ORTHOPAEDIC JOINT REPLACEMENT PROSTHESES
AND DENTAL IMPLANTS:
PERMANENT REPLACEMENT OF TISSUES

M. Spector, Ph.D.
Human Joints

Medical illustrations removed due to copyright restrictions.
Temporomandibular Joint
The temporomandibular joint connects the lower jaw (mandible) to the temporal bone at the side of the head.
Types of Natural Joints
(Morphologic Classification)

- Synovial; Diarthrodial (freely moving): fluid-filled (synovial)
- Syndesmoses: dense connective tissue (skull)
- Synchondroses: cartilage (epiphyses during growth)
- Synostoses: bone (from syndesmoses and synchondroses)
- Synphyses: grown together with dense fibrous tissue or cartilage (e.g., IVD)
## TISSUES COMPRISING JOINTS

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Permanent Prosthesis</th>
<th>Regeneration Scaffold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Articular cartilage</td>
<td>No</td>
<td>Yes*</td>
</tr>
<tr>
<td>Meniscus</td>
<td>No</td>
<td>Yes*</td>
</tr>
<tr>
<td>Ligaments</td>
<td>No</td>
<td>Yes*</td>
</tr>
<tr>
<td>Synovium</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
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* In the process of being developed
Medical illustrations removed due to copyright restrictions.
Video clips removed due to copyright restrictions:
- Total Knee Prosthesis Simulation
- Incision
- Lateral Release, ACL Transection, Denuded Condyle
- Bone Cuts
- Posterior Cruciate Ligament and Ligament Balance
- Application of Cement
- Trial Prosthesis
JOINT REPLACEMENT PROSTHESSES

- **Fit**
  - Anatomy
- **Function**
  - Kinematics; Range of Motion
- **Fixation**
- **Tribology**
  - Friction, Wear, and Lubrication
- **Other Effects**
  - Stress Shielding
JOINT REPLACEMENT PROSTHESES

Role of Biomaterial

- **Fit (Anatomy)**
  - Ability to manufacture the size/shape

- **Function**
  - Kinematics; ROM
    - Ability to manufacture the size/shape
  - Mechanics
    - Load-deform prop.

- **Fixation**
  - Surface features or porosity
  - Ca-containing coating

- **Tribology**
  - Friction, Wear, and Lubrication
    - Ability to be lubricated for low friction
    - Smooth and wear resistant surface

- **Other Effects**
  - Stress Shielding
    - Lower modulus of elasticity
Medical illustration removed due to copyright restrictions.
F. Netter (Ciba) drawing of degeneration of lumbar intervertebral discs.
Dental Implant Designs and Materials

- Alumina
- Titanium
- Sapphire
- Carbon
- Carbon
- Alumina

Photos removed due to copyright restrictions.
Blade Implant

Photos removed due to copyright restrictions.

“Commercially pure” Titanium
Two-Stage Design; to shield the artificial root from loading during the initial stage of healing.

Medical illustrations of dental implants removed due to copyright restrictions.
Why not a 2-stage hip prosthesis?
MECHANICAL LOADING OF TEETH

Natural dentition (first molar)

111 lbs

Dental Implants

100 lbs max.

30 lbs mean
STRESS IN BONE (SHEAR)

100lbs/0.12 in$^2 = 833$ psi

Shear Strength of Bone

Cortical 1500-2000 psi
Cancellous 200-600 psi
Screws work for dental implants but not for acetabular cups.

Medical illustration of dental implant removed due to copyright restrictions.

Medical illustration of hip prosthesis removed due to copyright restrictions.
JOINT REPLACEMENT PROSTHESSES

• **Fit**
  - Anatomy

• **Function**
  - Kinematics; Range of Motion

• **Fixation**

• **Tribology**
  - Friction, Wear, and Lubrication

• **Other Effects**
  - Stress Shielding
Total Hip and Knee Replacement Prostheses

Photos of knee prostheses removed due to copyright restrictions.

Figure by MIT OpenCourseWare.
JOINT REPLACEMENT PROSTHESSES

- **Fit**
  - Anatomy
- **Function**
  - Kinematics; Range of Motion
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- **Other Effects**
  - Stress Shielding
Bone Cement
Self-Curing Polymethylmethacrylate

PMMA

Bone

Metal

PMMA

Bone

Photo removed due to copyright restrictions.
Stem Designs with Irregular Surfaces for Bone Interdigitation

Images removed due to copyright restrictions.
Comparison of many different stem designs.
Photos removed due to copyright restrictions.

Fibrous tissue integration

Bone integration; “osseointegration”
Photos removed due to copyright restrictions.
Hydroxyapatite-Coated Implants for Bone Bonding

Photos removed due to copyright restrictions.
Plasma-sprayed HA coating on a canine femoral stem, 6 mos. post-op
EVALUATION OF BONE BONDING TO HA-COATED PROSTHESSES

The supposition is that as HA coatings dissolve or detach from the titanium substrate, the exposed metal becomes osseointegrated so as to maintain the fixation to bone.

