Abstract: The challenges inherent in spinal oncology are multi-dimensional, stemming from the complex anatomy of the spine, the high risk of neurological complications, and the indispensability of personalized treatment plans. These challenges are further compounded by the variability in tumor types and locations, which complicates the achievement of optimal treatment outcomes. To address these complexities, the manuscript highlights the pivotal role of technological advancements in surgical practices. The review focuses on the evolution of spinal oncology instrumentation, with a special emphasis on the adoption of carbon fiber implants in the management of spinal tumors. The advancements in instrumentation and implant technology are underscored as vital contributors to the improvement in patient outcomes in spine surgery. Carbon fiber implants are lauded for their reduced imaging artifacts, biocompatibility, and favorable mechanical properties. When combined with other technological innovations, these implants have substantially elevated the efficacy of surgical interventions. The review articulates how these advancements emphasize precision, customization, and the integration of innovative materials, significantly enhancing the effectiveness of surgical procedures. This collective progress marks a considerable advancement in the treatment of spinal tumors, highlighting a shift towards more effective, patient-focused outcomes in spinal oncology.

Keywords: spinal oncology; metastatic spine tumors; computer-aided surgical systems; carbon fiber implants; technological advancements; personalized treatment plans; surgical precision

1. Introduction

The progress registered in the early diagnosis and management of tumors has led to prolonged survival of cancer patients. Consequently, there is a significant rise in the number of patients with metastatic spine tumors which are noted to be more prevalent than primary spine tumors [1–3]. The past few decades have witnessed major advances in spinal oncology as it continues to face the challenges posed by the complex nature of spinal tumors. These challenges include the intricate anatomy of the spine, the potential for neurological complications, and the need for comprehensive, patient-specific treatment plans. Additionally, the high variability in tumor types and locations poses difficulties in achieving optimal treatment outcomes.

The management of spinal tumors requires a delicate balance between achieving oncological control and preserving spinal function and stability. Surgical intervention for spinal tumors often necessitated extensive tissue disruption and destabilization, leading to significant morbidity and compromised patient outcomes [3,4]. However, with the advent of advanced instrumentation and technologies, surgeons can now approach these cases with greater precision, efficacy, and safety [4,5]. This has arguably revolutionized the field of spine oncology, offering new hope and improved outcomes for patients facing spinal tumors.
Carbon fiber has garnered considerable attention in spine surgery due to its unique mechanical properties and biocompatibility [6]. One of the key applications of carbon fiber technology in spine oncology is in the development of implants and instrumentation that help optimize postoperative management. By leveraging advanced imaging modalities such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), carbon fiber implants can enhance the effectiveness of post-resection radiotherapy [7]. Furthermore, surgeons can monitor for recurrence or progression of tumor [7].

In this narrative review, we explore the latest developments in instrumentation and implants specifically tailored for spine oncology, with a special emphasis on the applications and benefits of carbon fiber materials. We delve into the evolving landscape of carbon fiber technologies in spine oncology, examining their clinical applications, outcomes, and future directions. We aim to provide insights into the transformative potential of carbon fiber instrumentation and implants in optimizing patient care and advancing the field of spine oncology. As the demand for minimally invasive yet effective solutions for spinal tumors continues to grow, carbon fiber technologies stand poised to play a pivotal role in shaping the future of surgical management. By harnessing the inherent properties of this innovative material, surgeons can navigate the complexities of spine oncology with precision and confidence, ultimately improving patient outcomes.

2. Historical Overview of Instrumentation in Spine Surgery

The history of instrumentation in spine surgery is marked by innovative milestones. Accounts of surgical intervention for spinal deformity in the modern era date back to the 19th century when Berthold Hadra, Jules Gerin, and W. T. Wilkins treated patients with spinal conditions including spinal bifida, scoliosis, and Potts disease [8,9]. In the early 20th century, efforts focused on treating spinal deformities associated with diseases like tuberculous spondylitis and poliomyelitis. The Hibbs method in 1911 introduced spinal arthrodesis, using autologous bone grafts via transposition of spinous processes [10,11]. Plaster casts were used to attempt a correction of the loss of curvature and stabilize the spine.

