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Case report

Utility of carbon fiber instrumentation in spinal oncology

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ABSTRACT

Spinal oncology has had many advancements often necessitating serial imaging for post-surgical treatment planning and close follow up. Traditional spinal instrumentation introduces artifact into MRI and CT imaging, which can reduce the efficacy of follow up imaging and treatment. Newly created carbon-fiber instrumentation can offer many advantages compared to traditional instrumentation while typically maintaining biomechanical stability. The utility of this new instrumentation continues to evolve as more surgeons utilize these materials, which can improve patient outcomes. We illustrate the utility of this new hardware technology through various patient examples.

1. Introduction

Spinal oncology has advanced over recent decades with more advanced tumor resection techniques, reconstructive options, and radiotherapies. Surgical treatment of oncologic lesions can include either intralesional or enbloc resection and can require spinal stabilization if there is significant invasion or resection of bony elements. Postoperatively, patients often undergo serial imaging to monitor for tumor recurrence or adjuvant radiotherapy for more comprehensive treatment [1].

Carbon fiber instrumentation has been used for interbodies and cages and was found to have minimal effect on radiographs, computed tomography (CT) or magnetic resonance imaging (MRI) [2]. The material has been adapted for the use in spinal instrumentation for purposes of stabilization with screw and rod constructs. Reports have shown that these systems have minimal interference with ionizing radiation and MRI, while maintaining the structural functions in a similar fashion to titanium. However, previous reports have focused on carbon fiber reinforced pedicle screws, while retaining traditional titanium rod and tulips that do not maximize radiolucency [3]. Newer technologies have allowed for the development of carbon fiber reinforced, radiolucent instrumentation including tulips and rods. We report our experience with and rationale for using carbon fiber instrumentation (Carboclear™ system, CarboFix Orthopedics Ltd., Israel) across a sampling of various treatment protocols related to spinal involvement of squamous cell carcinoma, pleomorphic xanthoastrocytoma, Ewing's sarcoma, and osteosarcoma without hardware failure.

2. Case presentations

A selection of patients who underwent fixation with carbon fiber instrumentation in the setting of spinal oncology was reviewed. Informed consent was obtained for participation in research and publication.

2.1. Pleomorphic xanthoastrocytoma (PXA)

A 49-year-old man presented with a history of a previously resected left temporal lesion initially thought to be glioblastoma multiforme (GBM) at an outside hospital and had undergone standard, concurrent temozolamide and radiation therapy. However, he declined post-radiation temozolamide. He developed worsening back pain centered around the T12 region. Imaging revealed a T12 region tumor as well as a T2 region tumor with other rib and chest wall lesions. Review of his previous outside pathology was instead more consistent with PXA. He underwent biopsies of these new spine lesions, which were molecularly consisted with his previous intracranial tumor - spinal pleomorphic xanthoastrocytoma (PXA). Repeat imaging months after initial presentation showed progression of both lesions so he underwent resection of the lesions and nearby bony involvement. Because of the need for close follow up with high resolution imaging and spinal radiotherapy, carbon fiber instrumentation was used for posterior fixation from T1-T4 and T10 to L2 after resection of the T2 and T12 lesions. A T12 vertebrectomy was also performed using a Synthes poly-ether-ether-ketone (PEEK) cage (DePuy Synthes, Switzerland) to span the T11-L1 defect. The T8 lesion was treated with radiotherapy without surgical intervention. Post-operative MRI and CT scans were effective in clearly evaluating the

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instrumentation, neural and bony elements, and was able to reveal the development of an additional lesion at T6 (Figure 1). After comprehensive molecular testing of the previous temporal lesion pathology and spinal lesions, he was diagnosed with metastatic PXA. He was continued on binimetinib and encorafenib after his surgery without undergoing spinal adjuvant radiotherapy. At most recent follow up, approximately 1.5 years after surgery, there was no evidence of hardware failure, but he had evidence of widely metastatic disease.

