Biomaterials: Properties, Types and applications

MECH 634- SPRING SEMESTER 2008

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OUTLINES

Biomaterials: Properties, Types, and Applications

3.1 Mechanical Properties and Mechanical Testing
3.2 Metals

MECHANICAL TESTING

- The most common way to determine mechanical properties is to pull a specimen apart and measure the force and deformation.

- Materials are also tested by crushing them in compression or by bending them.

- Standardized test protocols have been developed to facilitate comparison of data generated from different laboratories. The vast majority of those used in the biomaterials field are from the American Society for Testing and Materials (ASTM).

- For example, tensile testing of metals can be done according to ASTM E8, ASTM D412 is for rubber materials, and ASTM D638 is for tensile testing of rigid plastics. These methods describe specimen shapes and dimensions, conditions for testing, and methods for calculating and reporting the results.

www.astm.org

MECHANICAL TESTING EXAMPLE: ASTM E8

- Test done with a “dog bone” shaped specimen that has its large ends held in some sort of a grip while its narrow midsection is the “test” section.

- The mid portion is marked as the “gage length” where deformation is measured.

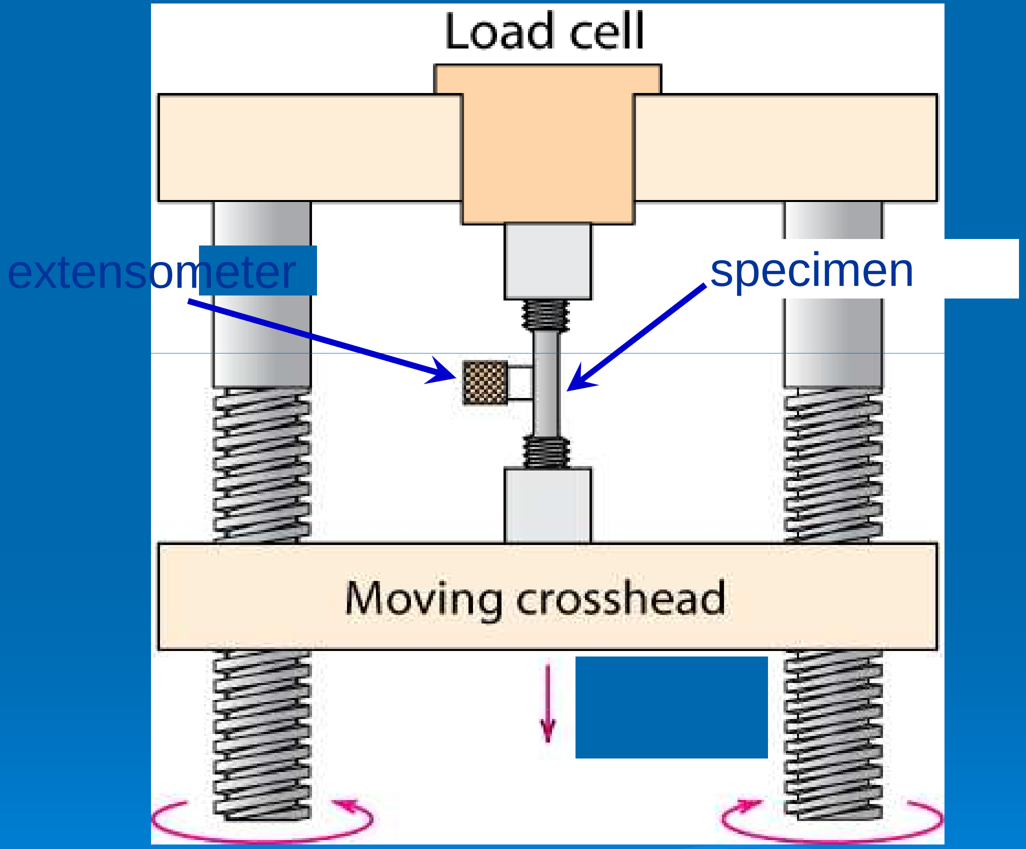
- A mechanical test machine uses rotating screws or hydraulics to stretch the specimen. Force is measured in Newtons (N), and how much the specimen stretches— deformation—is measured in millimeters.

$$\sigma(\mathrm{N/m^2}) = \text{force}/\text{cross-sectional area}$$

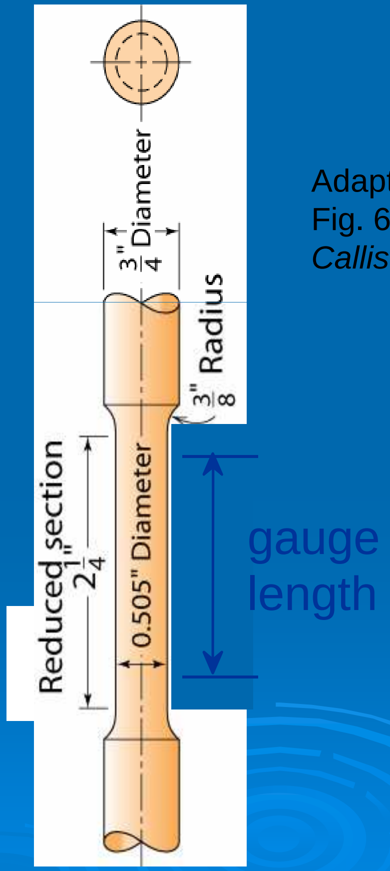
$$\varepsilon(\%) = [(\text{deformed length} - \text{original length})/\text{original length}] * 100\%$$

Stress-Strain Testing

- **Typical tensile test machine**
- **Typical tensile specimen**

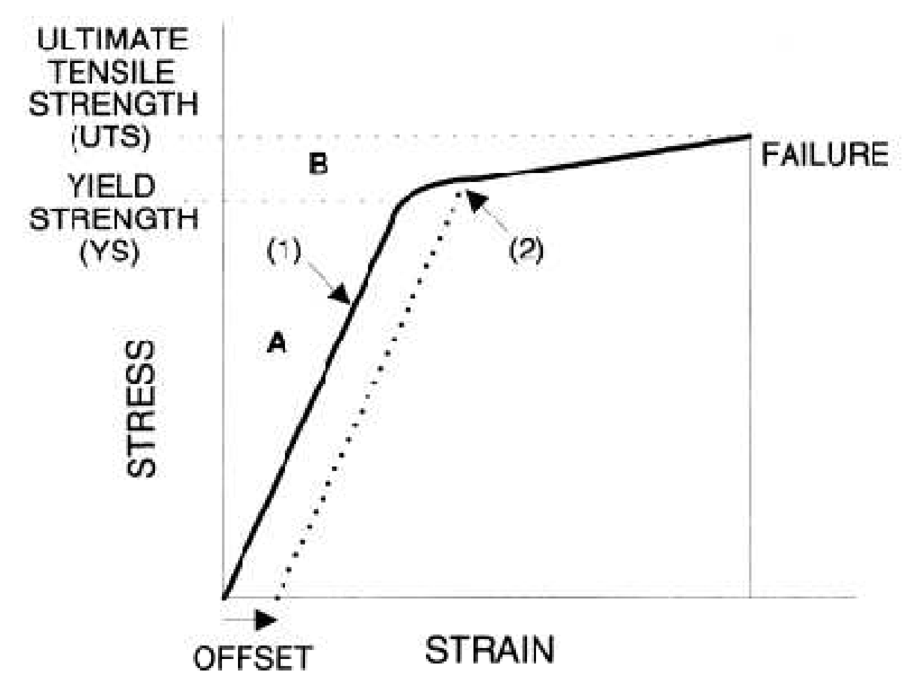


Adapted from Fig. 6.3, *Callister 7e.* (Fig. 6.3 is taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)



Adapted from Fig. 6.2, *Callister 7e.*

ASTM E8 (Cont.)



Typical stress–strain curve for a metal that stretches and deforms (yields) before breaking. Stress is measured in N/m2 (Pa) while strain is measured as a percentage of the original length. The minimum stress that results in permanent deformation of the material is called the yield strength (YS). The ultimate strength (UTS) is the maximum stress that is tolerated by the material before rupturing. The stress at which failure occurs is called the failure strength (FS). Region A represents the elastic region since the strain increases in direct proportion to the applied stress. If a small stress is applied
(e.g., to point 1), the material will return to its original length when the stress is removed. Region B represents the plastic region in which changes in strain are no longer proportional to changes in stress.
Stresses in this region result in permanent deformation of the material. If a stress is applied that results in the strain at point (2), the material will follow the dotted line back to the baseline when the stress is removed and will be permanently deformed by the amount indicated by the offset.

3.2 Metals

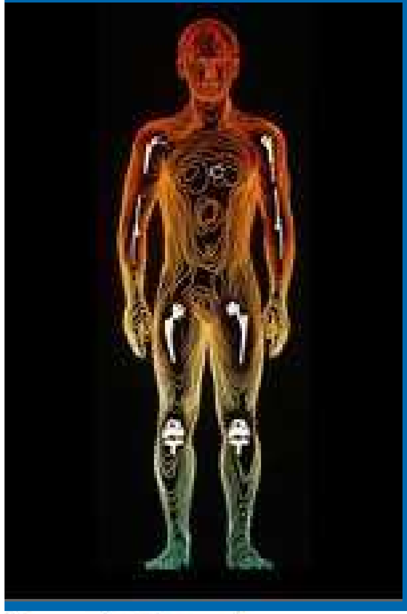
- Metals used as biomaterials have high strength and resistance to fracture and are designed to resist corrosion

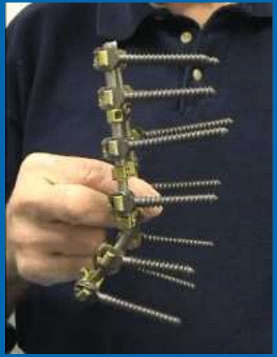
- Applications: see table 1-Case Study 1

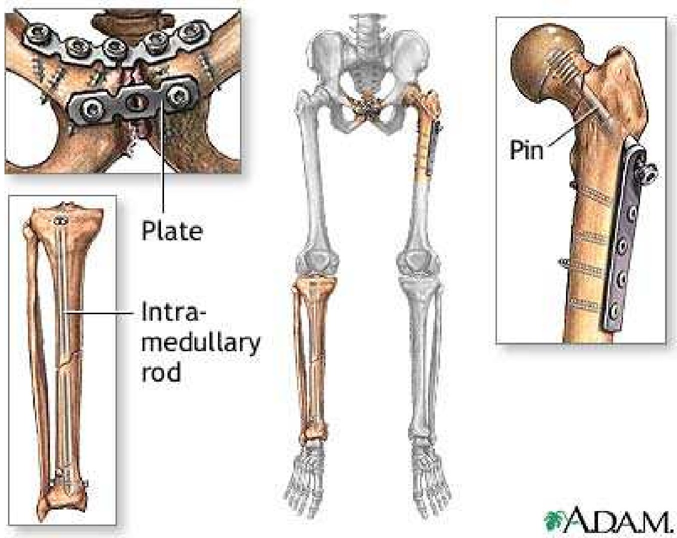
- Many orthopedic devices are made of metal, such as hip and knee joint replacements

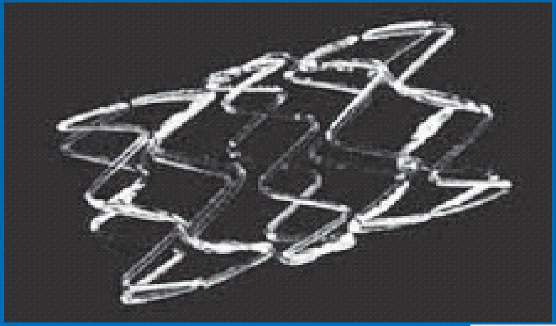
- The implants provide relief from pain and restore function to joints in which the natural cartilage has been worn down or damaged.