MATERIALS AND METHODS

- Six implants used in this study from patients treated for a fractured femoral neck with a Bimetric hemi-arthroplasty (Biomet, UK).
  - 3 HA-coated specimens (duration 173, 261 and 660 days, post-op)
  - 3 non-coated specimens (40, 650 and 1094 days)
- The plasma-sprayed HA coating had an average crystallinity >85% and an average thickness of 50μm.
ESEM of a non-HA-coated specimen retrieved 40 days after implantation.

A.E. Porter, M. S et al., Biomat. 200

Used with permission.
ESEM of a non-HA-coated stem after 1094 days

ESEM of an HA-coated stem

Used with permission.
ESEM of bone contiguous with the HA coating


ESEM of bone apposing exposed titanium


Graph showing the percentage of the implant surface apposed by bone. Mean±SEM for the multiple points of analysis along each stem.

RESULTS

• For the HA-coated stems:
  – 80±20% (mean±SEM, n=3) for the HA-coated regions versus 24±8% (n=3) for the titanium, originally underlying the HA and exposed with its loss (Student’s t test, p=0.01).

• For the non-coated titanium stems:
  – 24±5%; n=3, comparable with the bonding to the titanium regions on the HA-coated stems exposed by the loss of HA.
JOINT REPLACEMENT PROSTHESES

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- Other Effects
  - Stress Shielding
PROGRESSION OF OSTEOLYSIS:
“HYLAMER” CUP

Images removed due to copyright restrictions.
X-rays at 1, 2, 3, and 4 years.
Correlation
Linear regression
$R^2=0.76$

% Hylamer Hips with Osteolysis

Total Linear Wear (mm)
Spice, Byron. “Particle disease seen as plague on total joint replacement.” *Pittsburgh Post-Gazette.* [Date unknown].

Figure by MIT OpenCourseWare. Sources: University of Pittsburgh and Pittsburgh Post Gazette.
WEAR PROCESSES

Asperity

Abrasive plowing wear

Metal

Adhesive wear particle adherent to metal

Crack propagated by cyclic loading results in fatigue (delamination) wear

PE Component
EFFECT OF A SINGLE SCRATCH ON PE WEAR

- Profound effect of a single scratch; wear due to the ridge of metal bordering an scratch

No PE wear if the metal ridge is removed

10-fold increase in PE wear when the ridge bordering the scratch exceeded 2μm in height

(This type of scratch is not noticeable by eye.)

Dowson, et al., Wear 119, no. 3 (1987): 277

Used with permission
Do scratches form on Co-Cr femoral condyles?

Ant-post movement

Ridge of metal

Ridge of metal

Two photos removed due to copyright restrictions.

Dowson, et al., Wear (1987)
Profound effect of a single scratch; wear due to the ridge of metal bordering an scratch, >2μm high
SOURCES OF PARTICLES THAT CAUSE SCRATCHES ON CONDYLES

- Bone
- PMMA (bone cement)
- Wear and corrosion products from modular junctions
- Prosthetic coatings (viz., plasma sprayed Ti)
Is ceramic-on-PE the answer?

Alumina or zirconia heads

Ceramics can fracture

Photo of hip implant removed due to copyright restrictions.
COMPARISON OF THE OXIDE THICKNESSES ON Co-Cr AND Zr-Nb

Chromium Oxide layer

Typical scratch in the Co-Cr surface

Co-Cr Alloy

Zirconium Oxide layer

Zr-Nb Alloy

Thicker oxide layer (500x thicker) protects against scratches.
Composition of Orthopaedic Metals

- **Stainless Steel (316L)**
  - Cr (17 - 20%)
  - Ni (10 - 17%)
  - Mo (2 - 4%)
  - C (0.03%)
  - Mn, P, S, Si, (~2.8% total)

- **Cobalt Alloy (F 75)**
  - Cr (27 - 30%)
  - Mo (5 - 7%)
  - Ni (2.5%)
  - Fe, C, Mn, Si (~3.1% total)

- **Titanium (Ti - 6Al - 4V)**
  - Al (5.5 - 6.5%)
  - V (3.5 - 4.5%)
  - Fe, C, O, (~0.46% total)

- **Zr (2.5%)**

* Some patients have nickel sensitivity

Titanium alloy cannot be used as an articulating surface because of its poor wear properties.
Co-Cr ALLOY VERSUS Zr-Nb ALLOY: THICKNESS OF THE OXIDE

Zirconium oxide is the surface of oxinium in the same way that chromium oxide is the surface of Co-Cr alloys; not coatings.

- Co-Cr alloy
  - Chromium oxide: 0.01 μm
  - Zirconium oxide: 5 μm

- Zr-Nb alloy
  - 500 times thicker
JOINT REPLACEMENT PROSTHESSES

- Fit
  - Anatomy
- Function
  - Kinematics; Range of Motion
- Fixation
- Tribology
  - Friction, Wear, and Lubrication
- Other Effects
  - Stress Shielding
Bone (Trabecular) Structure

Normal

Osteoporotic: Postmenopausal

Photos comparing interior bone structure removed due to copyright restrictions.
Decrease in the Stress in the Distal Femur after TKA due to the Stiffness of the Co-Cr Femoral Component: Finite Element Analysis

Bone Loss due to Stress Shielding under a Femoral Component: Canine Model

Diagram removed due to copyright restrictions.

