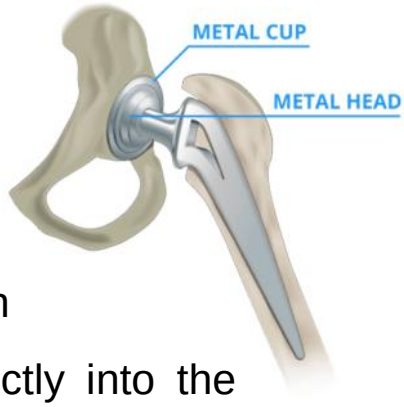
Hip Replacement Process



Introduction

The hip is one of the most important joints that support our body, having the task of joining the femurs with the pelvis. The smooth and spherical head of the femur fits perfectly into the natural seat of the acetabulum, which is a cup-shaped cavity; the whole joint is wrapped in very resistant ligaments that make the joint stable. The hip joint is subjected to high daily stresses, having to bear the weight of the upper part of the body. Thus, especially with advancing age, these stresses can jeopardize its functioning.

Replacement surgery of hip joint consists of the substitution of the joint with an implant able to recreate the articulation functionality. Hip implants can be realized with different combination of materials, such as **polymers**, **ceramics**, **metals and composites**.

MATERIAL REQUIREMENTS

In essence, there are four basic components to the artificial hip: (1) the femoral stem, (2) the ball that attaches to this stem, (3) the acetabular cup that is affixed to the pelvis, and (4) a fixation agent that secures the stem into the femur and the cup to the pelvis. The property constraints on the materials to be used for these elements are very stringent because of the chemical and mechanical complexity of the hip joint.

Whenever any foreign material is introduced into the body environment, rejection reactions occur. The magnitude of rejection may range from mild irritation or inflammation to death. Any implant material must be *biocompatible*, that is, it must produce a minimum degree of rejection. Products

resulting from reactions with body fluids must be tolerated by the surrounding body tissues such that normal tissue function is unimpaired.

Biocompatibility is a function of the location of the implant, as well as its chemistry and shape. Body fluids consist of an aerated and warm solution containing approximately 1 wt% NaCl in addition to other salts and organic compounds in relatively minor concentrations. Thus, body fluids are very corrosive, which for metal alloys can lead not only to uniform corrosion but also to crevice attack and pitting and, when stresses are present, to fretting*, stress corrosion cracking, and corrosion fatigue.

Another adverse consequence of corrosion is the generation of corrosion products that are either toxic or interfere with normal body functions.

The bones and replacement components within the hip joint must support forces that originate from outside the body, such as those due to gravity; in addition, they must transmit forces that result from muscular action such as walking. These forces are complex in nature and fluctuate with time in magnitude, in direction, and in rate of application. Thus, mechanical characteristics such as *modulus of elasticity, yield strength, tensile strength, fatigue strength, fracture toughness, and ductility* are all important considerations relative to the materials of choice for the prosthetic hip. For example, the material used for the femoral stem should have minimum yield and tensile strengths of approximately 500 MPa (72,500 psi) and 650 MPa (95,000 psi), respectively, and a minimum ductility of about 8%EL. In addition, the fatigue strength (for bending stresses that are fully reversed should be at least 400 MPa (60,000 psi) at 10^7 cycles. For the average person, the load on the hip joint fluctuates on the order of 10^6

times per year. Ideally the modulus of elasticity of the prosthetic material should match that of bone.

In addition, particulate debris will be generated as the articulating surfaces wear against one another; accumulation of this debris in the surrounding tissues can also lead to inflammation.