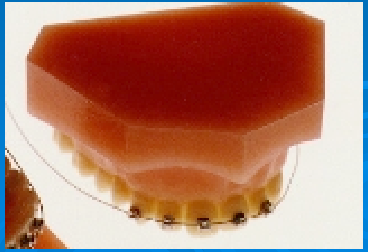
Metallic Biomaterials









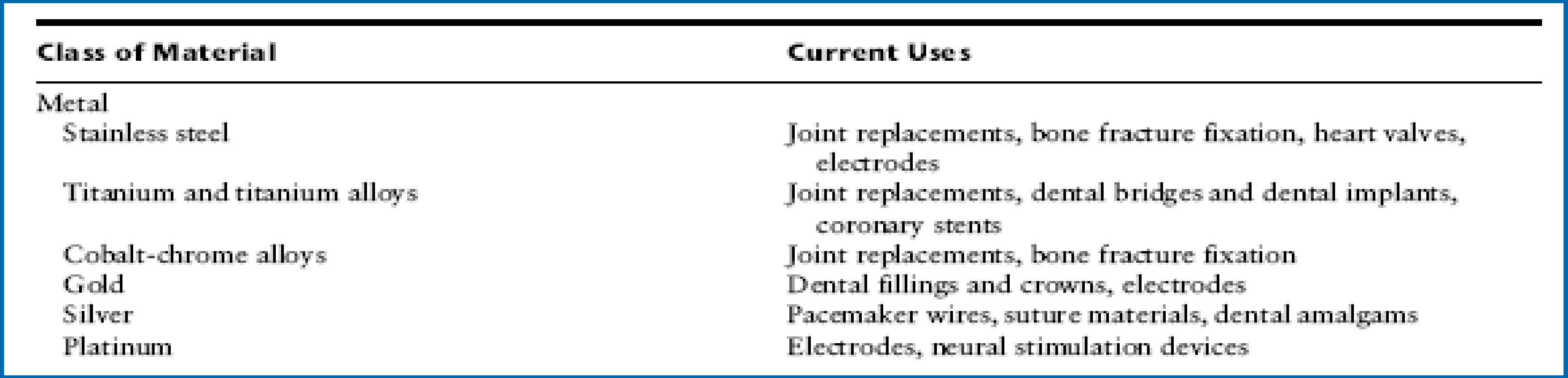


Metals

- Orthopedic implants
- Suture
- Staples

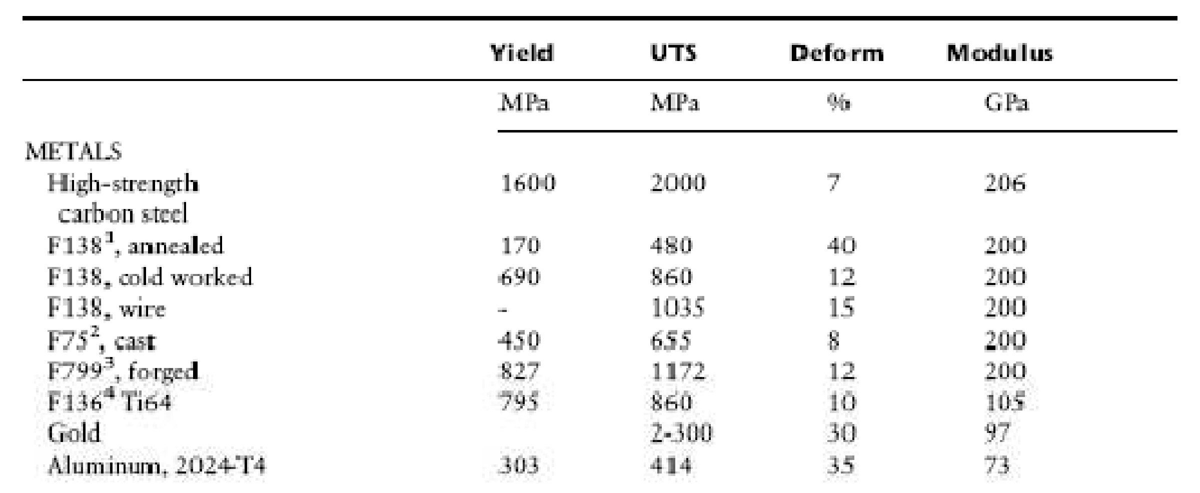
- **Alloy**
  - – homogenous substance composed of two or more metals or of a metal or metals with a nonmetal.

Materials and Their Medical Uses-I



Class of Material	Current Uses
Metal	
Stainless steel	Joint replacements, bone fracture fixation, heart valves, electrodes
Titanium and titanium alloys	Joint replacements, dental bridges and dental implants, coronary stents
Cobalt-chrome alloys	Joint replacements, bone fracture fixation
Gold	Dental fillings and crowns, electrodes
Silver	Pacemaker wires, suture materials, dental amalgams
Platinum	Electrodes, neural stimulation devices

Mechanical Properties of Materials with Literature Values or Minimum Values from Standards



	Yield	UTS	Deform	Modulus
	MPa	MPa	%	GPa
METALS				
High-strength carbon steel	1600	2000	7	206
F138[1], annealed	170	480	40	200
F138, cold worked	690	860	12	200
F138, wire	-	1035	15	200
F75[2], cast	450	655	8	200
F799[3], forged	827	1172	12	200
F136[4] Ti64	795	860	10	105
Gold		2-300	30	97
Aluminum, 2024-T4	303	414	35	73

Metals (cont.)

Plates and screws that hold fractured bone together during healing also are made of metal

(a) Metal plates and screws are used to hold fractured bone segments together during healing. Depending on the extent of injury, the plates and screws or rods may be removed when the bone is fully repaired. (Photograph of the HALLU1-FIX MTP Fusion System (registered mark of NEWDEAL) is courtesy of Wright Medical Technology, Inc.)

(b) Through the use of x-rays an implanted metal plate with screws can be visualized in this patient's foot and hand. (X-ray courtesy of Wright Medical Technology, Inc.)

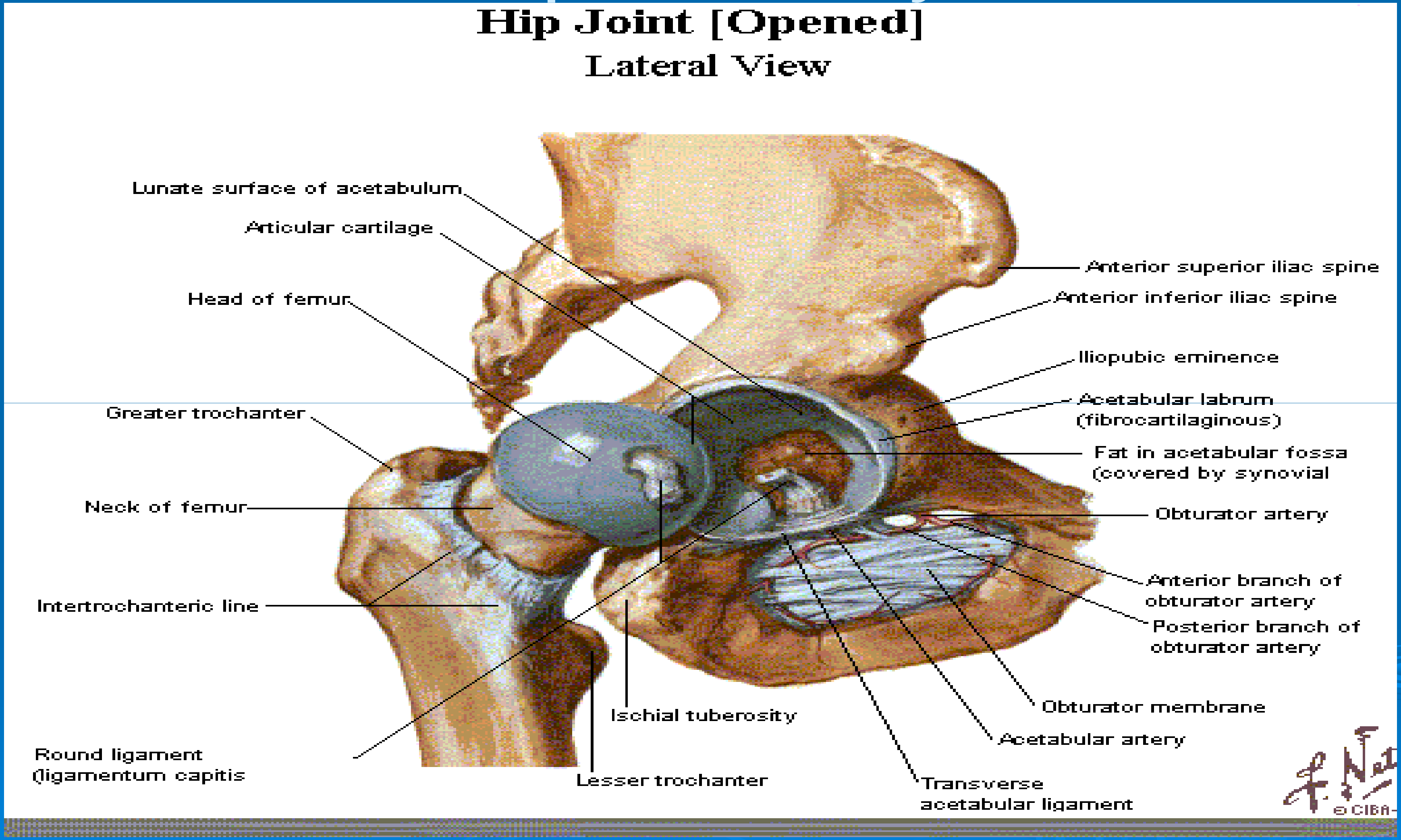
Metals (cont.)-Case Study involving metallic application

A typical total hip joint replacement is made primarily of metal. The ball of the femoral hip stem fits into a pelvic acetabular cup that is lined with ultra high molecular weight polyethylene (UHMWPE) for friction-free motion. (Photograph of the PROFEMUR 1 Z minimally invasive hip stemwith modular necks courtesy of Wright Medical Technology, Inc.)

General Anatomical Overview

- The hip is one of your body's largest weight-bearing joints.
- Consists of two main parts:
- a ball *(femoral head)* that fits into a rounded socket *(acetabulum)* in your pelvis.
- Ligaments connect the ball to the socket and provide stability to the joint
- The bone surfaces of your ball and socket have a smooth durable cover of *articular cartilage* that cushions the ends of the bones and enables them to move easily.

Hip Anatomy


Hip Joint [Opened]
Lateral View
Lunate surface of acetabulum
Articular cartilage
Head of femur
Greater trochanter
Neck of femur
Intertrochanteric line
Round ligament
(ligamentum capitis
Ischial tuberosity
Lesser trochanter
Anterior superior iliac spine
Anterior inferior iliac spine
Iliopubic eminence
Acetabular labrum
(fibrocartilaginous)
Fat in acetabular fossa
(covered by synovial
Obturator artery
Anterior branch of
obturator artery
Posterior branch of
obturator artery
Obturator membrane
Acetabular artery
Transverse
acetabular ligament

More…

- All remaining surfaces of the hip joint are covered by a thin, smooth tissue called *synovial membrane*. In a healthy hip, this membrane makes a small amount of fluid that lubricates and almost eliminates friction in your hip joint.
- Normally, all of these parts of your hip work in harmony, allowing you to move easily and without pain.

Total Hip Replacement

- A prosthetic hip that is implanted in a similar fashion as is done in people. It replaces the painful arthritic joint.
- The modular prosthetic hip replacement system used today has three components – the femoral stem, the femoral head, and the acetabulum. Each component has multiple sizes which allow for a custom fit.
- The components are made of cobalt chrome stainless steel and ultra high molecular weight polyethylene. *Cementless* and *cemented prosthesis* systems are available.

