Massachusetts Institute of Technology
Harvard Medical School
Brigham and Women’s Hospital
VA Boston Healthcare System

2.79J/3.96J/20.441/HST522J

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

M. Spector, Ph.D.

Wrist

Finger

Human Joints

Knee

Elbow

Medical illustrations removed due to copyright restrictions.

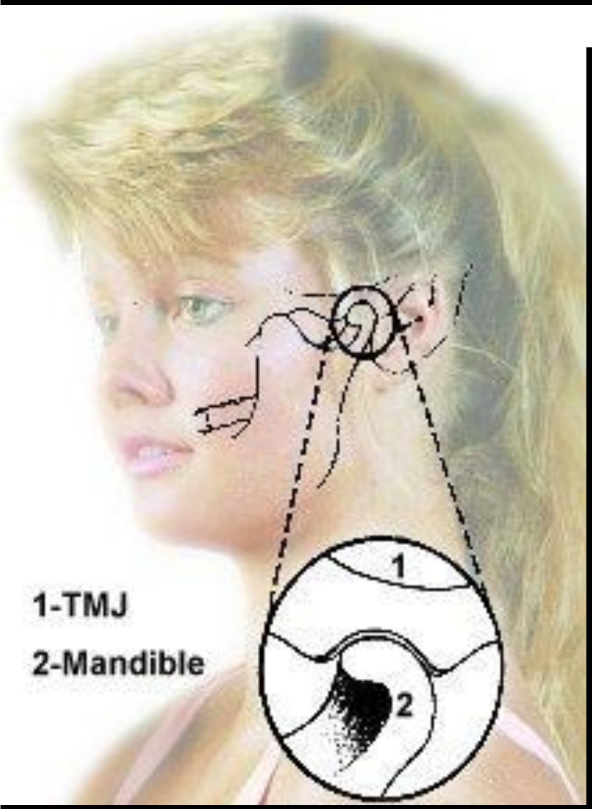
Spine

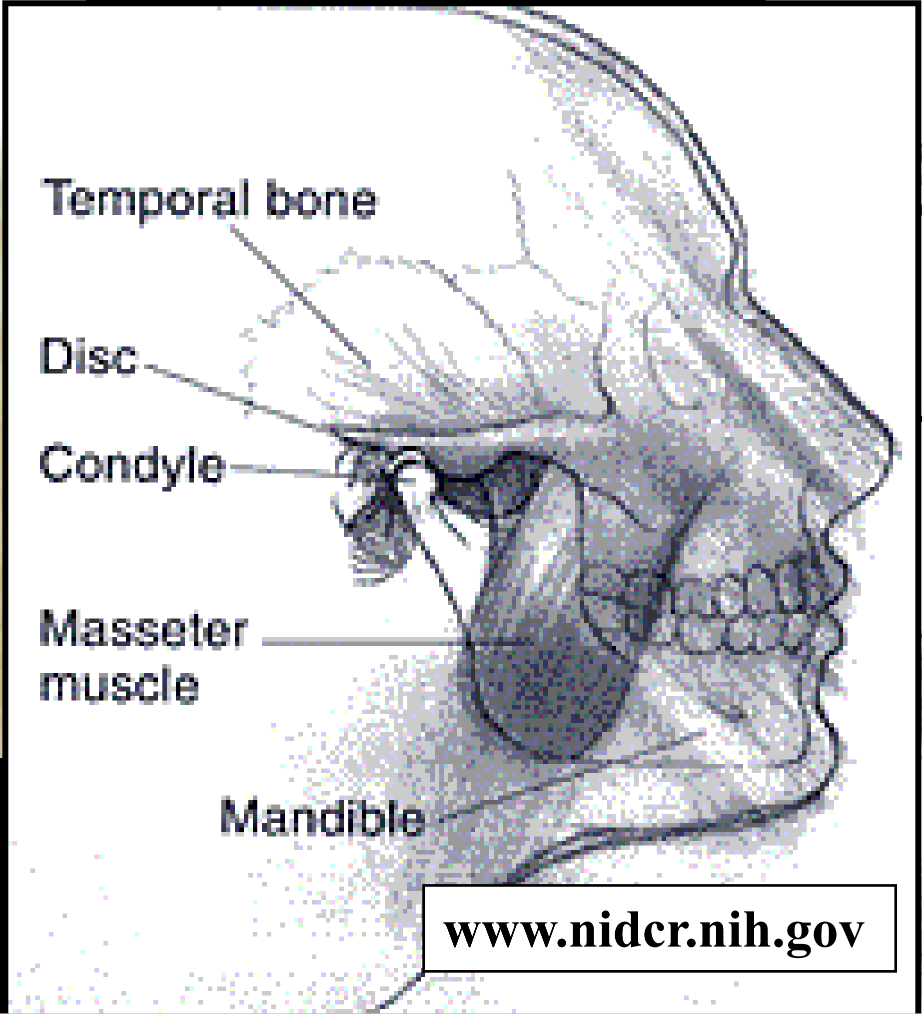
Hip

Shoulder

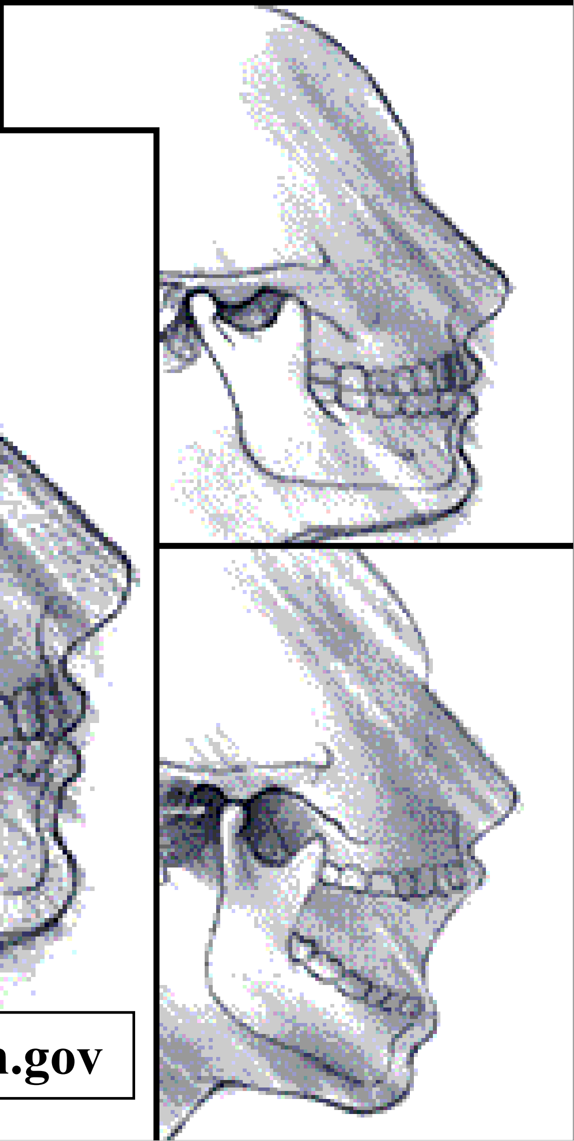
Temporomandibular Joint

The temporomandibular joint connects the lower jaw (mandible) to the temporal bone at the side of the head.





www.nidcr.nih.gov



JOINT REPLACEMENT PROSTHESES

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

	Permanent Prosthesis	Regeneration Scaffold
Bone	Yes	Yes
Articular cartilage	No	Yes*
Meniscus	No	Yes*
Ligaments	No	Yes*
Synovium	No	No

* In the process of being developed

Knee and Hip Replacement with Prostheses

Medical illustrations removed due to copyright restrictions.

Total Knee Replacement

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

T.S. Thornhill, M.D.

JOINT REPLACEMENT PROSTHESES

- 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

Spinal Implant: Artificial Disc

Medical illustration removed due to copyright restrictions.
F. Netter (Ciba) drawing of degeneration of lumbar intervertebral discs.

