HU, Hounsfield unit; iMAR, iterative Metal Artifact Reduction; MFO, multi-field optimization; MFO-IMPT, multi-field optimization, intensity-modulated proton therapy; OARs, organs-at-risk; ROIs, regions of interest; VMAT, volumetric modulated arc therapy.

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## Introduction

Chordoma, with an incidence of 300 new cases in the United States each year, represents one of the most common primary osseous neoplasms of the spine.<sup>1</sup> Standard therapy for the management of spinal chordomas consists of surgery followed

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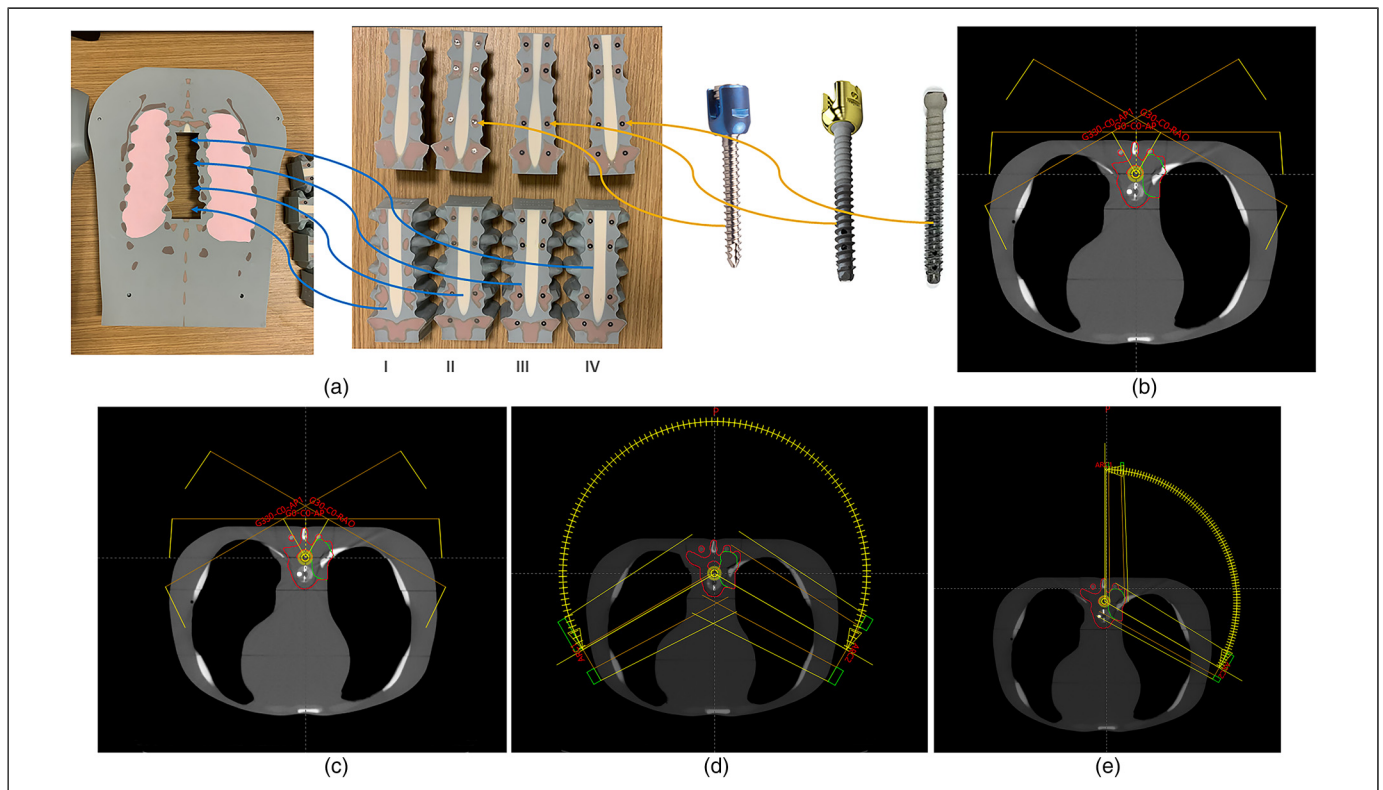
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by radiation therapy.<sup>2</sup> Following surgery, an insert may be placed to stabilize the spine, for which the traditional spinal insert material is Titanium. Titanium is a relatively heavy metal material with high density and stopping power. Given this unique property, titanium projects a significant amount of metal artifacts that underwent computed tomography (CT) imaging. During radiation therapy, the presence of this high-density material significantly attenuates photon fluence, and with charged particle radiation, the higher stopping power blocks the particles. These effects can cause treatment planning challenges for both photon and proton therapy, such as less coverage of the target and/or hot and cold spots near the insert region. For photon and proton therapy, the recommended tumoricidal dose is 70 to 74 Gy (RBE) or higher, while respecting normal tissue constraints, delivered in 1.8 to 2.0 Gy (RBE) per fraction to the target volume.<sup>3</sup> Other total doses and the fractional dose may also be used, which is determined by individual treating center guidelines. The major concerns are dose coverage for the target volumes while adequately sparing the spinal cord, skin, esophagus, and other organs-at-risk (OARs). Besides those major concerns, the variations in dose calculation accuracy due to the metal present may introduce dose perturbations of 5% to 10%.<sup>4,5</sup>

In recent years, a new type of implant material called carbon-fiber-reinforced polyetheretherketone (CFR-PEEK) has

been introduced and is strongly supported by a systematic review for the use of CFR-PEEK material in orthopedic implants.<sup>6,7</sup> This material is of low density, which allows the radiation beam to penetrate without major alteration. There are reports utilizing CFR-PEEK within radiation treatment fields, including dental, long bones, and spine implants.<sup>8-15</sup> Previous studies have been focused on the mechanical properties, biological properties, and radiation properties of the CFR-PEEK.<sup>6-17</sup> Radiation dosimetric comparisons of CFR-PEEK have been done to date,<sup>13-15,17</sup> however, there is still significant room for further investigation about the dosimetric effects of the new type of hardware in both proton and photon planning. The hardware effects will be affected by different CT modalities, treatment planning systems, treatment planning strategies, proton modalities, etc. Thus, more centers' experience will provide more useful clinical experience.

