Metallurgy

Metallurgy in orthopedic implants including total hip arthroplasty (THA) components involves most commonly three types of alloys: steel (iron based), titanium based, and cobalt based. For optimal performance in physiologic environments, they must have suitable mechanical strength, biocompatible and biologic stability structurally. The most important material mechanics to understand are elastic modulus, yield stress, ultimate tensile stress, and fatigue stress.

The Three Most Common Alloy Implants

- **316 L** (L = low carbon; greater corrosion resistance) **STAINLESS STEEL** contains iron-carbon as the majority base, chromium, nickel, molybdenum, and manganese.
  - Chromium allows passive surface oxidation to resist corrosion.
  - Nickel resists corrosion and stabilizes the molecular structure.
  - Molybdenum hardens the oxide layer and prevents pitting and crevice corrosion.
  - Manganese stabilizes the molecular structure.
  - Stainless steel is biotolerant (thin fibrous layer forms as direct leaching of chemicals irritate surrounding tissue) and is susceptible to corrosion. It is not used for THA implants but mostly for plates and screws.

- **TITANIUM ALLOYS (Ti-6 Al-4 V)** are extremely biocompatible, bioinert, light weight, and rapidly form passive oxide coat to resist corrosion.
  - They generate less wear when highly polished.
  - They have a low modulus of elasticity (half that of cobalt and stainless steel alloys) and high yield strength and are closest to the axial and torsional stiffness of bone (less stress shielding).
  - They are used mostly for femoral stems.
  - Titanium is not used in articulating components because of poor shear strength, wear resistance, and increased notch sensitivity.

- **COBALT ALLOYS** ([Co-Cr-Mo] 65% Cobalt, 35% Chromium, 5% Molybdenum, sometimes contains nickel to aid in forging process) are much stiffer materials (increased ability to stress shield) better able to resist wear and corrosion.
  - They have high fatigue resistance and high ultimate tensile strength.
  - These alloys are therefore used mostly for load bearing and articulating surfaces in THA like femoral heads.
  - Cobalt alloy is bioinert.

- **TANTALUM** is a transitional highly porous metal usually deposited on pyrolytic carbon backbones (created by heating and depositing hydrocarbons on graphite substrate).
  - It is highly corrosion resistant, highly inert, as well as highly resistant to wear and mechanical fatigue.
  - It has a low modulus of elasticity similar to cortical bone.
  - Tantalum is used in acetabular/femoral stem coatings to allow for better bone ingrowth (osteococonductive).

Corrosion

**Corrosion** is a chemical reaction that weakens the metal.

- There are three main types: fatigue, galvanic, crevice.
- Corrosion severity depends on chemical composition of metal (stainless steel > cobalt and titanium).
  - **Fatigue corrosion** occurs when the passive film layer is disrupted by micromotion and scratching between modular components (FRETTLING).
  - **Galvanic corrosion** usually occurs when electric current exists between two different metals (i.e., titanium stem and cobalt chrome femoral head). Mixed components will all have some degree of galvanic corrosion; however, to avoid catastrophic galvanic corrosion never mix stainless steels with cobalt chrome or titanium.
  - **Crevice corrosion** happens in a structural defect in metal and occurs when fluid in contact with a metal becomes stagnant, resulting in a decrease in oxygen and pH and speeding up destructive process and increases depth of defect and becomes self-propagating (Fig. 4.1).
Other Materials Used in TJA

- **UHMWPE (ultra-high molecular weight polyethylene)** has a low coefficient of friction, ideal for articulating bearing surface.
  - Several factors affect polyethylene wear: material quality, degree of cross-linking, strength, toughness, thickness, sterilization technique, storage, and shelf life.
  - A polyethylene wear rate <0.1 mm/yr is at low risk of developing osteolysis.
    1. High crystallinity (optimal is 45–65%) make it less resistant to crack initiation and propagation.
    2. UHMWPE is machined from ram-extruded bar stock or direct compression heat-molded from powder.
    3. Increased thickness is better because less stress (minimal thickness in acetabular liners usually 6 mm)
    4. Biomechanical properties affected by
      a. gamma irradiation for sterilization/cross-linking (25–40 K Gy, or 5–10 mrad) increases cross-linking and makes it more crystalline; thus better wear characteristics but also formation of free radicals.
      b. annealing (heat below melting point) prevents loss of crystalline structure and removes some oxidative free radicals. Remelting removes all free radicals but makes material more amorphous and decreases fracture toughness.
      c. storage/sterilization in inert atmospheric medium (argon/plasma gas) decreases reintroduction of free radicals—NEVER STERILIZED IN AIR.
      d. vitamin E doping or other antioxidants added to polyethylene to quench free radicals.