2.2. Squamous cell carcinoma (SqCC)

A 31-year-old woman with a previous history of SqCC of the tongue developed lung and spinal metastases with a L4 region lesion and underwent radiosurgery. Her initial symptoms of back pain resolved after radiotherapy but recurred with new left lower extremity radicular symptoms. She underwent a CT-guided biopsy of the lesion, which was consistent with metastatic disease. Given the failure of radiosurgery to control the lesion, she underwent a two-stage resection with L2-S1 posterior spinal fusion and resection of posterior elements of L4, followed by a retroperitoneal approach for L4 vertebrectomy and anterior cage reconstruction. Carbon fiber instrumentation was used for the posterior instrumentation and a PEEK distractable cage was used anteriorly. This instrumentation was chosen given her multiple metastatic lesions and concern for future recurrence or disease progression that would require close imaging follow up. Eventually, this allowed for the detection of a new L5 vertebral body lesion near the inferior aspect of her instrumentation, consistent with a metastatic lesion on CT-guided biopsy. Standard metallic instrumentation would likely have induced significant artifact prohibiting early diagnoses of disease at this location (Figure 2). She received 24 Gy via stereotactic radiosurgery in one fraction to this new L5 lesion, with excellent targeting and without complication. At 6 months follow up, she had no evidence of hardware failure, but unfortunately later passed away due to her disease process.

2.3. Ewing's sarcoma

A 50-year-old man presented with abdominal and groin pain, and was eventually found to have a paraspinal mass with associated L2 and L3 vertebral body fractures and ventral epidural lesions. CT-guided biopsy of the paraspinal lesion was consistent with Ewing's sarcoma. He underwent chemoradiation with significant decrease in the size of most lesions (Figure 3), however a residual lesion with increased fluorodeoxyglucose (FDG) uptake on positron emission tomography (PET/CT) remained. This residual lesion, located in the paraspinal region and nearby posterior elements from L1-L3, was concerning for viable Ewing's sarcoma on CT-guided biopsy. The patient underwent enbloc resection of the hypermetabolic lesion with associated nearby musculature and bony elements without vertebrectomy, and T11 to L4 posterior spinal fusion with carbon fiber instrumentation for fixation.

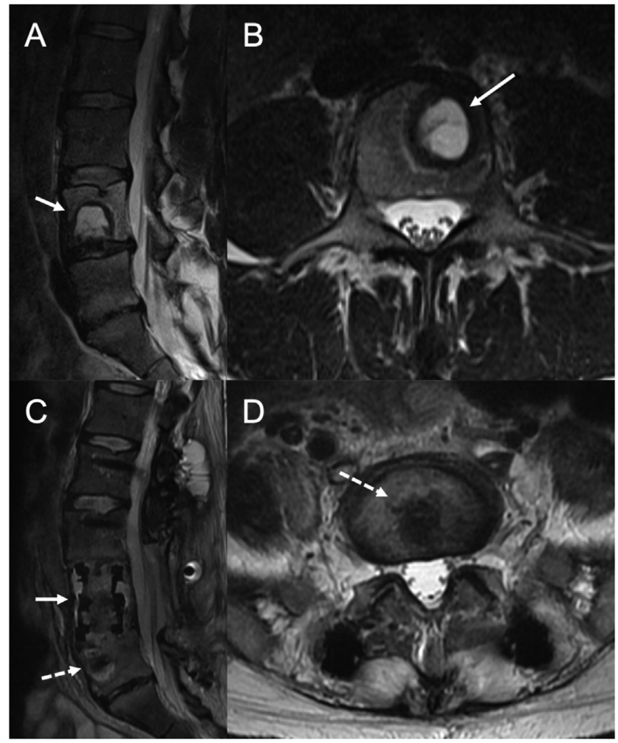

Figure 2. 31-year-old woman with SqCC metastasis to the spine. T2-weighted MRI showing L4 lesion (arrows) before surgery (A and B), and after resection with carbon fiber posterior instrumentation and PEEK cage (solid arrow) with new adjacent L5 lesion (dashed arrow) (C and D).