The introduction of the stainless-steel Harrington Rod in the mid-20th century addressed critical gaps in the treatment of neuromuscular scoliosis, thereby revolutionizing spinal surgery [12]. The invention of segmental pedicle screws, pioneered by Roy-Camille [13] paved the way for systems like the Cotrel–Dubousset technique in the 1980s. This approach utilized segmental spinal instrumentation, allowing selective distraction and compression for tailored corrections at individual spinal levels. The Cotrel–Dubousset system, with vertebral screws and hooks made of steel, showed enhanced alignment in sagittal, coronal, and axial planes [14].

A simple representation of the major evolution points of spinal instrumentation over the past century is highlighted in Figure 1. Contemporary spine surgery has seen significant progress with materials evolving beyond stainless steel to advanced options like titanium and cobalt chrome. Pedicle screws remain crucial, adapting to robotics and minimally invasive techniques. Fusion techniques, incorporating bone graft substitutes and biologics, have reduced pseudoarthrosis rates. The historical evolution reflects a journey from early attempts to address spinal deformities to the introduction of corrective instrumentation, setting the stage for sophisticated and patient-tailored approaches in modern spine oncology.
The integration of computer-aided surgical systems with robotic platforms significantly enhances the capabilities of robot-assisted surgery [17,20,21]. This fusion of technologies not only amplifies the precision and efficiency of surgical interventions but also expands the scope of what can be achieved through robotic assistance in the operating room.

To address these challenges, various surgical techniques have been developed. Decompression surgeries, coupled with implant-based stabilization, have gained prominence since the late twentieth century [16]. The widespread adoption of pedicle screw rod systems in the 1980s facilitated the increased utilization of spinal implants [16]. Posterior spinal fixation and decompression have become popular techniques with the advent of implants, while anterior decompression, with or without posterior fixation, was introduced subsequently [16].

These advances in techniques and approaches of spine oncology instrumentation are further amplified by the constant evolution of and advances in computer systems and information technology. Computer-aided surgical systems represent advanced technologies designed to support surgeons in both the planning and execution of surgical procedures. These systems harness the power of computer algorithms, imaging, and real-time feedback to improve surgical techniques by enhancing precision and decision-making throughout surgery [17]. This proves particularly valuable in delicate surgeries or when dealing with tumors invading intricate anatomical structures [18,19]. Surgeons leverage these systems for preoperative planning, utilizing patient-specific data to craft a personalized surgical plan. The integration of computer-aided surgical systems with robotic platforms significantly enhances the capabilities of robot-assisted surgery [17,20,21]. This fusion of technologies not only amplifies the precision and efficiency of surgical interventions but also expands the scope of what can be achieved through robotic assistance in the operating room.

Furthermore, advances in imaging technologies have markedly enhanced intraoperative navigation for spine surgery, empowering surgeons with superior visualization and precision [22]. The integration of cutting-edge imaging modalities, including 3D imaging, CT scans, and MRI data, furnishes surgeons with detailed and real-time visualization of...
the surgical site. They provide crucial insights into instrument positioning, alignment, and proximity to critical structures. This real-time information provides timely adjustments, improving overall surgical control [8].

In procedures that leverage imaging guidance, computer-aided systems play a pivotal role in minimizing the reliance on extensive intraoperative fluoroscopy [19,23]. This reduction not only reduces radiation exposure for both the patient and the surgical team but also underscores the commitment to safety. Collectively, these innovations contribute to the enhancement of safety and precision in spine surgeries. Surgeons benefit from improved capabilities to navigate intricate anatomy, visualize critical structures, and ultimately achieve optimal outcomes for their patients.

4. Introduction to Implant Technologies

Traditionally, a variety of metals and alloys have been adopted as implant materials in spine oncology. Common options for spine oncology implants include metals like titanium, cobalt, chromium, zirconium, steel, and tantalum [24–27]. These materials offer crucial qualities such as strength and stability vital in spine oncology instrumentation [28]. Non-metallic materials like the traditional polyetheretherketone (PEEK) have also gained prominence in spinal instrumentation. PEEK, a polymer, is sometimes favored in spine surgery due to its radiolucent properties which improve imaging visibility. In addition, its modulus of elasticity closely aligns with that of bone, distinguishing it from metal implants [29].

While these implant materials have become widely utilized in spine surgery, they present a myriad of challenges. The relatively high density and weight of metals, particularly in the context of spinal fusion constructs, raise concerns about physiological compatibility and functional outcomes. This weight can significantly increase the overall spinal load, especially in patients with compromised bone density [29]. The rigidity of metal implants may also hinder natural spine movement, potentially resulting in a reduced range of motion and stress on adjacent segments. Moreover, the radiopacity of traditional metals often interferes with imaging techniques like X-rays, making it challenging to assess bone healing and fusion.