- **CERAMICS** can be used as acetabular liners or in femoral head components.
  - They have low coefficient of friction, have high resistance to wear, are strong in compression, have high modulus of elasticity, are brittle (low yield strain), and are susceptible to cracking with sharp edges.
  - Strength is improved with increased density, increased crystallinity, and decreased porosity.
  - The hardness, wettability, inertness, and biocompatibility make them ideal for bearing surfaces.
  - Because of high Young modulus compared to bone, ceramics are never in direct contact with bone due to high incidence of loosening (Fig. 4.1).
  - With malpositioning of components, edge loading and femoral neck impingement can cause crack propagation and catastrophic failure.
  - Ceramics include aluminum oxide and zirconium oxide.
    - **Aluminum oxide (Al₂O₃)** is highly biocompatible with high frictional resistance, low fracture toughness, and tensile strength.
    - Fracture can result from microstructural flaws such as large grain size and impurities.

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**Figure 4.1** Young modulus.
Zirconium oxide (Zirconia) is also used as a stabilizing structure to prevent crack propagation when mixed with aluminum oxide.
- It can be maintained in a metastable tetragonal crystal structure with fine grain structure with the addition of stabilizing oxide (yttrium oxide \([\text{Y}_2\text{O}_3]\)).
- It can be used as an extremely thin (0.004 mm) but extremely adherent bearing surface from nitrogen ion implantation technique on metal bearings that significantly increases surface microhardness thus making surfaces highly wear resistant.
- Compared to aluminum oxide, zirconium oxide has increased fracture toughness, bending strength, and decreased elastic modulus.

PMMA (polymethylmethacrylate) is an acrylic cement used as a grouting agent to provide immediate fixation of total joint components to bone.
- The tensile strength is similar to cancellous bone and allows gradual transfer of load from implant to bone.
- It reaches its ultimate strength in 24 hrs.
- It is strongest in compression and weakest in tension.
- Poor fatigue strength is related to its porosity.
- Heat-stable antibiotics can be added without significant decrease in fatigue strength.

Hydroxyapatite \((\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2)\) resembles natural mineral in vertebrate bone and is a bioactive material used as a coating on some THA components to augment bone implant fixation.
- It is stronger in compression than tension but has low resistance to fatigue failure.
- It can be plasma sprayed on roughened implants (~20–50 μm thick) to act as an osteoconductive surface.
- It allows for more rapid closure of gaps between bone and prosthesis.

Femoral Stem Fixation: Biomaterial and Biomechanical Concepts

Cemented femoral stems allow microlinlock with endosteal bone. Cement will fatigue with cyclic loading; therefore, it is imperative to maintain a sufficient even mantle around the implant (not <2 mm)
- Mantle defect is an area where the prosthesis touches the bone = area of high stress.
- Better in low demand older patient with porous bone
- Cement success increased by cement porosity reduction (vacuum mixing), canal pressurization of cement, pulse lavage of bone, stem centralization, and use of stiffer stem.
- Also place stem in neutral or slight valgus to reduce stress on medial cement mantle.

Cementless femoral stems rely on two methods of biologic fixation: bone ingrowth and bone ongrowth
- Bone ingrowth: pores in metal alloy allow bone ingrowth. Optimal pore size (50–150 μm)
- Bone ongrowth: stability achieved when bone grows onto imperfections of rough grit-blasted titanium surface. Amount of on growth depends on surface roughness.
- Grit-blasted stems achieve initial rigid fixation with press fit technique of gradual tapered stems to allow for compression hoop stresses. Component is slightly oversized in regards to bone preparation. In acetabular shells press fit allows for hoop stresses at the rim of the acetabulum.
- Line-to-line technique is when bone contour is prepared, so it is the same size as the implant, which is utilized in fully porous coated implants, which allows for initial stability by frictional fit (scratch fit).

Femoral stem loading
- Proximal porous coating mechanical load is transferred to metaphysis and proximal diaphysis thereby maintaining proximal bone density
- Extensive porous coating and well-fixed cemented stem transmits load through well-adhered endosteum and is loaded distally, consolidation of bone will be seen near end of femoral stem called spot weld.
Because the load is bypassing the proximal bone, proximal stress shielding can occur and it implies a well-fixed distal loading implant as a result of modulus mismatch between femoral stem and femoral cortical bone.