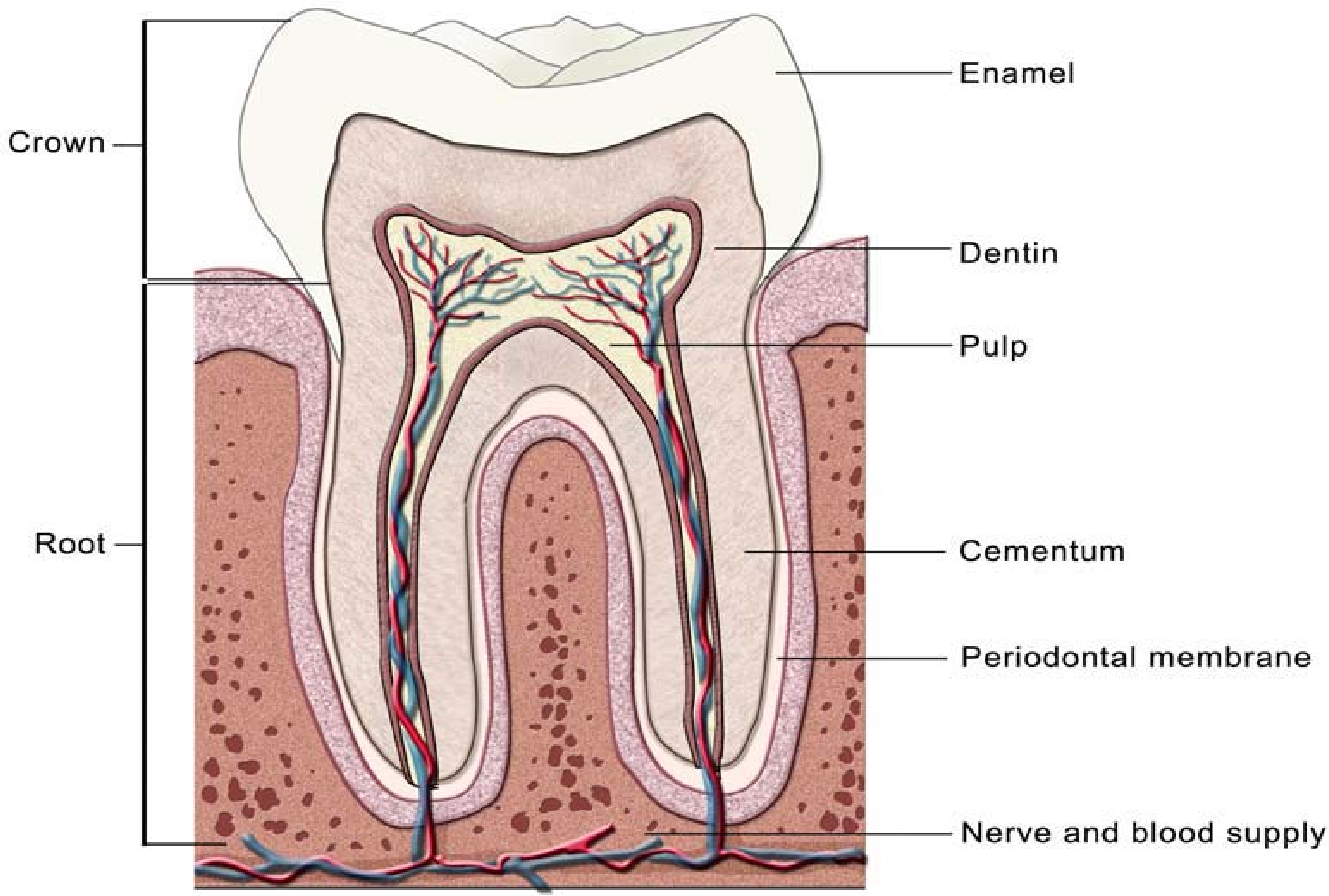


Figure by MIT OpenCourseWare.

Dental Implant Designs and Materials

Sapphire

Alumina

Titanium

Photos removed due to copyright restrictions.

Carbon

Alumina

Carbon

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.

Medical illustration of dental implant removed due to copyright restrictions.

Medical illustration of hip prosthesis 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 PROSTHESES

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

Total Hip and Knee Replacement Prostheses

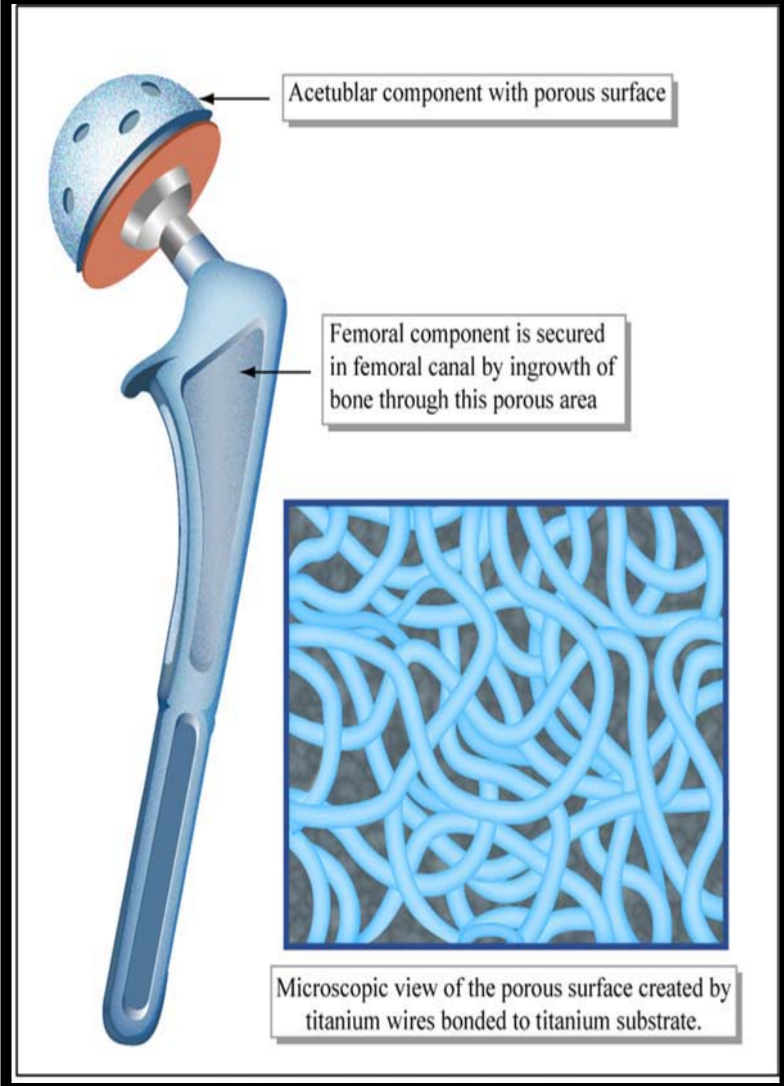


Figure by MIT OpenCourseWare.

Photos of knee prostheses removed due to copyright restrictions.

JOINT REPLACEMENT PROSTHESES

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

Bone Cement
Self-Curing Polymethylmethacrylate

PMMA

Photo removed due to copyright restrictions.

Bone

Metal

Photo removed due to copyright restrictions.

Bone

PMMA

Stem Designs with Irregular Surfaces for Bone Interdigitation

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

Polarized Light Microscopy **Conventional Light Microscopy**

Photos removed due to copyright restrictions.

Fibrous tissue integration

Bone integration; "osseointegration"