Non-metal implants such as PEEK are noted to be hydrophobic and biologically inert. This makes it challenging to achieve solid fusion and robust osseointegration due to their inability to properly fuse with bone [7,8]. This characteristic poses a significant challenge as it may hinder the seamless integration of the implant with surrounding bone tissue, potentially compromising its stability and longevity within the body.

Furthermore, the absence of inherent antimicrobial properties in PEEK further exacerbates the risk of implant failure [30]. Without the ability to resist microbial colonization and infection, implants made solely of PEEK are susceptible to microbial contamination, which can trigger inflammatory responses, impair healing processes, and ultimately jeopardize the success of the implantation procedure [30]. These issues often result in the need for revision surgery and the consequent complications including difficulties in removing implants due to possible bone ingrowth, tissue adhesion, and potential damage to surrounding structures.

5. Carbon Fiber in Spine Oncology

In response to these challenges, ongoing research and technological advancements in materials science are ushering in alternative materials. The past few decades have witnessed increasing adoption of carbon fiber-based implants. Carbon fiber is a polymer that possesses several unique properties that make it well-suited for spinal oncology implants. To begin with, it is generally biocompatible and bioinert [31,32]. Thus, it is well tolerated by the human body and does not elicit a significant immune response [33,34]. This property is crucial for spinal implants to minimize the risk of adverse reactions, inflammation, or rejection while promoting a stable environment around the implant when integrated into the spinal column.
Carbon fiber-reinforced (CFR) materials, functioning as electrically conductive microcircuits within a polymer matrix composite, have demonstrated promising experimental reliability in stimulating tissue growth [6]. This effect is achieved by their capacity to mitigate the detrimental effects of excess electrons generated during respiratory stress. Oxygen serves as the ultimate electron acceptor during efficient energy synthesis. However, in its absence or insufficiency, cells may produce free radicals and acidic byproducts, which can be damaging to cellular structures. Here, carbon fiber’s conductivity plays a pivotal role. By acting as a semi-antioxidant and establishing electrochemical gradients, carbon fiber facilitates the removal of excess damaging electrons, directing them towards areas of lower negative charges and lower concentrations [6]. This mechanism helps in maintaining cellular homeostasis and mitigating oxidative stress.

In addition, carbon fiber is comparable to metals such as titanium in terms of strength and stability despite being lightweight [35]. Table 1 shows a comparison of carbon fiber with traditional implant metals in terms of biomechanical properties and imaging compatibility. In spinal oncology, implants often need to provide stability and support to the spine. The strength of carbon fiber allows for the creation of implants that can withstand spinal loads while maintaining structural integrity [36]. Its excellent fatigue resistance is beneficial in spinal implants subjected to repetitive stress or load-bearing conditions [29]. This contributes to the long-term durability of the implant.

<table>
<thead>
<tr>
<th>Carbon Fiber</th>
<th>Titanium</th>
<th>Steel</th>
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<tbody>
<tr>
<td><strong>Strength-to weight ratio</strong></td>
<td>High tensile strength of 3.6 GPa and low density of about 1.8 g/cm$^3$. This gives it exceptional strength-to-weight ratio</td>
<td>Density of about 4.51 g/cm$^3$. Tensile strength of 240 Mpa. Good strength-weight-ratio</td>
</tr>
<tr>
<td><strong>Energy Conductivity</strong></td>
<td>Low thermal conductivity and not a conductor of electricity</td>
<td>Moderate thermal conductivity. Conductor of electricity</td>
</tr>
<tr>
<td><strong>Corrosion and Fatigue Resistance</strong></td>
<td>Elastic modulus of 233 Gpa. Good fatigue resistance, particularly with repetitive loading. Excellent corrosion resistant</td>
<td>Exceptional fatigue resistance. Elastic modulus of 120 GPa. Outstanding corrosion resistance</td>
</tr>
<tr>
<td><strong>Imaging Compatibility</strong></td>
<td>Safe MRI magnetic field. Does not cause artifact on CT</td>
<td>Safe on MRI magnetic field. Some artifact on CT</td>
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</table>

Carbon fiber offers a notable advantage in its radiolucency, making it highly beneficial in scenarios where minimizing electromagnetic interference is critical, such as during CT or MRI scans [31,35]. The radiolucent nature of carbon fiber allows for comprehensive visualization of anatomical structures during imaging studies. This enhanced clarity enables surgeons to accurately pinpoint the location, extent, and characteristics of spinal tumors, facilitating informed treatment decisions.