In light of the paucity of clinical data and the expectation for centers to increasingly use CFR-PEEK as spine surgery inserts, we performed a comprehensive study on the CFR-PEEK inserts with a torso phantom. The purposes are multifold: (a) to evaluate the CFR-PEEK performance on image quality; (b) to benchmark the treatment planning experience for photon and proton with/without the CFR-PEEK versus the most commonly used Titanium material; and (c) to investigate the CFR-PEEK dosimetry effects for treatment planning.



**Figure 1.** (a) A torso phantom with 4 types of spine inserts: (I) normal/native spine; (II) Titanium insert; (iii) Hybrid insert; and (IV) CFR-PEEK insert. Blue arrows show the insert location in the phantom and yellow arrows show screws inside the inserts, (b) photon planning for the initial, (c) CD axial views, (d) proton planning for the initial, and (e) CD axial views. The red contour is the initial target volume and the green side contour is the CD target volume.

Abbreviation: CFR-PEEK, carbon-fiber-reinforced polyetheretherketone.

## Materials and Methods

### CFR-PEEK Structure and Phantom

A torso phantom, provided by icotec Medical Inc. (Altstätten, Switzerland), with 4 types of spine configurations was used for this study. The 4 configurations were as follows: (I) normal/native spine without hardware insert; (II) Titanium screw and rod spine insert; (III) hybrid spine insert with CFR-PEEK screw and Titanium tulip head; and (IV) CFR-PEEK spine insert with CFR-PEEK screw and rod. Of note, type III and type IV are similar to each other except for the tulip component of the insert, which is composed of Titanium or CFR-PEEK, respectively.

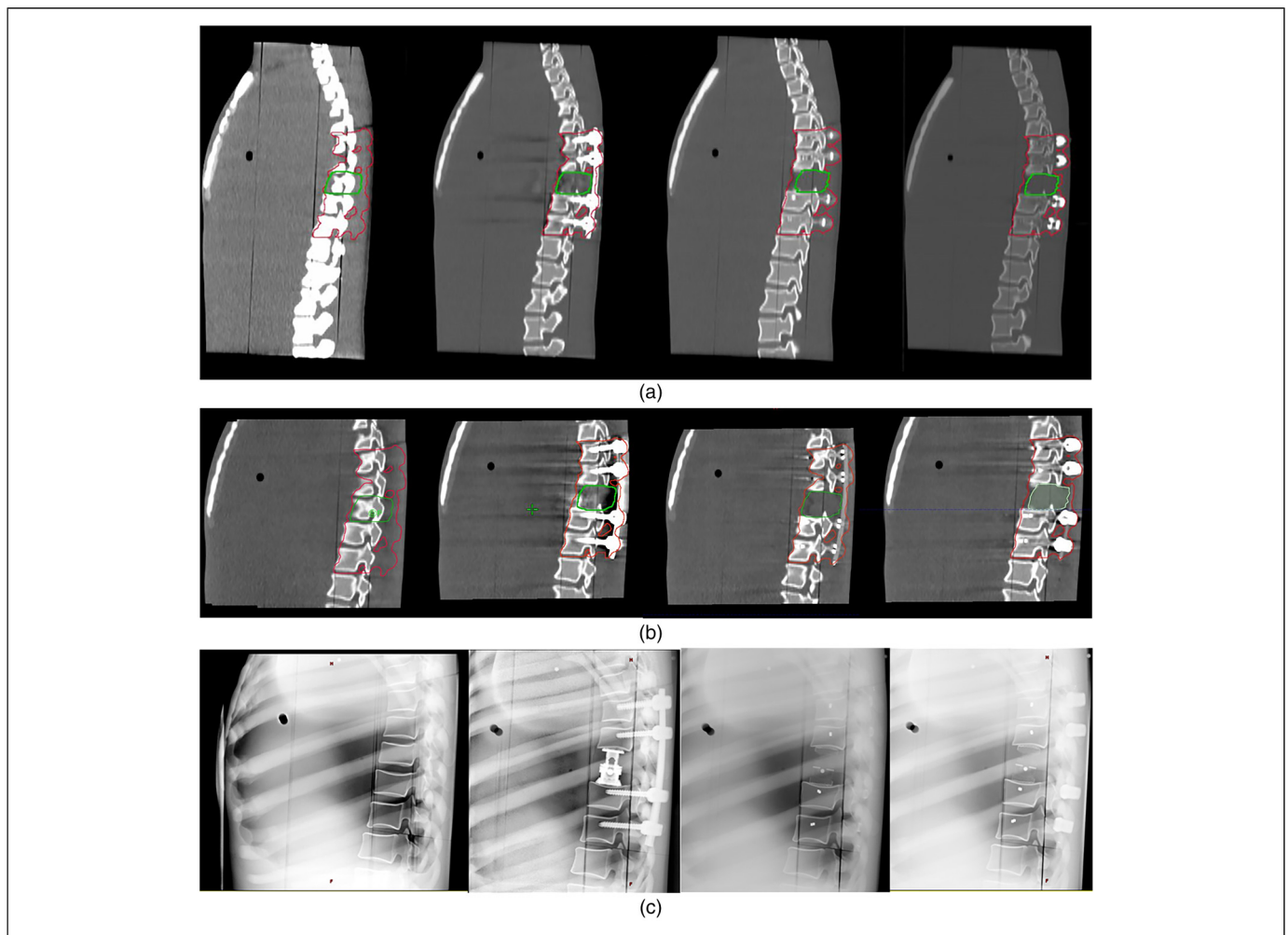
The torso phantom underwent CT imaging with each respective insert using our Siemens Somatom definite edge CT scanner (Siemens USA, Washington, DC, USA). iterative Metal Artifact Reduction (iMAR) CT scan was generated to reduce the metal artifacts. The CT images were sent to our Eclipse™ treatment planning station (Varian Medical Systems, Version 15.1, Palo Alto, CA, USA) for contouring and planning.

### Image Quality Study

The imaging quality study involved the assessment of the CT image datasets and the obtained setup imaging using cone-beam CT (CBCT) and orthogonal kV images. For the CT datasets, the artifact region was contoured out based on the streak artifacts mainly and checked by a physicist and an MD. To evaluate the effectiveness of the hardware, a volume called effective volume (EV) which is clinical target volume (CTV) 50 Gy minus the metal was defined. The ratio of EV/CTV 50 was calculated. The Hounsfield unit (HU) numbers for regions of interest (ROIs) were measured and compared between the CT images. Additionally, the CBCT and kV images were used to assess potential landmarks that could be utilized for treatment setup.