***Three final important material factors are density, property reproducibility, and cost.* It is highly desirable that lightweight components be used.**

It is difficult to a priori predict the biocompatibility of a material. For example, mercury, when ingested into the body, is poisonous; however, dental amalgams, which have high mercury contents, have generally been found to be very biocompatible. Because of this biocompatibility assessment issue, most manufacturers select only materials that have been approved for biomedical use. One final requirement for implant materials is that they be nonmagnetic [i.e., not exhibit ferromagnetic or ferromagnetic behavior]. A frequently used medical diagnostic tool is MRI (magnetic resonance imaging) spectroscopy, a medical test in which the patient is subjected to a very strong magnetic field. The presence of any ferromagnetic/ferromagnetic materials implanted in the patient will disrupt the applied magnetic field, and render MRI spectroscopy unusable. In addition, the magnitudes of these magnetic fields are such that significant forces may be brought to bear on any magnetic implant materials, which forces may loosen the implant and/or harm the patient. Ferromagnetic materials that should be avoided for implant applications include some ferrous alloys (i.e., ferritic and martensitic stainless steels), and alloys having high contents of nickel and/or cobalt.

1. Polymers

Polymer materials were the first choice for **low friction** hip replacements. Highly stable polymeric systems such as PTFE, UHMWPE or polyetheretherketone (PEEK) have been investigated due to their *excellent mechanical properties* and their *high wear resistance*.

PTFE

PTFE has a ***high thermal stability***; it is hydrophobic, stable in most types of chemical environments, and generally considered to be inert in the body. The material had a very ***high wear rate***, equal to 0.5 mm per month, and PTFE produced voluminous masses of amorphous material due to the vast number of foreign-body giant cells.

UHMWPE

The polymer is characterized by its excellent wear resistance, low friction and high impact strength. It is created by the polymerization of ethylene, and it is one of the simplest polymers. Its chemical formula is $(–C_2H_4–)n$, where n is the degree of polymerization, being the number of repeating units along the chain. The average degree of *n* is a minimum of 36000, having a molecular weight of at least 1 million g/mole as defined by the standard.

To limit the wear particle concentration and improve the overall mechanical characteristics, efforts have been made to improve the overall characteristics of UHMWPE for hip implants. In the 90s, scientists were able to correlate changes in the physical properties of the UHMWPE with the in vivo degradation of mechanical behaviors. UHMWPE was typically sterilized by gamma irradiation,

with a mean dose of 25 to 40 kGy. This process resulted in the formation of free radicals, which are the precursors of oxidation-induced embrittlement.

PEEK

Polyether-ether-ketone (PEEK) is a well-known *biocompatible* polymer used in orthopaedic applications. It has been considered as an alternative joint arthroplasty bearing material due to its *favourable mechanical properties and the biocompatibility of its wear debris.*

PEEK had been used as biomaterials, in particular in the spine, since the 1980s, due to its structure that confers outstanding *chemical resistance, inertness*, and *thermal stability* for in vivo conditions. In 1998, researchers tested acetabular cups made of PEEK on a hip simulator for 10 million cycles. They observed a reduction in the wear rate of almost two orders of magnitude in comparison to a conventional UHMWPE/metal or UHMWPE/ceramic couple. However, despite the good promises deriving from in vitro, low contact stress situations, when in high contact stress environments, there are questions about the suitability of this material as acetabular cups or knee tibial components.

2. Metals

Metallic materials have wide applications in the medical and bioengineering fields and are widespread as orthopedic implants components. The most common traditional metals used for THA[a] are stainless steels, titanium alloys (Ti6Al4V) and − mainly − cobalt-chromium-molybdenum alloys. *The latter have good corrosion resistance compared to other metals, and high toughness, high wear resistance and higher hardness (HV = 350) than other metals and polymers.*

.a *(THA)* Total Hip Arthroplasty

Table 22.4 Mechanical and Corrosion Characteristics of Three Metals Alloys That Are Commonly Used for the Femoral Stem Component of the Prosthetic Hip