Unlike traditional metal implants, carbon fiber is nearly invisible on imaging and does not distort surrounding structures [35]. The improved imaging compatibility of carbon fiber-based implants in spinal instrumentation is demonstrated in Figure 2. The absence of interference from carbon fiber implants ensures that imaging artifacts are minimized, resulting in clearer and more accurate images. The enhanced visibility of tissues and bones on imaging, facilitated by carbon fiber’s radiolucency, enhances the accuracy of diagnosis and postoperative assessment of spinal tumors. Consequently, this enhances the overall quality of patient care, allowing for prompt intervention and optimized patient management, ensuring that treatment plans are tailored to individual needs and that any issues are promptly addressed [20].
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Furthermore, the use of carbon fiber-reinforced instrumentation has been shown to improve postoperative radiation therapy planning [1,37,38]. The radiolucency of carbon fiber implants allows for precise delineation of tumor margins and surrounding anatomical structures, enabling oncologists to target radiation therapy more effectively while minimizing damage to healthy tissues. The value of this quality can be seen in proton beam radiation planning. Proton beams are sensitive to material changes as they pass through structures during targeted therapy [39]. This often results in range uncertainties and setup errors, thereby negatively affecting the quality of the therapy. Metallic implants, like titanium, can cause streak artifacts in 3D CT scans, leading to dose distribution uncertainties in treatment planning. CT scan artifacts can lead to errors in dose calculation [39,40]. As such, carbon fiber implants might be more suited for adequate planning and delivery of proton beam therapy.

Additionally, carbon fiber implants contribute to improved postoperative monitoring for tumor recurrence. As can be seen in Figure 3, imaging studies free from artifacts provide clearer visualization and interpretation of postoperative changes, aiding clinicians in early detection and management of recurrent disease [37,38,41].

In the last few years, carbon fiber-reinforced polyetheretherketone (CFR-PEEK) has now been adopted in spine surgery. CFR-PEEK composite implants harness the properties of carbon fiber and PEEK to develop a system with biomechanical properties comparable to cortical bone [42,43]. CFR-PEEK represents a viable option for semirigid stabilization in spinal surgery, offering a range of advantages over traditional titanium systems [42]. Studies have demonstrated that CFR-PEEK implants possess bending stiffness, yield strength, and ultimate loads that are on par with or even exceed those of rigid titanium constructs [29]. While CFR-PEEK may exhibit slightly lower torsional stiffness and yield torque compared to titanium, it remains robust enough to effectively withstand the physiological loads encountered in the spine [42].
Moreover, the utilization of CFR-PEEK rods in spinal stabilization procedures brings about notable enhancements in primary stability, kinematics, and load-sharing dynamics when compared to conventional titanium implants [42,44]. This improvement is particularly significant in scenarios where maintaining spinal motion and flexibility is desired while ensuring adequate support and alignment.

In terms of pedicle screw fixation, CFR-PEEK systems have shown remarkable pull-out strength, surpassing that of traditional implants [42]. Furthermore, they demonstrate equivalent or superior resistance to screw loosening when compared to titanium alternatives [42,45,46]. This superiority is largely attributed to the absence of a mismatch between the mechanical properties of CFR-PEEK and the surrounding bone tissue, resulting in reduced stress concentrations at the bone–implant interface and thus mitigating the risk of implant failure.

Beyond mechanical performance, CFR-PEEK possesses favorable biocompatibility, enhanced osteogenic properties, and bioactivity [47,48]. Modifying CFR-PEEK implants with amino groups can result in significantly improved osseointegration and bone healing [47,49]. These qualities contribute to ensuring a seamless and stable interface between the implant and the surrounding bone [6] which often results in long-term stability and functionality following spinal surgery. With its combination of mechanical robustness, enhanced stability, and biological compatibility, CFR-PEEK stands as a promising material for advancing spinal instrumentation technology and improving patient outcomes in spinal surgery. Table 2 highlights some of the studies that evaluated specific outcomes of carbon fiber and CFR-PEEK in the management of spinal conditions. Overall, CFR-PEEK has been shown to possess a relatively higher Young’s modulus than PEEK alone [7] and better strength and fatigue resistance, in addition to radiolucency and artifact-free imaging properties [7,29,50,51].