### Comparative Proton Versus Photon Planning

For comparison of proton versus photon planning, initially a representative 14 cm mid-thoracic chordoma tumor was



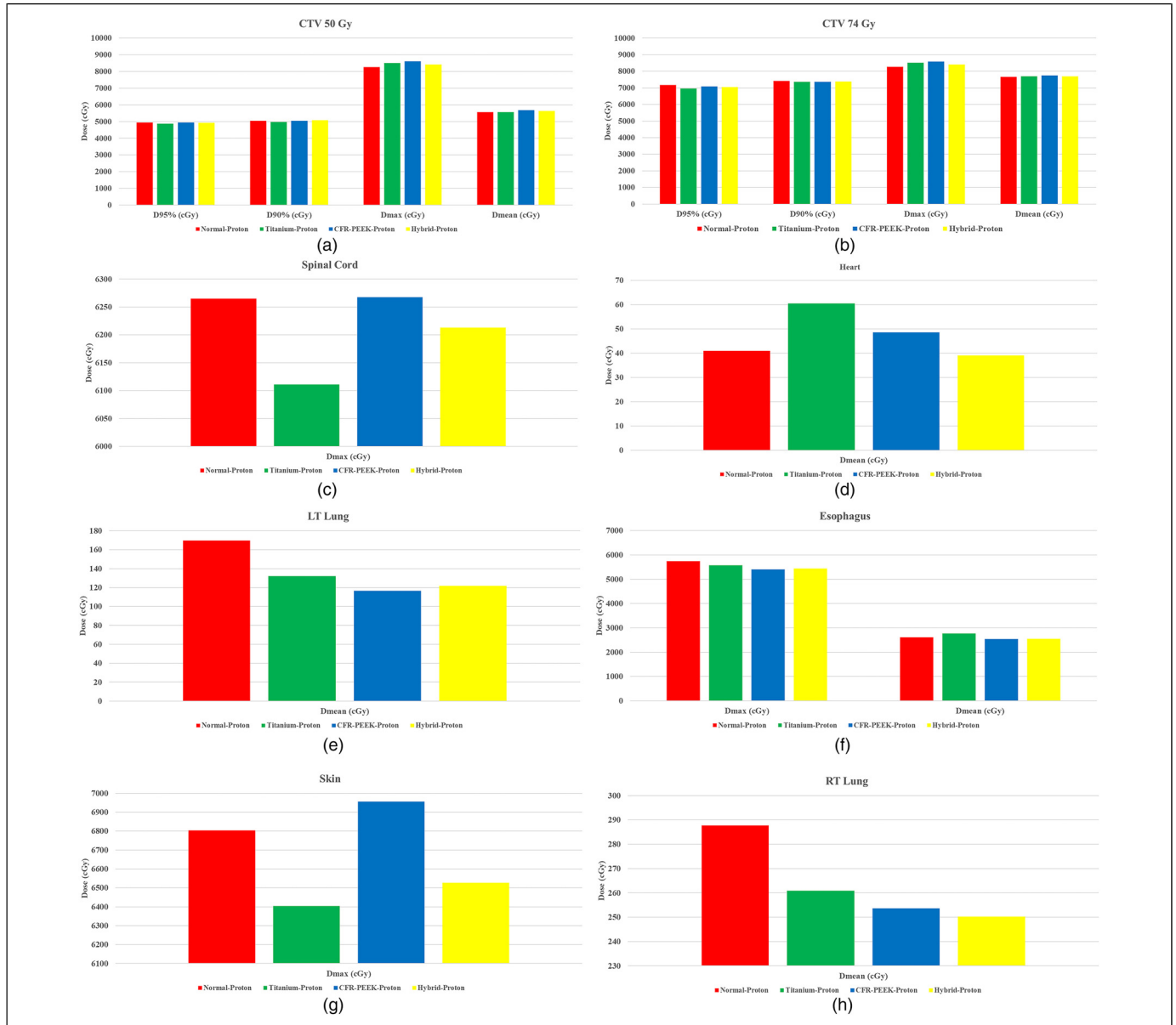
**Figure 2.** CT (top), CBCT (middle), and kV (bottom) image comparison for (from left to right) normal, Titanium, CFR-PEEK, and hybrid spine insert. The CT/CBCT view window was set to  $[-500, 1000]$ . The contours are CTV 50 Gy (larger red) and CTV 74 Gy (smaller green). Abbreviations: CT, computed tomography; CTV, clinical target volume; CBCT, cone beam CT; CFR-PEEK, carbon-fiber-reinforced polyetheretherketone.

**Table 1.** Targets, metal, and artifact volumes. Here, the effective volume (EV) is defined as the clinical target volume (CTV) 50 Gy volume minus the metal volume.

	Normal	Titanium	Hybrid	CFR-PEEK
CTV 50 Gy (cc)	305.64	302.90	303.10	303.30
CTV 74 Gy (cc)	22.37	22.00	22.40	22.40
Metal (cc)	0.00	37.55	12.32	3.38
Effective volume (cc)	305.64	265.35	290.78	299.92
Ratio (EV/CTV 50 Gy)	100%	88%	96%	99%
Artifacts overridden (cc)	0.00	77.46	9.54	0.50

Abbreviations: cc, cubic centimeter; CFR-PEEK, carbon-fiber-reinforced polyetheretherketone.

delineated on the CT images for each type of spine insert. A sequential plan was created delivering 50 Gy to the initial CTV 50 followed by 24 Gy to a boost volume (CTV 74) in the 4 configurations (8 plans for proton and 8 plans for photon). OARs such as the esophagus, spinal cord, lungs, heart, skin, and bones were contoured for dosimetric analysis. Multi-field optimization, intensity-modulated proton therapy (MFO-IMPT) technique was used for proton planning, whereas volumetric modulated arc therapy (VMAT) was used for photon planning. For the initial VMAT planning, 2 240-degree mirrored arcs were used with a 10-degree collimator rotation. The jaw sizes were auto-set during the plan