- This is especially seen in more rigid and stiff implants (i.e., large solid cylindrical cobalt chrome stem with porous coating).
- Cylindrical stem diameter effects stiffness: proportional to $R^4$.
- Stem breakage (cantilever bending) can result from thinner diameter stems fixed well distally but loose at the top as a result of cyclic loading and fatigue failure of the stem in the middle.
- “Rule of 50s” to determine if porous-coated stem component can provide solid fixation.
- Optimal pore size (50–150 μm), porosity (50%), gap between prosthesis and bone (50 μm), micromotion (50–100 μm) → anything >150 μm will lead to fibrous ingrowth.

**Articular Bearing Options in THA: Biomaterial and Biomechanical Concepts**

**Tribology** is the understanding of science of friction, lubrication, and wear with interacting surfaces.

- More traditional bearing options: **Hard on soft** (metal on poly, ceramic on poly)
- 3 types of PE wear
  - adhesive (submicron particles being delaminated and squeezed together between bearing surfaces)
  - abrasive (rough spots scratching the PE)
  - third body (from debris).
- Hard on PE liner prone to **ADHESIVE WEAR**, larger heads yield more volumetric wear.
- Alternative bearings: **hard on hard** (metal on metal, ceramic on ceramic, metal on ceramic).
- **Asperities** are carbide microscopic-elevated rough spots on bearing surfaces, which always make contact with each other → increase wear.
- Pits in ceramic bearings increase surface roughness and wear.
- **Lubrication** with boundary lubrication (synovial fluid will separate two surfaces enough to prevent wear → occurs when hip at rest or in slow motion.
- Hydrodynamic (fluid film) lubrication while walking, asperities are separated enough to not touch, this type of lubrication requires increased angular velocity of femoral head.
- Normal human joints have coefficient of friction of 0.002–0.04, THA (metal on PE = 0.05–0.15). Hydrodynamic lubrication is affected by
  - radial clearance: Radius of cup minus radius of head, optimal provides equatorial contact with high conformity, too small → no fluid ingress and components will seize (lock), too large → of a difference then contact point too small (in the polar region) = increased wear.
  - $ra$ (surface roughness): ultrasmooth surface allows better fluid film layer
  - **Bearing size**: bigger surface allows better fluid film mechanics.
  - **Sphericity**: any irregularity of perfect sphere will generate high stress points.
  - **Bearing material**: Smooth finishes with Co-Cr and ceramics = better wear.
  - Zirconia and titanium heads on poly perform poorly secondary to surface roughness → ABRASIVE WEAR.
  - Metal smearing on ceramic head is from perform poorly secondary to surface roughness → subluxation and edge loading → “stripe wear” when ceramic on ceramic, increased surface roughness in this region.
- **METAL ON METAL**: Very small but more numerous quantity of particles generated (0.015–0.12 μm) when compared to PE (0.5–5 μm), very low linear wear and volumetric wear compared to PE.
- Undergo “run in wear” where rough spots (asperities) from manufacturing process are polished out in vivo, in first 1 million cycles then reaches steady state wear.
- Particles generated can dissolve into cobalt and chromium ions detectable in blood and urine.
- T-cell lymphocyte is biologic response from metal debris (Co-Cr)
  - Soon after implantation = hypersensitivity reaction usually to Ni
  - 3–5 yrs later = particulate induced T-cell response (PITR) → involves highly activated RANKL system → pseudotumor formation (Co and Cr ions combine
with serum protein, which is recognized by T-cell) → stimulates cytokines IL-2, IL-6, INFγ → detectable sometimes massive effusion on MRI or ultrasound, osteolysis around implants, and tissues show inflammatory mass primarily of lymphocytes (ALVAL—aseptic lymphocytic and vasculitic-associated lesion).

• Do not use metal on metal in woman of childbearing age (ions cross placenta).
• Do not use metal on metal in renal failure patients (cannot excrete ions).
• Local tissues can be predisposed to local metaplasia/dysplasia but no long-term cancer risk proven.
• Have fallen out of favor.

