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The Performance Envelope of Spinal Implants Utilizing Thermoplastic Materials

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1. Introduction

Back pain is the second most common reason for physician visits in the United States, and affects up to 84 percent of patients at some point in their lives (Deyo & Tsui-Wu 1987). For many patients, neck and back pain is often due to injury or spinal instability through trauma, disease or degeneration. This can cause impingement of neural structures resulting in pain, numbness, or weakness. Also, this can be a consequence of changes in the vertebral bodies or degenerative changes in the intervertebral cartilaginous discs. Treatment of such disorders may require surgery if the pain or neurologic symptoms prove to be intractable to conservative treatments such as physical therapy or pain medications.

The spine is a load-bearing structure made of ligaments, tendons, and bone that allows for a functional range of motion while protecting the spinal cord. The vertebral bodies are joined by two bilateral facet joints in the posterior aspect of the spinal column and are separated at each level by a cartilaginous intervertebral disc. This three-joint complex, illustrated in Figure 1, comprises the smallest mobile segment of the spine, commonly referred to as the functional spinal unit (FSU). The posterior joints are diarthrodial joints, which include articular cartilage, synovial membrane, and a joint capsule (Yong-Hing et al. 1980).

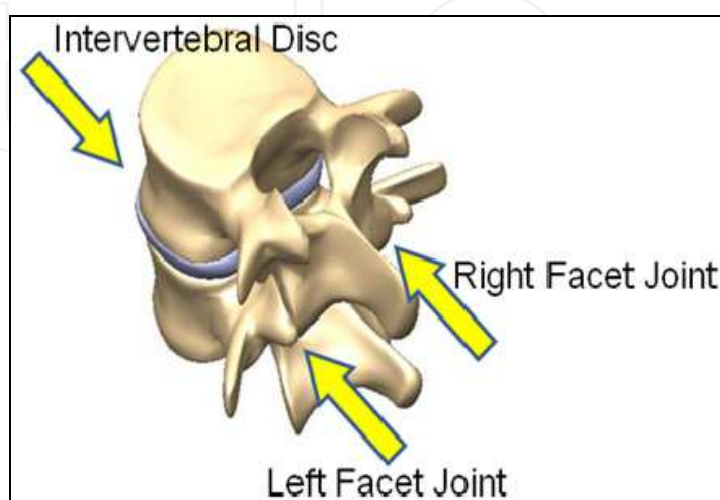


Fig. 1. Illustration of Three-Joint Complex

Spinal stability refers to the ability of the spine segment to limit excessive displacement that can possibly result in incapacitating deformity or neurologic symptoms due to impingement on the spinal cord and nerve roots (White & Panjabi 1990). Factors that can contribute to instability may affect the bones, disc, joints, or ligaments. These include trauma, tumors, infections, inflammatory diseases, connective tissue disorders, congenital disorders and degenerative disorders (Yong-Hing & Kirkaldy-Willis 1983). It is important to note that the surgical procedures performed in the interest of relieving neurologic symptoms may themselves contribute to instability.

Degenerative changes may affect the vertebrae and the intervertebral disc as well. The viscoelastic properties of the cartilaginous disc allow it to act as a shock absorber for the spine. As the disc degenerates, the ability for it to handle such stresses also changes (Panagiotacopoulos et al. 1987). As peripheral fibers of the disc are stressed, rupture may occur resulting in herniation of disc material outwards to compress nerve roots or the spinal cord, potentially causing neurological symptoms including pain and weakness (Benzel 2004).

Surgical treatment of the spine often involves widening of the spinal canal and decompression of the spinal cord, the removal of osteophytes or disc material impinging on neurologic structures, and careful consideration of alignment of the spinal segment (Benzel 2004). These procedures may lead to destabilization of the FSU. Vertebral fusion helps provide stabilization of the spine, and can prevent further deformation and additional neurologic symptoms (Gibson & Waddell 2005). If spinal fusion is performed, the intervertebral disc is removed and the endplates of the vertebral bodies are bridged by a bone graft, often with an interbody device that allows for preservation of disc height and appropriate sagittal balance. Bony union connects the two vertebrae together into a continuous structure providing the needed stability; this structure along with any new bone is often referred to as a "fusion mass." Clinically, if the fusion is successful, it is referred to as an arthrodesis. Immobilization of the vertebral bodies has been shown to significantly enhance the success of fusion (Bridwell et al. 1993). Currently, internal spinal instrumentation is thought to be the best therapy to ensure a good clinical outcome in this regard.