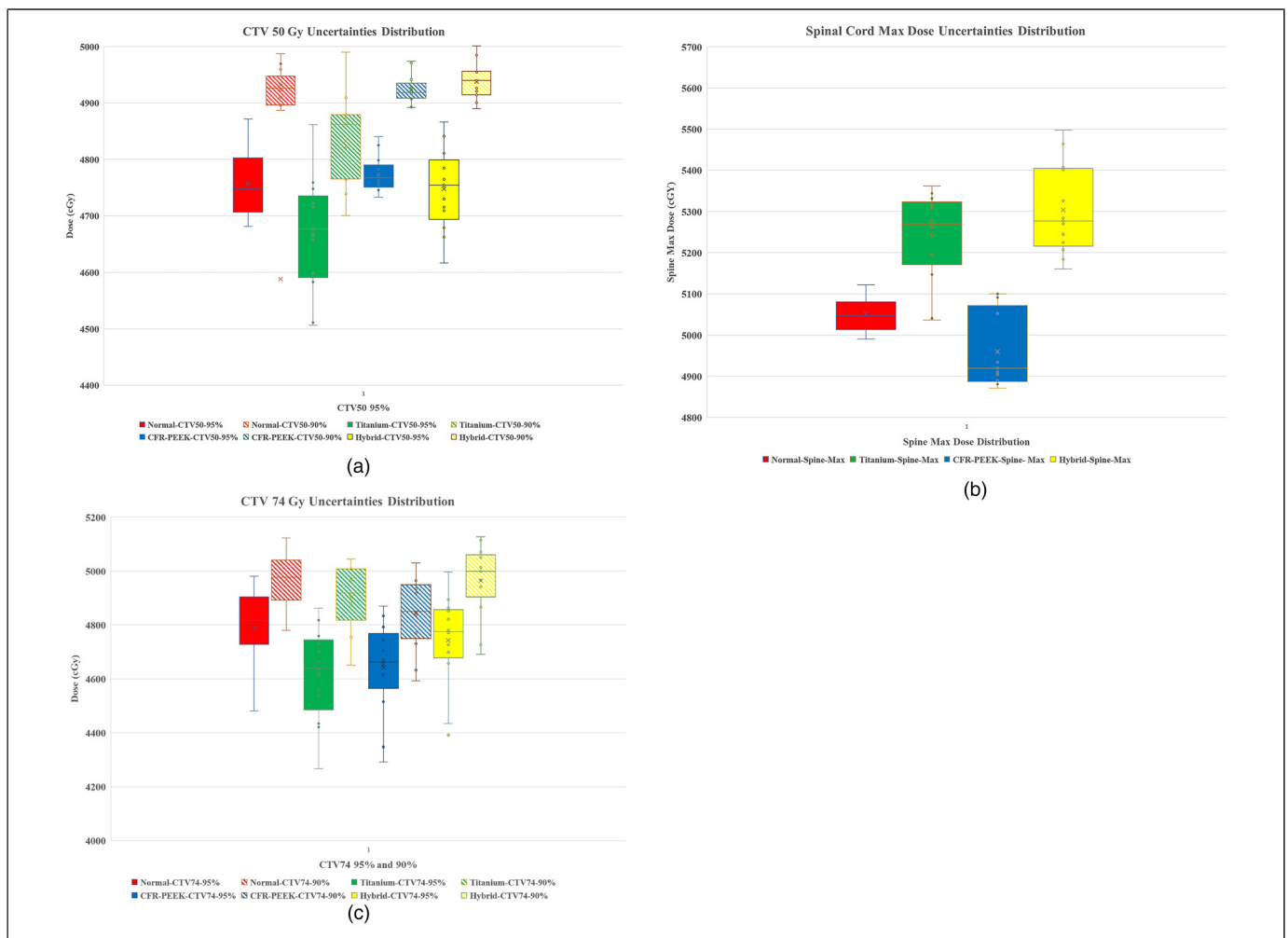
**Figure 3.** Proton planning results for the 4 types of spine inserts: normal/native spine; Titanium insert; CFR-PEEK insert, and hybrid insert. (a) CTV 50 Gy  $D_{95\%}$ ,  $D_{90\%}$ ,  $D_{max}$ , and  $D_{mean}$  (b) CTV 74 Gy  $D_{95\%}$ ,  $D_{90\%}$ ,  $D_{max}$ , and  $D_{mean}$  (c) spinal cord  $D_{max}$  (d) Heart  $D_{mean}$  (e) left lung  $D_{mean}$  (f) esophagus  $D_{max}$  and  $D_{mean}$  (g) skin  $D_{max}$ , and (h) right lung  $D_{mean}$ . Abbreviations: CTV, clinical target volume, CFR-PEEK, carbon-fiber-reinforced polyetheretherketone.

optimization. The 6X MV photon beam was used with a 2.5 mm dose grid calculation. For the Cone Down (CD) VMAT planning, due to the target location, 2 120-degree mirrored arcs were used with a 10-degree collimator rotation, and other settings are similar to the initial VMAT planning. For both the initial and CD proton planning, 3 beam angles were used with 30-degree separation, the dose grid was 2.5 mm. The proton and photon plans have no normalization applied. Figure 1 shows the torso phantom and the 4 types of spine inserts and the photon and proton axial views. OAR dose constraints were set according to our institutional guidelines, including spinal cord surface  $D_{\max} \leq 63$  Gy (maximal dose to the surface of the spinal cord). Dose parameters of  $D_{90\%}$ ,  $D_{95\%}$ ,  $D_{\max}$ , and  $D_{\text{mean}}$  were collected for the targets and OARs. For proton planning, the multi-field optimization (MFO) proton plans were developed using robust planning with a 3 mm setup and 3.5% range uncertainties. We avoided any direct proton beam path through the titanium screws or heads per our institutional practice.

Both proton/MFO-IMPT and VMAT treatment plans were compared considering target coverage and OAR dose. The target coverage was compared for the  $V_{90\%}$  and  $V_{95\%}$  and the OAR dose was compared based on the maximum and mean dose. The uncertainty dose for the proton plans was evaluated with perturbations of 3.5% stopping power uncertainties and 3 mm patient setup uncertainties in the patient's anterior/posterior, left/right, and superior/inferior direction.

