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. Furthermore, nearly all currently used intramedullary rods are composed of titanium alloy. Traditional stainless steel plating systems have been in use for decades for fracture stabilization. Many surgeons can choose either stainless steel or titanium plates and screws. There has been much research regarding decreasing bacterial adherence to titanium, which may be more prone to allowing adherence. They are also employed in a variety of spine surgery applications, including some pedicle screws, rods, and interbody devices.[1]

Relevant Biologic Activity

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.

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.[2]

Clinically Relevant Mechanical Properties

Modulus of elasticity describes the ability of a material to deform under stress. Specifically, it describes the amount of stress required for the material to deform elastically. This deformation occurs linearly and predictably. When comparing metals for implantation, titanium has a modulus of elasticity closer cortical bone than other choices. While still different by more than a factor of 10, titanium implants generally have 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.

The above properties can be manipulated to create favorable implant-bone biomechanics. Most importantly, when designed and applied appropriately, titanium allows for enough micro-motion at fracture sites in load-bearing and load sharing constructs to obtain callus formation. This relative motion is necessary for a robust biologic response and secondary bone healing.

Surgically 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.

Smoothness 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).

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.

Stainless Steel

Stainless steel was 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 mostly iron plus chromium, nickel, and molybdenum.

Common Uses

Stainless steel has been employed in the design of countless historical and modern implants for orthopedic care. It is frequently employed in the manufacturing of orthopedics plates, screws, sliding hip screws, some flexible nails, and early generation rigid intramedullary nails. Cerclage cables are also routinely made of braided stainless steel wires.[3][4]

Relevant Biologic Activity

Stainless steel has been implanted for several years. It is one of the earliest modern implant materials to be widely employed. Historical materials lacked the durability and strength that stainless steel could offer. Furthermore, it is was a widely available material. In the oxygen-rich environment of the body, this material does not demonstrate corrosion.

The literature has described allergic reactivity to this material.[5] Many stainless steel alloys contained nickel, which can (but infrequently) cause an allergic reaction. Reactivity to implants is somewhat controversial and has been a topic of debate in the literature. There have also been well-described cases of explantation (removal) of the nickel-containing materials with subsequent improvement of symptoms.

Clinically Relevant Mechanical Properties

Modulus of elasticity describes the ability of a material to deform under stress. Most importantly, it describes the amount of stress required for the material to deform elastically. That deformation occurs linearly and predictably. Stainless steel provides a high modulus of elasticity. This property allows for excellent construct rigidity. For fracture care constructs pursuing stable fixation, this makes stainless steel appealing as a material for implants.

Surgically Applicable Machining Properties

Originators of open reduction and absolutely stable fixation in Europe locally sourced many of their early implants. The relatively widely available stainless steel provided a substrate on which modern fracture care was developed. In many cases, implants were developed in very basic machining environments and built-to-spec on a case by case basis.

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 where "slotted" 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 steel 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 boney destruction.

Importantly, pseudotumor and metal debris induced osteolysis is not limited to metal-on-metal arthroplasty settings. Metalic fretting (trunionosis) 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]

Intra-operative manipulation of cobalt chrome is extremely limited due to the properties mentioned above. The material can prove to be very difficult to be cut or altered in the operating room, an exceptionally difficult in vivo.

Tantalum

Tantalum implants are less widely used in orthopedic surgery today but may see expanding use cases due to material cost and increasing revision rates in arthroplasty. There is also some consideration in tantalum implants for fracture fixation due to the low material cost and mechanical similarities to titanium. We will briefly discuss tantalum as it relates to orthopedic surgery.

The most common current application for tantalum is as an augment. Augments serve to fill bone defects in arthroplasty, tumor, and some fracture settings. This material can be worked to be highly porous and seems to allow bony ingrowth and effective biologic incorporation. This biologic incorporation couples with a high degree of intra-operative workability. Tantalum augments can be drilled and cut in the operative theatre and are regularly drilled in vivo.[8] These favorable characteristics have made it an attractive choice in complex acetabular reconstruction, among other applications. There is some conversation about expanded roles for tantalum, including tantalum fracture implants. These applications are not widely employed at this time.

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 periprosthetic 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. Conversion to 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

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 has 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.
- Comment on this article.

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Publication History

Last Update: August 4, 2020.

Publisher

StatPearls Publishing, Treasure Island (FL)

NLM Citation

Tapscott DC, Wottowa C. Orthopedic Implant Materials. [Updated 2020 Aug 4]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2021 Jan-.