Alloy	*Elastic Modulus [GPa (psi)]*	*0.2% Yield Strength [MPa (ksi)]*	*Tensile Strength [MPa (ksi)]*	*Elongation at Fracture (%)*	*Fatigue Strength or Limit, 10^7 Cycles [MPa (ksi)]*	*Corrosion Rate (mpy)*[a]
316L Stainless Steel (cold worked, ASTM F138)	200 (29.0×10^6)	689 (100)	862 (125)	12	383 (55.5)	0.001–0.002
Co–28Cr–6Mo (cast, ASTM F75)	210 (30.0×10^6)	483 (70)	772 (112)	8	300 (43.4)	0.003–0.009
Ti–6Al–4V (hot forged, ASTM F620)	120 (17.4×10^6)	827 (120)	896 (130)	10	580 (84.1)	0.007–0.04

[a] mpy means mils per year, or 0.001 in./yr

Sources: From Gladius Lewis, *Selection of Engineering Materials*, © 1990, p. 189. Adapted by permission of Prentice Hall, Englewood Cliffs, NJ; and D. F. Gibbons, "Materials for Orthopedic Joint Prostheses," Ch. 4, p. 116, in *Biocompatibility of Orthopedic Implants*, Vol. I, D. F. Williams, CRC Press, Boca Raton, FL, 1982. With permission.

Cobalt Chromium Molybdenum alloys

CoCrMo articulation is typically produced from cobalt-chromium-molybdenum (CoCrMo) alloys. CoCrMo alloys are composed of 58.9-69.5% Co, 27.0-30% Cr, 5.0-7.0% Mo, and small amount of other elements (Mn, Si, Ni, Fe and C). These metallic alloys can be divided in 2 categories: **high-carbon** alloys (carbon content >0.20%) and **low-carbon** alloys (carbon content <0.08%) [77,78]. In addition, metallic alloys can be manufactured using 2 different techniques such as casting and forging; the grain size of the forged alloy is typically less than 10 μm, whereas the grain size of the cast material ranges from 30 to 1000 μm.

Cobalt and chromium are both present in the environment and in food. They are necessary to human beings as trace elements in the body but are toxic when highly concentrated. Patients with Co-Cr metal-on-metal pairings are exposed to wear with release of cobalt and chromium into the synovial fluid. These are capable of migrating to the blood before being expelled through the urine. There is poor knowledge on the effects of circulating Co and Cr; they may affect mainly biological and cellular functions with potential effects on the immune system, mutagenesis, and carcinogenesis. In patients with metal-on-metal hip implant, elevated levels of circulating Co and Cr ions may be generated, and there is a positive linear correlation with a lymphocytic reactivity.

Other Metal Alloys

Metallic materials have high module of elasticity, which limits stress distribution from implant to bone. Therefore, new metallic components have been developed with lower elastic modulus and higher corrosion and wear resistance. There is continuous research for new metallic alloys for application in hip prostheses to obtain a better biocompatibility along with superior mechanical properties. Still, it is mandatory to find a compromise between the many optimal characteristics desired for an implant material. Co-Cr-Mo alloys have low chemical inertness but high wear resistance, whereas stainless steel alloys have low strength and ductility. Zirconium (Zr) and tantalum (Ta) are refractory metals−due to their great chemical stability and elevate melting point−and are very resistant to corrosion, due to the stability of the oxide layer. As vanadium is a relatively toxic metal, some attempts were made to replace it in the widespread Ti-6Al-4V alloys. To improve biocompatibility and mechanical resistance, this Ti-6Al-4V alloys was replaced with iron (Fe) or niobium (Nb), realizing the improved alloys Ti-5Al-2.5Fe and Ti-6Al-7Nb. These alloys with respect to the traditional Ti-6Al-4V have greater dynamic hardness and lower elastic module, allowing a better implant/bone stress distribution. A new class of titanium alloys introduced into the orthopedic field uses molybdenum in concentration greater than 10%. Its presence stabilizes the β-phase at room temperature; these are referred to as β-Ti alloys. Having 20% less elastic modulus, they behave closer to real bones and have better shaping possibilities. Femoral stems made of a β titanium alloy have been used as part of modular hip replacements since the early 2000's but were

recalled in 2011 by the US Food & Drug Administration (FDA) due to elevated levels of wear debris.