Figure 3. Images from Icotec Medical (Alkstätten, Switzerland). (A) MR artifact-free imaging of carbon fiber-reinforced PEEK pedicle screws; (B) Titanium screws creating significant artifacts on imaging.
Table 2. Summary of studies focusing on carbon fiber implants and outcomes.

<table>
<thead>
<tr>
<th>Title (Year)</th>
<th>Materials</th>
<th>Study/Tests</th>
<th>Conclusion</th>
<th>Overall Positive Outcome (Y/N)</th>
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<tbody>
<tr>
<td>Alvarez-Breckenridge et al. (2023)</td>
<td>Carbon fiber reinforced PEEK (CFR-PEEK)</td>
<td>Assessment of the perceived advantages of improved imaging quality,</td>
<td>CFR-PEEK is safe and effective for spinal stabilization in both primary and metastatic tumors. Better postoperative radiating planning and local tumor recurrence detection were achieved as a result of improved postoperative imaging quality [52]</td>
<td>Y</td>
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<tr>
<td>Henzen et al. (2022)</td>
<td>Carbon fiber reinforced PEEK and Titanium (CFP-T) hybrid implant</td>
<td>Feasibility of postoperative stereotactic body radiation therapy (SBRT)</td>
<td>Dosimetry and delivery of postoperative SBRT is feasible in patients with CFP-T implants using a CyberKnife system [54]</td>
<td>Y</td>
</tr>
<tr>
<td>Hubertus et al. (2022)</td>
<td>Carbon fiber reinforced PEEK (CFR-PEEK)</td>
<td>Evaluation of the performance and precision of 3D intraoperative imaging and navigation systems in thoraco-lumbar instrumentation with CFR-PEEK pedicle screws</td>
<td>Navigation accuracy was considerably lower for CFR-PEEK pedicle screws than reported for titanium implants. CT may be the best imaging modality for CFR-PEEK instrumentation assessment [55]</td>
<td>N</td>
</tr>
<tr>
<td>Joerger et al. (2021)</td>
<td>Carbon fiber reinforced PEEK (CFR-PEEK)</td>
<td>Comparative assessment of pedicle screw loosening and relapse with CFR-PEEK vs titanium in spondylodiscitis patients</td>
<td>More CFR-PEEK pedicle screw loosening than with titanium likely due to stronger bacterial adhesion in spondylodiscitis patients. No difference in fusion rates [56]</td>
<td>N</td>
</tr>
<tr>
<td>Neal et al. (2021)</td>
<td>Carbon fiber reinforced PEEK (CFR-PEEK)</td>
<td>Feasibility and advantages of CFR-PEEK implants in both primary and secondary osseous spinal tumors</td>
<td>CFR-PEEK is comparable to titanium in functionality. Additionally, the imaging characteristics of CFR-PEEK implants result in enhanced safety and efficacy for postoperative radiation planning and surveillance [1]</td>
<td>Y</td>
</tr>
<tr>
<td>Title (Year)</td>
<td>Materials</td>
<td>Study/Tests</td>
<td>Conclusion</td>
<td>Overall Positive Outcome (Y/N)</td>
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<tr>
<td>Oh et al. (2023)</td>
<td>Carbon fiber reinforced PEEK (CFR-PEEK)</td>
<td>Feasibility of CFR-PEEK to provide structural stability while allowing monitoring and treatment of spinal oncologic deformity</td>
<td>CFR-PEEK is safe, effective and may provide relatively more benefit than existing instrumentation for treatment of thoracolumbar posterior spinal pathology [57]</td>
<td>Y</td>
</tr>
<tr>
<td>Schwendner et al. (2023)</td>
<td>Carbon fiber reinforced PEEK (CFR-PEEK)</td>
<td>Assessment of the clinical and radiological outcomes in patients treated with CFR-PEEK dorsoventral instrumentation</td>
<td>The use of CFR-PEEK for vertebral body replacement in thoracic and lumbar spinal tumor patients offers an improved management option, particularly in terms of postoperative radiotherapy and MRI-based follow-up [37]</td>
<td>Y</td>
</tr>
<tr>
<td>Uri et al. (2020)</td>
<td>Carbon fiber reinforced PEEK (CFR-PEEK)</td>
<td>In vitro evaluation of Carbon Fiber-Refine PEEK</td>
<td>CFR-PEEK composite pedicle screw has superior fatigue properties than titanium-made implants of comparable mechanical properties. The fatigue resistance is similar to bone; it is radiolucent and results in artifact-free images on CT/MRI [29]</td>
<td>Y</td>
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</table>