2. Spinal instrumentation

Spinal instrumentation is designed to stabilize the spine and prevent excessive motion at the affected segment as the bones fuse together. It provides immediate stability of the affected segment of the spine and obviates the need for external fixation devices such as rigid collars, braces, and halo traction. This allows for a greater quality of life for patients immediately following surgery. These internal fixation devices such as screws, plates, and rods are affixed to the vertebral bodies and combine to form an instrumentation construct. This construct takes the load-bearing responsibility of the affected spinal segment until fusion has occurred. The instrumentation construct is therefore a temporary load-bearing adjunct to fusion (Benzel 2004). When arthrodesis is achieved, the fusion mass will become the principal bearer of load on the FSU, and the instrumentation becomes obsolete. Therefore, a principle of spine surgery is that spinal instrumentation is to maintain spinal stability until fusion occurs.

Modern spinal fixation devices have been made of biocompatible metallic alloys such as stainless steel and titanium. While these have become standard due to their strength and fatigue resistance, they possess radiographic challenges and biomechanical limitations. First, and foremost, metallic materials are radiologically problematic. Artifacts created by metals in computerized tomography (CT) and magnetic resonance (MR) imaging, as well as obfuscation of bone by metals in planar x-rays, inhibit visualization of new bone growth thus, making it difficult for physicians to assess progression of arthrodesis. Second, implants that are stiffer than natural bone are subject to so-called stress shielding. When two bones are fused together, the state of compressive forces between them determines the extent of modeling or remodeling. According to Wolff's law, bone apposition within a fusion graft is governed in part by the state of compressive stresses within it. Because of this it has been proposed that stiff metallic implants may shield the graft from the stress required for fusion, delaying or preventing the process. This can induce iatrogenic effects such as device-related osteopenia, intervertebral device protrusion into a neighboring vertebral body, and fracture or instability (Lippman et al. 2004). Implants developed out of less stiff materials may prevent this stress shielding and foster better clinical outcomes compared to traditional devices.

3. Thermoplastic spine implants

Thermoplastic polyetheretherketone (PEEK) polymers, a subset of the polyaryletherketone or PAEK class of polyaromatic polymers, were initially considered for use in spinal applications to overcome the aforementioned limitations due to their inherent material properties, such as biocompatibility, radiolucency, and the ability to tailor their elastic moduli with fiber reinforcement such as carbon filament. Neat or unfilled PEEK has an elastic modulus of approximately 3.6 GPa, however this can be tailored to closely match cortical bone (18 GPa) or even titanium alloy (110 GPa) (Kurtz & Devine 2007). These properties, along with validation of their strength, wear, creep and fatigue resistance have pushed PEEK implants to be the most viable and attractive alternatives to metallic spinal implants to date. (Brown et al. 1990; Brantigan & Steffee 1993; Kurtz & Devine 2007). Figure 3 is an x-ray taken from a patient following implantation of a PEEK cage along with a pedicle screw and titanium rod system. Notice the radiolucency of the PEEK cage; only the radiopaque markers inside the implant are visible.



Fig. 2. PEEK Lumbar Interbody Cage (Left) alongside Titanium Lumbar Interbody Cage (Right)



Fig. 3. Planar X-ray of Patient Immediately after Surgery with PEEK Cage and Titanium Rod Construct Implanted in the Lumbar Spine

Although PEEK implants offer improvements over titanium and titanium alloys, they are still subject to such complications as migration, subsidence, extrusion, wear debris and late foreign body reaction due to the fact that they are permanently implanted (Alexander et al. 2002; Smith et al. 2010). Furthermore, additional surgeries may be required to remove the constructs. These limitations have led clinicians to investigate bioresorbable polymers for use in surgical applications. Alpha-polyesters, mainly polylactic acid (PLA) and polyglycolic acid (PGA), are the primary bioresorbable materials used in clinical applications, and over the past decade such compounds have been used extensively in craniomaxillofacial, orthopedic and trauma applications for bone reconstruction and fixation.

Resorbable sutures and films have been found to be extremely useful in many surgical procedures. PLA sheaths have been used to protect neural elements from fibrotic adhesions and promote iliac crest harvest site reconstruction, while sutures and suture anchors have been extensively employed to mitigate foreign body effects and the need for further surgeries (Wang et al. 2002; Welch et al. 2002; Klopp et al. 2004).

