BMEN E3010 BME I

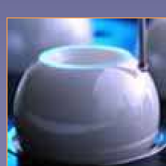
Biomaterials in Medicine – Ceramics and Polymers

Prof. Helen Lu

COLUMBIA | ENGINEERING

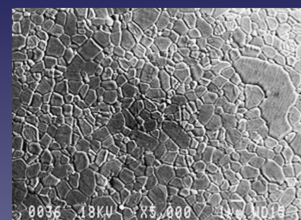
TYPES OF BIOMATERIALS

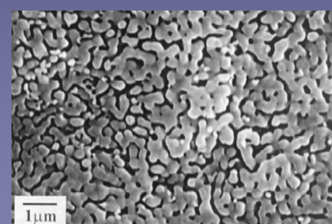
- Metals
- Ceramics
- Polymers
- Natural Biomaterials
- Composites



Classes of Bioceramics

- Bioinert Ceramics
- Bioactive Ceramics
- Bioresorbable Ceramics


Alumina, SEM, www.cermtec.com



Ca-P Thin Film, SEM, Langstaff et al, 1999

Types of Bioceramics

TABLE 1.2.4.2 Types of Bioceramic Tissue Attachment and Their Classification

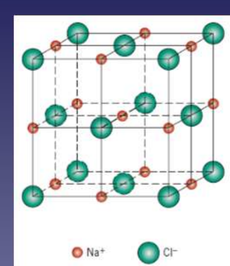
1. Dense, nonporous, nearly inert ceramics attach by bone growth into surface irregularities by cementing the device into the tissues or by press-fitting into a defect (termed "morphological fixation").	Al_2O_3 (single crystal and polycrystalline)
2. For porous inert implants, bone ingrowth occurs that mechanically attaches the bone to the material (termed "biological fixation").	Al_2O_3 (polycrystalline) Hydroxyapatite-coated porous metals
3. Dense, nonporous surface-reactive ceramics, glasses, and glass-ceramics attach directly by chemical bonding with the bone (termed "bioactive fixation").	Bioactive glasses Bioactive glass-ceramics Hydroxyapatite
4. Dense, nonporous (or porous) resorbable ceramics are designed to be slowly replaced by bone.	Calcium sulfate (Plaster of Paris) Tricalcium phosphate Calcium–phosphate salts

Biomaterial: Ceramics

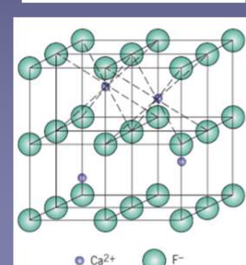
- Metallic+Non-Metallic elements
- Types of Ceramics used clinically
  - Al_2O_3
  - Calcium phosphate ceramics
  - Glass and Glass ceramics

- Fabrication
  - Casting
  - Solid state sintering-hot isostatic pressing
  - Plasma spraying as coatings on implants

Ceramic Crystal Structure



- More complex than those of metals
  - Two elements or more, ions instead of atoms
  - Depends on the magnitude of charge
  - Depends on relative size of cation vs. anion



- Bioceramics: A_mX_p-type crystal structure
  - Cation and Anion not of the same charge mag.
  - ZrO_2 and Al_2O_3

Ceramic Mechanical Properties

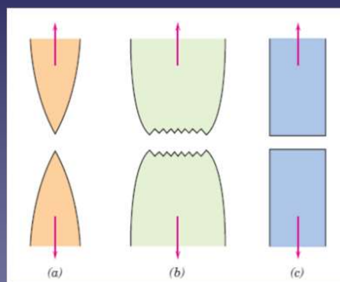


Figure 8.1 (*a*) Highly ductile fracture in which the specimen necks down to a point. (*b*) Moderately ductile fracture after some necking. (*c*) Brittle fracture without any plastic deformation.

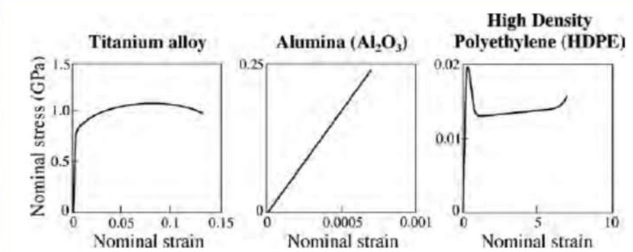


FIGURE I.1.3.2 Representative nominal stress versus nominal strain plots for three different classes of implantable material: ductile metal (titanium alloy; 6 wt% Al, 4 wt% V); ceramic (alumina); and crystalline polymer (high density polyethylene).

