Biomechanics of Titanium Foam Implants

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Intro

- Immerging material for biomedical purposes
  - Implants
  - Prosthetic attachment
- Titanium foam is porous in structure
- Quicker bone regeneration
- Integrates with bone
- Strengthens bone
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Current Applications

- **Dental implants**
  - small Ti foam screws

- **Hip replacements**
  - the most common biomedical use

- **Joint implants**
  - for knee, elbow, and shoulder
History of Titanium: Dental

**Ancient:** Egyptians used animal teeth and shaped seashells to inserted directly into gums. Mayan teeth modifications.

**1800s:** Gold, silver and platinum materials were used to replace freshly removed teeth. Procedure had poor long term success.

**1965:** Brånemark places the first dental implant on a human patient, Gosta Larsson. She died in 2005 with the original implants a little more than 40 years later.

**2002:** ADA survey stating dental implants have doubled in the period 1995 - 2002.

**1700s:** Lost teeth were replaced with human donors' teeth. The foreign material was generally rejected.

**1952:** Per-Ingvar Brånemark, a Swedish orthopedic surgeon, accidentally makes the discovery of osseointegration (more of this later) while studying implants on rabbit femurs.

**1983:** After twenty years in a Toronto conference Brånemark's work is accepted by the scientific community.
Mayan teeth modifications

Brånemark: "father of modern dental implantology."

Implant versus a natural tooth
Prosthesis

- More comfortable fit
- Earliest evidence dates back to 500 BC
- In 1863 using a vacuum to secure the prosthetic.
- Osseointegration using titanium is a new method of attaching the artificial limb to the body:
  - Extended period of time
  - Ability to better control the prosthesis
  - Transfemoral amputees to drive a car
Bones

- Connective tissue
- Endoskeleton of humans and others
- Different tissues: marrow, nerves, blood vessels, cartilage
- Complicated fractures
- Collagen and Calcium appatite
  - Collagen: good tensile strength. Poor compressive strength
  - Calcium appatite: stiff, brittle, high compressive strength
Bone Structure

Different tissues of the bone

Notice the difference between the compact and spongy bone
• The two most common types of bones in mammals

1) **Cortical bone**: also known as compact bone.
2) **Trabecular bone**: also known as cancellous or spongy bone.

• They are classified as on the basis of porosity and the unit microstructure.

• Cortical bone is much denser with a porosity ranging between 5% and 10%.

• Cortical bone is found primary is found in the shaft of long bones and forms the outer shell around cancellous bone at the end of joints and the vertebrae.
Human Bone Strength

- Human femur
- Compressive longitudinal strength, 205 MPa; strain 0.019
- Compressive transverse strength, 131 MPa; strain 0.028-0.087.
- Tensile longitudinal strength, 135 MPa, strain 0.031,
- Tensile transverse strength, 53 MPa, strain 0.007.
- Shear strength, 65-71 MPa.
Why do we need implants?

- Most common problems with severe bone fractures:
  - Neurovascular injury
  - Infection
  - Post-traumatic arthritis
  - Growth abnormalities
  - Delayed union
  - Nonunion
  - Malunion

- The titanium implants can help with the bottom five out of the seven problems.
- Specific solutions later.
Bone Implants

• Types of bone implants:

  • **Autologous** – bone is taken from patient’s own body (usually from the femur)
    - low chance of rejection

  • **Allopathic** – bone taken from a donor. Donor can be human, animal, or a synthetic material
Bone Implant Procedure

1. Patient is put under anaesthesia and the site is opened up
2. Create an ideal surface for implantation
3. Insert bone implant
4. Pins or surgical cement may be used to hold it in place
5. Site is closed up and patient brought out of anaesthesia
6. Weeks later, doctors xray the implant site to check if the implant has successfully integrated with surrounding tissue
What wrong with current implants and prosthesis?

**Suspension System:**
- The suspension system is what keeps the prosthetic limb attached to the body.
- The suspension mechanism can come in several different forms

**Type 1 - Adjustable sleeve:** A strap is used to fasten the limp onto the prosthesis.
- It's usually only used temporary while the limb might be changing shape.
- The silesian belt to the side is an example.
• **Type 2 - Elastic sleeve:** A frictional elastic sleeve covers the patient’s stump.
  • The sleeve is usually made of silicone for ease of handling.
  • Silicone gel can be used for a softer and more comfortable interface, preventing rashes and other possible skin damage.