Bone replacement criteria include the following:

- 1. Appropriate tissue-material interface
- 2. Non-toxic
- 3. Non-corrosive
- 4. Adequate fatigue life
- 5. Proper design
- 6. Proper density
- 7. Relatively inexpensive
- 8. Elastic and mechanical properties comparable to those of bone

Early history

http://www.ibiblio.org/wm/paint/auth/bruegel/beggars.jpg

Joseph Lister

http://history.amedd.army.mil/booksdocs/misc/evprev/fig23.jpg

John Charnley

news.bbc.co.uk/2/low/in_pictures/4949528.stm

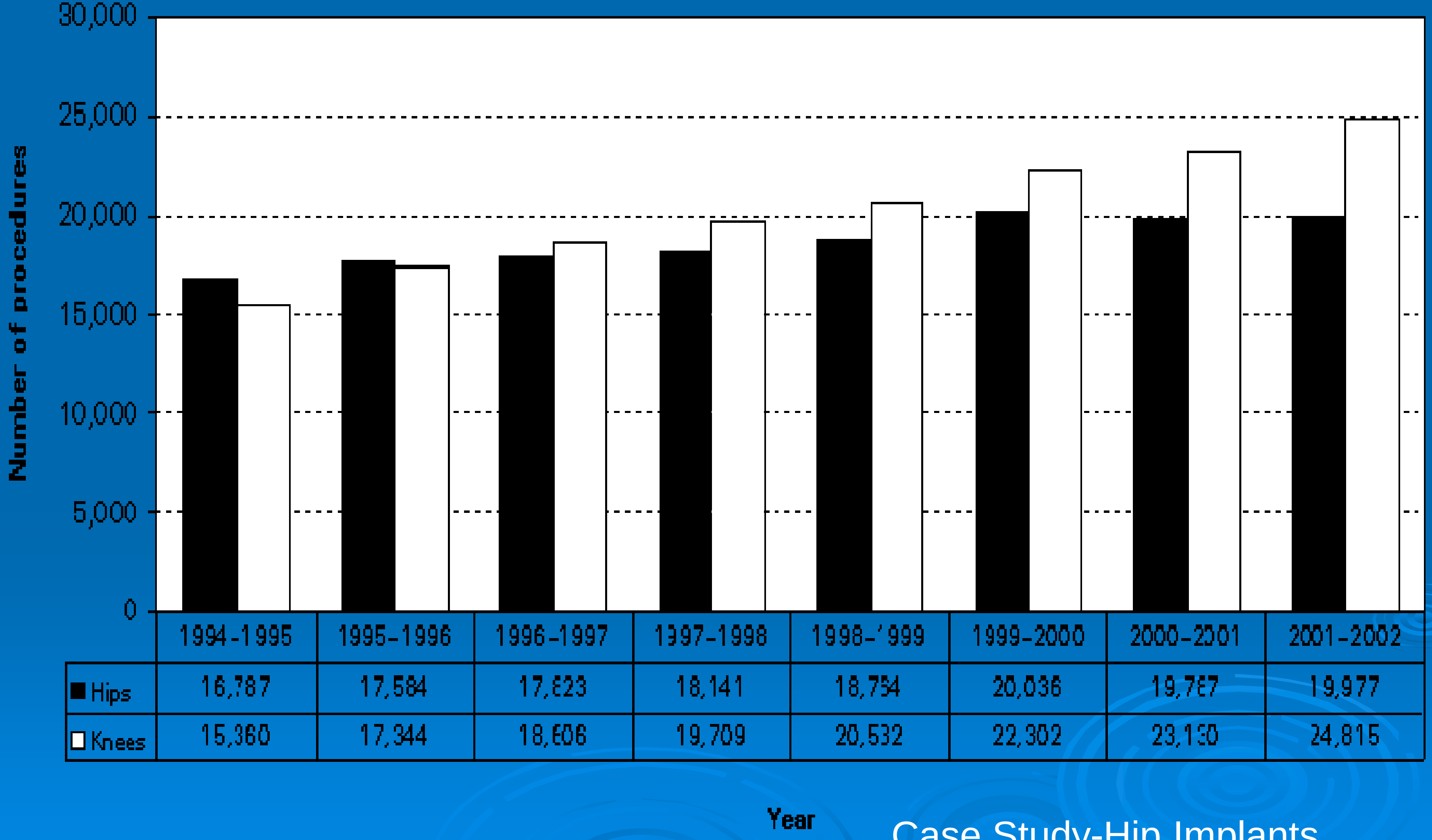
Charnley Prosthesis

news.bbc.co.uk/2/low/in_pictures/4949528.stm

Statistical Overview

- First performed in 1960.
- Since then, improvements in joint replacement surgical techniques and technology have greatly increased the effectiveness of this surgery.

Number of Total Hip and Total Knee Replacement Procedures Performed in Canada, 1994–1995 to 2001–2002



	1994-1995	1995-1996	1996-1997	1997-1998	1998-1999	1999-2000	2000-2001	2001-2002
■ Hips	16,787	17,584	17,823	18,141	18,754	20,036	19,787	19,977
□ Knees	15,360	17,344	18,606	19,709	20,532	22,302	23,130	24,815

Source: Hospital Morbidity Database, CIHI, 2001-2002

Case Study-Hip Implants

Case Study-Hip Implants

Number and Distribution of Total Hip Replacement Procedures by Age Group and Sex, Canada, 2001–2002 Compared to 1994–1995

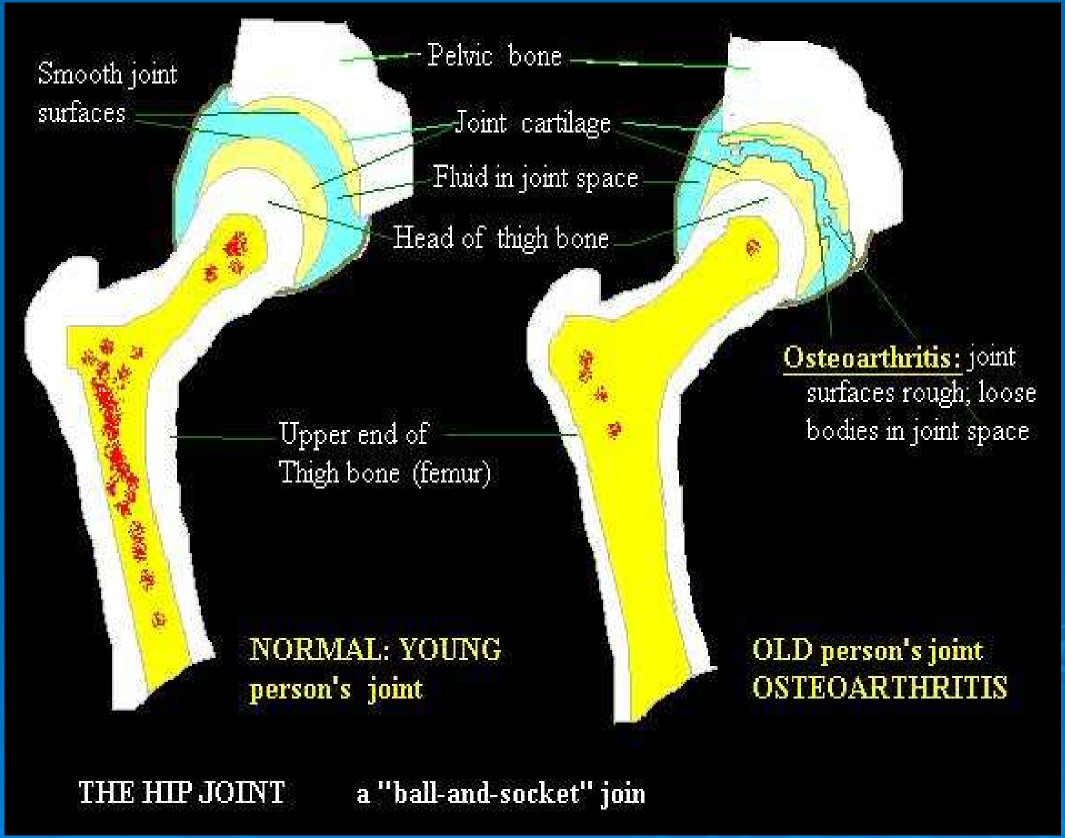
Age group	Males			Females		
	1994-1995	**2001-2002**	**7-year % change**	**1994-1995**	**2001-2002**	**7-year % change**
<45 years	489	553	13.1%	475	484	1.9%
45-54 years	716	1,055	47.3%	630	943	49.7%
55-64 years	1,609	1,753	8.9%	1,659	1,966	18.5%
65-74 years	2,475	2,798	13.1%	3,746	3,748	0.1%
75-84 years	1,470	1,976	34.4%	2,798	3,547	26.8%
85+ years	194	315	62.4%	526	839	59.5%
Total	**6,953**	**8,450**	**21.5%**	**9,834**	**11,527**	**17.2%**

***Source**: Hospital Morbidity Database, CIHI*

Common Causes of Hip Pain and Loss of Hip Mobility

Osteoarthritis

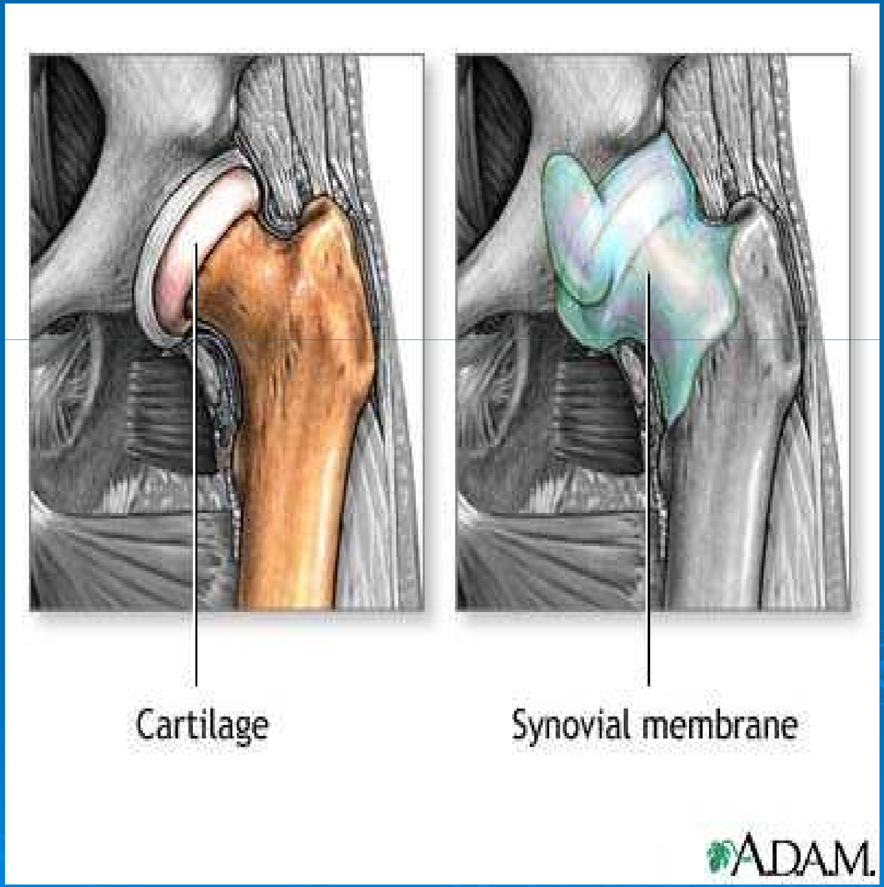
- Usually occurs after age 50 and often in an individual with a family history of arthritis. In this form of the disease, the articular cartilage cushioning the bones of the hip wears away. The bones then rub against each other, causing hip pain and stiffness.