Ceramic Mechanical Properties

Critical stress for crack propagation

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2} \quad (8.3)$$

E = modulus of elasticity

γ_s = specific surface energy

a = one half the length of an internal crack

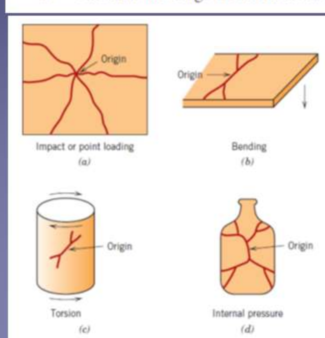


Figure 12.29 For brittle ceramic materials, schematic representations of crack origins and configurations that result from (*a*) impact (point contact) loading, (*b*) bending, (*c*) torsional loading, and (*d*) internal pressure. (From D. W. Richerson, *Modern Ceramic Engineering*, 2nd edition, Marcel Dekker, Inc., New York, 1992. Reprinted from *Modern Ceramic Engineering*, 2nd edition, p. 681, by courtesy of Marcel Dekker, Inc.)

Ceramic Mechanical Properties

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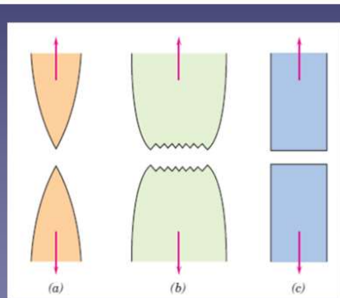


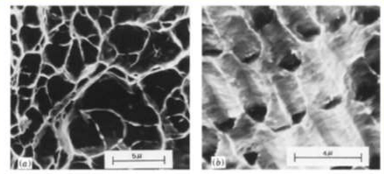


Figure 8.4 (*a*) Scanning electron fractograph showing spherical dimples characteristic of ductile fracture resulting from uniaxial tensile loads. 3300×. (*b*) Scanning electron fractograph showing parabolic-shaped dimples characteristic of ductile fracture resulting from shear loading. 5000×. (From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

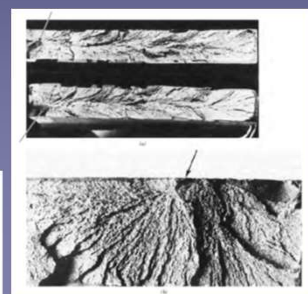


Figure 8.5 (*a*) Photograph showing V-shaped "chevron" markings characteristic of brittle fracture. Arrows indicate origin of crack. Approximately actual size. (*b*) Photograph of a brittle fracture surface showing radial fan-shaped ridges. Arrow indicates origin of crack. Approximately 2×. [(*a*) From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc. Photograph courtesy of Roger Slutter, Lehigh University. (*b*) Reproduced with permission from D. J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.]

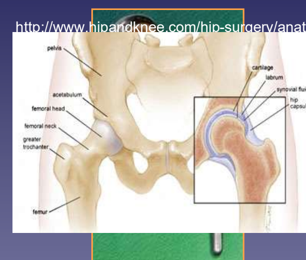
Classes of Bioceramics

- Bioinert Ceramics
  - Exhibit morphological fixation without biochemical bonding
  - Ceramic bearing surfaces
    - Alumina
    - Zirconia
- Bioactive Ceramics
- Bioresorbable Ceramics

Ceramics for Hip: Cartilage or Bone

- Most Common
  - Alumina and Zirconia
    - Cartilage
  - Calcium Phosphate Coating
    - Bone bonding
  - Bioactive Glass Coating
    - Bone bonding

http://www.hipandknee.com/hip-surgery/anatomy-of-



Stryker Trident® Ceramic System

  - Readings (Ratner: Sec.I.2.4, 1.2.6, Sec. II.5.6; Callister: Chaps. 12, 13 and 22.10-hip)

Alumina

- Structure
  - Hexagonal organization with Al ions at octahedral interstitial sites
  - 99.5% Al_2O_3, 0.5% MgO (aids sintering)

FIGURE B.1 Crystal structure of alumina (○ aluminum, ● oxygen).