### Acuros<sup>®</sup> XB and Proton Monte Carlo Calculation

Monte Carlo algorithms are superior to conventional analytical dose calculation for both photon and proton, especially for sites with high heterogeneity. To study the dosimetric impact of the metal implant on both proton and photon dose calculation accuracy, Acuros<sup>®</sup> XB was used to forward calculate the dose for photon plans. For the proton plans, the MCsquare (<http://www.openmcsquare.org/>) program was also used independently to



**Figure 4.** Uncertainties of the proton planning results among the 4 types of spine inserts: normal spine; Titanium insert; CFR-PEEK insert; and hybrid insert. (a) CTV 50 Gy uncertainty analysis for  $D_{90\%}$  and  $D_{95\%}$  (b) spinal cord  $D_{\max}$  uncertainties, and (c) CTV 74 Gy uncertainty analysis for  $D_{90\%}$  and  $D_{95\%}$ .

Abbreviations: CTV, clinical target volume, CFR-PEEK, carbon-fiber-reinforced polyetheretherketone.

calculate the individual dose as a second check and for a study of the heterogeneity correction of the treatment planning. The MCsquare has been validated for proton therapy in previous publications.<sup>18–22</sup>

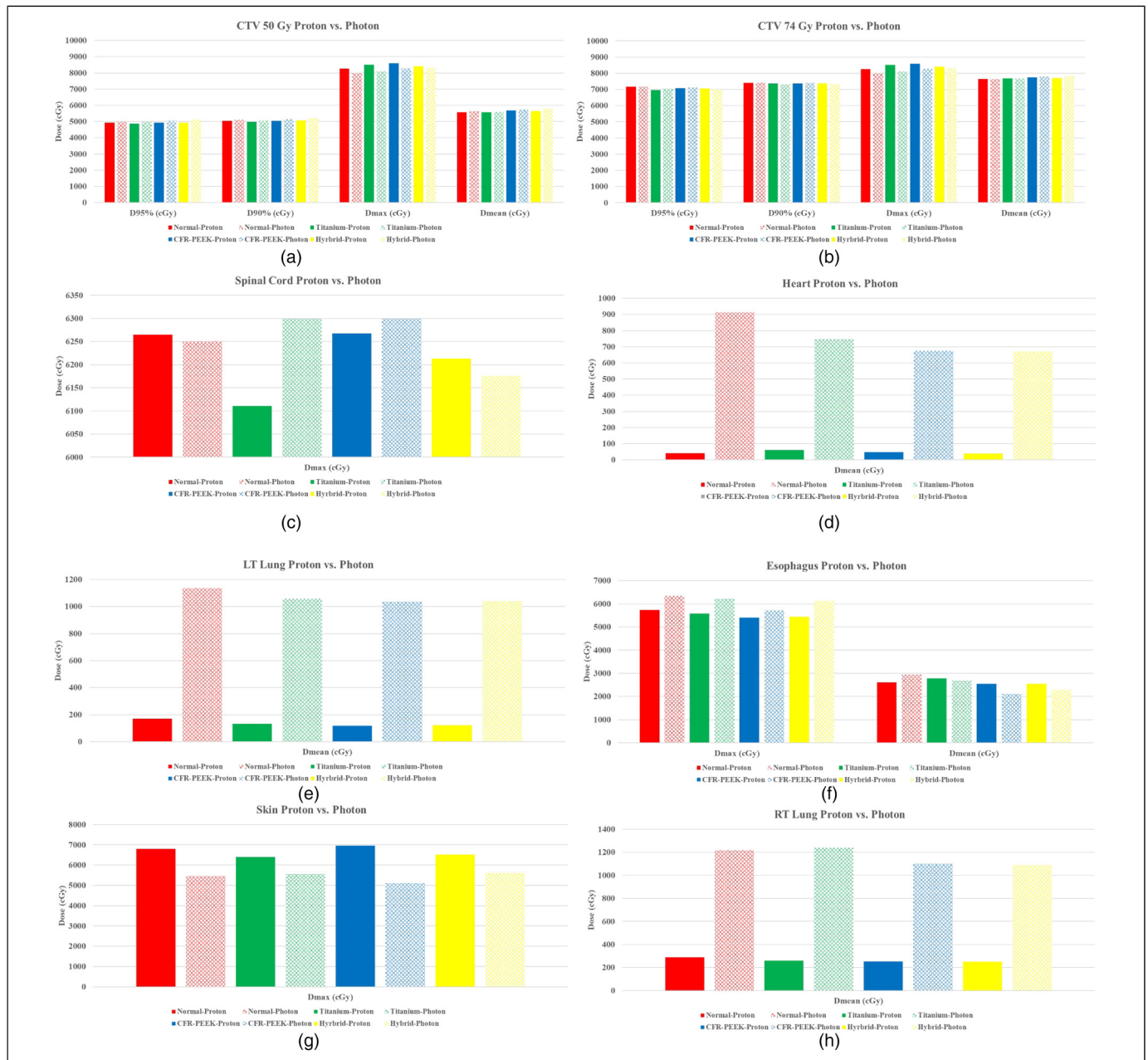
## Results

### CT Quality Study

Figure 2 shows the representative CT, CBCT, and kV images for the 4 configurations of spine inserts: (a) normal/native

spine; (b) Titanium insert; (c) CFR-PEEK insert, and (d) hybrid insert. Since the normal/native spine configuration had no hardware, there was no resultant artifact, and the CTV 50 Gy total volume of 305.64 cubic centimeters (cc) served as reference (Table 1).