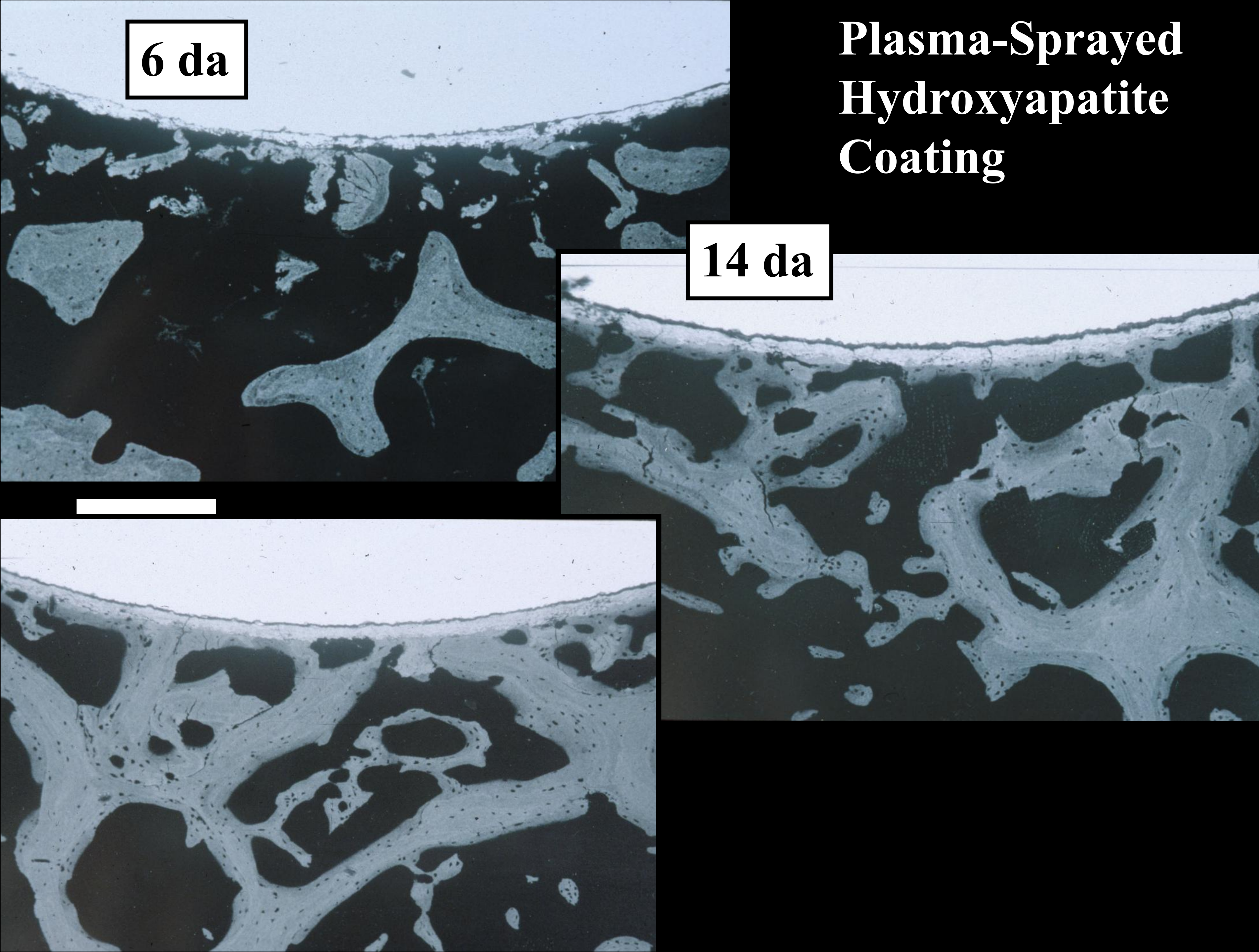
Porous Coatings for Bone Ingrowth

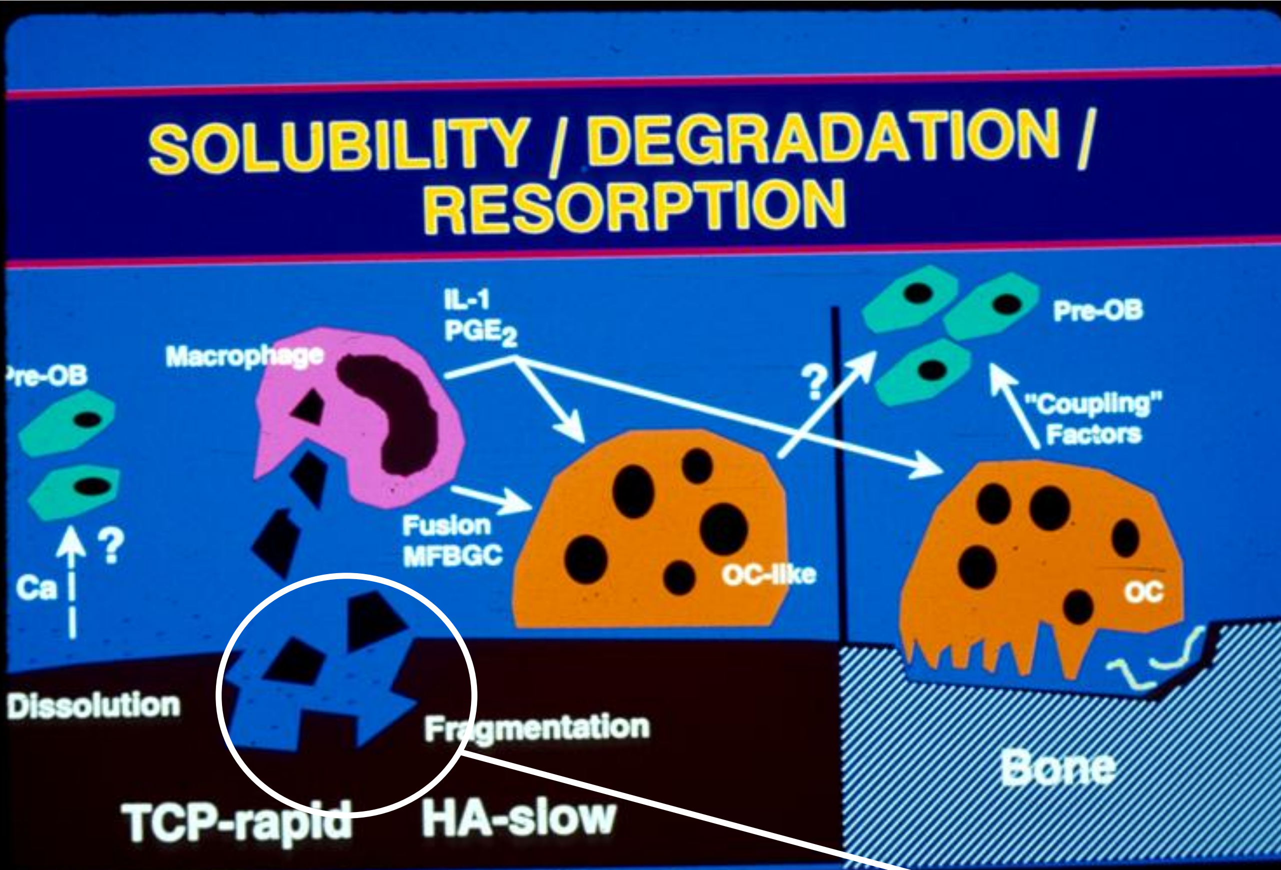
Photos removed due to copyright restrictions.

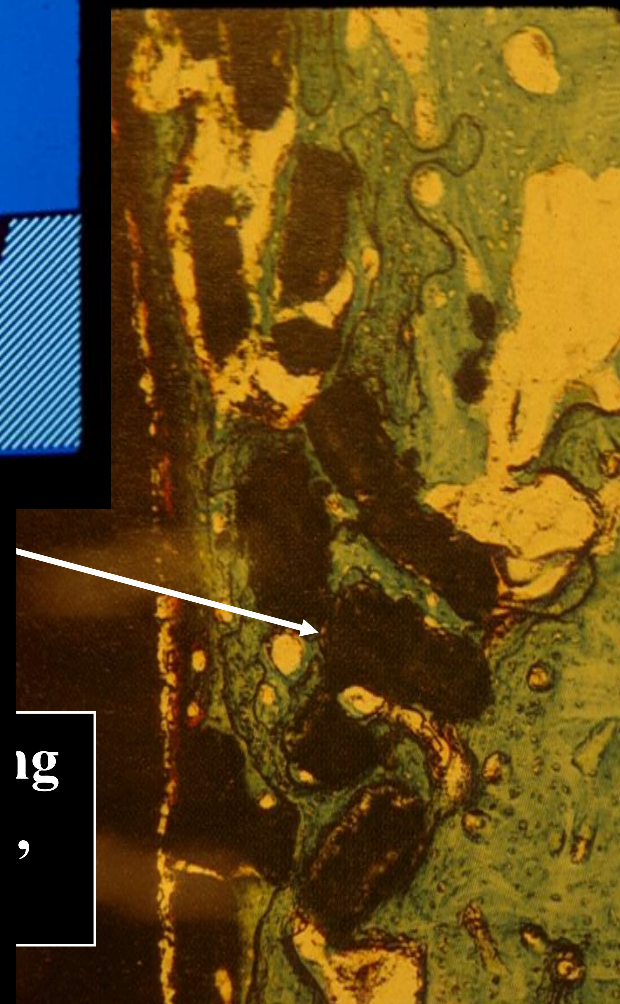
Hydroxyapatite-Coated Implants for Bone Bonding

Photos removed due to copyright restrictions.

Plasma-Sprayed Hydroxyapatite Coating







Plasma-sprayed HA co ng
on a canine femoral st ,
6 mos. post-opc

Human femoral stem with a plasma-sprayed HA coating, retrieved 4.5 mos. post-op

Photo removed due to copyright restrictions.

T. Bauer, *et al*., J. Bone Jt. Surg., 73-A (1991)

EVALUATION OF BONE BONDING TO HA-COATED PROSTHESES

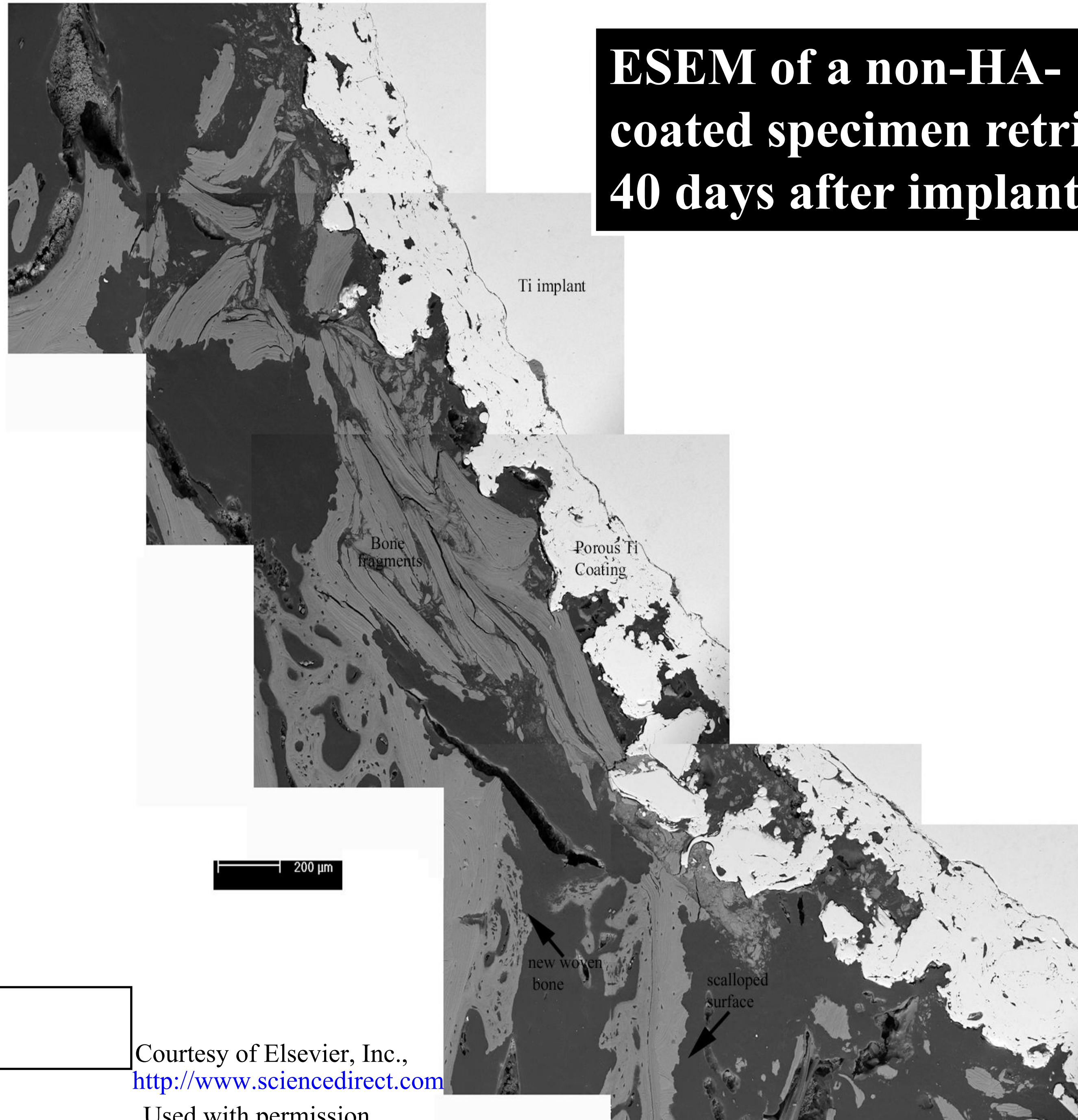
The supposition is that as HA coatings dissolve or detach from the titanium substrate, the exposed metal becomes osseointegrated so as to maintain the fixation to bone.