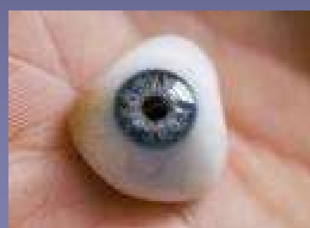
- Properties
  - High strength and high abrasion resistance
  - Density of 3.97 g/cm^3, E = 300 GPa
  - Kc = 3-5 MPa $\sqrt{m}$ – low fracture toughness
  - Low coefficient of friction
    - Surface roughness <0.02 microns
  - Biocompatible

TABLE B.1 Mechanical Properties of 99.5% Alumina

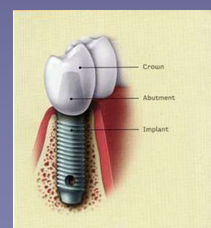
Density	3.97 gm/cm^3
Flexural strength	345 MPa
Elastic modulus	300 GPa
Shear modulus	124 GPa
Bulk modulus	172 GPa
Poisson's ratio	0.21
Compressive strength	2100 MPa
Hardness	1000 kg/mm^2
Fracture toughness	3.5 MPa.m$^{1/2}$

Alumina

- **Fabrication**
  - Hot isostatic pressing (1600-1700ºC)
  - Small grain size (<4 mm)
    - If increased size to 17 mm, reduces yield stress by 20%
- **Applications**
  - Used as artificial eye, in dental and orthopedics



Source: medgadget.com



Source: premieroralsurgery.com

Ceramic Mechanical Properties

Table 8.1 Room-Temperature Yield Strength and Plane Strain Fracture Toughness Data for Selected Engineering Materials

	Yield Strength		K_{Ic}	
Material	*MPa*	*ksi*	$MPa\sqrt{m}$	$ksi\sqrt{in.}$
Metals				
Aluminum Alloy[a] (7075-T651)	495	72	24	22
Aluminum Alloy[a] (2024-T3)	345	50	44	40
Titanium Alloy[a] (Ti-6Al-4V)	910	132	55	50
Alloy Steel[a] (4340 tempered @ 260°C)	1640	238	50.0	45.8
Alloy Steel[a] (4340 tempered @ 425°C)	1420	206	87.4	80.0
Ceramics				
Concrete	—	—	0.2–1.4	0.18–1.27
Soda-Lime Glass	—	—	0.7–0.8	0.64–0.73
Aluminum Oxide	—	—	2.7–5.0	2.5–4.6
Polymers				
Polystyrene (PS)	—	—	0.7–1.1	0.64–1.0
Poly(methyl methacrylate) (PMMA)	53.8–73.1	7.8–10.6	0.7–1.6	0.64–1.5
Polycarbonate (PC)	62.1	9.0	2.2	2.0

[a] **Source:** Reprinted with permission, *Advanced Materials and Processes,* ASM International, © 1990.

Alumina

- **Advantages**
  - Relatively chemically inert
    - Used for over 20 years in orthopedic applications
  - Biocompatible
    - Thin fibrous capsule formed which allows cementless fixation of prosthesis
  - Good wear resistance and high strength
  - Provides lubrication
- **Disadvantages**
  - Poor shear strength
    - Less useful as screws or plates
  - Stress shielding
    - 380-420 GPa vs. 0.05-5GPa for cancellous or 7-25 for cortical bone

Stryker Trident® Ceramic System

Zirconia

- ZrO_2
  - Tetragonal structure stabilized by yttrium oxide, Y_2O_3
- Articulating ball in total hip prostheses
- Low surface roughness (Ra) vs. Co-Cr
- Advantages over alumina
  - Hardness
  - Higher strength
- Composites

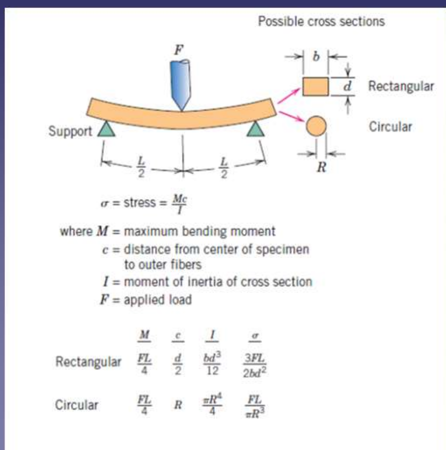
FIGURE B.5 BIOLOX®* delta ceramic femoral head.