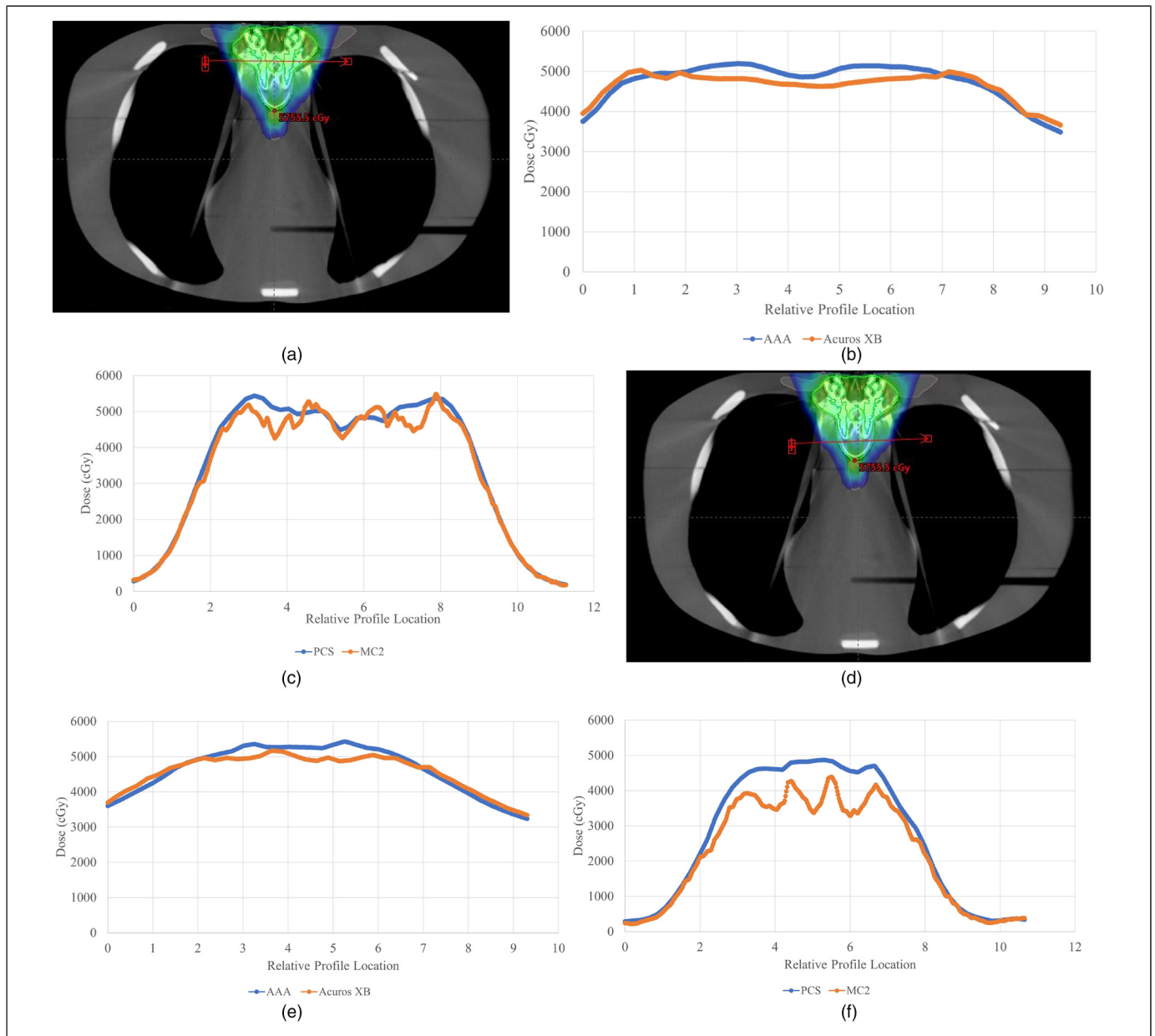
In the presence of titanium screw and rod, there was a need to contour 37.55 metal and 77.46 cc of artifacts on the CT, which resulted in an effective target of 265.35 cc. For the hybrid insert, there was 12.32 cc metal and 9.54 cc of artifacts, and an effective target volume of 290.78 cc. Lastly, the CFR-PEEK inserts only created 0.5 cc of the artifacts with an



**Figure 5.** Proton versus photon planning comparison among the 4 types of spine inserts: normal spine; Titanium insert; CFR-PEEK insert; and hybrid insert. (a) CTV 50 Gy, (b) CTV 74 Gy, (c) spinal cord, (d) heart, (e) left lung, (f) esophagus, (g) skin, and (h) right lung. Abbreviations: CTV, clinical target volume, CFR-PEEK, carbon-fiber-reinforced polyetheretherketone.

EV of 299.92 cc, which closely approximated that of the normal/native spine configuration. The ratio of target/CTV volumes for the CFR-PEEK, hybrid, and Titanium spine inserts compared to normal/native spine were 99%, 96%, and 88%, respectively. The Titanium screw HU was measured at 2818.3, whereas the CFR-PEEK screw was 270.6. The spinal canal HU measured for the phantom with and without Titanium implant were 121.2 and 57.4, respectively. The relatively larger spread of HU with

Titanium means the CT scan was affected by the Titanium part to a certain degree. By contrast, the spinal canal HU for the phantom with and without CFR-PEEK implant were 53.3 and 59.4, respectively. The CBCT/kV setup images for the Titanium insert have the Titanium rods and screws as landmarks that can help to align the phantom. The hybrid insert has a small part of the metal piece on the top of the screw (ie tulip), which can also be used as a landmark for image alignment.



**Figure 6.** MCsquare versus Proton Convolution Superposition (PCS) and Acuros<sup>®</sup> XB versus Anisotropic Analytical Algorithm (AAA) for proton and photon dose calculation respectively. (a) Illustration of the location profile taking in the middle of Titanium screw, (b) photon Acuros<sup>®</sup> XB versus AAA profile plot at (a) location, and (c) proton MCsquare versus PCS profile plot at (a) location. (d) Illustration of the location profile taken at the tip of Titanium screw, (e) photon Acuros<sup>®</sup> XB versus AAA profile plot at (d) location, (f) MCsquare versus PCS profile plot at (d) location, (g) illustration of the location profile taking in the middle of skin contour, (h) photon Acuros<sup>®</sup> XB versus AAA profile plot at (g) location, and (i) MCsquare versus PCS profile plot at (g) location. The red line represents MCsquare for proton or Acuros<sup>®</sup> XB for the photon. The cyan line represents PCS for proton or AAA for the photon.