Advances in spine oncology have led to the development of new techniques aimed at improving the treatment of spinal tumors, preserving spinal function, and enhancing patient outcomes. Minimally invasive surgery (MIS) techniques in spine surgery utilize smaller incisions, minimize muscle dissection, and employ specialized instruments for treating various spinal conditions. Robot-assisted minimally invasive spine surgery techniques have also been implemented in percutaneous pedicle screw fixation, kyphoplasty, and vertebroplasty [17,19,58]. They offer several advantages, including expedited recovery, diminished postoperative pain, reduced muscle trauma, lower infection risk, and shorter hospital stays.

In contrast to traditional open surgery, the primary goal of these techniques is to limit tissue damage, decrease blood loss, and facilitate a speedier recovery process [20,59]. Spinal decompression procedures are often combined with radiotherapy in a holistic approach to the treatment of spinal tumors [23]. These procedures entail removing a section of vertebrae elements or tumors, particularly in cases of radioresistant tumors and spinal cord or nerve root impingement. This is then followed by radiotherapy [23,35].

Significant advances have been made in spinal stabilization after resection of both primary and metastatic tumors [37]. There seems to be an increasing emphasis on dynamic stabilization as an important element in the recovery of patients after spinal surgery [60]. Dynamic stabilization systems allow controlled motion at the stabilized segment of the spine. These systems aim to preserve some nonpathological spinal mobility while providing stability, reducing the risk of adjacent segment degeneration and promoting better long-term outcomes [60]. However, it remains to be seen if there could be a role for dynamic stabilization techniques in spinal tumor reconstructive surgery.

Preserving spinal alignment and function is often an important consideration in spine surgery. There are questions of whether spinal fusion is necessary in the management of spinal tumors, especially metastatic tumors [61]. This issue becomes more pressing when considering the survival time of patients after fusion surgery and how long it takes to achieve fusion. That said, advancements in the development of materials for spinal fusion could lead to faster fusion times. Consequently, patients with expected improved survival time might benefit from fusion surgery.

For patients who might be candidates for spinal fusion, balanced fusion techniques involve meticulous consideration of the number of fused segments and their alignment [62,63]. The use of biological agents, including bone morphogenetic proteins (BMPs) enhances spinal fusion outcomes by promoting bone formation, restoring vertebral height, reducing deformity, and stabilizing the spine [64]. In the context of spinal tumor treatment, where maintaining spinal stability and repairing bone defects is crucial, there might be an expectation for bone morphogenetic proteins (BMPs) to play a beneficial role in improving surgical outcomes. However, their potential to cause cancer has been under investigation for some time, and therefore, they are not currently used in spine oncology [65–68]. Using traditional autologous bone grafts might be considered another option for spinal reconstructive surgery after tumor resection, but concerns about tumor cell seeding make it less favorable [69]. Structural grafts, such as vascularized strut grafts from neighboring ribs or non-vascularized grafts with donor bone fragments placed in synthetic cages, have been suggested as potential solutions to some of these challenges. Nonetheless, further research is necessary to assess their effectiveness fully [70].

Stem cell therapy represents a promising frontier in the management of primary spinal tumors, offering potential advantages in tissue regeneration, immunomodulation, and targeted drug delivery [71]. While its application in spine oncology remains limited and necessitates further investigation, there are documented instances of its use in immunotherapy for spinal conditions [72]. Additionally, progress has been made in identifying the stem cell lineage implicated in spinal metastasis [73,74]. As research continues to advance and clinical experience grows, leveraging stem cell-based techniques alongside bone grafting holds promise for substantially enhancing outcomes in patients with spinal tumors. These
reflect the evolving landscape of spine surgery, where the emphasis is adequate tumor control and achieving optimal functional outcomes.