• **Type 3 - Suction socket:** A pump is used to compress the hair between the prosthesis and the patient.
  • This pressure is responsible for holding the prosthesis in place.
  • The patient can open a valve and take off the artificial limb as required.
  • Picture of a P-3 vacuum pump, by Otto Bock, on a Freedom Foot, the Renegade
Titanium

- Titanium widely used for production of dental and orthopedic implants
  - Biocompatible
  - Highly corrosion resistant
  - Durable
  - Strong, but light weight
  - Non-magnetic
  - Easily prepared in many different shapes and textures
Titanium vs other metallic materials

- Other metals used for biomedical purposes include:
  - Stainless steel
  - Cobalt–Chromium alloys
- Why choose titanium?
• Stainless steel
  • Strong alloy, most often used in implants that are intended to help repair fractures
  • Metals such as chromium is added to make more resistant to corrosion
• Co-Cr
  • Strong, hard, biocompatible, corrosion resistant
  • Used in variety of joint replacement implants and fracture repair implants that require a long service life
• Titanium & alloys
  • More flexible
  • Lighter weight
  • Although not as strong, closer match in young’s modulus to cortical bone
    • Addresses bone resorption
- Stainless steel

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Why Titanium?

- At the time of the invention of osseointegration, ultrastructural studies didn't support the idea.
- Osseointegration came to be defined as the absence of interfering fibrous tissue.
- In recent scientific articles, there is evidence of titanium chemically bonding to bone.

“Mechanical evaluations concerning the fixation of titanium to bone have mainly measured shear strength (Cook et al. 1987, Thomas et al. 1987). This is dependent on surface characteristics, since the inevitable roughness of any surface will cause mechanical resistance to shear (Takatsuka et al. 1995). In contrast, pure tensile forces can be transmitted only by chemical bonds (Gross et al. 1981, Osborn 1989).”
Ti-Bone Chemical Bonding

- Department of Orthopedics Lund University Hospital
- Titanium plates polished and treated
- 18 Rats
- 386g medium weight
- 4 weeks
- Mounting plate -> tibia
- Pure tensile test
Osseointegration

The integration of the implant with surrounding bone tissue
• Saturate the Ti foam with a simulated bodily fluid (contains artificial bone material “organoapatite”)
• Coats the foam with bioactive layer
• Organoapatite layer encourages the regrowth of real bone around it
• This technique used for other kinds of bone implants
Complications

- Dense titanium/alloy implants can lead to such problems:
  - Bone resorption
  - Implant loosening

- Due to biomechanical mismatch of elastic modulus
Solution

- Porous structures
  - Reduction in elastic modulus coupled with bone integration through tissue ingrowth into pores
  - Bone ingrowth provides a strong implant-to-bone bond

- Advantages:
  - Better long term fixation
  - Good bio functionality and biocompatibility
Mechanical Properties

- Open pore metallic foams are well suited for load bearing applications
  - Due to matched stiffness of bone, high strength, and toughness
- 50% to 80% porosities for applications in human skeleton
  - Desired properties can be matched by adequate porosity
    - 50% → mechanically similar to cortical bone
    - 80% → matches behaviour of trabecular bone
Open pore metallic foams are well suited for load bearing applications due to matched stiffness of bone, high strength, and toughness. Desired properties can be matched by adequate porosity: 50% \(\rightarrow\) mechanically similar to cortical bone; 80% \(\rightarrow\) matches behaviour of trabecular bone.
Making Titanium Foam

- Three Methods to make Ti foam:
  1. Spaceholder Method
  2. Argon Bubbles Method
  3. Polyurethane Method
1. Spaceholder Method

- Put spaceholder particles \((\text{NH}_4\text{HCO}_3)\) in with a Ti powder
- Press and heat the ceramic
- Vapourize the spaceholder particles in an oven
- Sinter the remaining Ti in an oven
2. Argon Bubble Method

- Inject argon gas bubbles into Ti powder while pressing
- Heat the ceramic to expand gas bubbles to appropriate size (200-500µm)
- Argon is released through its open pores

- Produces stronger Ti foam than spaceholder method - pores are spherical, providing stronger arches
3. Polyurethane Method

- Open pored PU foam is saturated with a solution of a binding medium and fine Ti powder
- Powder cleaves to the structure of the foam
- PU and binding medium is vapourized in an oven
- Remaining structure is sintered to form the Ti foam
Testing on Specimens

- Various tests have been performed on lab specimens (rabbit and rats)
- Results have been more or less the same
• 13 rats were used for testing
• Lateral incision in the skin and circumferential stripping of the muscle in order to drill two 2mm diameter holes in the femur
• Cylindrical implants (3mm in length, 2mm in diameter) were pressed fit into these holes
• After 4 weeks, animals were sacrificed and implants retrieved for analysis
Results

- Analysis revealed grown of new bone from cortical bone toward the implant
  - Created a rim of bone encircling the implant in bone marrow
- New bone highly mineralized and had same structure as cortical bone
- Bone seen forming inside pores of the implant
- Evidence of neo vascularization around implant
Future of Titanium Foam

- Still a relatively new technology
- More uses in humans
  - Repair larger breaks in bones
  - Ability to replace many more bones
- Better osseointegration
  - Current Ti foam does not fully emulate the function of real bone
References

**Papers**
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Images

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