In this patient's case, carbon fiber instrumentation was chosen because there was previous evidence of tumor leading to pathologic fractures of the vertebral bodies with extension into portions of the pedicle, and close follow-up with MRI would be necessary. After chemoradiation, MRI and PET/CT showed resolution of disease in those locations. No hardware was placed into the L2/L3 vertebrae given the previous fractures. At two months after surgery, the patient was found to

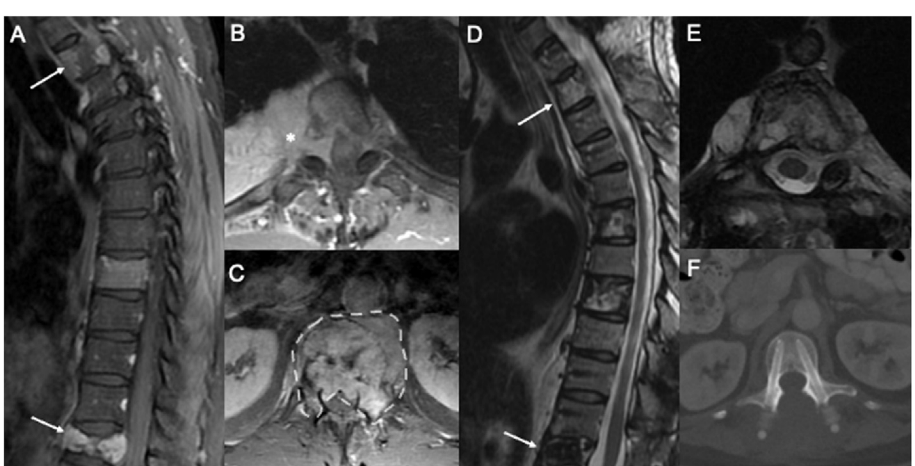

Figure 1. 49-year-old man with initial diagnosis of PXA involving the spine. A, B and C Post-gadolinium T1-weighted MRI showing T2 (B) and T12 (C) lesions before surgery (arrows, asterisk and within dashed line). D and E T2-weighted MRI showing sagittal view of lesions after resection (D) (arrows), and level of T2 lesion resection (E). Demonstration of carbon fiber instrumentation at L1 on post-operative axial CT (F).

Figure 3. T2-weighted MRI showing initial lesion showing initial paraspinal region lesion (asterisk) before any treatment (A sagittal, B axial). Post-operative, follow-up T2-weighted MRI sequences showing implanted hardware (arrow) and area concerning for disease progression (asterisk) near left psoas muscle despite surgical resection and chemoradiation therapy (C sagittal, D axial).

have increased metastatic disease and began irinotecan and temozolamide chemotherapy. At four month follow up, the patient has no evidence of hardware failure.

2.4. Osteosarcoma

A 16-year-old male began developing low back pain into his right lower extremity two years prior, but workup of this was delayed due to his social condition. He was found to have a large mass of the sacrum with CT-guided biopsy confirming osteosarcoma. He initially underwent 10 weeks of chemotherapy without any change in his neurologic condition. He continued to have significant pain with bowel and bladder dysfunction, but otherwise remained full strength. He had a large mass that involved the entire sacrum and extended dorsally into the paraspinal musculature with extension into the right sacroiliac joint (Figure 4).

The patient underwent a two-stage resection of sacral osteosarcoma with total sacrectomy, right internal hemipelvectomy, enbloc resection of tumor, and L3 to pelvis carbon fiber instrumentation. Given the high risk of recurrence with this disease and potential for significantly distorted anatomy with traditional metallic implants, the use of carbon fiber instrumentation was critical for appropriate and accurate follow up imaging. There was no evidence of hardware failure at 1.5 years after surgery and he tolerated chemotherapy well.

3. Discussion

The multidisciplinary approach to spinal oncology often requires a variety of treatment modalities from chemotherapy, surgical resection and radiotherapy. Diagnostically, this includes acquiring CT and/or MRI scans to monitor for disease progression or recurrence. As a part of treatment, adjuvant radiotherapy can also be necessary depending on the type of malignancy. Consequently, these diagnostic and treatment aspects of spinal oncology must be accounted for during the surgical planning process. Careful consideration of spinal instrumentation in those cases needing reconstruction is especially important.