7. Integration of Carbon Fiber Technology with Advanced Techniques

As highlighted so far, carbon fiber and carbon fiber composites, thanks to their remarkable strength-to-weight ratio, enable the creation of robust and enduring spinal implants capable of withstanding the biomechanical demands on the spine [29]. Spinal cages and stabilization systems have been used in various spinal procedures, including fusion surgeries and motion-preserving interventions [50]. Indeed, the role of carbon fiber-reinforced PEEK implants in achieving fusion in managing degenerative spinal diseases has been demonstrated in biomedial and clinical studies [42,75]. Similarly, they have shown promise in biomechanical studies for interbody fusion and vertebral reconstruction in cancer patients, especially compared to bone allografts and titanium devices [76–78]. The distinctive properties of carbon fiber contribute to an environment conducive to bone fusion, minimize micromotions, and enhance load-sharing, supporting the long-term stability of the spinal construct without significant subsidence [42,79–81]. These qualities position carbon fiber-based spinal cages and stabilization systems as a promising and innovative option in contemporary spine surgery [50,82].

Minimally invasive surgery (MIS) approaches increasingly employ carbon fiber instrumentation. By integrating with computer-assisted MIS systems, carbon fiber instruments facilitate preoperative planning and intraoperative navigation using various imaging modalities [38]. Surgeons can leverage this integration for precise tumor interventions, resulting in reduced invasiveness and improved patient outcomes. This often translates to smaller incisions, minimizing disruption to surrounding tissues and reducing blood loss compared to traditional open surgeries, thereby enhancing the accuracy and efficacy of spinal oncology procedures [37].

Moreover, the integration of carbon fiber technology with customizable and modular systems in spine oncology represents another significant advancement in surgical instrumentation [21,83]. Achieving the goal of preserving spinal alignment and function often requires a customized approach, considering the specific pathology, patient characteristics, and treatment goals. Modular spinal stabilization systems provide flexibility and versatility in addressing complex cases. The adaptability of carbon fiber systems to the specific characteristics of tumors ensures a personalized solution aligned with individual patient pathology [21]. Modular spinal stabilization systems offer flexibility and adaptability in addressing complex cases. The adjustability of carbon fiber systems allows for precise modifications, ensuring an optimal anatomical fit that promotes stability while minimizing disturbances to surrounding tissues.

Furthermore, carbon fiber-based modular polyaxial pedicle screws offer options for adaptive connection and configuration and provide great intraoperative visualization [8,84]. Surgeons can customize the implant constructs based on the specific needs of the patient, allowing for better adaptation to the individual’s anatomy and pathology [85]. These ongoing advancements in technology, surgical techniques, and an enhanced understanding of spinal biomechanics drive continuous innovations aimed at optimizing patient outcomes and sustaining spinal health.

8. Patient-Centered Outcomes and Carbon Fiber Implants

Carbon fiber implants contribute to several factors that positively influence the overall quality of life for individuals undergoing spine surgery with these advanced implants [42]. As previously emphasized, carbon fiber implants, especially in minimally invasive procedures, lead to smaller incisions. They have also led to improved postoperative radiation planning and enhanced the ability to detect tumor recurrence due to their radiolucency. The adaptability and modular design of carbon fiber systems allow for a customized fit, minimizing disruption to surrounding tissues during surgery. This often results in de-
creased postoperative pain and discomfort, thereby enhancing the immediate post-surgery experience for patients and lowering the risk of complications [51,52,86].

It is essential to acknowledge that individual experiences may vary, and the overall quality of life post-operation is influenced by various factors, including the patient’s overall health, as well as the specific pathology being addressed. Nevertheless, the unique properties of carbon fiber implants offer promising advantages that contribute to positive postoperative functional outcomes for many individuals [38]. The positive impact of improved spinal function can significantly affect the psychological well-being of patients [87,88]. Reduced pain, enhanced mobility, and a quicker return to normal activities contribute to an overall sense of well-being and satisfaction.

While carbon fiber implants in spine surgery offer numerous advantages, potential complications and challenges accompany their use. While carbon fiber itself is resistant to corrosion, the potential for infection exists, especially during the surgical placement of implants. Indeed, it has been reported that CFR-PEEK screws are likely to loosen in infectious cases, probably due to a stronger adhesion to bacteria than traditional metal implants [53,56]. As such, strict adherence to aseptic techniques is essential to minimize the risk of infections.

Beyond postoperative complications, technical challenges arise with carbon fiber in spine oncology. Carbon fiber’s radiolucency can make visualizing the implant on X-rays, CT scans, and MRI challenging, affecting the ability to monitor its position or fusion progress or detect potential issues [7,55]. Thus, postoperative monitoring with imaging, such as CT scans or MRIs, may be challenging in some patients with carbon fiber implants. Cost considerations may also impact the widespread adoption of carbon fiber technology, as it may be more expensive than traditional materials, potentially limiting accessibility for some patients [36,89].