BIOLOX®* Delta Ceramic Femoral Head

The new alumina matrix composite, BIOLOX® delta developed by CeramTec AG, is used by Zimmer Inc. to fabricate femoral heads. This composite has excellent biocompatibility, low wear rates, high hardness, and is very stable in *in vivo*-like environments. The implant made from this composite meets the increasing demands of development of a durable implant for young and active patients. The heads fabricated from this ceramic have improved mechanical properties compared to standard alumina heads. The composite consists of about 75% alumina, 24% zirconia, and 1% chromium oxide. Alumina provides the hardness and the wear resistance, while zirconia along with chromium oxide provides improved mechanical properties. The pink color of the implant is also derived from chromium oxide (Figure B.5).

Sou

Ceramic Mechanical Properties



where F_f is the load at fracture, L is the distance between support points, and the other parameters are as indicated in Figure 12.32. When the cross section is circular, then

$$\sigma_{fs} = \frac{3F_f L}{2bd^2} \qquad \sigma_{fs} = \frac{F_f L}{\pi R^3} \qquad (12.7b)$$

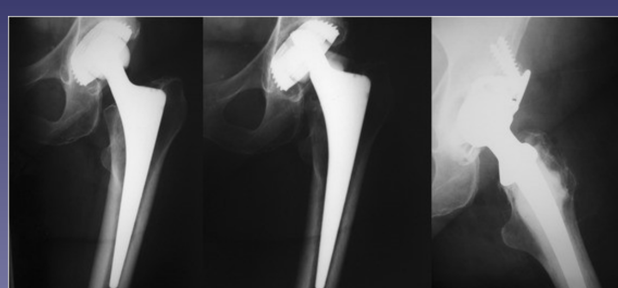
where R is the specimen radius.

	Flexural Strength		*Modulus of Elasticity*	
Material	*MPa*	*ksi*	*GPa*	*10^6 psi*
Silicon nitride (Si_3N_4)	250–1000	35–145	304	44
Zirconia[a] (ZrO_2)	800–1500	115–215	205	30
Silicon carbide (SiC)	100–820	15–120	345	50
Aluminum oxide (Al_2O_3)	275–700	40–100	393	57
Glass-ceramic (Pyroceram)	247	36	120	17
Mullite ($3Al_2O_3$-$2SiO_2$)	185	27	145	21
Spinel ($MgAl_2O_4$)	110–245	16–35.5	260	38
Magnesium oxide (MgO)	105[b]	15[b]	225	33
Fused silica (SiO_2)	110	16	73	11
Soda-lime glass	69	10	69	10

[a] Partially stabilized with 3 mol% Y_2O_3.

[b] Sintered and containing approximately 5% porosity.

Durability of Biolox Al_2O_3 Ceramic on Polyethylene (coP) bearings in THA 0.29% in 22 years



Radiographs of the hip with the fractured ceramic head. Left: directly post-OP: Middle: Fracture of ceramic head at 6.25 years postop; Right: After revision arthroplasty

Beckmann et al., BMC Muscul. Disord. 2015, 16:249

Ceramic-on-Ceramic (C-on-C) Bearings

- Used largely in Europe (~50%)
  - 1970: introduced in France by Pierre Boutin
  - <10% in UK and USA
  - Good for young, active patients
- Advantages
  - High level of Hardness and Scratch resistance
  - Superior lubrication and wear
  - Inert degradation products
- Disadvantages
  - Poor shear strength
    - fracture often occurs at the OR
  - Stress shielding
  - Costly

Stryker Trident® Ceramic System

Comparison of THA Articulation

Orthopedic Reviews 2011; volume 3:e16

Total Hip Arthroplasty - over 100 years of operative history

Stephen Richard Knight,[1] Randeep Aujla,[2] Satya Prasad Biswas[3]

[1]University of Leicester; [2]University Hospitals of Leicester, Medical School, Leicester; [3]Kettering General Hospital, Kettering, UK

Figure CS4.6 Diagram representing possible hip-replacement systems based on femoral head-acetabular liner material combinations. "MoM" = metal-on-metal, "MoP" = metal-on-polymer, "CoP" = ceramic on polymer, and "CoC" = ceramic-on-ceramic.