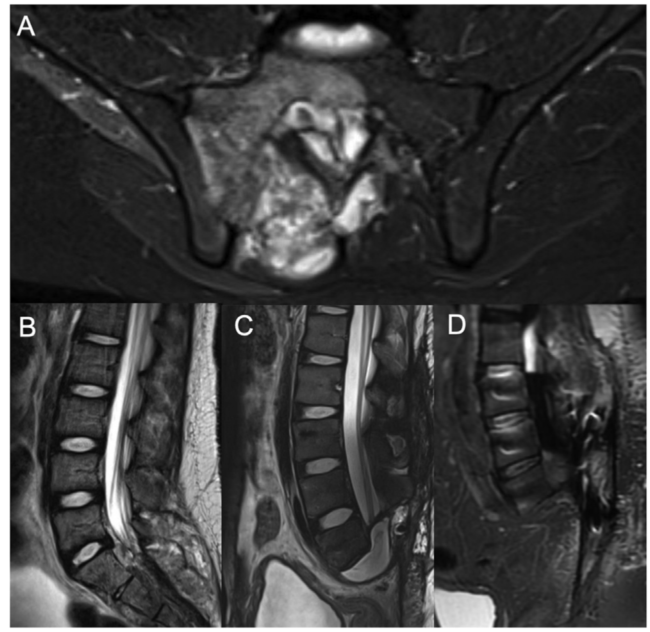

Figure 4. A and B: Short-T1 inversion recovery (STIR) and T2 MRI sequences showing large osteosarcoma involving the sacrum and right sacroiliac joint, extending dorsally past the spinous processes into the paraspinal musculature. C: Post-operative T2-weighted MRI of same patient after total sacrectomy and internal hemipelvectomy with carbon fiber instrumentation with ability to visualize bony and neural elements. D: Post-operative STIR MRI of different patient who underwent similar sacrectomy and hemipelvectomy procedure, but with traditional titanium instrumentation with significant artifact obscuring critical elements.

Metal implants are considering “high-Z” due to their higher atomic number and as a result have greater scattering effect and quantum noise that can affect diagnostic imaging and radiotherapy [4]. Carbon-based implants such as carbon fiber reinforced instrumentation are described as “low-Z” due to the lower atomic number of the material components. This more favorable “low-Z” characteristic makes carbon-based implants especially suited for spinal instrumentation in spinal oncology.

3.1. Imaging and radiotherapy

Various studies have shown superiority in artifact reduction on MRI and CT imaging modalities for carbon-fiber based instrumentation. Traditional metal instrumentation is known to create artifact that can critically alter the utility of imaging despite artifact reduction techniques [5]. In contrast, carbon-fiber based instrumentation significantly reduces artifact on these modalities as a result of its “low-Z” characteristics [6, 7]. This allows for more meaningful follow up imaging with minimal artifact to monitor for tumor recurrence or residual disease after treatment.

Stereotactic radiotherapy, carbon ion therapy, and proton therapy are useful treatment modalities in spinal oncology. In the cases of tumors typically classified as radioresistant, newer forms of radiotherapy have proven beneficial [8, 9]. Particle therapy, especially, has been shown to have dosimetric superiority over photon therapy, but needs to be properly dosed to maintain treatment efficacy [10]. Metal hardware, unfortunately, can have negative effects during treatment due to scattering on planning imaging, just as it does on routine diagnostic imaging. This scattering introduces artifact that can obfuscate target tissue, making it difficult to avoid normal structures. This can result in poorer effective treatment doses regardless of modality, and more significant manual corrections that increase planning time [11, 12, 13, 14].

In proton therapy specifically, inaccuracies in distinguishing target tissue from the surrounding tissue results in inaccuracies in estimating particle range. Density mapping using Hounsfield Units (a key component of estimating range along with a particle's stopping power) must then be performed manually, and results in uncertainty regarding dosing. Even without evidence of increased treatment backscatter from metallic hardware during proton therapy, implant-related artifacts can still require hybrid treatments with protons and photons to maintain safe dosing that may not be sufficient for treatment [14, 15]. By minimizing artifact during radiotherapy planning, carbon fiber instrumentation makes treatment more reliable and effective in spinal oncology [16, 17].