Causes (cont'd)

Rheumatoid Arthritis

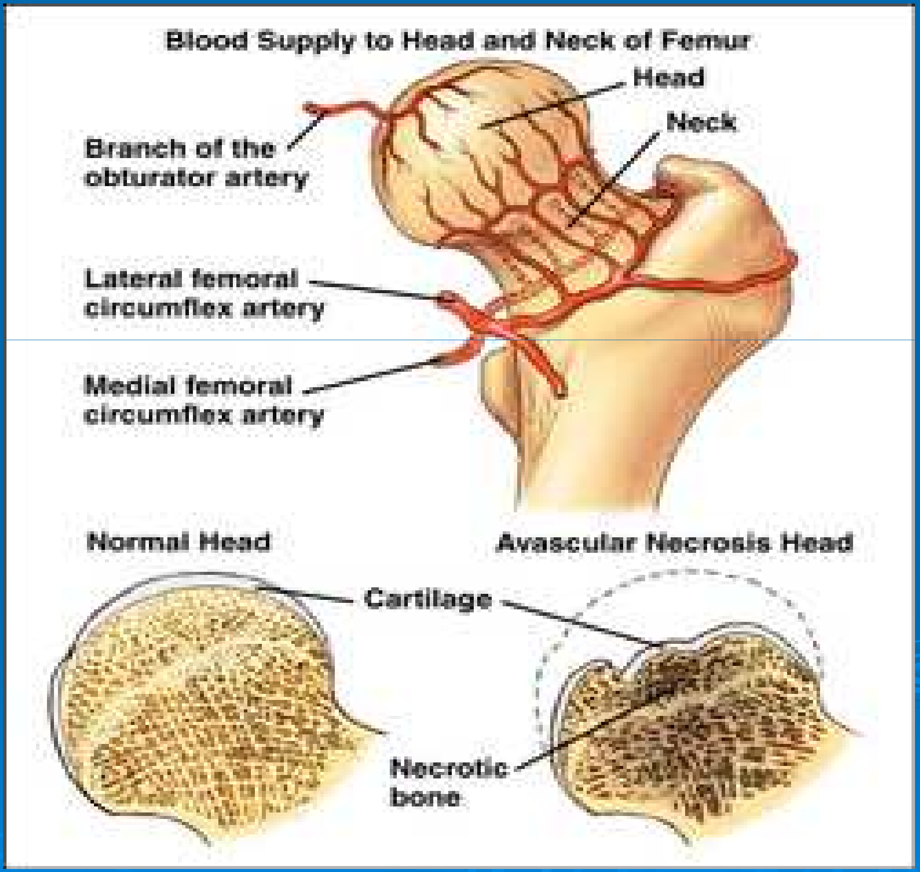
- a disease in which the synovial membrane becomes inflamed, produces excessive synovial fluid, and damages the articular cartilage, leading to pain and stiffness.



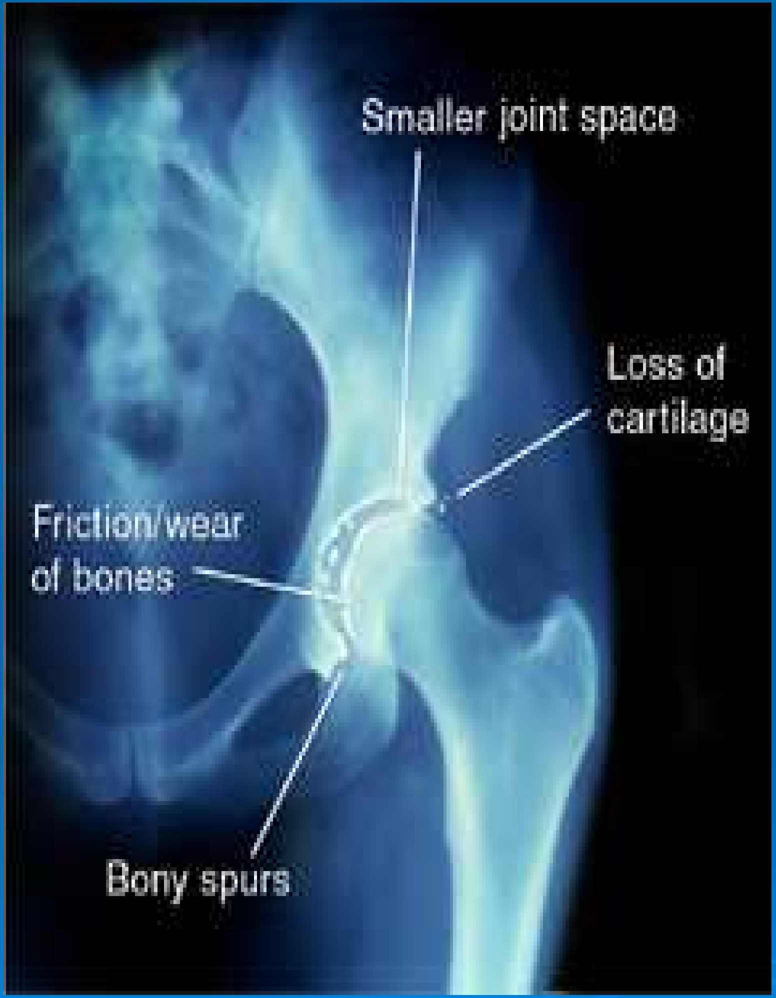
Causes (cont'd)

Traumatic Arthritis

- Can leads to a serious hip injury or fracture. A hip fracture can cause a condition known as *avascular necrosis*. The articular cartilage becomes damaged and, over time, causes hip pain and stiffness.



Osteoarthritis

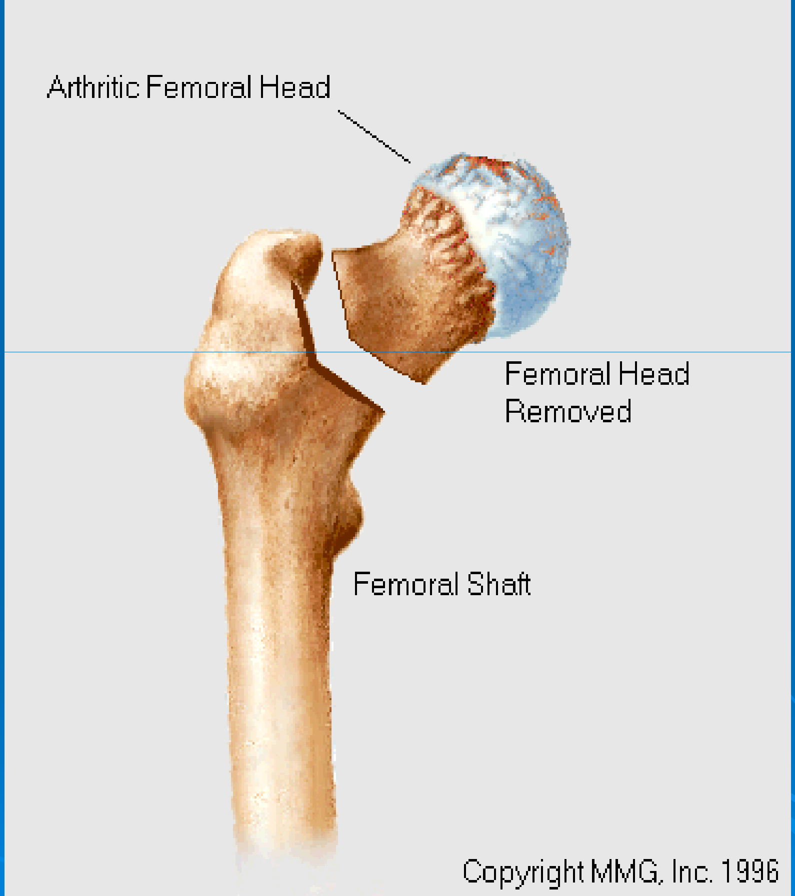


Fracture

Operation

Removing the Femoral Head

- Once the hip joint is entered, the femoral head is dislocated from the acetabulum.
- Then the femoral head is removed by cutting through the femoral neck with a power saw.



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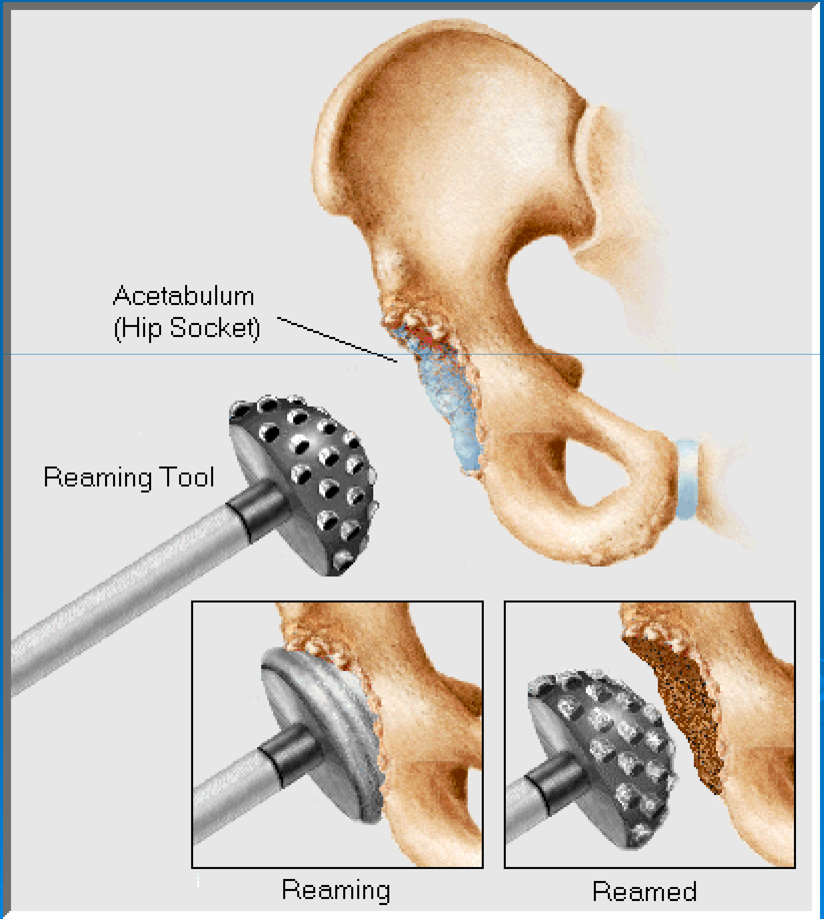
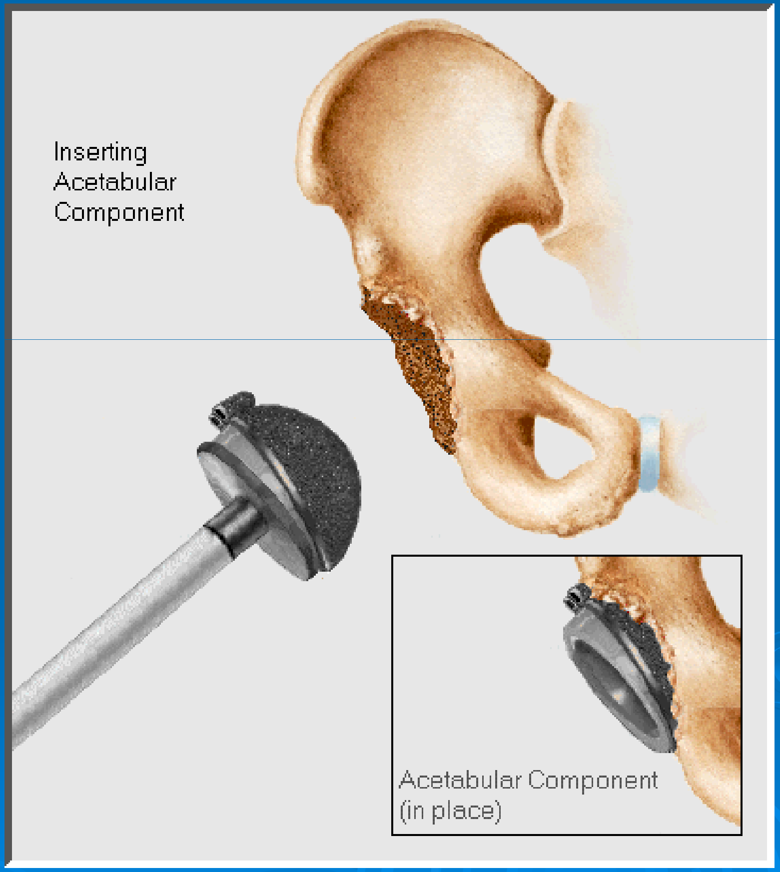
Reaming the Acetabulum

- After the femoral head is removed, the cartilage is removed from the acetabulum using a power drill and a special reamer.
- The reamer forms the bone in a hemispherical shape to exactly fit the metal shell of the acetabular component.



