An Overview of Currently used Biomaterials

Wednesday, April 3, 2013
Course update

• Please e-mail me your partners for LBLs by Friday (groups of 4 or 5)

• Biomaterials: metals and ceramics; polymers on Friday
  – For these and future lectures, I concentrate more on certain topics than others
    • While you are “more likely” to see what I go over in class for an exam, you are still responsible for the content in the assigned text sections!
Today’s biomaterials

• No material implanted in living tissue is inert; all materials elicit some level of biological response

• An alternate definition of a biomaterial:
  – “any substance (other than a drug) or combination of substances, synthetic or natural in origin, which can be used for any period of time, as a whole or as a part of a system, which treats, augments, or replaces any tissue, organ, or function of the body”

• 3 main classes of synthetic biomaterials used today are...
Classes of biomaterials

- Metals
- Ceramics
- Polymers
A comparison of general material properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Ceramic</th>
<th>Metal</th>
<th>Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>↑</td>
<td>↓</td>
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<tr>
<td>Elastic modulus</td>
<td>↑</td>
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<tr>
<td>High temperature strength</td>
<td>↑</td>
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<tr>
<td>Thermal expansion</td>
<td>↓</td>
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<td>↑</td>
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<tr>
<td>Ductility</td>
<td>↓</td>
<td>↑</td>
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<tr>
<td>Corrosion resistance</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
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<tr>
<td>Resistance to wear</td>
<td>↑</td>
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<tr>
<td>Electrical conductivity</td>
<td>↑</td>
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<tr>
<td>Density</td>
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<tr>
<td>Thermal conductivity</td>
<td>↑</td>
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</tr>
</tbody>
</table>

- ↑ Tendency to high values
- ↓ Tendency to low values

http://www.keramverband.de/brevier_engl/5/5_1.htm
Classes of biomaterials

Metals

Ceramics

Polymers
An overview of metals – bonding characteristics

The lattice structure affords high stiffness (modulus) and strength.
Mechanical properties of metals

• ...however, even within metals, a great degree of heterogeneity in material properties exists!

Mechanical properties of metals

- Typical shape of a metal’s stress strain curve:
Mechanical properties of metals versus ceramics and polymers

This is a very general graph; the shapes/magnitudes of stress/strain can very greatly **within** each class of biomaterial (as we will see)

Metallic biomaterials

• Metallic biomaterials are used almost exclusively for load bearing applications
  – Knee or hip implants, dental implants, fracture fixation

• Some are pure metals, but alloys are more common
  – Alloys are metals containing 2 or more elements
  – Relative to pure metals, they typically have greater corrosion resistance and/or strength
  – In fact, only copper and the precious metals (gold, silver, platinum, etc...) are found in nature in their metallic state!
    • For example, aluminium is found mainly in minerals such as bauxite (AlO$_x$(OH)$_{3-2x}$)
Strength of pure metals versus alloys

- **Scenario 1: a pure metal**

- **Scenario 2: an alloy**

Dislocation occurs especially at grain boundaries (misaligned planes of atoms)

Packing of two different sizes of metal elements prevents physical dislocation of the lattice structure

http://scienceshine.wordpress.com/2012/11/06/nutshell-alloy-vs-pure-metals/
Commonly used metals in medicine

- 3 metals commonly used as biomaterials are:
  - **Stainless steel** (alloy of Ni, Fe, Cr, Mn) (316L grade – better corrosion resistance)
  - **Cobalt-chromium-molybdenum** (“COCRMO” or “CMM”)
  - **Titanium** (Ti) or **Ti alloys** (Ti6Al4V is a very common variant)
Heterogeneity of alloy mechanical properties

What type of implant application might benefit from a material that is lighter and can strain farther? vascular stents
Metallic biomaterials – importance of surface properties

• Almost all interactions between cells/tissues and a metal implant occur at the implant surface
  – As such, the surface properties of metals implant materials are of great importance

  “The XPS analysis showed that dental implants surfaces consisted of oxidized titanium (mainly TiO$_2$), carbon, oxygen, and...contaminants like N, P and Si...Some authors have reported that surface findings vary according to each manufacturer procedure technique...”

  Takeaway $\rightarrow$ metal ions not bound tightly within the lattice will want to react to lower their energy state!
  Think of linoleum versus carpet

Scanning electron microscopy (SEM) image of a Ti dental implant

Corrosion of metal implant materials

- The physiological environment contains dissolved gases, electrolytes, cells and proteins at 37°C.
- In this environment, immersion of metals can lead to corrosion
  - Corrosion – the deterioration and removal of the metal by chemical reactions
  - Implants with “rough” surfaces as in the previous slide are especially susceptible!
- Ions released from the implant:
  - Are potentially cytotoxic
  - Can reduce the biocompatibility of the implant and jeopardize its function

Hold onto this concept for a moment...
A simple form of metallic corrosion that occurs naturally is rust formation.

A very thin oxide film forms on the metal surface:
- For most metals/alloys, occurs naturally in air as long as some water vapor is present.

The primary reactions:

\[
\begin{align*}
\text{Fe} & \rightarrow \text{Fe}^{2+} + 2 \text{e}^- \quad \text{(oxidation of Fe)} \\
\text{O}_2 + 4\text{e}^- + 2\text{H}_2\text{O} & \rightarrow 4\text{OH}^- \quad \text{(reduction of O)} \\
\text{Fe}^{2+} + \text{OH}^- & \rightarrow \text{Fe(OH)}_2 \quad \text{(acid-base rxn)} \\
\text{Fe(OH)}_2 & \rightarrow \text{FeO} + \text{H}_2\text{O} \quad \text{(dehydration)}
\end{align*}
\]
Metallic biomaterials – surface passivation

• Though rust formation is often undesired for aesthetic reasons (e.g., on bridges and other types of public infrastructure), how might it be useful for metal implant materials?