Resorbable rod and screw systems have been well documented in the treatment of extremity fracture, however little experience has been gained with these devices in spinal surgery (Tormala et al. 1991; Majola et al. 1992; Springer et al. 1998). Bezer et al. recently employed resorbable self-reinforced PLA rods for use in posterior lumbar fixation in a rabbit model

(Bezer et al. 2005). They were found to be comparable to titanium, however no studies to date have examined the the ability of these devices to withstand higher loads in larger animal models or the human spine.

Resorbable plate and screw systems (RPSSs) have been used as far back as the 1970's, shortly after the introduction of their clinical potential, to fix mandibular fractures (Kulkarni et al. 1966; Kulkarni et al. 1971). More recently, RPSSs have been used to successfully treat distal radial fractures with no statistical difference compared to a titanium control (van Manen et al. 2008). RPSSs have also been shown to successfully treat rib fractures in trauma patients (Mayberry et al. 2003). Once adapted for use in spinal applications, RPSS's have been investigated for supplemental anterior fixation to cervical interbody fusion constructs. Although prospective randomized studies to date are limited, many retrospective analyses have concluded resorbable anterior cervical plating as a reasonable alternative to metal (Vaccaro et al. 2002; Franco et al. 2007; Tomasino et al. 2009). RPSSs have also been considered for supplemental lumbar fixation (DiAngelo et al. 2002), however in-vivo loading conditions of the lumbar spine may prove too intense for this application.



Fig. 4. Resorbable Plate and Screw System (Left) beside Nonresorbable titanium system (Right)

The most pervasive usage of alpha-polyesters within the field of spinal implants has been as resorbable interbody cages which serve as temporary adjuncts to fusion. Resorption of the material allows for gradual load transfer from the implant to the surrounding bone, eventually eliminating effects of stress shielding. Resorption also mitigates risks associated with explantation, corrosion, wear debris, migration or late foreign body reaction associated with non-resorbable devices. Furthermore, as with other thermoplastic materials, alpha-polyesters are radiolucent and do not interfere with the clinicians ability to assess the fusion mass during the course of post-surgical follow up.

From a design perspective the greatest advantage thermoplastics possess over other materials for the construction of spinal implants is the ability to tailor material properties to suit the requirements of the given application. The choice of polymer and specific manufacturing parameters allow for a broad range of material and bioactive properties. PGA polymers degrade more rapidly than do PLA polymers while copolymers of the two compounds degrade at intermediate rates. Due to the relatively long time period required for successful spinal fusion (6-12 months), PLA has emerged as the material of choice for resorbable spinal implants. The ratio of L- and D-lactides comprising the PLA polymer influences the mechanical and biochemical properties of the material. Poly (L-lactic acid) (PLLA) is semi-crystalline and is characterized by high strength and long resorption time while the racemic poly (D,L- lactic acid) (PDLLA) is amorphous and characterized by lower strength and shorter resorption time. Amorphous polymers are generally preferred for bioresorbable implants because crystalline portions of the polymer degrade much more slowly and may remain in the host much longer, potentially leading to long term complications. As a result most materials used in spinal implants consist of a mixture of L-lactide and racemic D,L-lactide. The most common among these is 70:30 poly(L-lactide-co-D,L-lactide) (PLDLLA) which consists of 70% molar ratio of L-lactide and a 30% molar ratio of D,L-lactide (Smit et al. 2008). This material has been chosen for interbody fusion devices because of its long resorption time (18-36 months), relatively high elastic modulus (3.15 GPa) and high compressive strength (100 MPa) (Alexander et al. 2002; Toth et al. 2002).