RADIOGRAPHIC BONE LOSS AFTER TKA*

• Retrospective radiographic analysis of 147 TKAs.
  – 3 designs
  – Cemented and porous-coated, non-cemented

• Determination of whether bone loss was evident in the post-op radiographs.
  – 3 examiners

Bone Loss After TKA: Radiographic Study

A-P Radiograph

Lateral Radiograph

Sites at which changes in bone density were evaluated.

X-ray image removed due to copyright restrictions.

X-ray image removed due to copyright restrictions.

Bone Loss Under the Femoral Component of a Total Knee Replacement Prosthesis: Stress Shielding

1 year post-op

Images removed due to copyright restrictions.

BONE LOSS UNDER THE FEMORAL COMPONENT OF TKA

- Bone loss occurred in the majority of cases (68% of patients).
- Bone loss occurred within the first post-operative year and did not appear to progress.
- Bone loss was independent of implant design and mode of fixation (i.e., cemented vs. non-cemented).

EFFECT OF BONE LOSS ON BONE STRENGTH

How much bone loss needs to occur before it is detectable in a radiograph?

- Radiographic evidence of bone loss in the distal femur = 30% reduction in bone density.*

How does bone loss affect bone strength?

- Bone strength is proportional to density².
- Therefore a 30% decrease in bone density means a 50% decrease in bone strength.

BENDING STIFFNESS

= Modulus $\times$ Cross Section of Elasticity $\times$ Moment of Inertia

= $E \times \pi D^4/64$
Photos removed due to copyright restrictions.
Stems that reduce the cross-sectional moment of inertia

Photos removed due to copyright restrictions.
Table 1  Synthetic materials historically utilized for ligament replacement (5)

<table>
<thead>
<tr>
<th>Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Ultimate tensile strength (N)</th>
<th>Stiffness (N/mm)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gore-Tex®</strong></td>
<td>High strength and fatigue life, limited particulate debris</td>
<td>Lack of tissue ingrowth, fraying at bone tunnels, chronic effusions, ultimate longevity</td>
<td>5300</td>
<td>322</td>
<td>9</td>
</tr>
<tr>
<td><strong>Dacron®</strong></td>
<td>High strength, supported collagenous ingrowth</td>
<td>Stress-shielding of collagenous in-growth, rupture of the femoral or tibial insertion, rupture of the central body, elongation</td>
<td>3631</td>
<td>420</td>
<td>18.7</td>
</tr>
<tr>
<td>Carbon fiber®</td>
<td>Synthetic material</td>
<td>Particulate matter, foreign body response in synovium</td>
<td>660</td>
<td>$230 \times 10^9$</td>
<td>1</td>
</tr>
<tr>
<td><strong>LAD</strong></td>
<td>Protects graft during maturation</td>
<td>Inflammatory reaction, high complication rate</td>
<td>1730</td>
<td>56</td>
<td>22</td>
</tr>
</tbody>
</table>

LIGAMENT DEVICES

Prosthesis

• Does not require an autograft for support
• Sufficient strength for immediate stabilization
• Do not rely on intra-articular healing to augment strength

Augmentation Device

• Acts as mechanical support to reinforce autograft to increase initial strength
• Load sharing with graft tissue to prevent stress shielding
LIGAMENT REPLACEMENT AND AUGMENTATION DEVICES

Issues

• Strength
• Load-deformation
• Insertion site integrity
• Tensioning
<table>
<thead>
<tr>
<th>Year</th>
<th>Researcher(s)</th>
<th>Material &amp; Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>Emery &amp; Rostrup</td>
<td>Teflon tube; fraying in tunnel</td>
</tr>
<tr>
<td>1969</td>
<td>Gupta and Brinker</td>
<td>Dacron cord/rubber coat; fragmentation</td>
</tr>
<tr>
<td>1973</td>
<td>James, et al.</td>
<td>Proplast; breakage</td>
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<tr>
<td>1977</td>
<td></td>
<td>Polyethylene; breakage</td>
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<tr>
<td>1978</td>
<td>Jenkins</td>
<td>Carbon fibers; fragmentation; migration to lymph nodes</td>
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## SYNTHETIC LIGAMENTS

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<th>Material</th>
<th>Indication</th>
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<tr>
<td>Gore-Tex</td>
<td>PTFE (Teflon)</td>
<td>Failed intra-art. reconstruction</td>
</tr>
<tr>
<td>Stryker</td>
<td>Dacron</td>
<td>Failed intra-art. reconstruction</td>
</tr>
<tr>
<td><strong>Augmentation Device</strong></td>
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<td></td>
</tr>
<tr>
<td>Kennedy</td>
<td>Polypropylene</td>
<td>Augmentation of autograft ACL</td>
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Photos removed due to copyright restrictions.

LIGAMENT PROSTHESES

- Wear/fraying occurs
- Wear particles of all synthetic ligaments elicit production of inflammatory agents
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