A.E. Porter, *et al*., Biomat. 2004;25:5199

MATERIALS AND METHODS

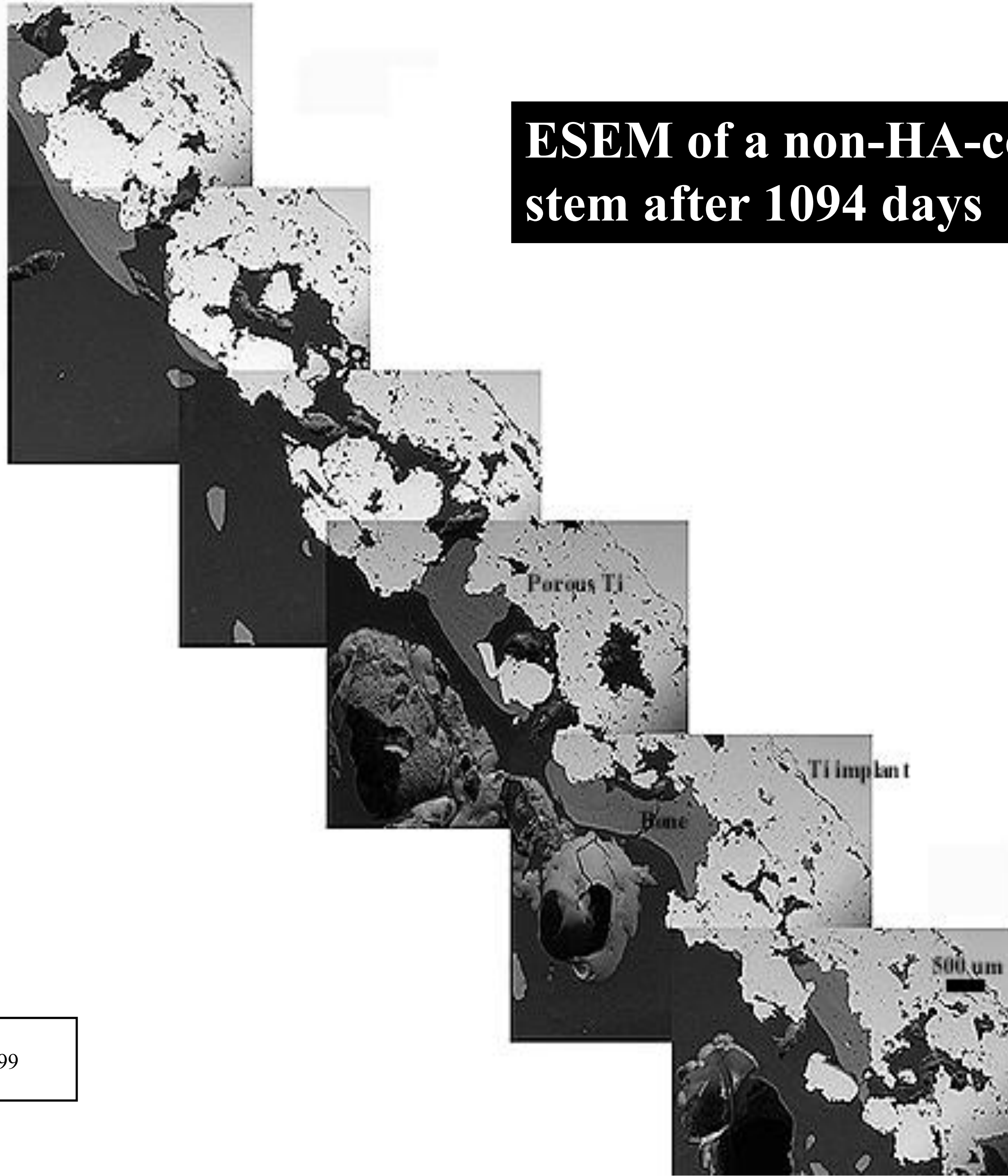
- Six implants used in this study from patients treated for a fractured femoral neck with a Bimetric hemi-arthroplasty (Biomet, UK).
  - 3 HA-coated specimens (duration 173, 261 and 660 days, post-op)
  - 3 non-coated specimens (40, 650 and 1094 days)
- The plasma-sprayed HA coating had an average crystallinity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

