Carbon Fiber Implants in Orthopaedic Oncology

Subjects: Orthopedics | Oncology

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Carbon fiber offers numerous material benefits including reduced wear, high strength-to-weight ratio, a similar elastic modulus to that of bone, and high biocompatibility. Carbon fiber implants are increasingly used in multiple arenas within orthopaedic surgery, including spine, trauma, arthroplasty, and oncology. In the orthopaedic oncologic population, the radiolucency of carbon fiber facilitates post-operative imaging for tumor surveillance or recurrence, the monitoring of bony healing and union, and radiation mapping and delivery.

Keywords: carbon fiber ; orthopaedic oncology ; prophylactic fixation ; pathologic fracture ; radiation therapy

1. Introduction

Orthopaedic surgery and materials science are closely intertwined, as the success of many orthopaedic devices are contingent on the material properties of the components used. Specifically in orthopaedic oncology, advancements in implant materials and design are crucial to preservation of function and quality of life in oncology patients after the tumor resection or treatment of metastatic disease. Reconstructive implants in orthopaedic oncology ideally maintain limb function and bone strength, allow for full bone healing, minimize risk of infection and implant failure, and facilitate the specific needs of oncology patients, including surveillance imaging, the visualization of bony union or healing, and radiation mapping and delivery. Historically, metallic implants, frequently used for such reconstructive purposes, have been associated with the tradeoff of imaging artifact. Carbon fiber has more recently been making inroads within orthopaedic surgery and oncology, as its material properties have particular advantages in comparison to metallic materials. As a material, its benefits have long been recognized and applied to numerous industrial needs, ranging from aerospace to civil engineering [1]. Within orthopedic oncology, carbon fiber implants have demonstrated promising applications as a material for implants utilized for pathologic fracture fixation or reconstruction.

2. Material Properties and Benefits of Carbon Fiber

When employed in composite materials within the medical domain, carbon fiber is typically combined with several types of resin matrices, one of the most common of which is carbon fiber–polyether ether ketone (CF–PEEK). There are numerous properties of carbon fiber that make it ideal for orthopaedic applications. It is highly biocompatible and chemically inert [2], generating no cellular toxicity in in vitro studies [3] and only a non-specific foreign body reaction in animal studies [4]. Its elastic modulus, a measure of resistance to deformity under stress, is close to that of bone, an important advantage over other implant materials [5]. The estimated elastic modulus of carbon fiber is 3.5 gigapascals (GPa); cortical bone has an elastic modulus of 12–20 GPa and cancellous bone 1 GPa. By contrast, the elastic modulus of stainless steel is 230 GPa and titanium ranges from 106–155 GPa [6][7][8]. The similar elastic modulus of carbon fiber implants to bone helps to lessen stress concentration at the bone–implant interface [9][10], though it is important to note that additional studies are needed to better validate whether this allows for improved healing potential, or may simply translate to insufficient stiffness for healing in certain unstable fracture types in the trauma setting [11][12]. Importantly, in this regard, the modulus of carbon fiber can be adjusted in manufacturing to match either cortical or cancellous bone [13].

The ability to withstand fatigue strain is yet another benefit of carbon fiber implants. Traditional implants demonstrate higher failure rates, especially in pathologic fractures, often due to non-union or hardware failure [14]. By contrast, CF–PEEK demonstrates the ability to withstand high strain loading, up to one million loading cycles, without evidence of failure [15]. The interface wear characteristics of carbon fiber are similarly encouraging. One study simulating a total hip arthroplasty investigated the wear results of a ceramic head on a CF–PEEK cup, and demonstrated a volumetric wear rate of 0.3 mm^3/Mc (million cycles), lower than that of ceramic on cross-linked, ultra-high-molecular-weight polyethylene (UHMWPE), metal on cross-linked UHMWPE, or ceramic or metal on conventional UHMWPE [16]. This is particularly important when considering potential toxicity or allergic reactions from wear particles [17][18]. As a relatively more recent material used in the orthopaedic setting, there are relatively fewer large, long-term studies concerning carbon fiber implants compared to their metallic counterparts, but their durability has appeared promising thus far in the literature [19].