While carbon fiber implants show promise in providing positive functional outcomes and durability, the long-term durability of carbon fiber implants remains a subject of ongoing research. This necessitates continuous monitoring and studies to assess their performance over extended periods. Furthermore, there is the question of the application of carbon fiber for longer fusion. The rod contour in carbon fiber composite implants can prove challenging to shape to match the screws on the operative field [7,89]. As such, longer follow-up studies are needed [36], as well as large prospective cohort studies to further evaluate oncological outcomes in patients treated with carbon fiber-reinforced implants [57,90].

9. The Future of Spine Oncology Instrumentation and Implants

Spine oncology has come a long way, with significant progress recorded over the past decades. That said, there are still unexplored frontiers and unexploited potentials that could further lead to improved diagnosis, treatment, and overall patient outcomes. This is particularly evident with the recent advancements in information technology and artificial intelligence (AI). The application of data analytics and AI in spine oncology is still in its early stages. AI will be an invaluable tool in the development of better data-driven predictive algorithms and clinical decision-making tools in spine oncology [91]. AI tools, particularly deep neural networks, offer the potential to predict surgical outcomes and postoperative complications [15]. These sophisticated algorithms can analyze vast amounts of data, including patient demographics, medical history, imaging results, laboratory values, and surgical details, to generate predictive models with high accuracy and precision. Recent research has focused on developing models capable of accurately predicting spine infections by analyzing various factors [15,92,93]. By harnessing the power of machine learning algorithms, these predictive models can identify subtle patterns affording clinicians valuable insights into individual patient risk profiles, allowing for personalized risk stratification and tailored interventions [15,92].

Furthermore, the utilization of customizable and modular systems enables the customization of surgical procedures based on specific patient characteristics. There is a
growing interest in expanding this concept by integrating the genetic profiles of individual patients into the treatment of spinal tumors. Consequently, a genomics-driven approach to spine oncology shows great potential for the future [94].

Another largely uncharted horizon is in the implementation of Enhanced Recovery After Surgery (ERAS). ERAS protocols aim to expedite recovery and reduce surgical stress through the implementation of optimized multimodal pre- and postoperative care methods and pathways to reduce surgical stress [95–97]. Although not yet relatively well-defined in neurosurgical settings [97–99], ERAS has been widely recognized and implemented globally in many surgical fields [100–102]. Carbon fiber instrumentation can play an invaluable role in further developing and implementing Enhanced Recovery After Surgery (ERAS) protocols in spine oncology patients after surgery. As earlier discussed, its lightweight, strength, and radiolucent properties often result in significantly reduced surgical trauma, enhanced stability, and compatibility with advanced imaging techniques. These characteristics align with ERAS goals. As such, carbon fiber-based implants could be incorporated in the ERAS framework and recommendations for spine oncology and spine surgery in general, thereby expediting postoperative mobilization and adjuvant treatment, facilitating quicker recovery, shorter hospital stays, and improved patient outcomes.

All these point to the importance of a multidisciplinary approach in advancing the field of spine oncology [103,104]. The complexity of spinal tumors calls for the collaboration of diverse professionals, including healthcare providers, scientists, engineers, and industry leaders to drive advancements in research and technology. This will most likely foster innovation in treatment modalities, surgical techniques, and diagnostic tools to deliver comprehensive, specialized care and improve overall outcomes in spinal oncology.

10. Conclusions

Significant progress has been recorded in spine oncology, particularly in instrumentation and materials. Computer-aided surgical systems, integrated with robotic platforms, enhance precision and decision-making in surgeries. Imaging technologies, including 3D imaging, CT scans, and MRI, improve intraoperative navigation, reducing reliance on fluoroscopy and minimizing radiation exposure. Carbon fiber and carbon fiber composite instrumentation have emerged as a tool that further advances the areas of progress outlined above, offering strength, stability, and biocompatibility. Carbon fiber’s radiolucency aids in imaging, facilitating postoperative monitoring and radiation therapy planning.

This has led to improvements in patient-centered outcomes including the use of smaller incisions, decreased postoperative pain, and enhanced mobility, contributing to an improved quality of life. However, there is still need for ongoing research in spine oncology, with a focus on information technology, artificial intelligence (AI), and genomics. A multidisciplinary approach involving healthcare providers, scientists, engineers, and industry leaders is crucial for advancing research, technology, and treatment modalities in spinal oncology.


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