ESEM of a non-HA-coated stem after 1094 days

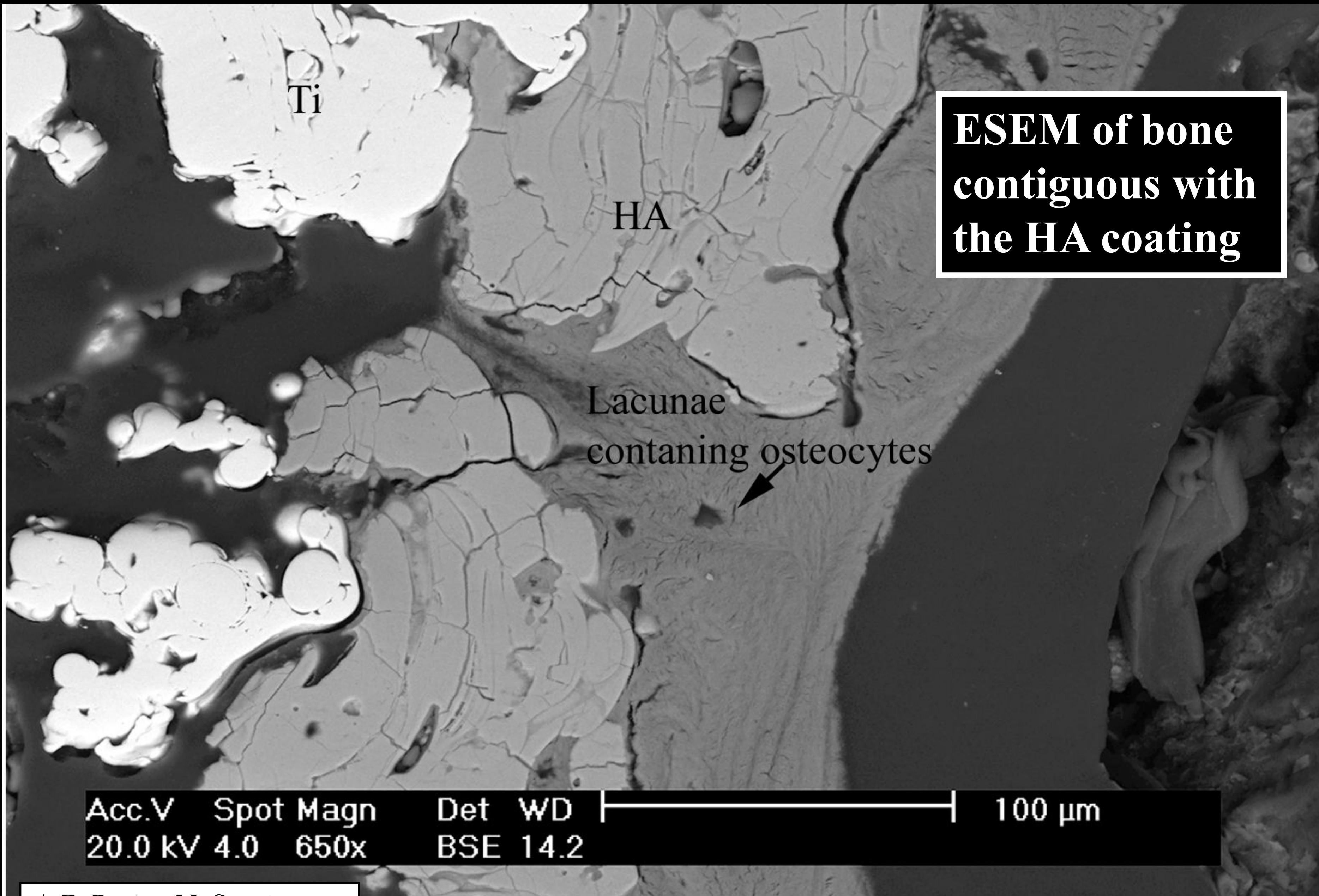


See A.E. Porter, M. Spectoret al., Biomat. 2004;25:5199

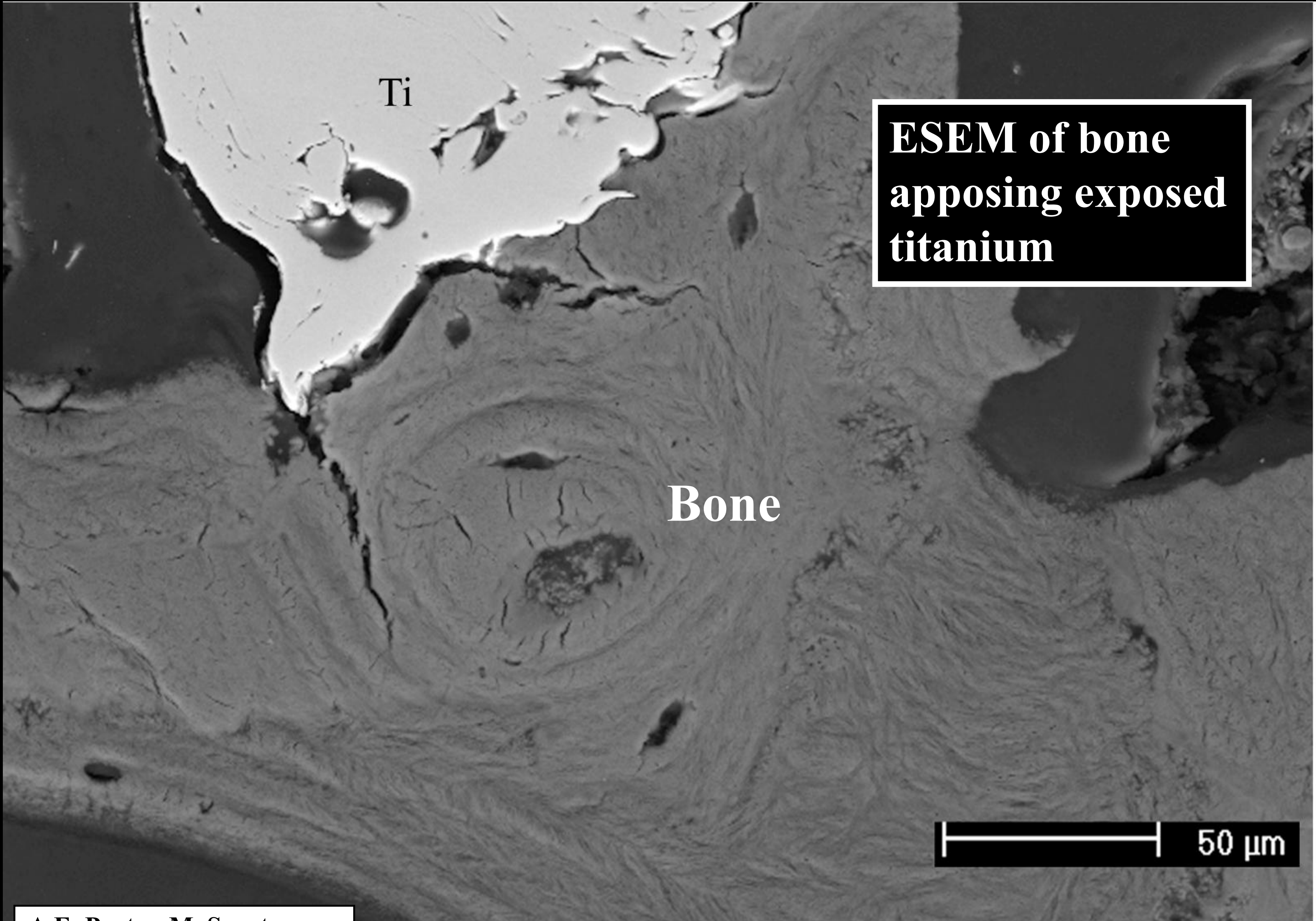
ESEM of an HA-coated stem

Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

A.E. Porter, M. Spector *et al.*, Biomat. 2004;25:5199

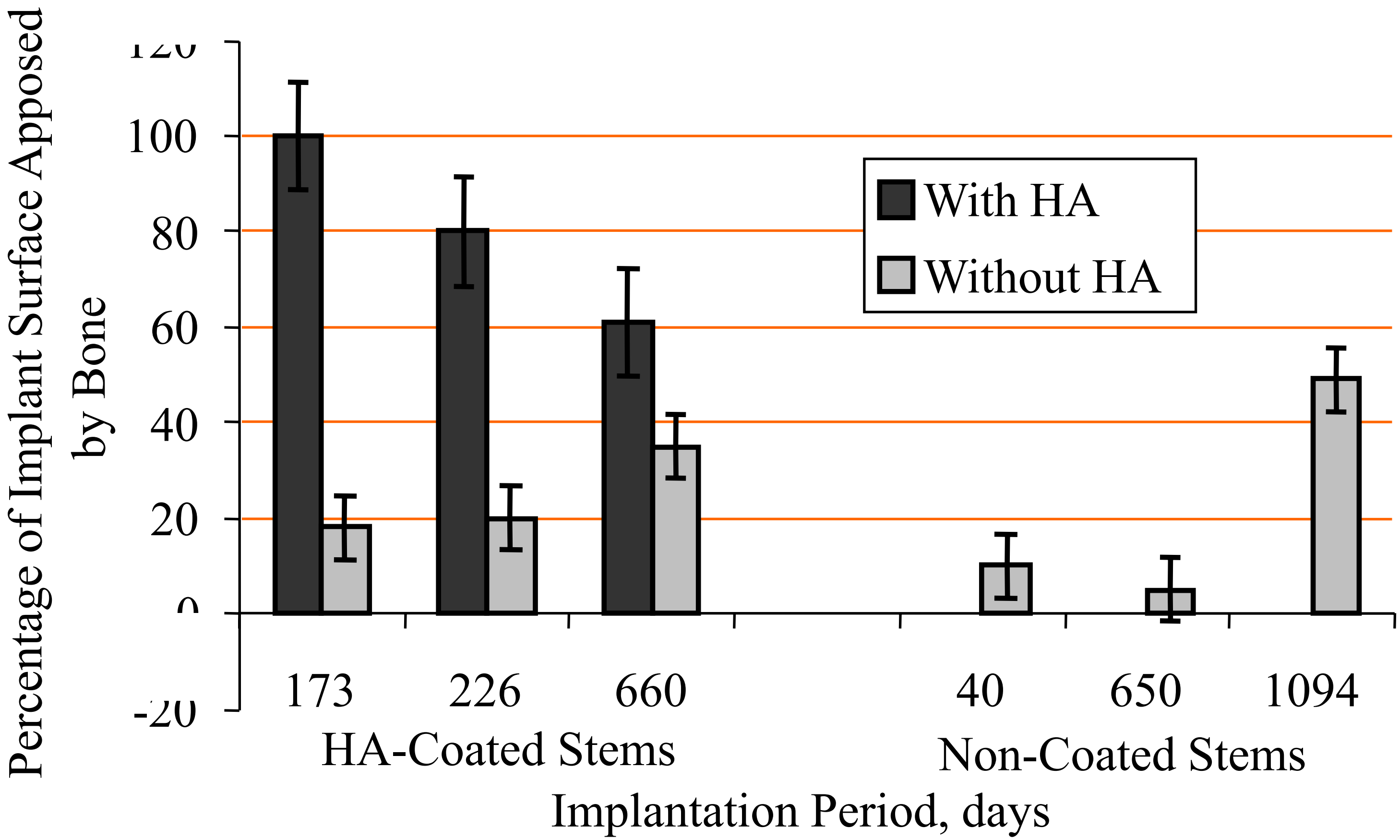


A.E. Porter, M. Spector *et al.*, Biomat. 2004;25:5199



A.E. Porter, M. Spector *et al.*, Biomat. 2004;25:5199

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



See A.E. Porter, M. Spector *et al.*, Biomat. 2004;25:5199

RESULTS

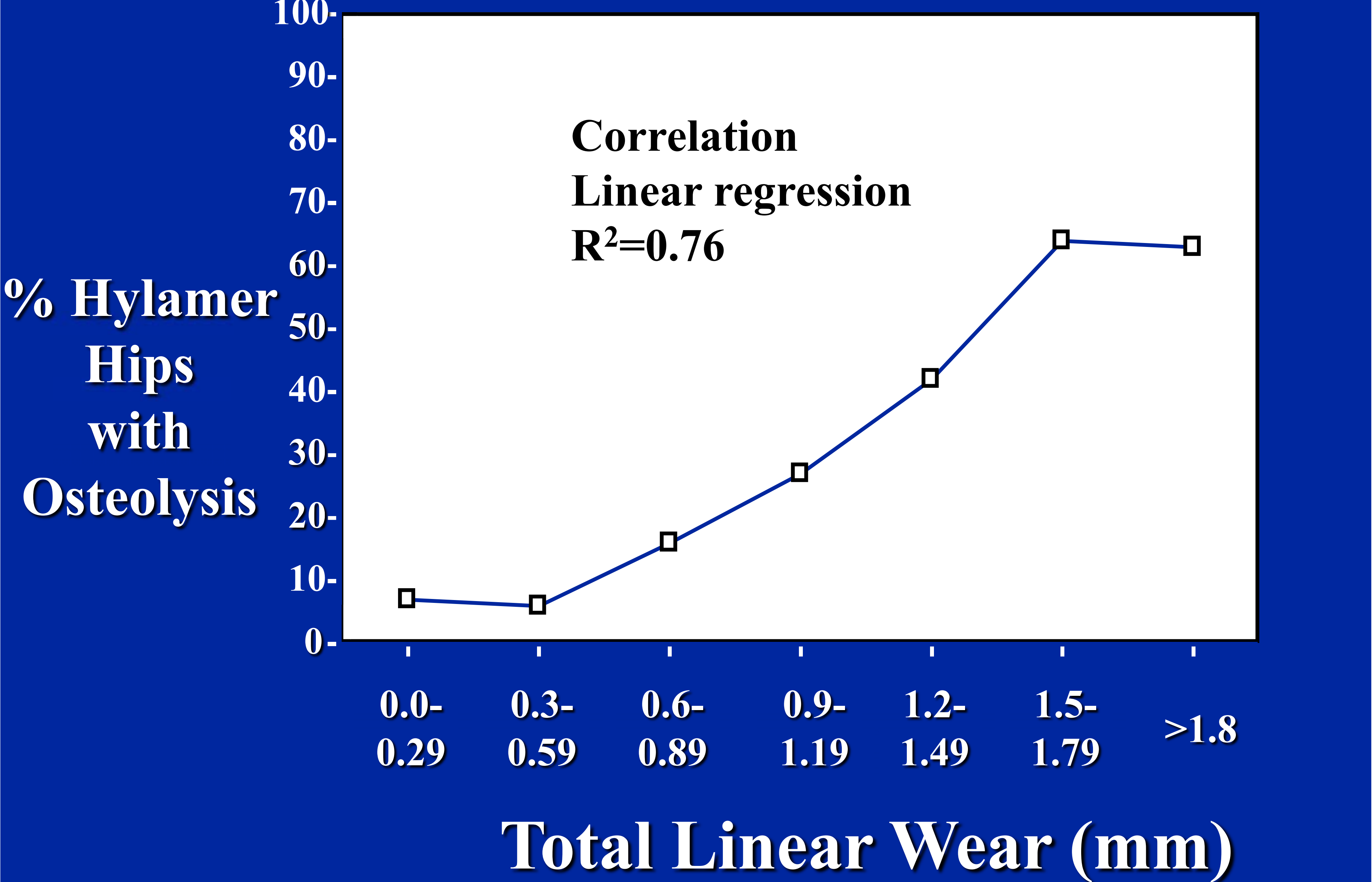
- For the HA-coated stems:
  - 80±20% (mean±SEM, n=3) for the HA-coated regions versus 24±8% (n=3) for the titanium, originally underlying the HA and exposed with its loss (Student's t test, $p=0.01$).
- For the non-coated titanium stems:
  - 24±5%; n=3, comparable with the bonding to the titanium regions on the HA-coated stems exposed by the loss of HA .