Table 1. Comparison of materials used in total hip arthroplasty.

Prosthesis	Advantages	Disadvantages
Metal-on-polyethylene	Large volume of evidence to support use Predictable lifespan Cost effective	Polyethylene debris leading to aseptic loosening
Metal-on-metal	Potentially longer lifespan than polyethylene due to reduced wear Larger femoral head - therefore lower dislocation rate	Metallosis Potential carcinogenic effect of metal ions
Ceramic-on-ceramic	Low friction Low debris particles Inert substance	Expensive Require expert insertion to prevent early damage Can produce noise on movement

THA – Wear Debris

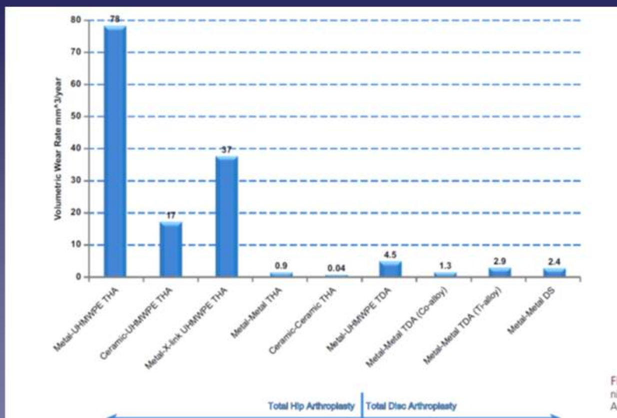


FIGURE II.5.6.13 A comparison of the amount of wear debris generated from different types of total joint arthroplasties. There is relatively less (10×) polymeric debris generated by a total disc arthroplasty with a metal-on-polymer articulation. Note: Figure References: Metal-Poly (Holt et al., 2007); Ceramic-Poly (Jacobs et al., 1994c); Metal-X-linked Poly (Martinon et al., 2006); Metal-X-linked Poly (Jacobs et al., 1994c); Metal-X-linked Poly (Hallab, 2009); Metal-X-linked Poly (Hallab, 2009); Metal-Metal (Huk et al., 1994); Ceramic-Ceramic (Hallab, 2009); Metal-UHMWPE TDA (Hallab, 2009); Metal-Metal TDA (Hallab, 2009).

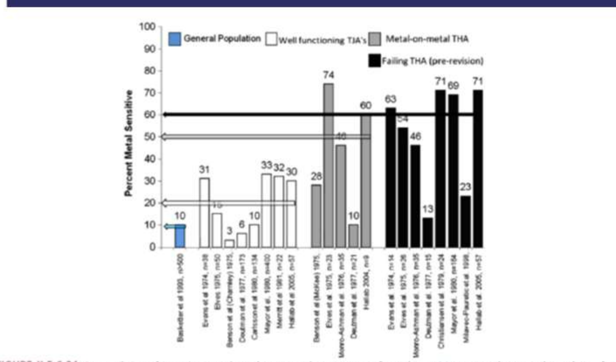


FIGURE II.5.6.24 A compilation of investigations show the averaged percentages of metal sensitivity among the general population for nickel, cobalt, and chromium, among patients after receiving a metal-containing implant, and among patient populations with failed implants. All subjects were tested by means of a patch or metal-LTT (lymphocyte transformation test).

