Orthopedic Implant Materials

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Definition/Introduction

This article will attempt to outline the basic concepts of orthopedic biomaterials. This article will remain focused on the core materials used in orthopedics. This article will not discuss suture materials, biologics, graft materials, or implant coatings such as hydroxyapatite.

Issues of Concern

Titanium and Titanium Alloys

Titanium is a common metal used for implantation in orthopedic surgery. While titanium is a metallic element, the majority of orthopedic "titanium implants" are, in fact, alloys. These alloys are typically proprietary blends - differing from manufacturer to manufacturer. For this article, we will consider them all closely related and discuss them as such. The physical properties (below) make titanium a desirable material in orthopedic applications.

Common Uses

Titanium is a common material in a variety of orthopedic implants. Most total hip femoral stem components are made of a titanium alloy. The same can be said of most total shoulder arthroplasty stems.

Relevant Mechanical Properties

Titanium, unlike these examples, predictably oxidizes when implanted. The oxidized titanium creates a very thin layer of oxidized titanium that acts to coat the implant. This layer is biologically inert. The advantages of this included retained and predictable mechanics of the material, lack of host biologic response, and long term material stability.

Stainless Steel

Stainless steel is and continues to be the choice material for a wide range of orthopedic implants. A host of stainless steel alloys have been developed for industrial as well as medical uses. These blends are employed to alter structural properties and biologic response to alloy ingredients. While a significant difference exists between alloys, the majority of medical grade stainless steel is an alloy called 316L. It is a smaller second moment of area (directly related to the cross-sectional area) than the bone. Conversely, stainless steel has a higher modulus of elasticity than titanium. Using an implant or device that has similar mechanical properties to bone (like titanium), is advantageous in orthopedic applications.

Titanium plates and other implants are readily worked in the operating room and in-vivo. Implant benders, burs, and cutting devices are common tools used to customize implants to specific needs.

Surgical Applicable Machining Properties

Titanium is a readily workable material and can be cold or hot worked into a variety of shapes. Modern metallurgical techniques allow for nearly limitless implant design, which has resulted in multiple implant manufacturing techniques and a variety of widely available implants for arthroplasty and trauma care.

Smoothes is a quantifiable material property widely that is important in bearing design. Many early total knee designs, including the Miller-Galante, had a titanium surface. While these M-G implants were very successful in their time, wear characteristics of the titanium were supplanted by "smoother" metals (like cobalt-chrome alloys). Titanium is unable to be polished and machined to a surface smoothness competitive with other implant materials such as cobalt chrome. Modern total knee implants are mostly titanium alloy at the bone interface and cobalt chrome alloys at the load-bearing surface. This property allows for favorable bone-implant interface (titanium) and desirable smoothness for load-bearing (cobalt-chrome).

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Issues of Concern

Implanted materials, especially those intended to be retained for the life span of the host, must become biologically inert or near biologically inert. For example, if the material were implanted, which could be metabolized (see absorbable suture material below), the body would readily change the mechanical properties of the material. This would create unpredictable and somewhat inevitable long term consequences related to implantation. Similarly, material that is prone to oxidation or releases biologically active particles is undesirable.

Surgically Applicable Machining Properties

Titanium and titanium alloys have been employed in a variety of spine surgery applications, including some pedicle screws, rods, and interbody devices.

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Early intramedullary nails rod were made of stainless steel, including tri-flange nails, among others.[6] Many early intramedullary nails were successful, but some went on to atrophic non-union due to the marked stiffness of these nails. In an attempt to improve these complications, some nails were "alloyed" or given a horseshoe-like cross-section to make them less rigid. Fracture care with hardware has been evolving as we gain more experience. In the 1970s through the 1990s, rigid constructs (stainless steel) were preferred. In the past 20 years, there has been a shift away from "complete rigidity." Modern fracture fixation theories favor a less rigid construct to enhance bone healing.