JOINT REPLACEMENT PROSTHESES

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

PROGRESSION OF OSTEOLYSIS: "HYLAMER" CUP

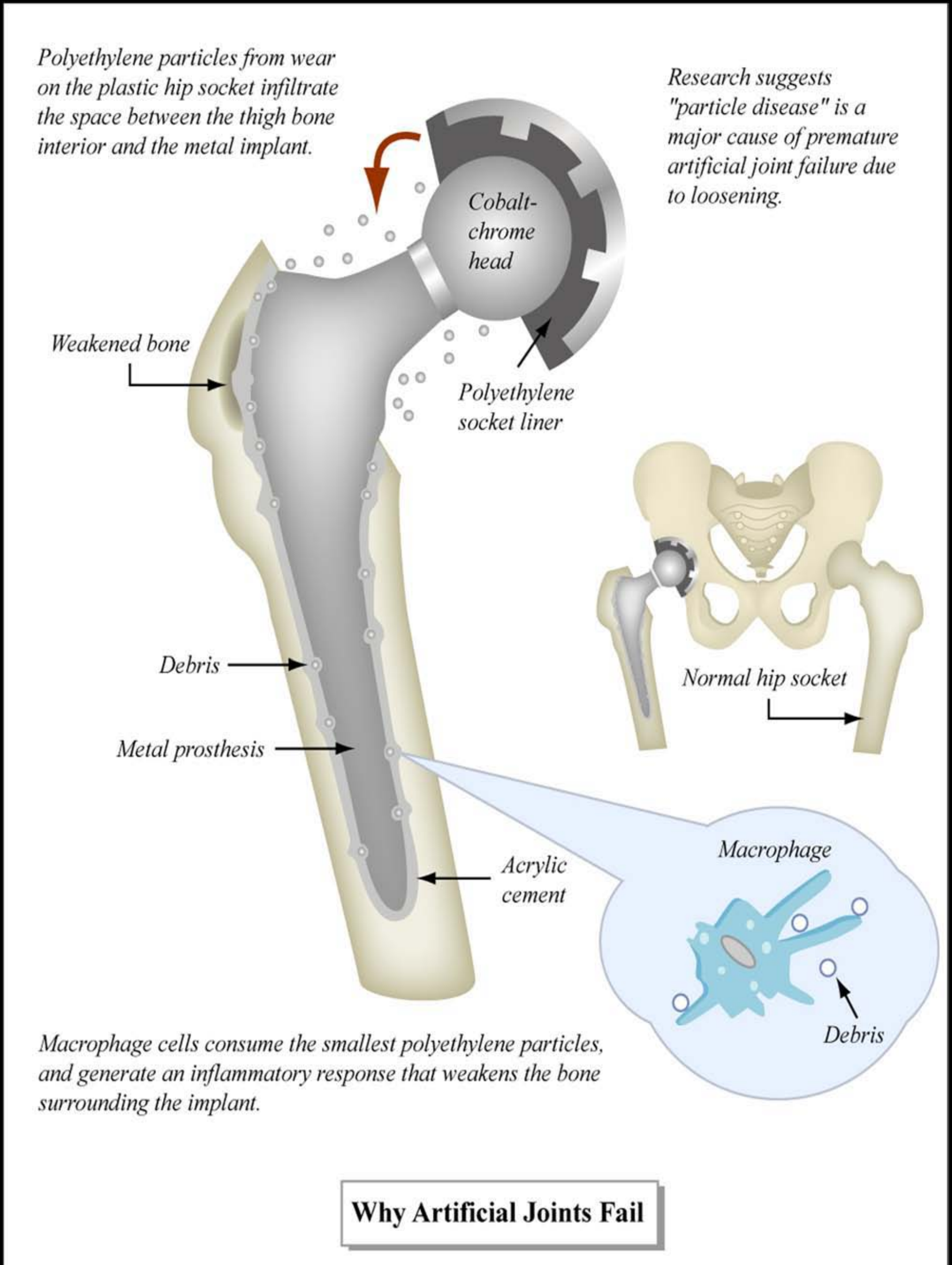
Images removed due to copyright restrictions.
X-rays at 1, 2, 3, and 4 years.



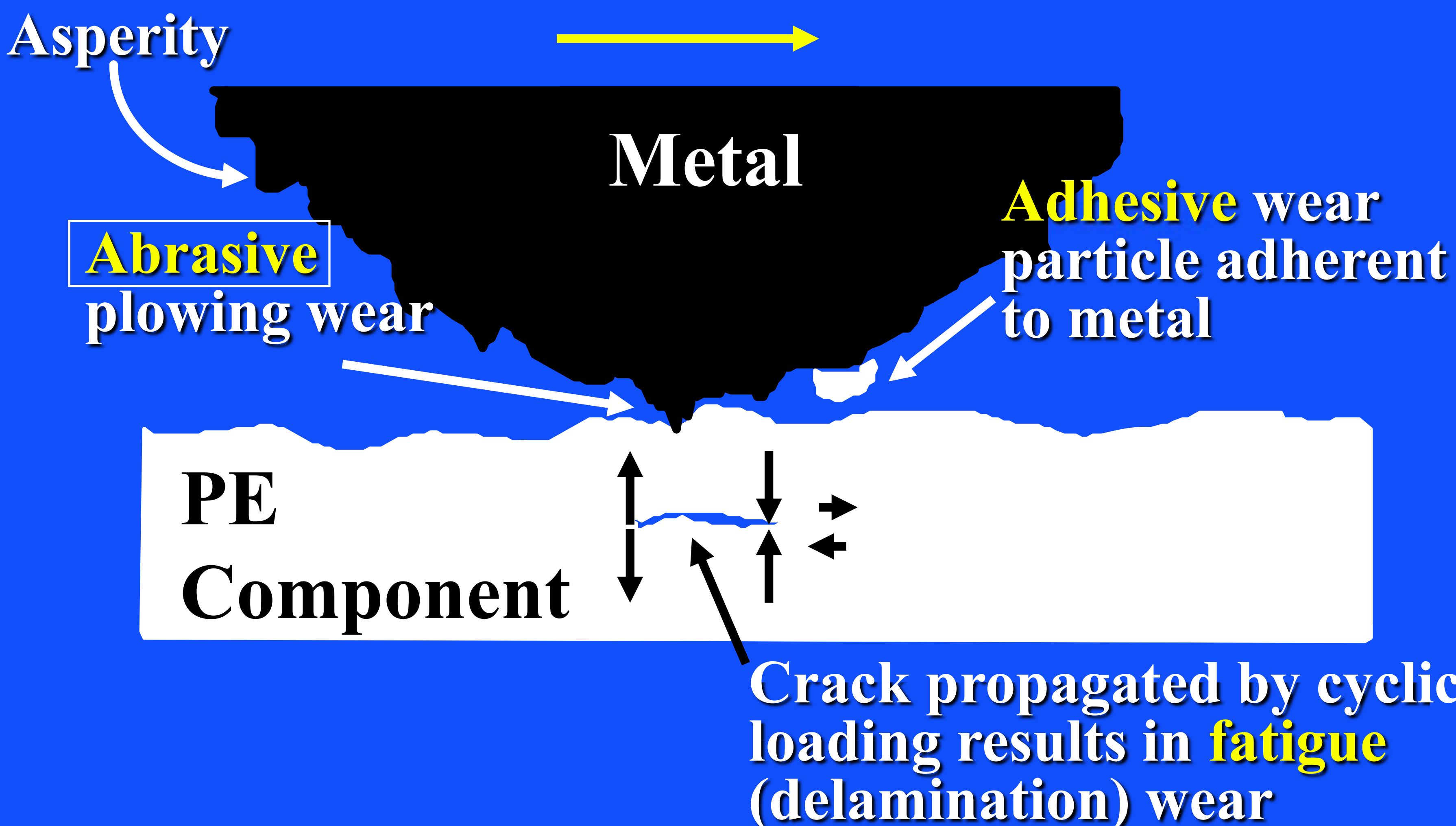
% Hylamer Hips with Osteolysis
100-
90-
80-
70-
60-
50-
40-
30-
20-
10-
0-
Correlation
Linear regression
R²=0.76
0.0-0.29
0.3-0.59
0.6-0.89
0.9-1.19
1.2-1.49
1.5-1.79
>1.8
Total Linear Wear (mm)

News clipping removed due to copyright restrictions.
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.

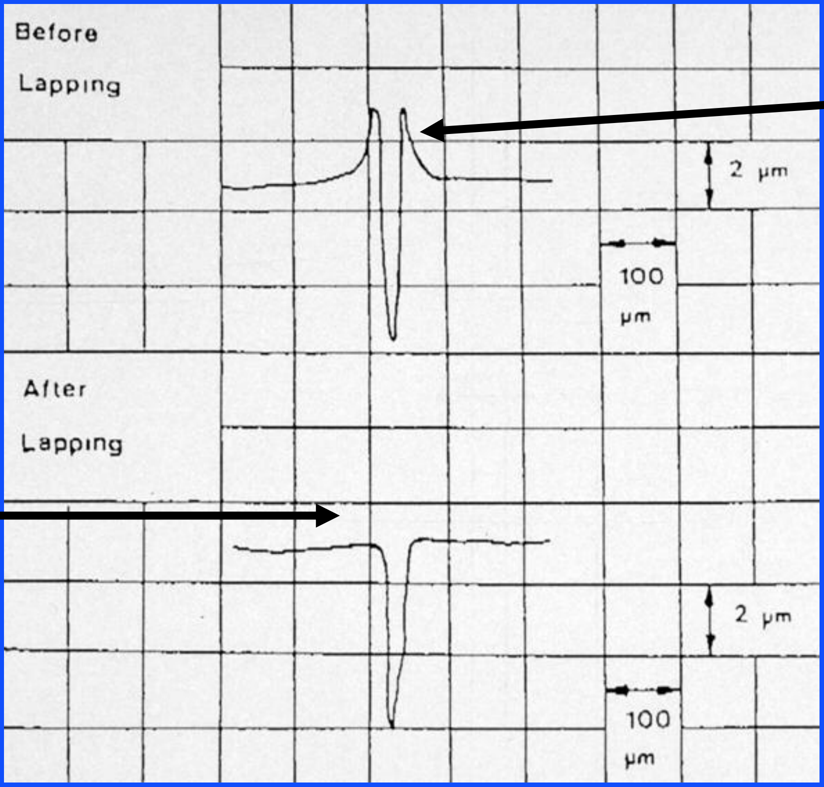


WEAR PROCESSES



EFFECT OF A SINGLE SCRATCH ON PE WEAR

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



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.)