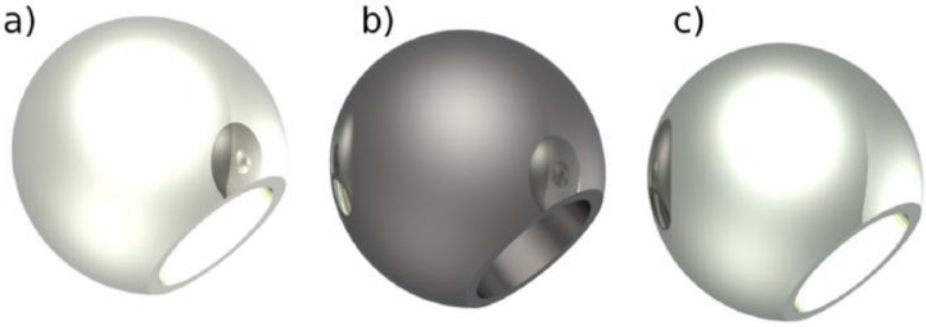


Figure 4. Metal femoral heads: (**a**) stainless-steel; (**b**) Oxinium; (**c**) CoCrMo.

Another recently introduced metal material is the oxidized zirconium (Oxinium), with a metal core and abrasion-resistant ceramic surface. The niobium alloy of zirconium has proven to decrease the UHMWPE wear rate and particle production considerably [86]. In Figure 4 it is possible to see the design of metal implants with different material renderings.

Ceramics

Alumina

Alumina ceramics have been used in clinical applications for their tribological properties due to their hardness. Among the ceramics, alumina is probably the most commonly used material.

The alumina used for hip replacements was different from the first generation of the material used for industrial applications. In particular, the first generation of alumina showed poor microstructure with low density, scarce purity, and large grain size. This generation of alumina was unsuited for biomedical use. The continuous efforts performed in this field allowed researchers to purify and improve this process, leading to an alumina for medical use, commercially known as Biolox®.

Recently, concerns have been raised because of some clinical reports on the presence of audible noise in some ceramic-on-ceramic THA patients. The so-called "clicks" or "grinds" have been described after THA, regardless of whether metal-on-polyethylene, metal-on-metal, or ceramic-on-ceramic bearings were used. The "squeak" appears to be limited, however, to hard-bearing couples. It is probably related to implant design or cup orientation and the exact etiology of squeaking is the object of debates; there is neither a specific definition for post-surgery squeaking nor a universal categorization for the sound.

Zirconia

Zirconia has high toughness and good mechanical properties; among all the monolithic ceramics, it has outstanding crack resistance; these are the main reasons that made zirconia a very widespread alternative to alumina for THA.

Figure 3. Zirconia femoral head.

First attempts were focused on magnesia partially stabilized zirconia (MgPSZ), that did not satisfy the wear resistance requirements. Therefore, further developments were focused on yttria stabilizing oxide (Y-TZP), a ceramic that is completely formed by submicron-sized grains, representing the current standard for clinical application. A picture of such a ceramic femoral head is shown in Figure.

Conclusions

Advances in technology, improved materials and better understanding of natural tissue reactions will certainly result in breakthroughs of implant selection.

Questions

(1) What are the main materials which can be used to substitute the damaged hip joint?

(2) State briefly the advantages and disadvantages of each one of those materials? Make a comparison.

(3) Benefits of using PTFE to replace the hip joints are:
(i)----------, (ii)----------, (iii)---------- and (iv)---------.

(4) True or False?

UHMWPE was typically sterilized by gamma irradiation.

(5) Choose the right choice:
Alumina ceramics have been used in clinical applications for their properties:
(i) optical properties, (ii) tribological properties, or (iii) chemical properties

---

* Fretting is a combination of corrosion and wear in which corrosion produces small debris (generally oxide particles) that increases the friction and induces greater abrasion.

References

Materials Scince and Engineering _Callister