While the conceptual advantages outlined above have to some extent successfully been reduced to practice, the materials described are not without their limitations. While significant clinical success in terms of fusion and appropriately timed resorption has been achieved in animals studies (Toth et al. 2002; Thomas et al. 2008), subsequent research in humans has indicated poor clinical outcomes (Smith et al. 2010; Jiya et al. 2011). Particularly, in a prospective cohort study including 81 patients who underwent Transforaminal Lumbar Interbody Fusion (TLIF) surgery with either a resorbable PDLLA cage or a similar non-resorbable carbon fiber cage, Smith et al. found significantly higher incidence of non-union and cage migration in PDLLA cages compared to the carbon fiber cages. Four of the eight patients that exhibited cage migration experienced the adverse event within six months of implantation. Cages that were explanted exhibited moderate plastic deformation, a finding consistent with insufficient material strength discussed previously (Smith et al. 2010). In a randomized prospective human study, Jiya et al. compared PDLLA lumbar interbody fusion cages to similar non-resorbable PEEK implants and found no significant improvement in clinical outcomes upon 2-year follow-up when compared to preoperative values in the PDLLA group. Conversely, significant improvements in all clinical parameters were found in the PEEK group indicating the potential inferiority of the PDLLA implant (Jiya et al. 2011).

Other studies have found anterior cervical plate systems to be inadequate or potentially problematic in providing fixation in both animal and clinical studies. Lyons et al. recently investigated a PDLLA cervical RPSS in an ovine model. Results showed a fusion rate of 25% after 3 months, and plate or screw fracture in 50% of specimens (Lyons et al. 2011). Bindal et al. clinically evaluated a PLDLLA RPSS, supplemental to anterior cervical discectomy and

fusion. With a mean follow up time of 15 months, implants were found intact, however psuedoarthrosis and kyphosis was found to be significantly greater in resorbable plates compared to titanium (Bindal et al. 2007).

Through investigations of the time-dependent material properties of 70:30 PDLLA, Smit et al. have shown that the strength of the material decreases with lower loading rates, higher temperature and higher humidity. The authors conducted long-term, static failure experiments at various loads and found that PDLLA cages loaded to approximately 50% of their static compressive strength failed within one day. The authors attribute this time dependent behavior of the polymer to its structure, stating that the material maintains to some extent its behavior as a fluid, resulting in plastic flow under sustained loads (Smit et al. 2008; Smit et al. 2010). These conclusions correlate well to some of the clinical failure experience in PDLLA cages described in the literature. Attempts have been made recently to address this limitation of PLA by combining the polymer with other materials such as beta tricalcium phosphate (β TCP), a commonly used ceramic bone substitute. Debusscher et al. investigated resorbable composite anterior cervical fusion cages consisting of 40% PLLA and 60% β TCP implanted into 20 patients. The authors reported positive clinical and radiologic results in terms of improved pain scores and CT-based fusion evaluation at a mean follow-up of 27 months. No incidences of cage migration or material complications were reported, and an average resorption of 64% was reported at latest follow-up (Debusscher et al. 2009).

4. Conclusion

Thermoplastics have demonstrated a track record of success in medical device applications. The prevalent use of PEEK is evidence of widespread acceptance of thermoplastic materials in spinal fixation procedures. The ability to tailor the properties of the device suitable for each design application continues to present thermoplastics as attractive design materials. Furthermore, the existence of biodegradable thermoplastic polymers has provided an opportunity to develop resorbable medical implants. These materials have exhibited widespread success in applications in which they are subjected to loads of relatively low magnitude and/or short duration, such as in sutures, sheaths and in extremity fixation. However, in the case of biodegradable spine implants, it is important to understand the balance between the benefits of biodegradation and potential strength limitations. In spite of investigations into the use of these materials in a wide array of spinal fixation devices, they have yet to achieve wide clinical acceptance in the field, ostensibly due to their poor performance under the sustained loads borne by the spine.

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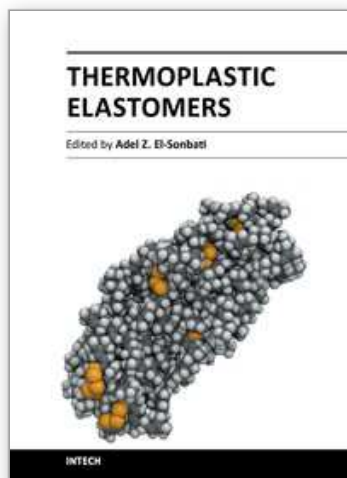
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Thermoplastics can be used for various applications, which range from household articles to the aeronautic sector. This book, "Thermoplastic Elastomers", is comprised of nineteen chapters, written by specialized scientists dealing with physical and/or chemical modifications of thermoplastics and thermoplastic starch. Such studies will provide a great benefit to specialists in food, electric, telecommunication devices, and plastic industries. Each chapter provides a comprehensive introduction to a specific topic, with a survey of developments to date.

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