3.2. Structural integrity

Carbon-fiber reinforced instrumentation such as reinforced PEEK has been shown to maintain imaging and treatment benefits, while also performing similarly to titanium instrumentation regarding axial load and compression [18]. Additionally, stiffness, multicycle loading and pull-out strength was found to be similar to titanium instrumentation and in some studies better [19, 20]. Other studies report improved biomechanical compatibility of carbon-fiber based instrumentation emphasizing its density and elastic modulus that are more similar to bone especially when integrated with PEEK [21]. The newer implants (Carbofix and Icotec) use continuous carbon fiber strands reinforced with PEEK. These have been reported to have superior compressive force resistance, as well as superior tensile strength properties compared to previous PEEK-reinforced, carbon fiber instrumentation [19]. Bending load and bending stiffness was reported to be comparable to and superior to titanium alternatives, respectively [19]. For these reasons, rods and screws are being made with this carbon fiber strand material, while cages continue to be made from PEEK-reinforced carbon fiber particles. As a result, hardware failure rates appear within a year to be minimal and likely comparable to traditional hardware in oncologic cases [22, 23].

Unfortunately, there has not been sufficient long-term follow-up reporting in the literature to rigorously assess hardware failure rates for carbon fiber screws and rods on the order of years. Studies have been limited at most to just under two years in very few patients and in limited contexts [22, 23, 24]. Further research on long-term outcomes is necessary to be certain carbon fiber instrumentation is a reasonable alternative to titanium with regards to structural integrity.

3.3. Drawbacks

There is limited long-term data regarding carbon-fiber instrumentation in humans. Carbon fiber materials can be brittle by comparison to their metal counterparts, and as a result carbon fiber instrumentation used in spinal instrumentation is often PEEK-reinforced, such as in traditional cage technology [25, 26]. Unfortunately, this configuration is significantly more expensive to produce compared to metallic instrumentation and as a result may not always be available to patients [27].

From an operative perspective, carbon fiber instrumentation in its current state has many challenges. While the literature has shown similar efficacy of carbon fiber instrumentation in maintaining structural integrity, its implementation can prove cumbersome. Given the structural properties of the material, screw insertion and rod placement require excellent planning without the same options for in situ modification afforded by metal instrumentation, and risk of fracturing instrumentation during placement even with manually applied force. While feasible, our anecdotal experience with carbon-fiber instrumentation is that it increases operative time and is currently limited as far as construct customization. Since the rods cannot be contoured, a patient's spinal contour may not match available rod options in certain circumstances. In general, there is a steep learning curve to implanting carbon fiber instrumentation which limits its practicality and lead surgeons to favor more traditional methods.

Additionally, given the subtle appearance of carbon fiber hardware on imaging that lends many advantages from an oncologic perspective, detecting if this hardware has failed can be difficult. There is some suggestion that using this hardware in the setting of infection may lead to earlier hardware failure, although the mechanism as to which this happens is unclear [28]. Pain is typically used as a clinical marker of either recurrence or hardware failure, so our practice in situations of worsening, localized pain is to obtain CT and MRI to rule out recurrence or disease progression. If this imaging is unremarkable, a discussion with the patient to undergo exploration for possible revision of hardware may be considered if pain cannot be controlled.

3.4. Application

Given the current state of carbon fiber instrumentation, with high cost and limited customizability, we limit the patients who receive this instrumentation to those we expect will need close radiographic follow-up such as in the case of high-grade malignancies, significant risk of nearby metastatic disease, or lacking definitive diagnosis. Additionally, those patients with specific plans of post-operative adjuvant radiotherapy, particularly proton therapy, are strongly considered given previously discussed radiation dosing benefits. We do not see clear advantages of this instrumentation in cases of benign tumors at this time given the disadvantages of cost and customizability and maintain the use of metallic hardware implants in those cases.

4. Conclusion

Carbon fiber-based instrumentation is increasingly used in spinal oncology given the various benefits related to post-treatment imaging and radiotherapy. While still considered significantly more expensive than traditional metal instrumentation, the utility of carbon fiber-based instrumentation in the setting high-grade, malignant spinal lesions could outweigh the costs. Longer-term follow-up is needed to ensure the upfront advantages of this instrumentation are not outweighed by hardware failure down the road. Further development of carbon fiber-based composites with diminishing costs and increased hardware options would further justify using this instrumentation for broader oncologic disease in the future.

Declarations

Author contribution statement

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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