(continued)

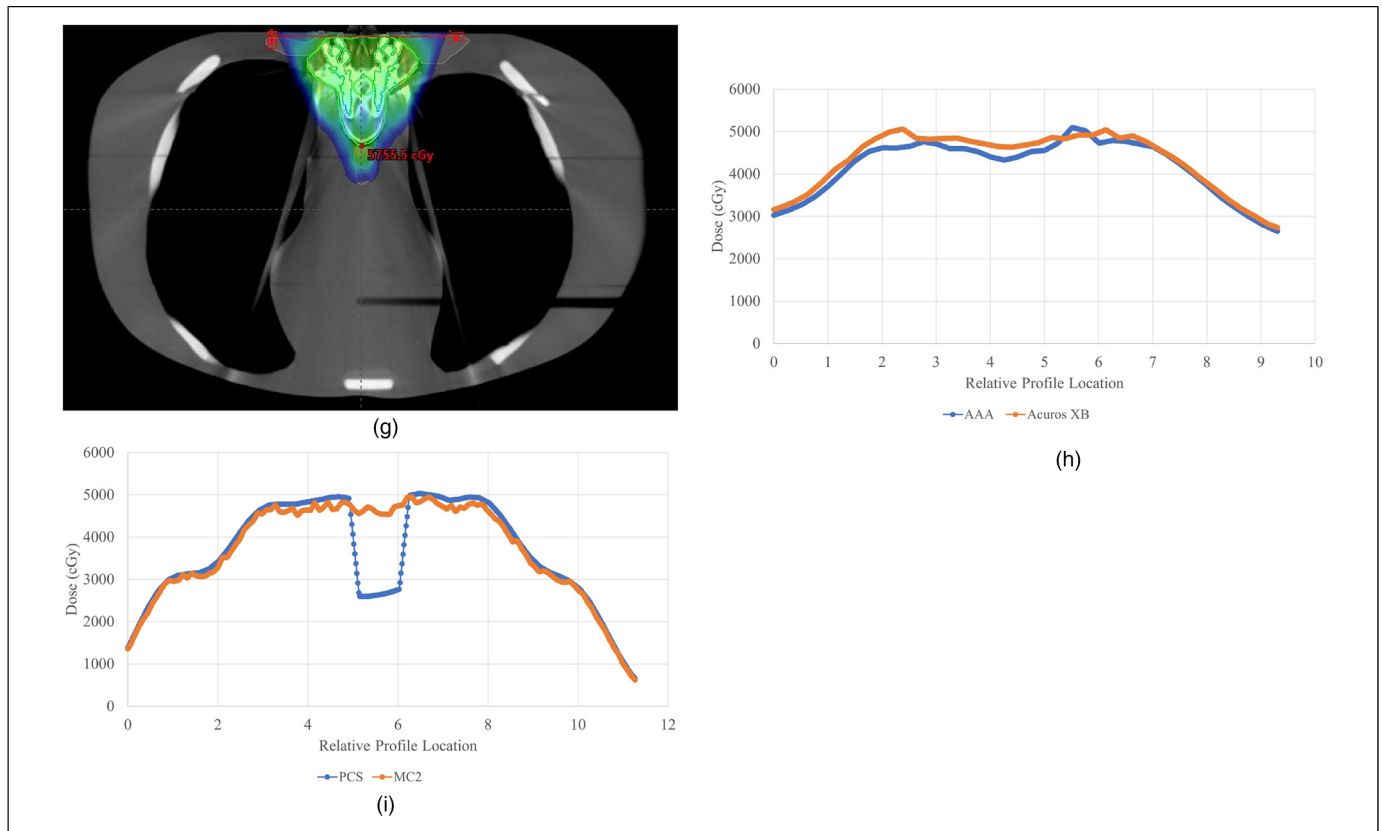


Figure 6. Continued.

### Proton Planning and Uncertainty Analysis

Figure 3 shows the composite (initial + boost) proton plan quality merit, including dose to CTVs and OARs, for 4 different spine configurations: (a) normal/native spine; (b) Titanium insert; (c) CFR-PEEK insert; and (d) hybrid insert.

Figure 4 shows the CTV 50 Gy, CTV 74 Gy, and spine initial plan uncertainty analysis for the four types of spine inserts. The boost plan uncertainty is not shown here since the CTV 74 Gy is away from the screws and heads and not a strong function of the spine configuration. The uncertainty parameters for proton planning were 3 mm for set up and 3.5% for range uncertainty.

Proton planning with different spine inserts can achieve similar nominal target coverage and OARs doses (Figure 3). For uncertainty analysis in Figure 4, the higher mean value and a narrower box of coverage for  $D_{95\%}$  and  $D_{90\%}$  indicate more robust plan quality. Therefore, combining all of those variables, the normal spine and the CFR-PEEK insert plans produce similar plan quality, and both are superior to that of the Titanium and the hybrid insert plans.

### Photon versus. Proton Planning

Figure 5 shows the composite (initial + boost) MFO-IMPT and VMAT plan comparisons for the  $D_{90\%}$  and  $D_{95\%}$  of CTV 50 Gy target, CTV 74 Gy target, spinal cord  $D_{max}$ , heart  $D_{mean}$ ,

left lung  $D_{mean}$ , esophagus  $D_{max}$  and  $D_{mean}$ , skin  $D_{max}$ , and right lung  $D_{mean}$ .

No larger differences in target coverage were present between proton and photon plans. No larger difference in maximum dose to the spinal cord was present between proton and photon plans as all plans were limited to our institutional constraint of spinal cord surface  $D_{Max} < 63$  Gy. However, proton plans consistently achieved a lower mean heart (47.20 cGy vs 752.35 cGy), mean left lung (135.05 cGy vs 1067.73 cGy), and mean right lung dose (263.13 cGy vs 1160.03 cGy), as well as reduced maximum (5539.28 cGy vs 60974.10 cGy) esophageal doses comparing to photon plans. The proton plans, however, had a higher maximum skin dose (6672.33 cGy vs 5437.58 cGy).

### Monte Carlo Versus Analytic Dose Calculation

Figure 6 shows the Acuros<sup>®</sup> XB algorithm versus AAA algorithm for photon planning dose calculation differences and PCS algorithm versus MCsquare algorithm for proton planning dose calculation differences in color wash distribution and profiles comparisons indicated by the corresponding lines. For proton planning, the Monte Carlo dose calculation revealed up to a 16% local dose shadow within the target in the presence of Titanium screw and rod, which depends on the dimensions of the metal implant and beam arrangement. The  $D_{95}$  of CTV 50



Gy decreased by 8.2% and 4.5% for Titanium and hybrid implants, respectively, but almost no difference was found for CFR-PEEK and normal implants by comparing TPS with MCsquare. Monte Carlo results show no impact on doses to the OARs. Figure 6i shows PCS algorithm considered less backscattering rather than MCsquare, which caused the dip of the profile.