Classes of Bioceramics

- Bioinert Ceramics
- Biomimetic and Bioactive Ceramics
  - Elicit a specific biological response which results in biological bonding
    - Formation of carbonated hydroxyapatite layer at tissue-material interface
    - Bioactive glasses
- Bioresorbable Ceramics

Calcium Phosphates

- **Calcium sulfate**: Plaster of Paris
- **Hydroxyapatite:** $Ca_{10}(PO_4)_6(OH)_2$
  - Ca/P=1.67, E = 40-116 GPa
  - Carbonate, fluorine, and chlorine Ions incorporated into structure
- **Tricalcium Phosphate:** $Ca_3(PO_4)_2$
  - Ca/P=1.50
  - Alpha and beta crystal form
  - Ionic substitution with carbonate

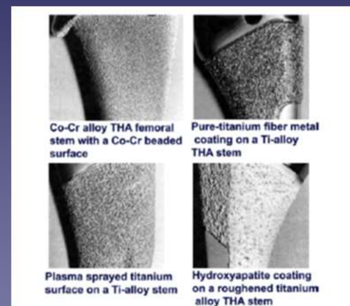


FIGURE II.5.6.12 Examples of currently used surface coatings on stems of THA to enhance both short- and long-term fixation.

Apatites and other phosphates

- Hydroxyapatite
  - $Ca_{10}(PO_4)_6(OH)_2$
  - Hexagonal symmetry
  - a=0.95 nm, c=0.68 nm
  - Most similar to bone mineral
  - Bioactive, osteoconductive
- Ca/P ratio, acidity, and solubility are closely related
  - Ca/P<1, high acidity and solubility
  - Ca/P=1.67 for stoichiometric HA

TABLE I.2.4.10 Typical Mechanical Properties of Dense Hydroxyapatite Ceramics

Theoretical density	3.156 g cm^3
Hardness	500–800 HV, 2000–3500 Knoop
Tensile strength	40–100 MPa
Bend strength	20–80 MPa
Compressive strength	100–900 MPa
Fracture toughness	approx. 1 Mpa m$^{0.5}$
Young's modulus	70–120 GPa

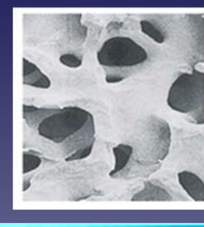
(Vallet-Regí M et al., 2004)

	Bone site (rabbits)			
Sex	Rear tibia	Femur	Front tibia	Rib
Male	2.07 ± 0.12	2.08 ± 0.13	2.06 ± 0.09	1.97 ± 0.05
Female	2.07 ± 0.09	2.08 ± 0.08	2.11 ± 0.08	1.95 ± 0.05

(Kourkoumelis N et al., 2011)

Calcium Phosphates

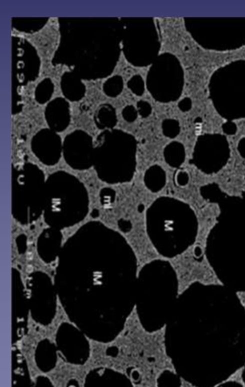
- **Biological or synthetic**
  - Porous, derived from coral, pore>100 μm
- **Bioactive**
  - Osteointegration, osteoconduction, osteoinduction
- **Biodegradable**
  - β-TCP>HA

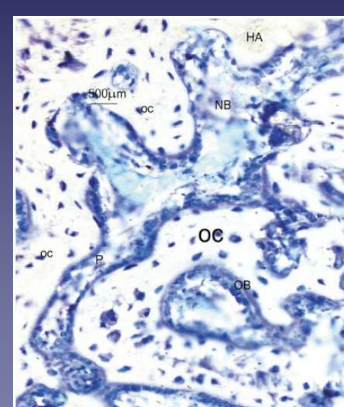


news.bbc.co.uk

Degradation and Osteointergration of HA

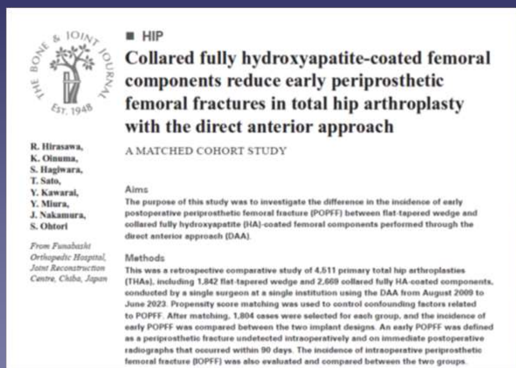
- **Physical properties**
  - Form (particulate or bulk)
  - Porosity (interconnectivity, size)
  - Crystallinity (grain size, crystal size)
- **Chemical properties**
  - Ionic substitutions
  - Other elemental impurities
- **Biological properties**
  - pH
  - Age, species, sex