No PE wear if the metal ridge is removed

Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission

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

Do scratches form on Co-Cr femoral condyles?

Ridge of metal
>2μm

Ant-post movement

Two photos removed due to copyright restrictions.

50 μm

Dowson, *et al*., Wear (1987)
Profound effect of a single scratch; wear due to the ridge of metal bordering an scratch, >2μm high

100 μm

Ridge of metal

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)

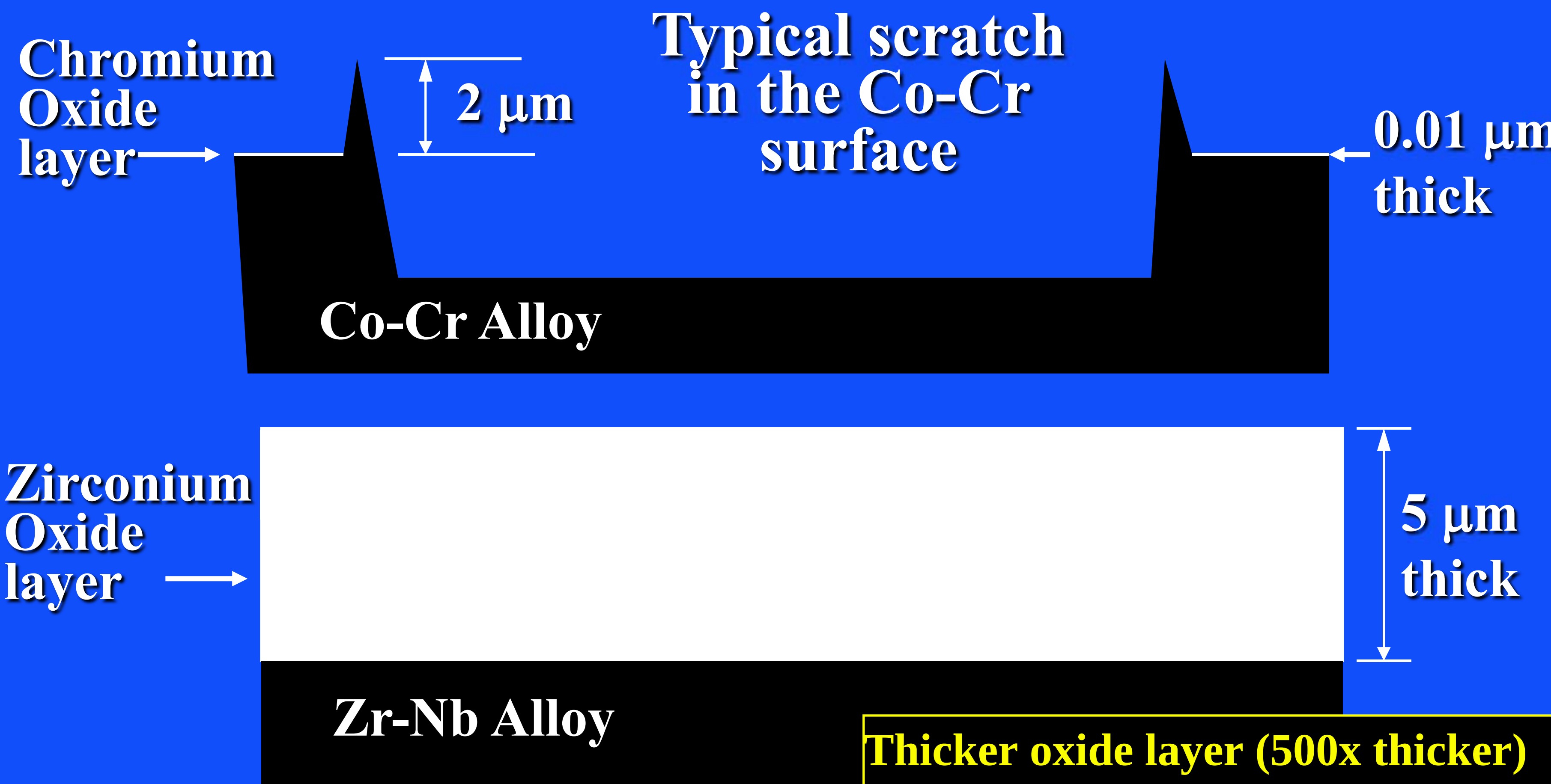
Is ceramic-on-PE the answer ?

Alumina or zirconia heads

Ceramics can fracture

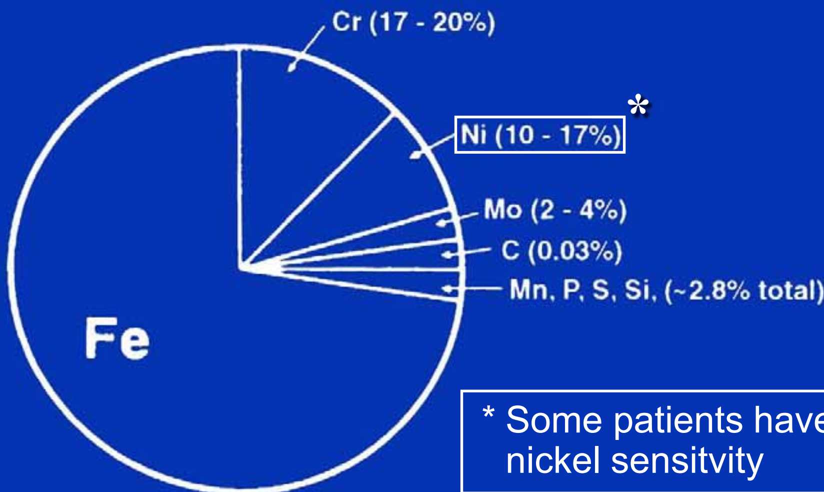
Photo of hip implant removed due to copyright restrictions.

COMPARISON OF THE OXIDE <u>THICKNESSES</u> ON Co-Cr AND Zr-Nb

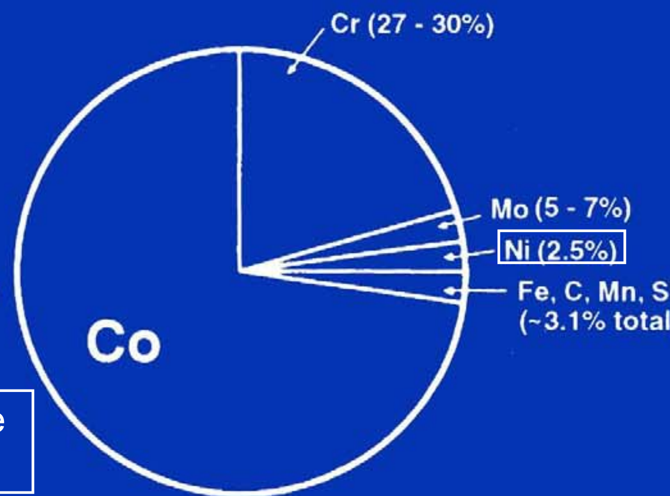


Thicker oxide layer (500x thicker) protects against scratches.

Composition of Orthopaedic Metals

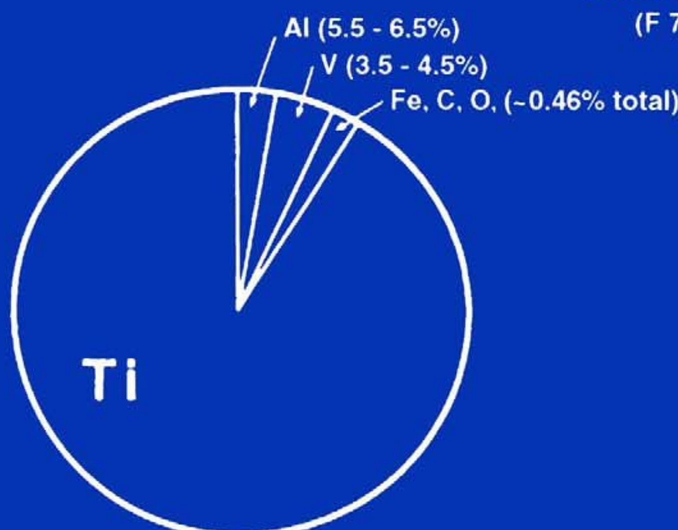


* Some patients have nickel sensitvity

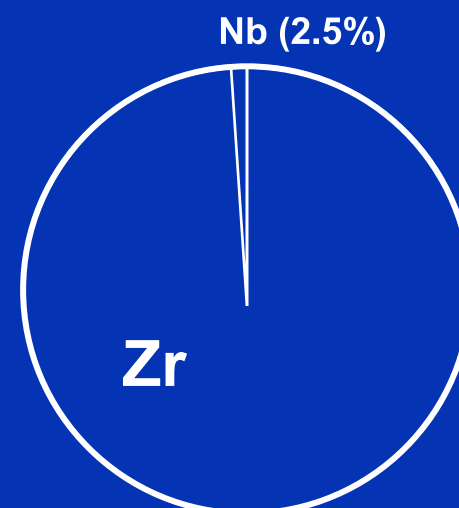


Stainless Steel
(316L)

Cobalt Alloy
(F 75)