Stainless steal can be polished to a relatively high smoothness and has been is in use in many arthroplasty applications. Stainless steel plates are ductile enough to be altered in the operative theatre in many situations. Benders, burrs, and cutting tools are commonly available to alter this material in the operative theatre.

Cobalt Chrome

Cobalt chrome has become a widely used bearing surface in orthopedic surgery. Cobalt chrome has become most commonly used in arthroplasty for this reason.

Common Uses

Cobalt chrome has become a common-place bearing surface in orthopedic surgery today. It is a commonly used bearing surface in metal on polyethylene (plastic) bearing applications. During the rise, and subsequent fall, of metal on metal total hip arthroplasty cobalt chrome was a frequently employed bearing surface. Some cerclage wires are made of a more ductile cobalt chrome alloy as well.

Relevant Biologic Activity

Bulk cobalt chrome seems to be biologically inactive. It is commonly implanted in intra-articular settings. It contains nickel and may lead to metal hypersensitivity reactions. While a still debated topic, many practitioners will avoid cobalt chrome in arthroplasty patients with a severe nickel allergy. This distinction has documentation in both total knee and total hip literature.

Cobalt chrome particles from metal on metal wear have a host of associated surgical issues and are widely documented as immunogenic. These micro-particles are produced during metal-on-metal wear situations and generate a lymphocyte-mediated response. Unresorbed metal debris may form pseudotumors. The immune response to metal debris can also lead to widespread bone destruction.

Importantly, pseudotumor and metal debris induced osteolysis is not limited to metal-on-metal arthroplasty settings. Metallic fretting (trumoniosis) can occur at the junction of total hip stems and total hip heads. Relative motion at a total hip morse taper (head/stem junction) creates similar wear particles and generates cobalt chrome and titanium micro-particles.

Clinically Relevant Mechanical Properties

Modulus of elasticity describes the ability of a material to deform under stress. Cobalt chrome has a very high modulus of elasticity. As such, it is not a choice when elastic or plastic material deformation properties are desired. Furthermore, it has a surface that can be highly polished and can obtain an incredibly high surface smoothness, which allows for minimal wear in metal on polyethylene bearing situations. Furthermore, cobalt chrome is highly durable during impact and will withstand extreme force before fracturing.

Surgically Applicable Machining Properties

Cobalt chrome is a workable material but can provide machining challenges due to its high modulus of elasticity and low ductility. The most desirable property of cobalt chrome is due to its highly polishable surface. This smoothness decreases abrasive wear on polyethylene bearing surfaces.[7]

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Polyethylene

Various forms of polyethylene have been employed since the inception of modern arthroplasty. Arthroplasty pioneer Sir John Charnley's low friction total hip arthroplasty became the first long-surviving total hip arthroplasty and employed a polyethylene bearing surface. Since that time, designers have striven to improve the mechanical properties of this useful product. The fundamentals of polyethylene materials will be discussed below in an attempt to create a broad and general understanding of concepts surrounding polyethylene variants and applications in orthopedic surgery.

Important Fundamental Concepts

Polyethylene's most common application within the orthopedic community has primarily focused on arthroplasty. The most common use is as an artificial joint surface. This plastic-like material is present in most knee and hip replacement systems. Typically, metal (cobalt chrome) and plastic (polyethylene) joint replacements are subject to tremendous loads. The enormous number of arthroplasty procedures and their eventual failures have provided a constant demand for more durable and less biologically active bearings. Polyethylene bearing surface research and development has improved the mechanical properties of this material. Increasing the molecular weight and increased cross-linking are two advancements made in succession to attempt to decrease the material wear rates in-vivo.[9]

Biologic Challenges

Bulk polyethylene has proven to be mostly inert from a host response standpoint. Wear debris from polyethylene, however, has proven to be quite reactive in vivo. Early reports of host reactions to wear debris were mistaken for host response to polymethyl methacrylate bone cement and were labeled as "cement disease" and wrongly attributed to a cement driven process of bone resorption. The belief now is that polyethylene wear particles (debris) can lead to implant loosening.