Dose calculation accuracy of TPS is limited for scenarios with metal heterogeneity. Titanium implants, in certain circumstances, cause dose shadowing and could compromise target coverage. On the contrary, based on this analysis, the use of CFR-PEEK improves the overall dosimetric accuracy.

For photon Acuros<sup>®</sup> XB versus AAA algorithm, except the normal insert plan right lung maximum dose and skin mean dose having 6% and 4% difference, respectively, and the Titanium skin mean dose having 25% difference, the other dosimetry comparison showed no more than 5% dose differences. Therefore, photon planning and VMAT technique are less sensitive to the presence of hardware inserts.

## Discussions

In this study, we have quantitatively and qualitatively compared 4 spine inserts/configurations for proton and photon planning inclusive of plan quality, challenge, and robustness analysis. When we use normal spine configuration as the baseline, the result of artifact reduction shows the CFR-PEEK image set is closer to the baseline followed by hybrid configuration and Titanium configuration. We subsequently compared proton versus photon planning, which showed that while target coverage and cord dose were the same, protons were superior for other OAR sparing. As such, we further evaluated proton plan dosimetry, uncertainty, and plan integrity across spine configurations, which showed similar target coverage and OARs doses can be achieved; however, the CFR-PEEK and normal spine configurations have superior robustness than the hybrid and Titanium spine configuration considering non-shoot through planning technique. Our current institutional practice is not shooting through the Titanium inserts. The Titanium inserts can be visualized on the DRR or CBCT images for patient alignment purposes to reduce the setup uncertainties. With current setup uncertainties and range uncertainties for treatment planning and treatment, it is still adequate to treat patients with Titanium inserts. The Titanium parts will introduce further dosimetry calculation challenges and if shooting through metal is utilized, more accurate techniques like Monte Carlo must be implemented. In addition, there was enhanced and more accurate proton planning and delivery with the use of CFR-PEEK-based inserts when compared to Titanium as shown in this study.

The CFR-PEEK spine insert has fewer artifacts than the Titanium implants (0.5 cc vs 77.46 cc). A similar study has been done by Huber et al<sup>23</sup> and found a significant difference ( $P < .001$ ) for the artifacts between CFR-PEEK and the Titanium insert. Without artifact correction, the dose difference may be up to 20% to 25%, which is clinically unacceptable

when treating tumors requiring doses at the upper limits of spinal cord tolerance.<sup>5</sup> Thus, the CFR-PEEK spine insert has clinical dosimetry advantages over Titanium considering the artifacts reductions. An artifact identification is also user-dependent and the time spent on the contouring will further favor the artifact-free image sets.

Chordoma treatment requires a conformal dose to the targets while sparing the spinal cord, and a high-density spine insert will result in compromise of the treatment goal due to either no-fly zone in the spine inserts or heterogeneity of the environment created. The CFR-PEEK insert has properties similar to the normal spine, which helps to improve the target coverage and meet the planning goals. These physical properties are similar for both proton and photon treatment planning and allow for simpler planning considerations, such as direct shoot through of beam through the implant. Avoiding directly shooting through the Titanium insert during proton planning is challenging. The plan quality is limited by beam angles and potential hot and cold dose regions near the Titanium materials. Proton planning coverage is also limited to account for the field-specific target margin uncertainties to avoid the Titanium hardware. With the CFR-PEEK material insert, those challenges are overcome and can achieve normal spine plan quality. The uncertainty analysis showed better results than the Titanium insert.

Photon planning has more freedom for spine inserts since it can deliver the beamlets from multiple beam angles and can penetrate high-density materials. Compared to proton plans, the photon plan appears to achieve similar target coverages. However, some OARs still receive higher doses due to the nature of the limitations governed by physics. Multibeam angles also reduce the impact of heavy metals on dose perturbation. Muller<sup>13</sup> et al did retrospective planning for five patients with Titanium and five with CFR-PEEK system and they found VMAT plans showed no relevant difference in dosimetric quality. On the other hand, IMPT plans demonstrated the benefit of CFR-PEEK screws compared to Titanium. Poel<sup>14</sup> et al did the same phantom study for proton planning using a single-field plan and multi-field optimized plan. They also found that the CFR-PEEK versus Titanium has the advantages of CT artifacts reduction, robustness, and final dosimetry accuracy. Compared to Poel's study, we used a multi-field approach and non-shooting techniques, with different CT scanners, treatment planning systems, and dose calculation engines, we confirmed the CFR-PEEK versus Titanium advantages.

The Monte Carlo study of the proton and photon planning shows some limitations of the current treatment planning default algorithms (PCS and AAA) for heterogeneity environment. The photon plans are less impacted compared to the proton plans. For proton planning, careful validation of the heterogeneity correction must be performed to achieve acceptable clinical tolerance.

While the CFR-PEEK spine insert has clear imaging and treatment planning advantages, widespread adoption is still pending due to operative clinical concerns. For example, Joerger et al<sup>24</sup> reported the CFR-PEEK spine inserts may be

associated with screw loosening and bacterial adhesion effects more than Titanium inserts. Therefore, although its use is increasing, the wide application of the CFR-PEEK insert for patients is still under further study.

Overall, the CFR-PEEK spine insert has similar physical properties to the normal spine for both proton and photon treatment, which improves treatment planning quality and the ability to achieve target coverage and OAR constraint goals. In contrast, titanium spine inserts can create a more heterogeneous environment for dose calculation, and careful handling of the hardware region must be taken into account to lower the uncertainties and potential hot and cold doses near the hardware.

## Conclusions

We have performed comprehensive testing for the CFR-PEEK spine insert based on CT imaging, proton and photon treatment planning, and Monte Carlo dose calculation for the heterogeneity effects studies. The CFR-PEEK implant presents properties similar to a normal spine in both proton and photon planning. In proton plans, it allows proton particles to pass through as dealing with normal spines, thus able to achieve superior target coverage and OAR sparing for both nominal and uncertainty conditions in comparison to that in the presence of Titanium hardware.

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## Declaration of Conflicting Interests

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## Ethics Approval

Not applicable.

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