Damien et al, 2002

Hip Implant – with or without HA collar



■ HIP

Collared fully hydroxyapatite-coated femoral components reduce early periprosthetic femoral fractures in total hip arthroplasty with the direct anterior approach

A MATCHED COHORT STUDY

R. Hirasawa, K. Oinuma, S. Hagiwara, T. Sato, Y. Kawarai, Y. Miura, J. Nakamura, S. Ohtori

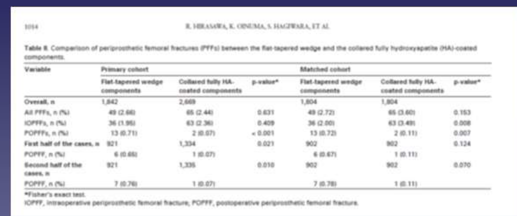
From Funabashi Orthopedic Hospital, Joint Reconstruction Centre, Chiba, Japan

Aims

The purpose of this study was to investigate the difference in the incidence of early postoperative periprosthetic femoral fracture (POPFF) between flat-tapered wedge and collared fully hydroxyapatite (HA)-coated femoral components performed through the direct anterior approach (DAA).

Methods

This was a retrospective comparative study of 4,511 primary total hip arthroplasties (THAs), including 1,842 flat-tapered wedge and 2,669 collared fully HA-coated components, conducted by a single surgeon at a single institution using the DAA from August 2009 to June 2023. Propensity score matching was used to control confounding factors related to POPFF. After matching, 1,804 cases were selected for each group, and the incidence of early POPFF was compared between the two implant designs. An early POPFF was defined as a periprosthetic fracture undetected intraoperatively and on immediate postoperative radiographs that occurred within 90 days. The incidence of intraoperative periprosthetic femoral fracture (IOPFF) was also evaluated and compared between the two groups.



1014 R. HIRASAWA, K. OINUMA, S. HAGIWARA, ET AL.

Table II. Comparison of periprosthetic femoral fractures (PFFs) between the flat-tapered wedge and the collared fully hydroxyapatite (HA)-coated components.

Variable	Primary cohort			Matched cohort		
	Flat-tapered wedge components	Collared fully HA-coated components	p-value*	Flat-tapered wedge components	Collared fully HA-coated components	p-value*
Overall, n	1,842	2,669		1,804	1,804	
All PFFs, n (%)	49 (2.66)	65 (2.44)	0.631	49 (2.72)	65 (3.60)	0.153
IOPFF, n (%)	36 (1.95)	63 (2.36)	0.409	36 (2.00)	63 (3.49)	0.008
POPFFs, n (%)	13 (0.71)	2 (0.07)	< 0.001	13 (0.72)	2 (0.11)	0.007
First half of the cases, n	921	1,334	0.021	902	902	0.124
POPFF, n (%)	6 (0.65)	1 (0.07)		6 (0.67)	1 (0.11)	
Second half of the cases, n	921	1,335	0.010	902	902	0.070
POPFF, n (%)	7 (0.76)	1 (0.07)		7 (0.78)	1 (0.11)	

*Fisher's exact test.
IOPFF, intraoperative periprosthetic femoral fracture; POPFF, postoperative periprosthetic femoral fracture.

Fig. 2

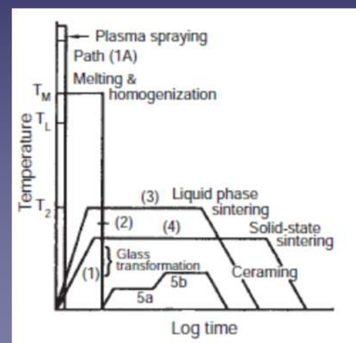
Representative radiograph images of Vancouver classification type A(G) and A(L) fractures. a) Radiograph immediately after surgery (case 14). b) Type A(G) fracture at the time of fracture occurrence (three days postoperatively). c) Radiograph immediately after surgery (case 2). d) Type A(L) fracture at the time of fracture occurrence (14 days postoperatively).