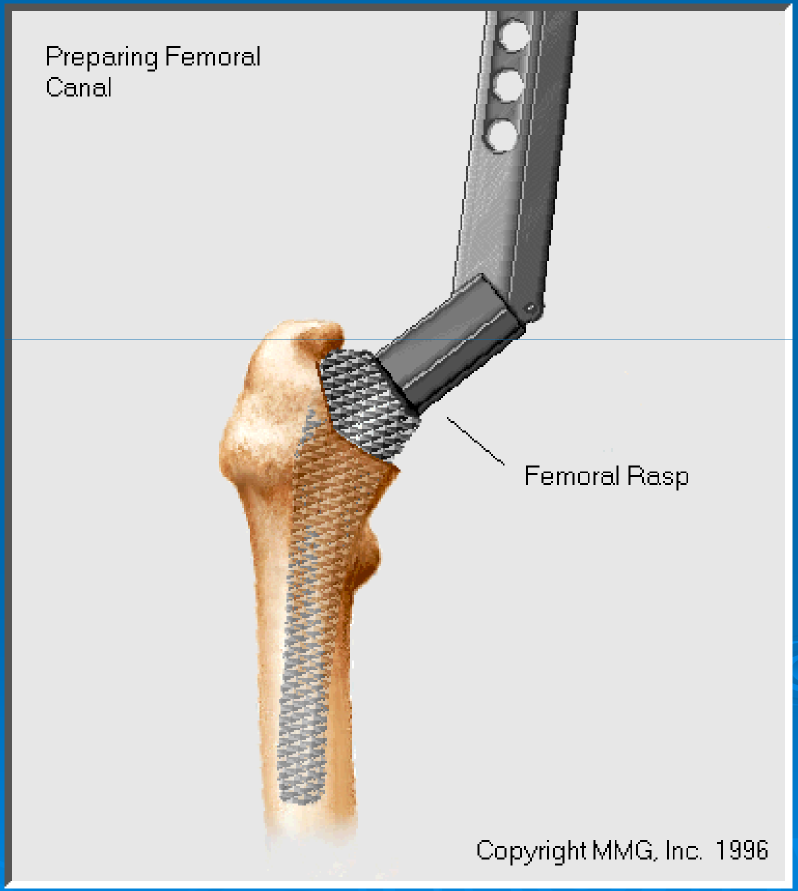
Inserting the Acetabular Component

- A trial component, which is an exact duplicate of your hip prosthesis, is used to ensure that the joint will be the right size and fit for the client.
- Once the right size and shape is determined for the acetabulum, the acetabular component is inserted into place.



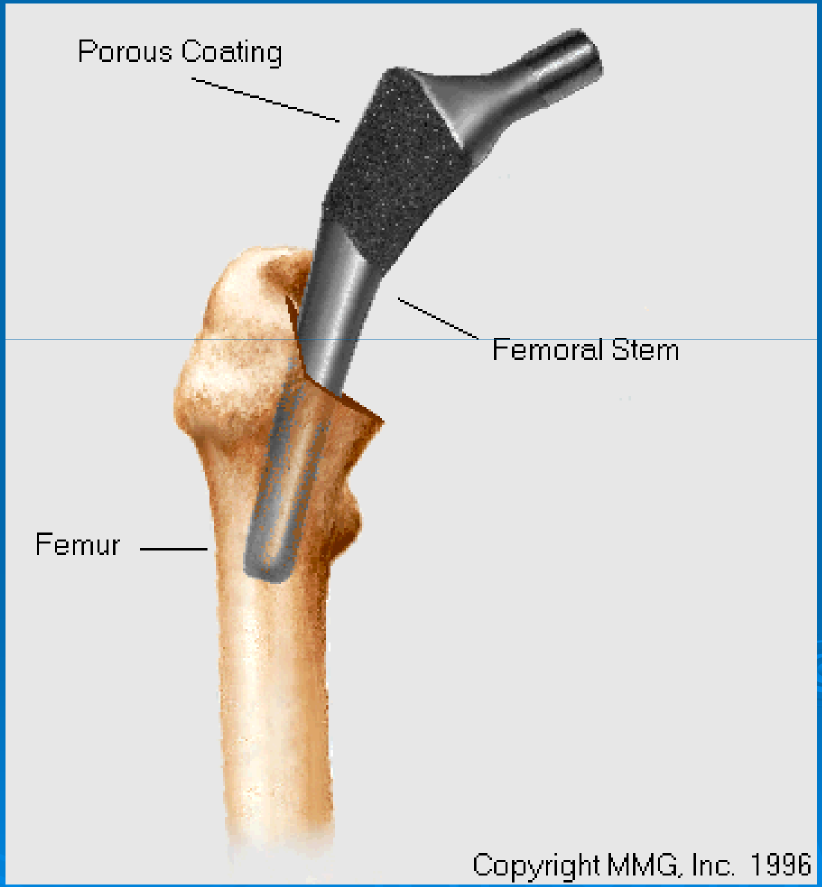
Preparing the Femoral Canal

- To begin replacing the femoral head, special rasps are used to shape and scrape out femur to the exact shape of the metal stem of the femoral component.
- Once again, a trial component is used to ensure the correct size and shape. The surgeon will also test the movement of the hip joint.



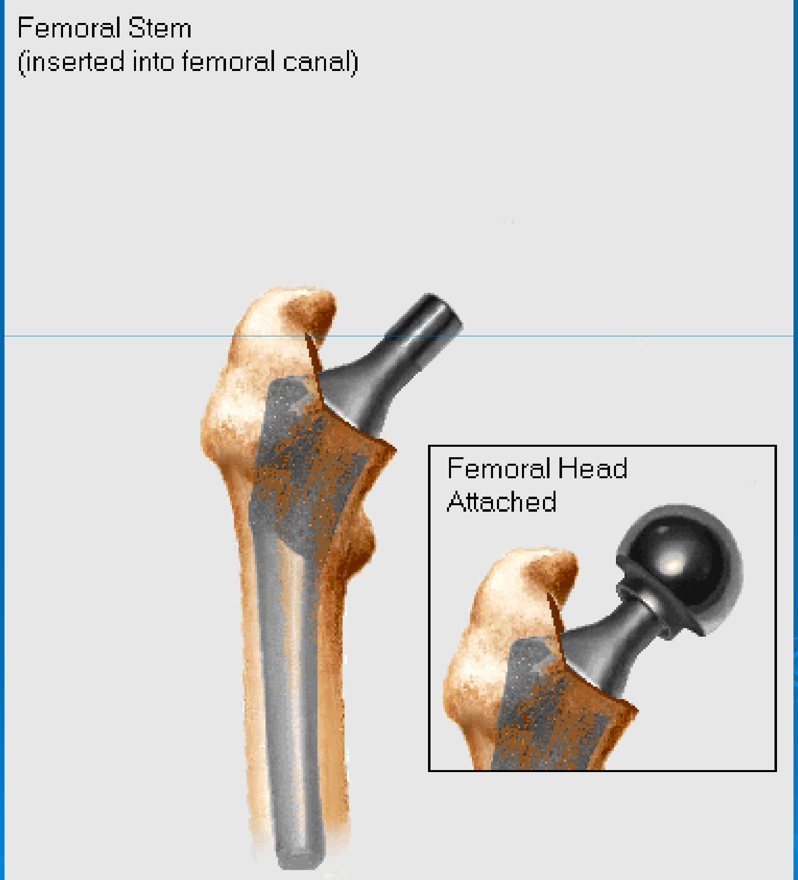
Inserting Femoral Stem

- Once the size and shape of the canal exactly fit the femoral component, the stem is inserted into the femoral canal.



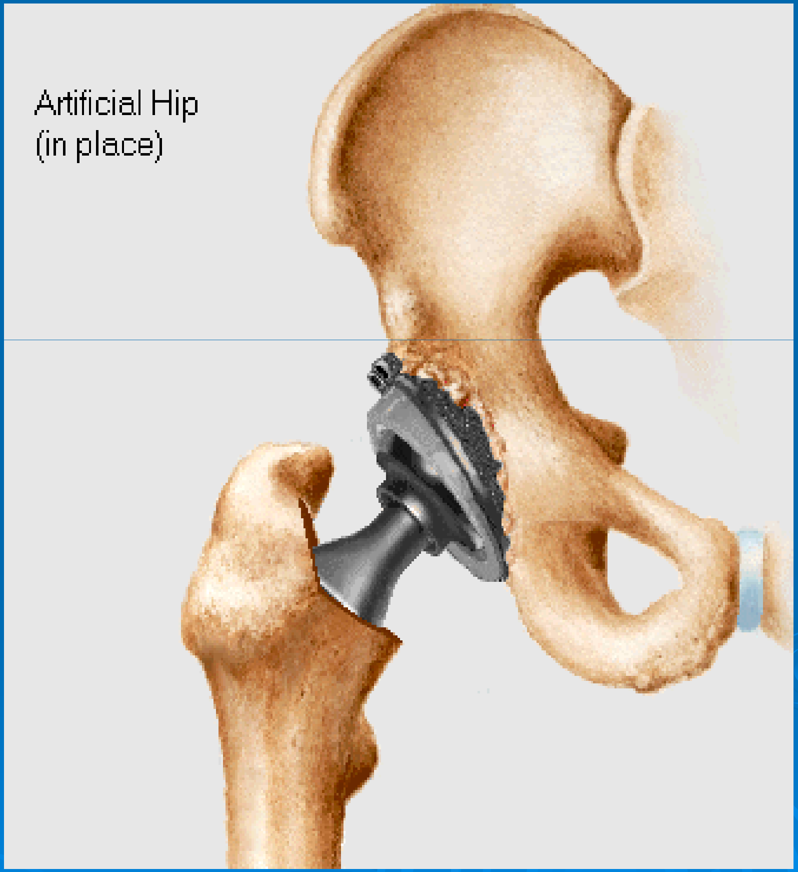
Attaching the Femoral Head

- The metal ball that replaces the femoral head is attached to the femoral stem.