• Surface passivation is purposely applied to metal implants to provide a “shielding layer” to prevent further corrosion!
  – Often is accomplished by immersion in acidic solution (for the oxidation step)
  – The resulting oxide surface is an electrical and thermal insulator

• Alloys are generally more corrosion resistant after implantation because of the increased stability of the oxides formed through passivation (relative to pure metals)
Classes of biomaterials

- Metals
- Ceramics
- Polymers
An overview of ceramic biomaterials

• Ceramics are materials composed of metallic and nonmetallic elements held together by ionic and/or covalent bonds
  – The oxides described earlier for metals are actually ceramics!
• Like metals, have a long-range 3D crystal structure
• Some common material properties:
  – Usually inorganic (not containing carbon)
  – Highly inert (non-chemically reactive)
  – Hard and brittle
  – High compressive strength
• Applications
  – Orthopaedic implants
  – Dental applications

Why are ceramics particularly good to replace bones and teeth?
So, what are these ionic/covalent crystal structures? A couple familiar examples…

**Ionic**

![Table Salt NaCl Diagram]

**Covalent**

![Structure of Diamond Diagram]

For perspective: if NaCl has the MW of 58.44 g/mol, and you have a grain of salt in hand that weighs 0.01 mg, how many individual Na-Cl pairs are there?

About 103,000,000,000,000,000!

The extent to which a ceramic lattice is ionic or covalent in nature will depend on the electronegativities of the atoms involved.
Mechanical properties of ceramics

- ceramics exhibit good **compressive strength** (UCS; below), but lower **tensile strength** (UTS) compared to those of metals
Nature features ceramic composites

- Natural hard tissues are ceramic-polymer composites
  - e.g., bones and teeth
- Tissue constituents
  - Organic polymer fibers
  - Cells
  - Mineral component
- Mineral component (ceramic)
  - hydroxyapatite (HA) – \( \text{Ca}_5(\text{PO}_4)_3\text{OH} \)
  - Gives teeth and bones their hardness!

HA found in the dentin of teeth (indicated by the gray arrow above)
Hydroxyapatite

- HA is a mineral with structure $\text{Ca}_5(\text{PO}_4)_3\text{OH}$
- More generally, an apatite is of the form $\text{Ca}_5(\text{PO}_4)_3X$
  - The X ion can also be fluoride (F), chloride (Cl) or carbonate ($\text{CO}_3^{2-}$)

HA crystal structure

Bone HA (SEM)
HA-like materials for bone/dental implants

- Tricalcium phosphate (TCP) – \( \text{Ca}_3(\text{PO}_4)_2 \) – is a commonly used ceramic material
  - Very commonly, materials marketed under this name are actually powdered HA!

\[
\begin{align*}
\text{O}^- & \quad \text{Ca}^{2+} & \quad \text{O}^- & \quad \text{Ca}^{2+} & \quad \text{O}^- \\
\text{O=PO}_2^- & \quad \text{O=PO}_2^- & \quad \text{O=PO}_2^- & \quad \text{O=PO}_2^- \\
\quad & \quad \text{O}^- & \quad \text{O}^- & \quad \text{O}^- & \quad \text{O}^- \\
\quad & \quad \text{Ca}^{2+} & \quad \text{OH}^- & \quad \text{Ca}^{2+} \\
\end{align*}
\]

\( \beta \)-TCP (one of the two crystal forms, along with \( \alpha \))

\( \beta \)-TCP (SEM)
Degradation of ceramic biomaterials

- Unlike *corrosion* (the passivation of a metal surface), *degradation*, which refers to the chemical breakdown of the bulk material, occurs for ceramics
  - However, even this statement requires a caveat – what we are referring to mostly for ceramics is *dissolution*, not true degradation:
    - “patches” of solid crystal lattice – break-up of these bonds would be true *degradation* (not what we see with ceramics!)
    - Instead, pieces of the solid break apart from each other at the grain boundaries where the crystal patches meet (also is why ceramics are much stronger in compression than tension)
Degradation of ceramic biomaterials

- ...however, osteoclasts (bone-resorbing cells) mediate true degradation of the ceramic component of bone:
  - For this reason, ceramics such as TCP can undergo degradation upon implantation into the body

![Osteoclasts sitting atop a bony surface](image1)

Don’t worry about the mechanism here!

Takeway is that osteoclasts “eat” crystal fragments, which are then metabolized intracellularly!
Ceramics for implant applications

- Tensile and compressive strength of ceramics still below that of metals, both initially and particularly upon their more rapid bulk degradation

- Thus, HA and certain other ceramics typically used for non-load bearing applications:
  - Bone fillers
  - Coatings on orthopaedic or dental metallic biomaterial implants
    - The underlying metal carries the load, while the surrounding bone bonds strongly to the HA – “osteointegration”

Ceramic biomaterials for bone regeneration?

- Rather than using metal as a “placeholder” for the bone, another approach is to **regenerate** it! (still primarily *in vitro*)
- The goal is to create “tunnels” within a ceramic biomaterial into which cells can invade and lay down new bone matrix while degrading the scaffold
  - ...leaching techniques used to create **macroporous** ceramic scaffolds:
    - **water** (contains TCP slurry, paraffin non-soluble)
    - **Ethanol** (solubilizes paraffin at high temps)
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