**CERAMIC ON CERAMIC**

**Advantages:** lowest wear, thus fewer particles generated (size 5–90 nm), no ions and bioinert.

**Disadvantages:** limit on head sizes and length, manufacturing constraints on thickness of insert.

**Hip squeak:** psychologically disturbing to patients, stripe wear/edge loading.

• If ceramic on ceramic fails then must revise to another ceramic on ceramic because microshards will remain and cause rapid PE wear.

• If changing femoral head in revision on used stem trunnion with ceramic head must use metal jacket to prevent roughened trunnion from causing burst fracture on ceramic head with loading.

**Osteolysis in THA**

• In THA wear occurs from femoral head on PE-bearing surface (adhesive wear) and from micromotion of PE liner on acetabular shell (backside wear) → generates submicron particles, which can elicit osteolytic response.

• Macrophages become activated after uptake of submicron PE particles → activates additional cytokines (TNF-α, IL-1, TNF-β, IL-6, PDGF-receptor activator of nuclear factor B ligand (RANKL)).

• RANKL made by osteoblast and attaches to RANK receptor on osteoclast → stimulates bone resorption.

• Osteoprotegerin (competitive inhibitor) will bind and block RANKL from activating osteoclast.

• In THA the buildup of inflammation to PE particles increases intra-articular hydrostatic pressure.

• This results in dissemination of PE particles throughout effective joint space.

• Linear wear (distance head penetrates into the cup) → rates that exceed 0.1 mm/yr are associated with osteolysis.

• Small heads will have relatively more linear wear (failure from PE cup penetration) than volumetric wear, and larger heads show the opposite (failure more from osteolysis).

• X-rays show endosteal scalloping in femoral canal and round lytic lesions behind cup especially around screws.

**Biomechanics after THA**

Prevent chance of dislocation by considering component design, alignment, and soft tissue function and tension.

• Component design

  • Primary arc range = functional range of motion of bearing components before impingement.

  • Controlled by head/neck ratio: increased primary arc and decreased risk of impingement by maximizing ratio.

  • Examples that decrease head/neck ratio: neck skirt, acetabular hoods/lipped liners, or constrained liners, whereas larger heads and tapered necks or thinner liners increase the ratio.

  • Lever range is controlled by head radius → larger head has more excursion distance before impinging on cup and risk levering out.

• Component alignment

  • Goal is to center primary arc within patient’s functional hip range of motion. Malalignment will generate a stable and unstable side to functional hip range, either retroversion/excess anteversion.

  • Angles: cup anteversion 20°, coronal tilt angle 35–50°, stem anteversion 10–15°

  • Excess anteversion of cup and or stem-risk anterior dislocation, retroversion-risk posterior dislocation.
• High coronal tilt angle = vertical cup-risk posterior-superior dislocation and increased wear.
• Low coronal tilt angle = horizontal cup-risk impingement
• Soft tissue tension and function
  
  Most important is abductor complex (gluteus medius and minimus) and must restore and maintain proper hip abductor tension to remain stable.
  
  This is done by restoring the following: normal hip center of rotation, femoral neck length, and head offset.
  
  Added benefit is decreased joint reaction force (JRF).
  
  Problems if hip mechanics not restored: offset decreased → weak abductor tension, increased JRF.
  
  This will result in Trendelenburg gait/lurch, increased risk for dislocation.
  
  Can also be caused by using short neck or low neck cut → can result in greater troch impingement against pelvis.
  
  Using high offset stem/neck can restore abductor tension and lever arm thus decreasing JRF without increasing leg length, however, if too much can cause troch bursitis/chronic lateral hip pain.
  
  Increasing head or neck length to restore tension can be done but can risk lengthening the leg.

Changes to decrease JRF: in other words shift center of rotation medial

1. Move acetabular component medial/anterior/inferior
2. Increasing femoral component offset
4. Others: lateralization of greater troch (increase abd tension and lever arm) or long neck prosthesis.

BIBLIOGRAPHY


HIP PAIN, ARTHRITIS, AND OSTEONECROSIS

PARMINDER S. KANG • TAJINDER KANG • RITESH R. SHAH

Hip Anatomy and Pathoanatomy

The hip joint (femoracetabular joint) is a diarthrodial or ball and socket joint. The acetabulum is formed by the fusion of three bones: ilium, pubis, and ischium. There are three main ligaments or thickenings of the hip capsule that provide stability to the hip joint: the iliofemoral (Y ligament of Bigelow), ischiofemoral, and the pubofemoral.

The blood supply to the femoral head comes primarily from the medial circumflex femoral artery that forms the extracapsular arterial ring with the lateral circumflex

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