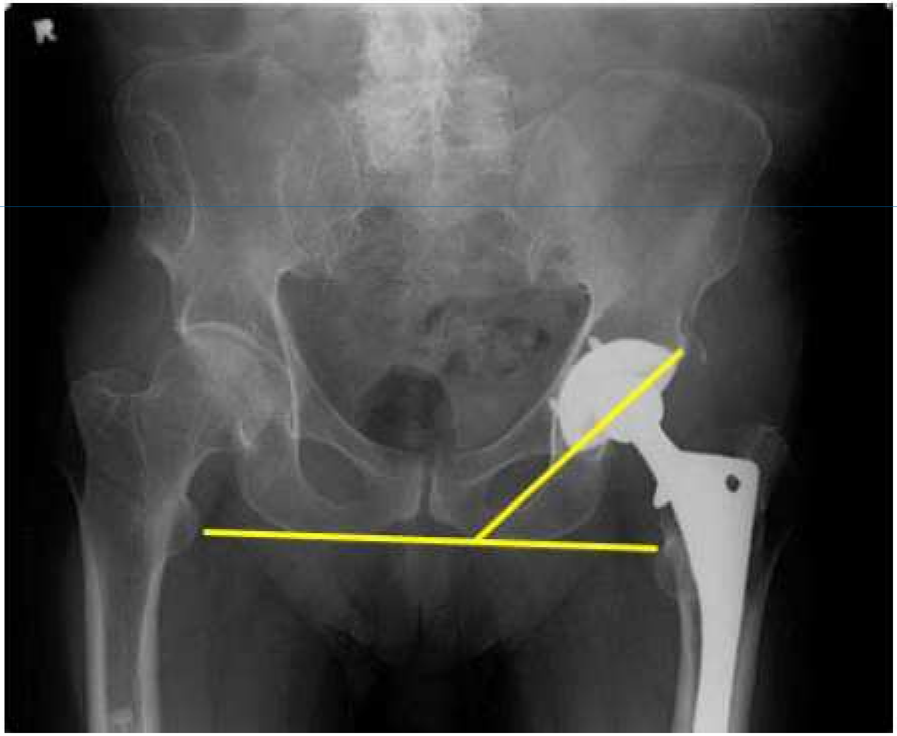
The Completed Hip Replacement

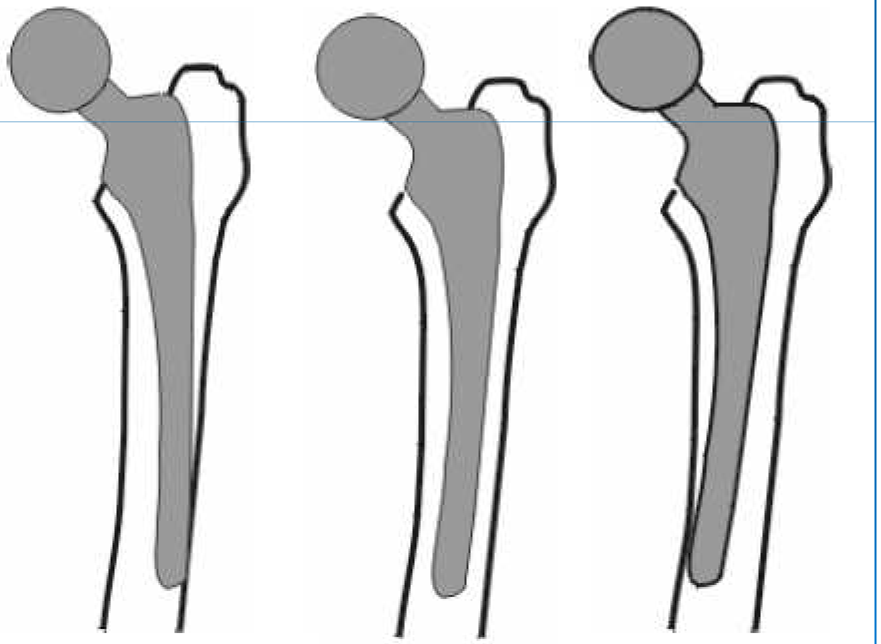
- Client now has a new weight bearing surface to replace the affected hip.
- Before the incision is closed, an x-ray is made to ensure new prosthesis is in the correct position.



See video(s)

HIP ARTHROPLASTY:
Alignment and Stem Position





A Number of Components to Choose from:

Polyethylene and porous acetabular cups, back and front views

Metal acetabular cup with polyethylene liner, disassembled and assembled

Metal acetabular cup with metal liner, disassembled and assembled

Metal acetabular cup with polyethylene liner disassembled, with various ceramic and metallic femoral component heads

Acetabular cups – ceramic, metal and polyethylene, and porous ingrowth

Porous ingrowth femoral stem with various metal and ceramic heads

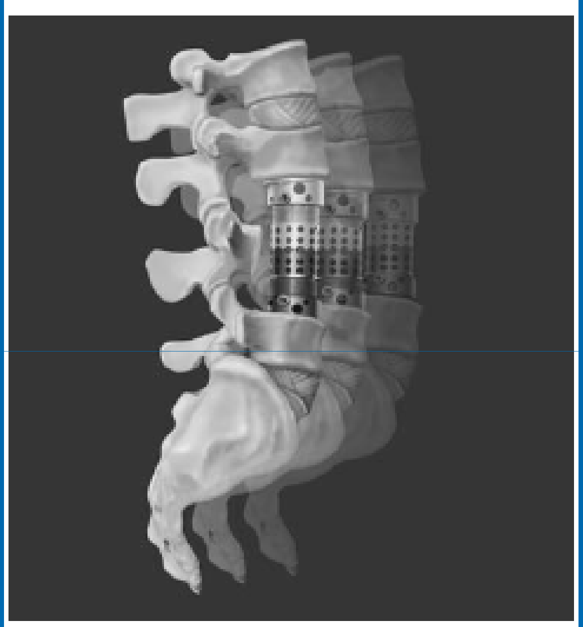
Porous ingrowth total hip replacement with polyethylene cup

Major factors causing failure of total joint replacements include:

1. Infection during orthopedic surgery;
2. Fracture of the implants;
3. Fixation problem of the implants;
4. Wear of the implant materials; and,
5. Osteolysis induced by wear particles.

Metals (cont.)

Metallic devices are also used to fuse segments of the spine together when the disk has degenerated and as dental root prosthetic implants



Metallic devices are used to fuse segments of the spine together when vertebral bones are fractured due to osteoporosis or back injury. The metal cage can accommodate the patient's own bone particles to assist with new bone formation which will eventually span and fuse the adjacent vertebral bones. (Photograph of the VERTESPAN1 spinal fusion cage courtesy of Medtronic Sofamor Danek.)

As an alternative to dentures, patients can have metallic dental root prosthetics implanted to replace each missing tooth. The implant is then topped with a porcelain crown. One advantage of dental implants over dentures is that the implant transmits mechanical forces into the jaw bone and stimulates it, resulting in less bone recession over time. (Photograph courtesy of Dr. Martin Freilich of the University of Connecticut Health Center.)

Metals choice-I

- The selection depends on a number of factors, including the mechanical loading requirements, chemical and structural properties of the material itself, and the biological requirements.

- The longstanding use of metals for knee and hip joints, bone plates, and spinal fusion devices is due to the high mechanical strength requirements of these applications and proven biocompatibility in these settings.

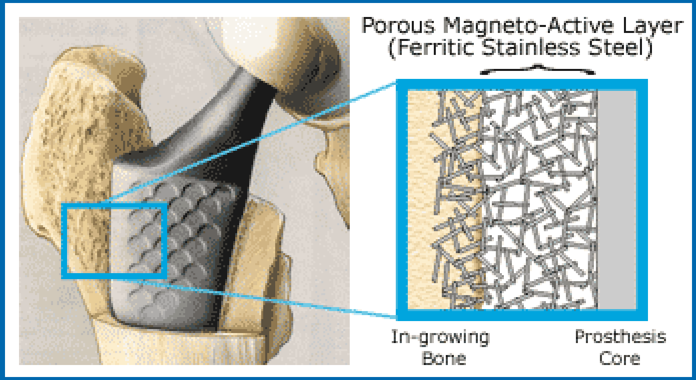
- The advantages of metals over other materials such as ceramics and polymers are that they are strong, tough, and ductile (or deformable, particularly as compared to ceramics).

- Disadvantages include susceptibility to corrosion due to the nature of the metallic bond (free electrons).

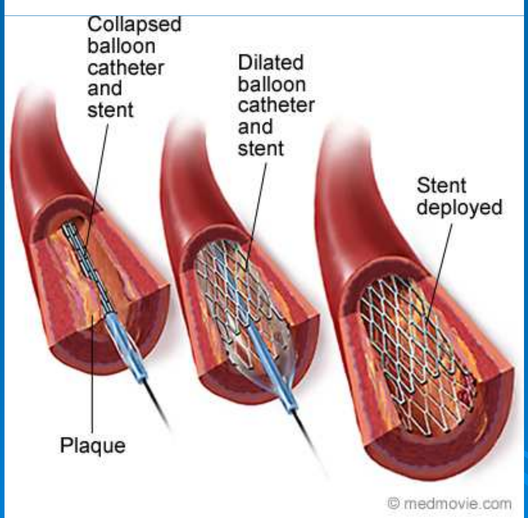
Metals choice-II

The steels that were used in the early 1900s for hip implants corroded rapidly in the body and caused adverse effects on the healing process.

Today: preferred selection of alloys of titanium or cobalt-chrome for hip, knee, and dental implants.



Certain metals known as shape memory alloys (e.g., nitinol) can be bent or deformed and still return to their original shape when the stress is released. These metals have found application in eye glasses and coronary artery stents that can be inserted through a catheter while collapsed and then spring into a cylindrical shape once they are pushed beyond the confines of the catheter.



Metals choice-III

- Metallic devices are typically made by investment casting, computer-aided design and machining (CAD/CAM), grinding, or powder metallurgy techniques.
- The specific steps involved in the fabrication of a medical device will depend on factors such as final geometry of the implant, the forming and machining properties of the metal, and the costs of alternative fabrication methods.

Metallic Biomaterials

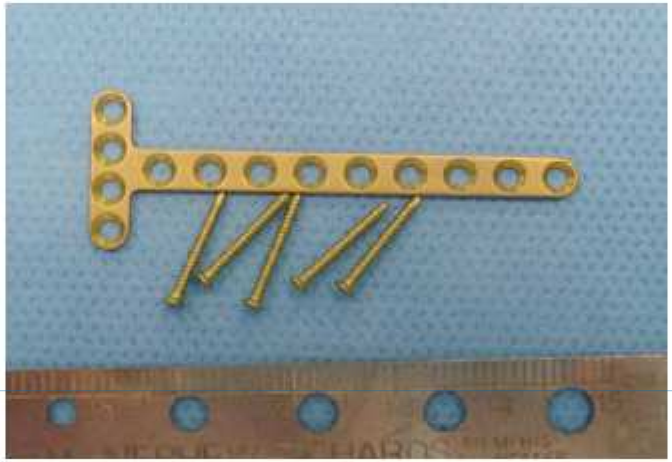
- There are 3 main groups of metals used as biomaterials:
  - stainless steels
  - Co-based alloys
  - titanium-based alloys

Cobalt-chromium alloys

- Cast cobalt-chromium-molybdenum
- Wrought cobalt-nickel-chromium-molybdenum alloys
- Best combination of high abrasion resistance, low-corrosion characteristics, and high fatigue strength
- Cost prohibitive

Titanium

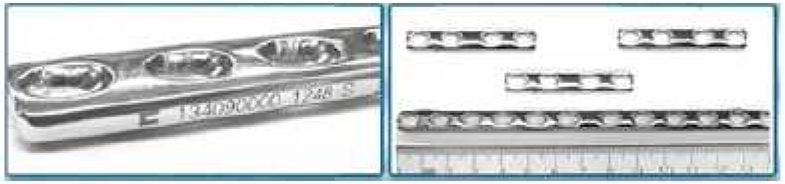
- Pure form
- Most resistant to corrosion
- Most brittle implant
- Best overall fatigue life of implants
- Low torsional strength
  - Screws are titanium alloys
    - titanium (90%), aluminum (6%), and vanadium (4%)



http://prehealthfiq2007.wikispaces.com/III.+Chantel+McCallson+&+Aaron+Seawell

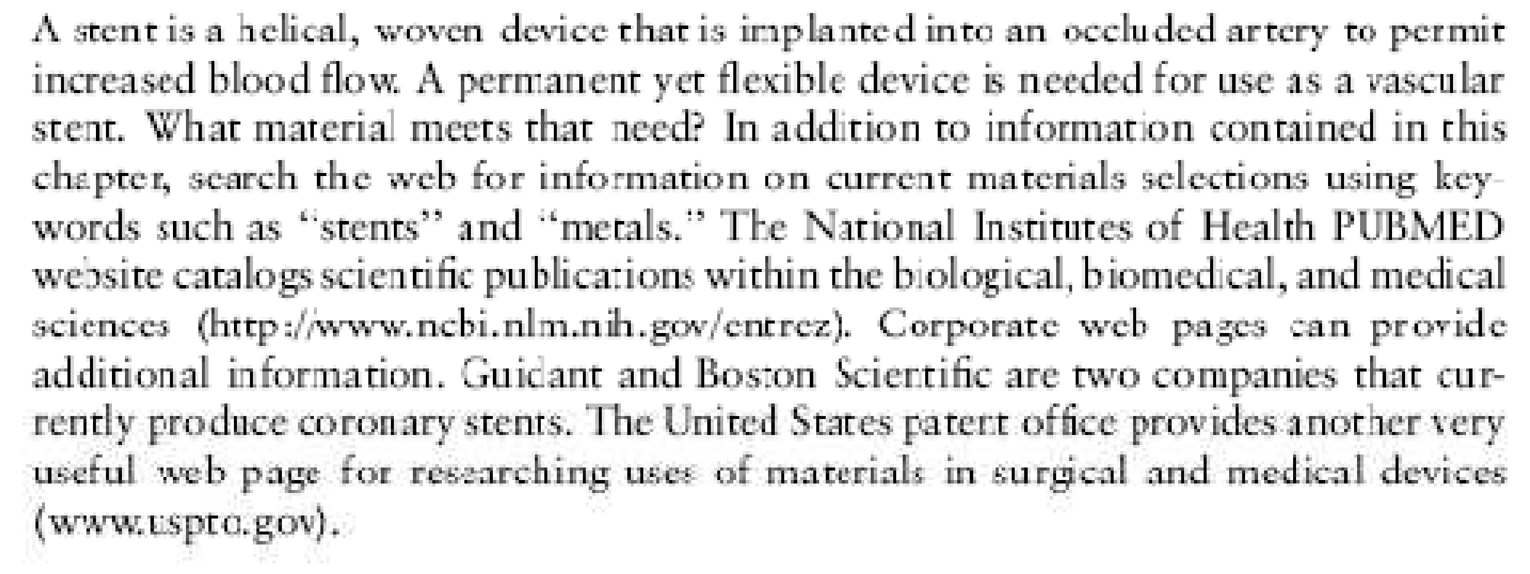
Stainless Steel

- 316L (low carbon) alloy
  - iron (55-60%), chromium (17-20%), nickel (10-14%), molybdenum (2-4%), and carbon (<0.03%)
- Most corrosive of the orthopedic implants
  - chromium
    - decrease corrosiveness
- Ferromagnetic
  - MRI