One of the most important advantages of carbon fiber implants over metallic implants is their radiolucency. On both magnetic resonance imaging (MRI) and computed tomography (CT), carbon fiber has minimal scatter or susceptibility artifact, respectively [20]. This radiolucency allows for improved post-operative monitoring of fracture healing and surveillance for local disease recurrence or progression in the orthopaedic oncologic population. In a comparative study comparing MRI signal loss in patients with femoral or tibial CF–PEEK or titanium implants, CF–PEEK implants demonstrated substantially less signal loss and MRI susceptibility artifact than titanium nails. Visualization scores, as graded by a musculoskeletal radiologist, were significantly higher in the CF–PEEK group across all MRI sequences, including T1-weighted, short tau inversion recovery (STIR), and contrast-enhanced, T1-weighted, fat-saturated sequences [20]. Additionally, many orthopaedic oncology patients require post-operative radiotherapy. The artifact generated by conventional metallic implants often interferes not only with mapping for radiation planning, but also with accurate dose calculation and delivery [21][22][23].

3. Carbon Fiber Implants in Orthopaedic Surgery

Given the numerous material strengths of carbon fiber, it is no surprise that their use in orthopaedic implants has been increasingly studied across nearly all orthopaedic subspecialties in multiple applications. Since the 1990s, carbon fiber implants have been used for spinal surgical procedures such as posterior lumbar interbody fusion [24] and anterior cervical discectomy and fusion, demonstrating low rates of complications and specifically implant-related complications, as well as favorable outcomes [25]. They have also been employed in cages used for spinal column reconstruction in patients undergoing thoracolumbar corpectomies, again demonstrating promising long-term results with regards to cage durability, facilitation of radiographic monitoring of fusion, and low complication rates [26].

Orthopedic trauma surgery has more recently explored the use of carbon fiber plates in a variety of applications, including intramedullary nailing, proximal humerus or distal radius plating, and dynamic compression plating. When compared to their corresponding metallic implant counterparts, carbon fiber implants have been found to have similar performance in four-point bending, torsional, and bending fatigue, as well as reduced particle generation in wear testing [15].

Carbon fiber implants have promising applications particularly with regard to spinal tumor and spinal metastatic surgery. A large comparison of 78 patients with spinal metastases who underwent fixation with CF–PEEK versus titanium implants noted similar rates of post-operative clinical complications and hardware failure. Of note, the CF–PEEK group had longer operative times and higher blood loss, which might suggest a learning curve with these newer implants [27].

4. Conclusions

There are several important factors that must be considered in the use of carbon fiber implants in orthopaedics. Firstly, in comparison to metallic implants, carbon fiber has a lower load to failure, suggesting titanium or steel may carry a lower risk of implant failure in patients expected to have a high functional status post-operatively [28]. Secondly, unlike metallic implants, carbon fiber implants cannot be bent or contoured intra-operatively. Therefore, surgeons must precisely pre-operatively plan to ensure good implant fit. Thirdly, while the radiolucency of carbon fiber is certainly advantageous for imaging studies post-operatively, intra-operatively it may prove challenging to confirm implant position. With regard to radiation planning, screws for carbon fiber plate fixation or interlock screws are metallic, which still does lead to some imaging artifact.

An additional consideration is the potential for undetected implant failure given the radiolucency of carbon fiber implants, which has been reported in case studies [29]. Finally, other considerations include the higher costs for carbon fiber implants and decreased availability, though these factors are both subject to change with time and increasing usage [30].

Carbon fiber implants have numerous promising advantages for use in orthopaedic oncology, including favorable material and radiologic properties. Additional studies are needed as these implants are more widely utilized in the orthopaedic oncologic population to better characterize long-term implant survival and complications as well as the clinical outcomes associated with their use.

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