Polyethylene wear debris can generate a macrophage-mediated response, which can lead to bone resorption; this has manifested clinically in bony resorption at and around implant interfaces. This resorption has resulted in complications including periarticular fracture, implant loosening, subsidence, pelvic discontinuity, and other catastrophic bone loss related complications.

Irradiation, Cross-linking, and Sterilization

Prosthetic joint infections are devastating complications. These infections are often difficult to treat, rather expensive, and terrible for the patient. Thus, implant sterilization is of paramount importance. Initially, manufacturers were irradiating polyethylene in-air as an alternative to ethylene oxide sterilization. The research found doing this in-air was harming the wear tolerance of the polyethylene but was producing more cross-linking. Conventional irradiation in an inert gas with subsequent annealing or remelting has improved the wear and led to better material cross-linking.[10]

Vitamin E Infused Polyethylene

Vitamin E has been introduced into multiple bearings and remains popular within the market today. As discussed above, free radicals are a concern due to the deleterious effects on the bearing. Vitamin E was introduced to act as a scavenger, picking up any free radicals produced during or after the cross-linking process. There has been a theoretical advantage when using this bearing surface above standard polyethylene concerning polyethylene bearing longevity, although the effect on long term outcomes is a topic of debate.[11]
Ceramics have developed an ever-expanding role in arthroplasty. The most common application today include bearing surfaces for hip replacements. There has also been a place in the market for zirconium-based implants in total knee arthroplasty. Ceramic bearing surfaces have demonstrated some of the best wear properties of any bearing surfaces used in orthopedic surgery today.[7]

Most notably, ceramic presented a viable alternative to other hard on hard bearing surfaces, including metal on metal, which developed an unacceptable track record in most hip arthroplasty applications. Ceramic on ceramic produces some of the lowest wear particle volumes of any arthroplasty surface. The immune response to a well-placed and intact ceramic on the ceramic bearing surface has yet to have consistent documentation as deleterious. Ceramic on ceramic bearing surfaces have been widely used in younger arthroplasty patients, given its more favorable wear characteristics.

Furthermore, ceramic can provide a surface with very high smoothness. This smoothness and the associated desirable adhesive wear characteristics create the lowest rates of polyethylene debris in hard on soft bearing settings, more specifically when comparing metal on polyethylene to ceramic on polyethylene.

Complications of ceramic heads are well known. Hard of hard ceramic total hip arthroplasties have caused an audible squeak in some patients during ambulation.[12] This effect creates very low patient satisfaction and is a known reason for revision in an otherwise asymptomatic arthroplasty. Ceramic is also quite brittle and can shatter in vivo, especially in a hard-on-hard setting, creating a catastrophic joint failure resulting in a joint loaded with microscopic ceramic debris.

Clinical Significance

Much has changed in the field of orthopedic implants. Newer designs, improved materials, and surgical innovation have improved patient outcomes. There are areas of concern, despite these advances. Peer-reviewed data and non-biased implant research are essential for the deployment of newer devices that are safe and effective.

Implants are used in a variety of orthopedic procedures. The importance of understanding how to select the right implant based on the task at hand cannot be overstated.

Orthopedic implant design continues to evolve, and as we attempt to tackle the challenges of cost, reliability, longevity, and infection prevention.

Nursing, Allied Health, and Interprofessional Team Interventions

As orthopedic interventions become more complex and more of a team-based approach to care is undertaken, it becomes very important that all providers have an understanding of the implant materials. As we move toward a more multi-disciplinary approach, having all our providers conversing with a universal understanding of the basics of implant materials allows for a more productive discussion when delivering care.

Continuing Education / Review Questions

- Access free multiple choice questions on this topic.
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References


Publication Details

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