http://www.securos.com/index2.asp

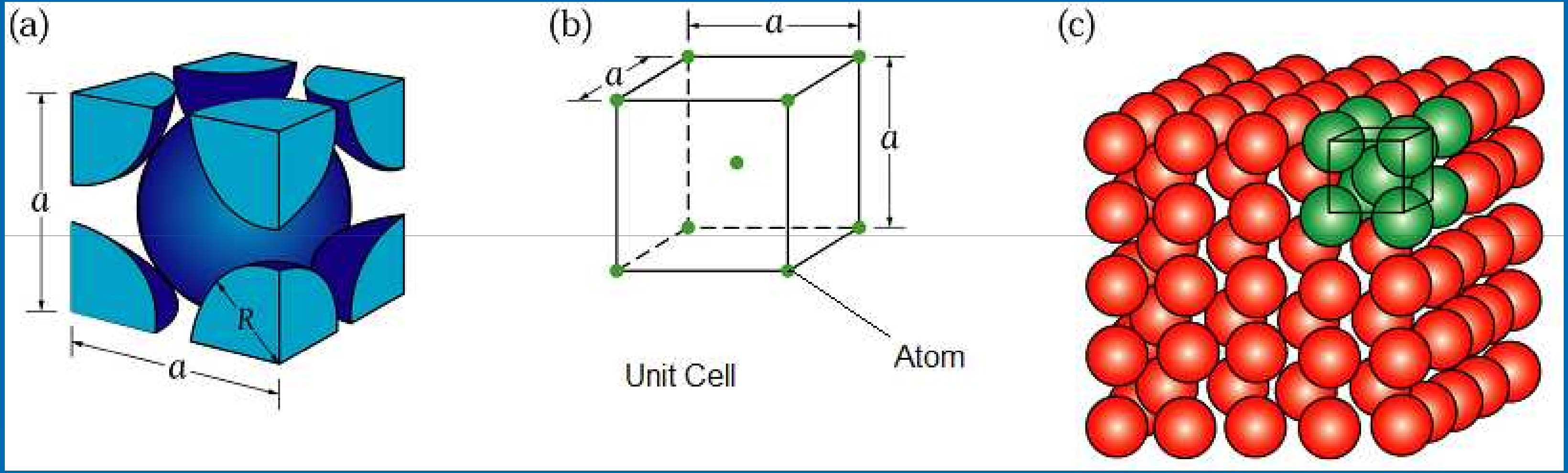
HOMEWORK –Question 1



A stent is a helical, woven device that is implanted into an occluded artery to permit increased blood flow. A permanent yet flexible device is needed for use as a vascular stent. What material meets that need? In addition to information contained in this chapter, search the web for information on current materials selections using keywords such as "stents" and "metals." The National Institutes of Health PUBMED website catalogs scientific publications within the biological, biomedical, and medical sciences (http://www.ncbi.nlm.nih.gov/entrez). Corporate web pages can provide additional information. Guidant and Boston Scientific are two companies that currently produce coronary stents. The United States patent office provides another very useful web page for researching uses of materials in surgical and medical devices (www.uspto.gov).

Metals Are Crystalline

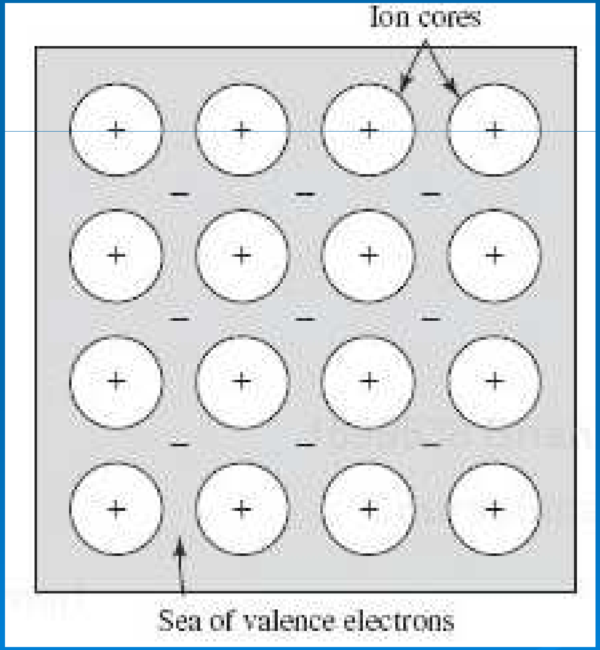
Body-Centered Cubic



The body-centered cubic (bcc) crystal structure: (a) hard-ball model; (b) unit cell; and (c) single crystal with many unit cells. *Source*: W. G. Moffatt, et al., *The Structure and Properties of Materials,* Vol. 1, John Wiley & Sons, 1976.

Metal Bonding

- The electrons in metals are mobile and surround a core of cations. This gives rise to their high electrical conductivity.



Product Manufacture

- There are different methods of metal product manufacture:

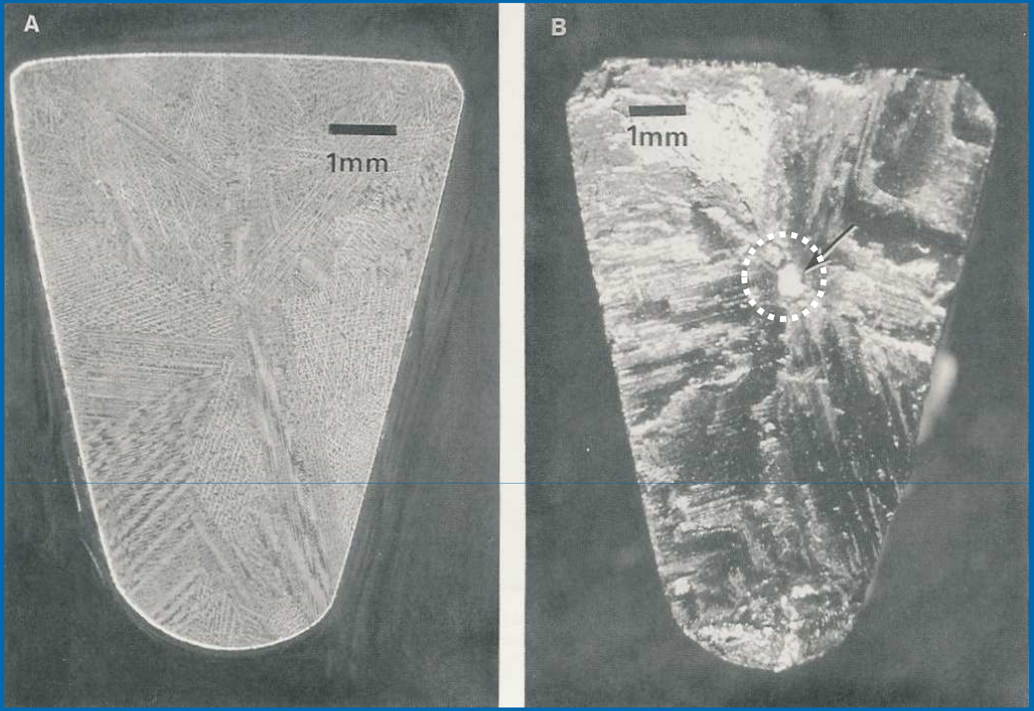
- machining

- melt casting

- Forging

Influence of Manufacturing Process

Casting Defect



Polished-etched view of a cast ASTM F75 femoral hip stem. Note dendrites and large grains

In ***vivo*** fracture initiated from an inclusion formed during the casting process

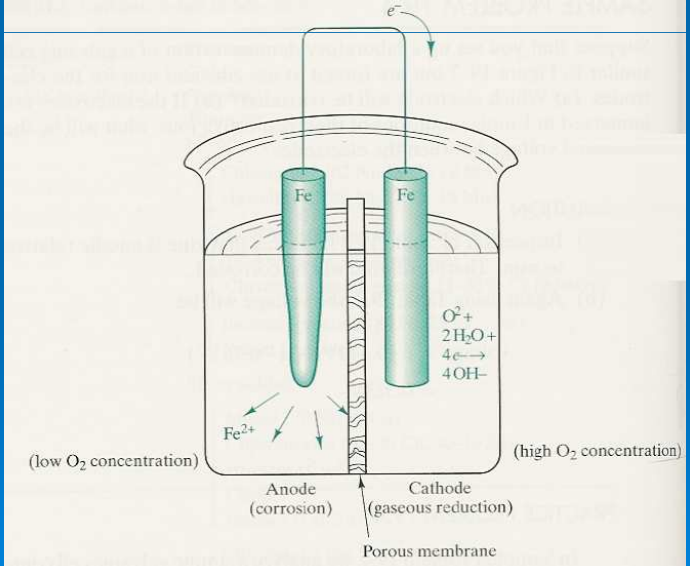
From : H. Alexander et al., Chapter 2, Biomaterials Science, BD Ratner et al., Academic Press, 1996.