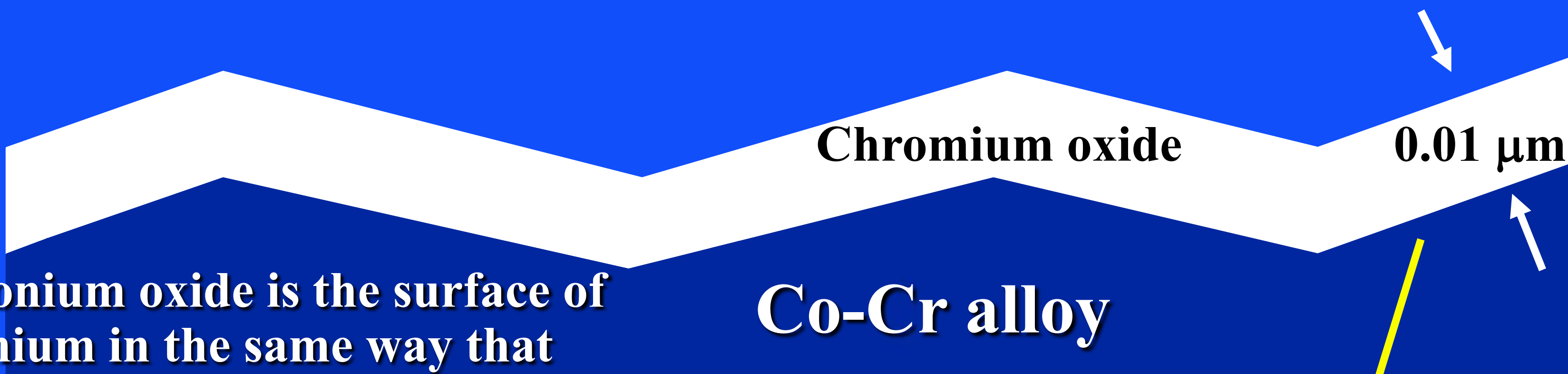
Titanium
(Ti - 6Al - 4V)



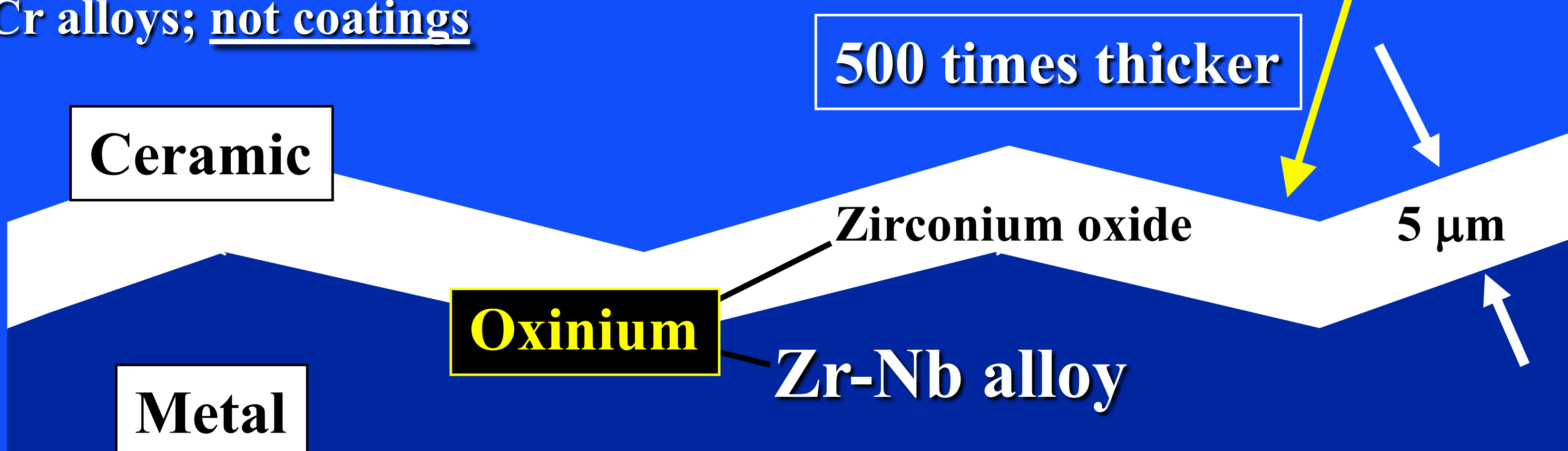
Oxinium
ASTM B550

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



Zironium oxide is the surface of oxinium in the same way that chromium oxide is the surface of Co-Cr alloys; <u>not coatings</u>



JOINT REPLACEMENT PROSTHESES

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

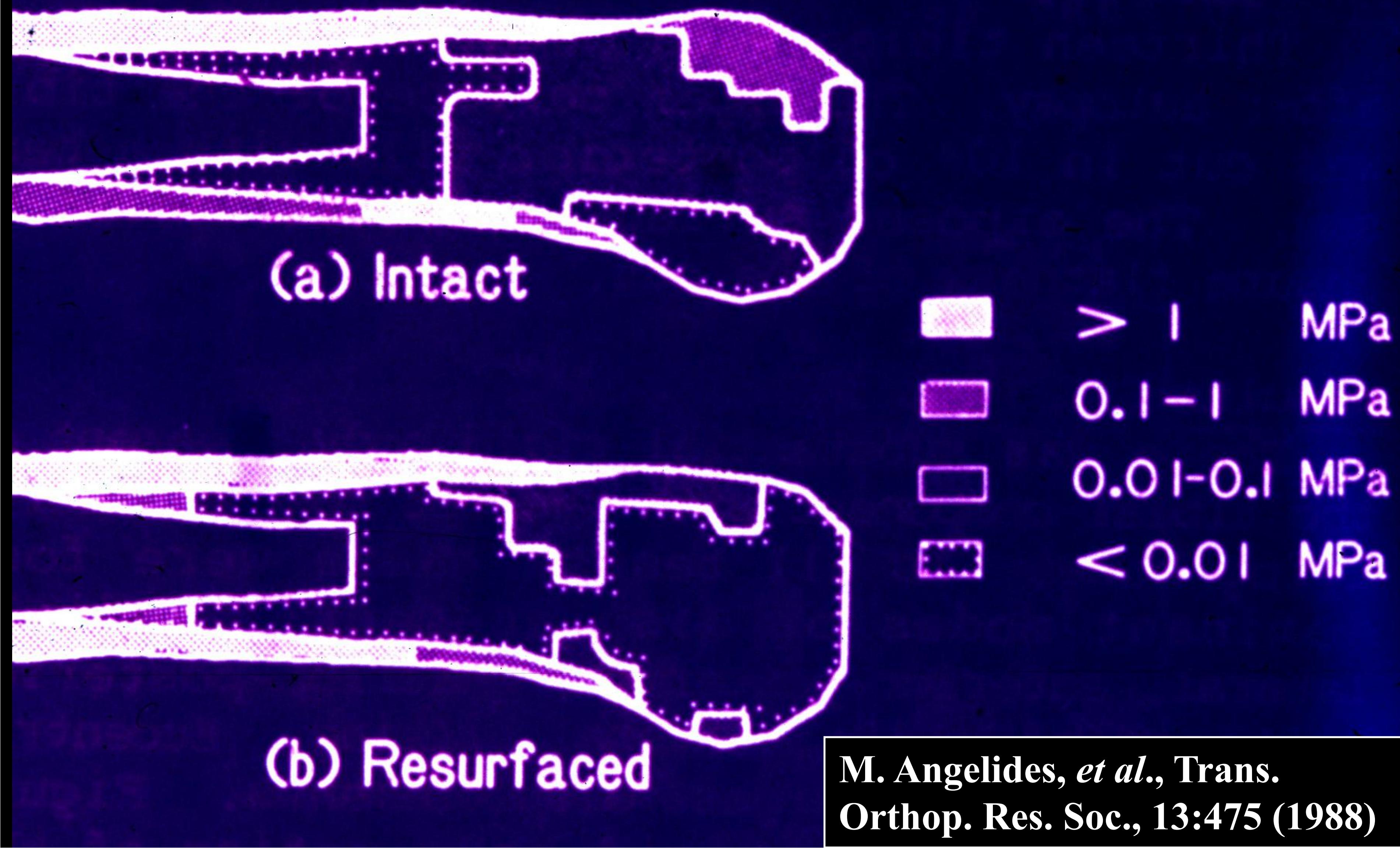
Bone (Trabecular) Structure

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



M. Angelides, *et al*., Trans. Orthop. Res. Soc., 13:475 (1988)

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

Diagram removed due to copyright restrictions.

J.D. Bobyn, *et al.*, Clin. Orthop., 166:301 (1982)

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

* Mintzer CM, Robertson DD, Rackemann S, Ewald FC, Scott RD, Spector M. Bone loss in the distal anterior femur after total knee arthroplasty. Clin Orthop. 260:135 (1990)

Bone Loss After TKA: Radiographic Study

A-P Radiograph

Lateral Radiograph

Sites at which changes in bone density was evaluated.

X-ray image removed due to copyright restrictions.

X-ray image removed due to copyright restrictions.

C.M. Mintzer, *et al*., Clin Orthop. 260:135 (1990)

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

1 year post-op

Images removed due to copyright restrictions.

C.M. Mintzer, *et al*., Clin Orthop. 260:135 (1990)

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).

C.M. Mintzer, *et al.*, Clin Orthop. 260:135 (1990)

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 $density^2$.
- Therefore a 30% decrease in bone density means a 50% decrease in bone strength.

*D.D. Robertson *et al*., J. Bone Jt. Surg. 76-A:66 (1994)

BENDING STIFFNESS

=	Modulus of Elasticity	x	Cross Section Moment of Inertia
=	E	x	$\pi D^4/64$

Polyacetal Stem

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)

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

See G. Vunjak-Novakovic, Ann Rev Biomed Engr 6:131 (2004)

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

LIGAMENT PROSTHESES
HISTORICAL PERSPECTIVE

1960	Emery & Rostrup	Teflon tube; fraying in tunnel
1969	Gupta and Brinker	Dacron cord/rubber coat; fragmentation
1973	James, et al.	Proplast; breakage
1977		Polyethylene; breakage
1978	Jenkins	Carbon fibers; fragmentation; migration to lymph nodes

SYNTHETIC LIGAMENTS

Device	Material	Indication
Prostheses		
Gore-Tex	PTFE (Teflon)	Failed intra-art. reconstruction
Stryker	Dacron	Failed intra-art. reconstruction
Augmentation Device		
Kennedy	Polypropylene	Augmentation of autograft ACL

Polyethylene Fiber Braid: Canine Model

Photos removed due to copyright restrictions.

Image removed due to copyright restrictions.
Excerpt from Olson, E. J. et al. “The biochemical and histological effects of artificial ligament wear particles: In vitro and in vivo studies.” *American Journal of Sports Medicine* 16, no. 6 (1988): 558-570.

LIGAMENT PROSTHESES

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

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