Design Considerations

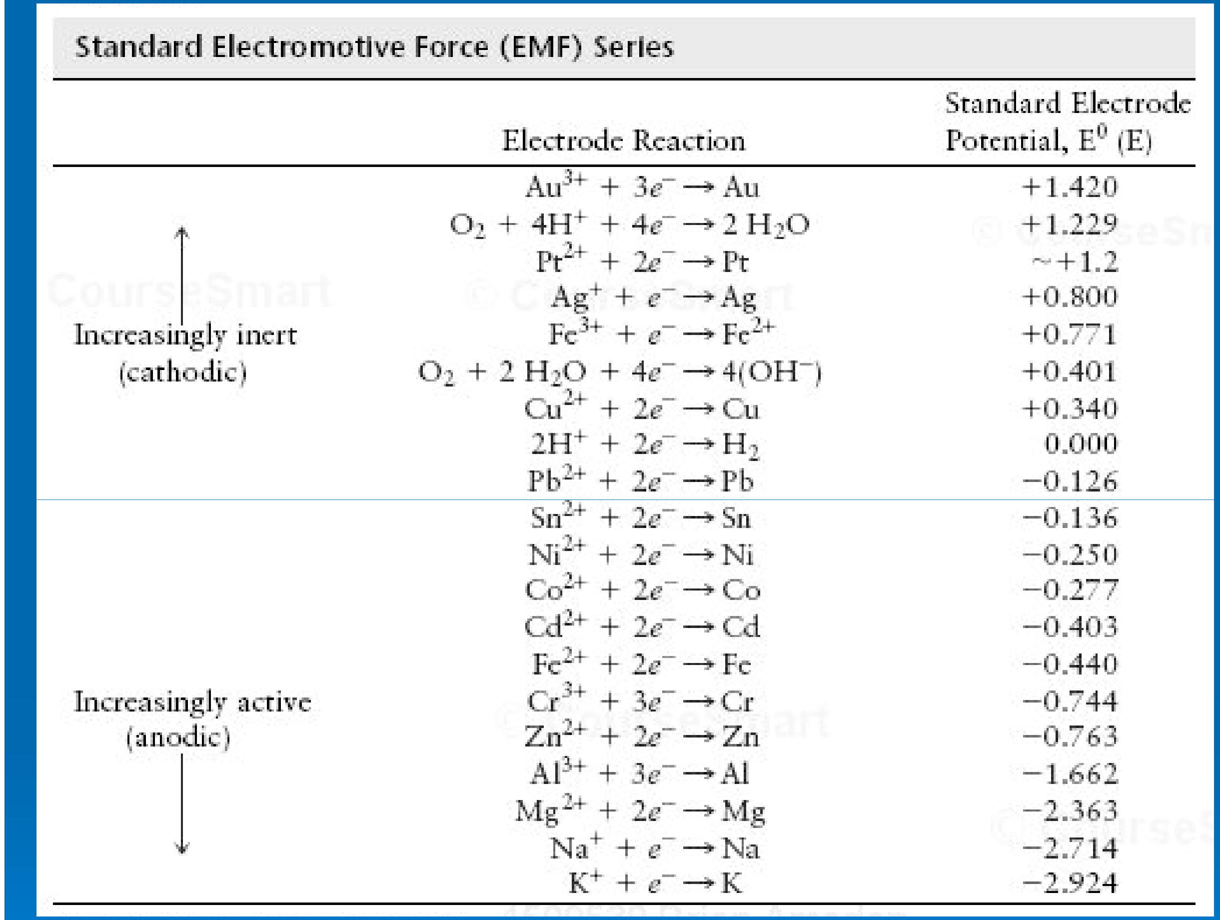
- typically want to match mechanical properties of tissue with mechanical properties of metal
- have to consider how the metal may fail in vivo
  - corrosion
  - wear
  - fatigue
- need to consider cost

Corrosion

- The extra-cellular environment is a chemically aggressive space. Metallic biomaterials are good conductors in an electrolyte solution, leading to galvanic corrosion.

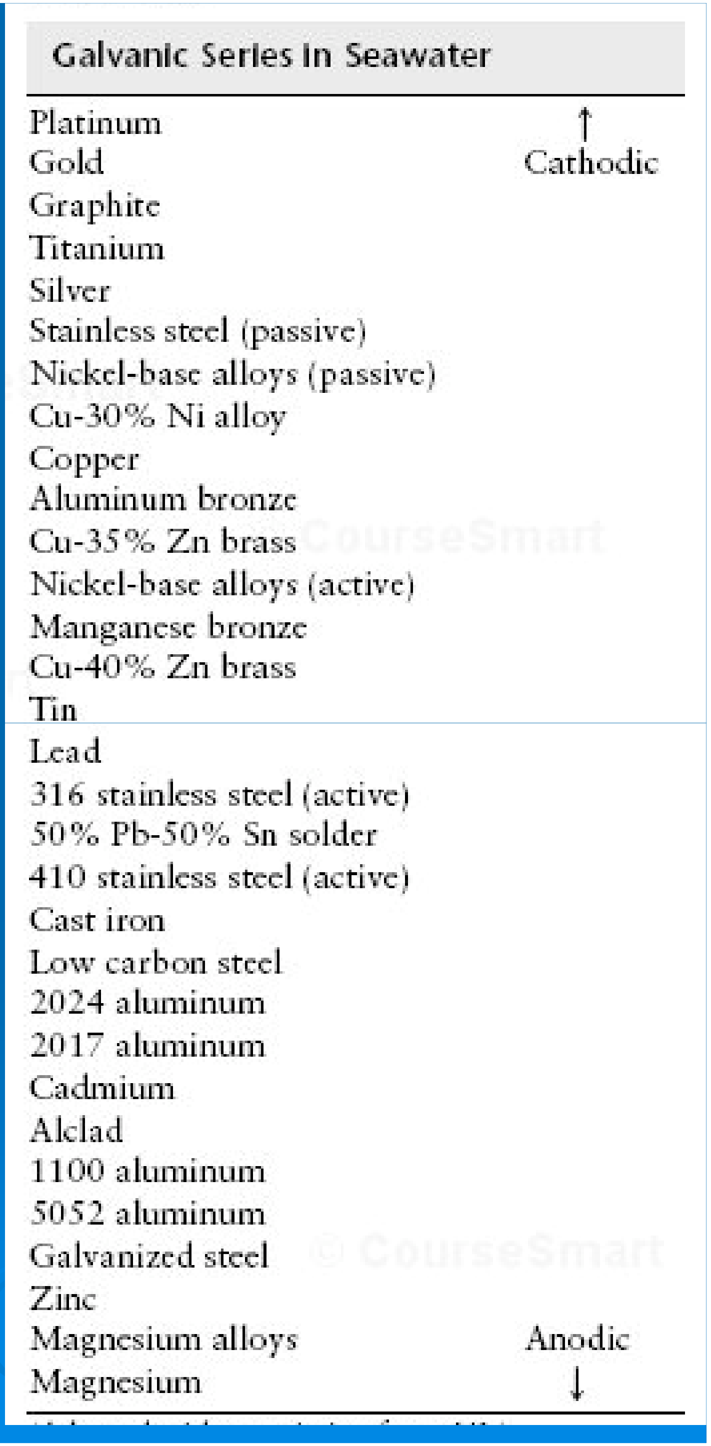


Corrosion



Standard Electromotive Force (EMF) Series

	Electrode Reaction	Standard Electrode Potential, E^0 (E)
↑ Increasingly inert (cathodic)	$Au^{3+} + 3e^- \rightarrow Au$	+1.420
	$O_2 + 4H^+ + 4e^- \rightarrow 2\,H_2O$	+1.229
	$Pt^{2+} + 2e^- \rightarrow Pt$	~+1.2
	$Ag^+ + e^- \rightarrow Ag$	+0.800
	$Fe^{3+} + e^- \rightarrow Fe^{2+}$	+0.771
	$O_2 + 2\,H_2O + 4e^- \rightarrow 4(OH^-)$	+0.401
	$Cu^{2+} + 2e^- \rightarrow Cu$	+0.340
	$2H^+ + 2e^- \rightarrow H_2$	0.000
	$Pb^{2+} + 2e^- \rightarrow Pb$	−0.126
Increasingly active (anodic) ↓	$Sn^{2+} + 2e^- \rightarrow Sn$	−0.136
	$Ni^{2+} + 2e^- \rightarrow Ni$	−0.250
	$Co^{2+} + 2e^- \rightarrow Co$	−0.277
	$Cd^{2+} + 2e^- \rightarrow Cd$	−0.403
	$Fe^{2+} + 2e^- \rightarrow Fe$	−0.440
	$Cr^{3+} + 3e^- \rightarrow Cr$	−0.744
	$Zn^{2+} + 2e^- \rightarrow Zn$	−0.763
	$Al^{3+} + 3e^- \rightarrow Al$	−1.662
	$Mg^{2+} + 2e^- \rightarrow Mg$	−2.363
	$Na^+ + e^- \rightarrow Na$	−2.714
	$K^+ + e^- \rightarrow K$	−2.924



Galvanic Series in Seawater

Platinum	↑
Gold	Cathodic
Graphite	
Titanium	
Silver	
Stainless steel (passive)	
Nickel-base alloys (passive)	
Cu-30% Ni alloy	
Copper	
Aluminum bronze	
Cu-35% Zn brass	
Nickel-base alloys (active)	
Manganese bronze	
Cu-40% Zn brass	
Tin	
Lead	
316 stainless steel (active)	
50% Pb-50% Sn solder	
410 stainless steel (active)	
Cast iron	
Low carbon steel	
2024 aluminum	
2017 aluminum	
Cadmium	
Alclad	
1100 aluminum	
5052 aluminum	
Galvanized steel	
Zinc	
Magnesium alloys	Anodic
Magnesium	↓

Wear

- The effects of wear are most predominant in joint prostheses.

- There are two types of wear :

- Interfacial Wear

- Fatigue Wear

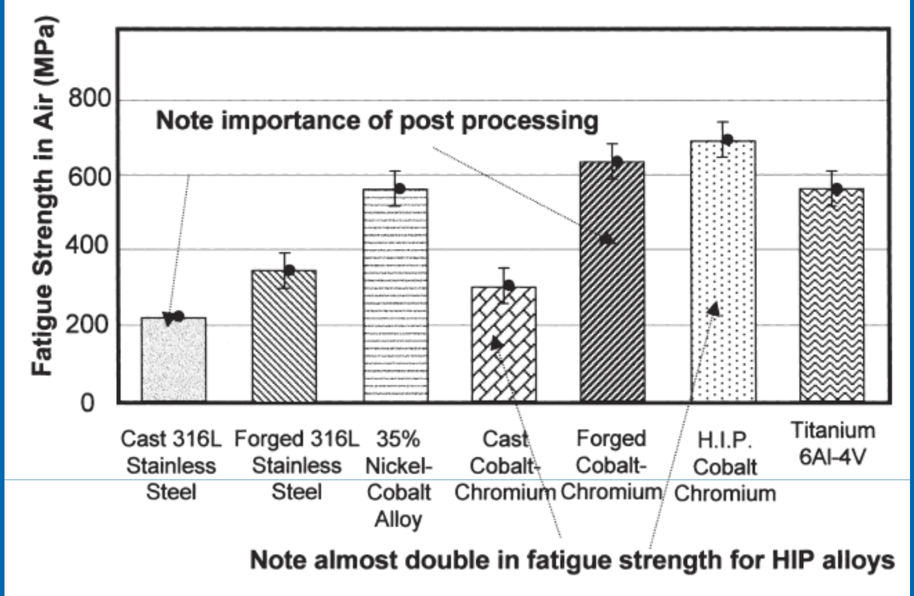
Fatigue

- Recall that fatigue is progressive failure of a material due to the application of cyclical stresses below the ultimate stress of the material causing crack propagation.

- Crack usually starts at a stress concentrator or stress riser.

- Methods for reducing fatigue failure :

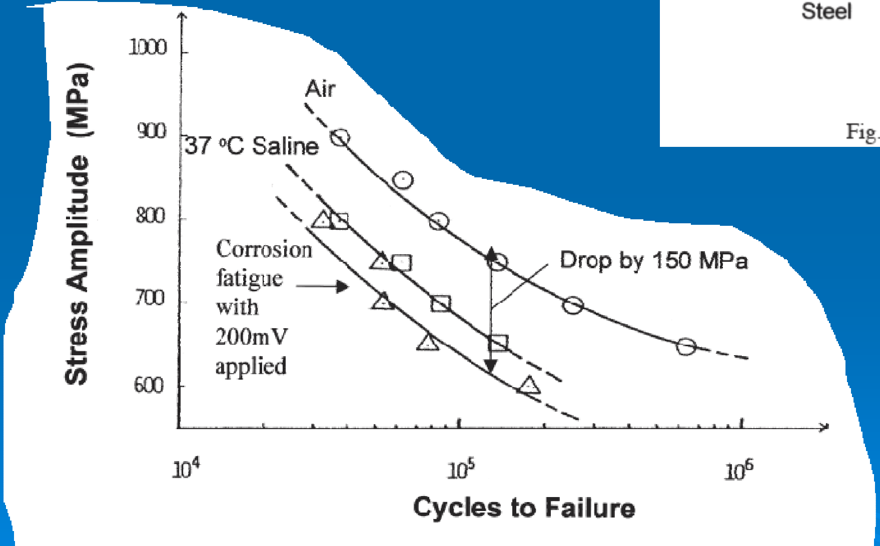
Fatigue



Note importance of post processing

Note almost double in fatigue strength for HIP alloys

Fig. 4. Fatigue strength of some common implant alloys.



Drop by 150 MPa

Fig. 6. Corrosion fatigue of 316L cold worked stainless steel (after Taira and Lautenschlager [27]).