Porosity vs. Mechanical Properties

- **Material Porosity**
  - Total void volume
  - Average Pore diameter
  - Total surface area
  - Interconnectivity between pores
- **Compressive & Tensile strength**
  - Compressive strength (σ_c) vs. total pore volume (Vp)
    - $\sigma_c = 700e^{-5Vp}$
  - Tensile strength (σ_t) vs. volume fraction of microporosity (Vm)
    - $\sigma_t = 200e^{-20Vm}$

Ceramics

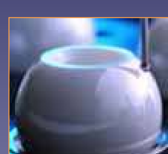
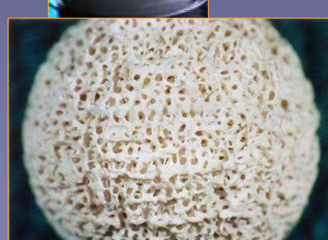
- Bioactive
  - Bioactive surface functionalization
- Biomimetic
- Degradation products well tolerated
- Poor Mechanical Properties
  - Low shear strength
  - Low ductility
  - Low viscoelastic response
  - Low fracture toughness
  - Brittle fracture
  - →Not used in high load-bearing condition



BIOMATERIALS: Ceramics

Applications

Load bearing conditions
Joint replacement
Orthopedic/Dental

Advantages

Controllable design
Biocompatible/Inert
Lubrication
Biomimetic
Bioactive

Limitations

Stress Shielding
Low fracture toughness

TYPES OF BIOMATERIALS

- Metals
- Ceramics
- Glasses Ceramics
- Polymers
- Natural Biomaterials
- Composites

Biomaterials: Polymers

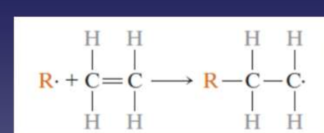
- Readings: Ratner - Sec.I.2.2, II.5.6
  Callister – Chap. 14, 15, 8.12
- Two Classes
  - Homopolymer
    - Listed in Figure 5, p.71 Ratner
  - Co-Polymer
    - Listed in Figure 6, p.72 Ratner
- Application
  - Wound healing (skin)
  - Cardiovascular and Orthopedic

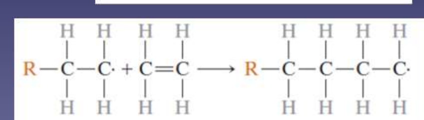
Polymers in Medicine

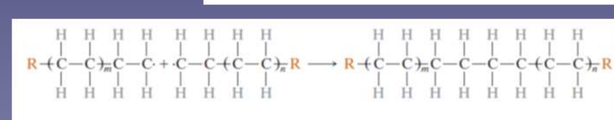
- **Homopolymers**
  - Polymethylmethacrylate (PMMA)
  - Polyethylene (PE)
  - Polytetrafluoroethylene (PTFE)
  - Polyvinyl Chloride (PVC)
  - Polydimethylsiloxane (PDMS)
  - Polyacrylamides (PAGE)
  - Polyamides (Nylon)
  - Polycaprolactone (PCL)
- **Co-Polymers**
  - Polyurethanes
  - Polyhydroxethylmeth acrylate (pHEMA)
  - Polyesters (PGA, PLA,PLGA)

Polymers Synthesis

- **Addition Polymerization**
  - Unsaturated monomers are attached one at a time to form a chain
  - Reactive species (R) disrupts the double bond
  - Initiation: R can be free radical
  - Propagation
  - Termination



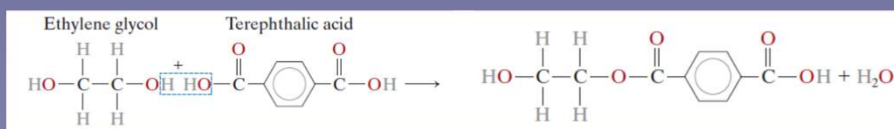




- MW depends on rate and duration of each step of the reaction, especially the propagation

Polymers Synthesis

- **Condensation Polymerization**
  - Two monomers react via condensation reaction
  - Monomer has at least two reactive sites, functional groups instead of double bonds
  - Small molecule (water or methanol) is condensed or released
  - Reaction time is longer than Addition Polymerization
  - More expensive
- **Production of Poly(ethylene-terephthalate)**



Polymer Structure

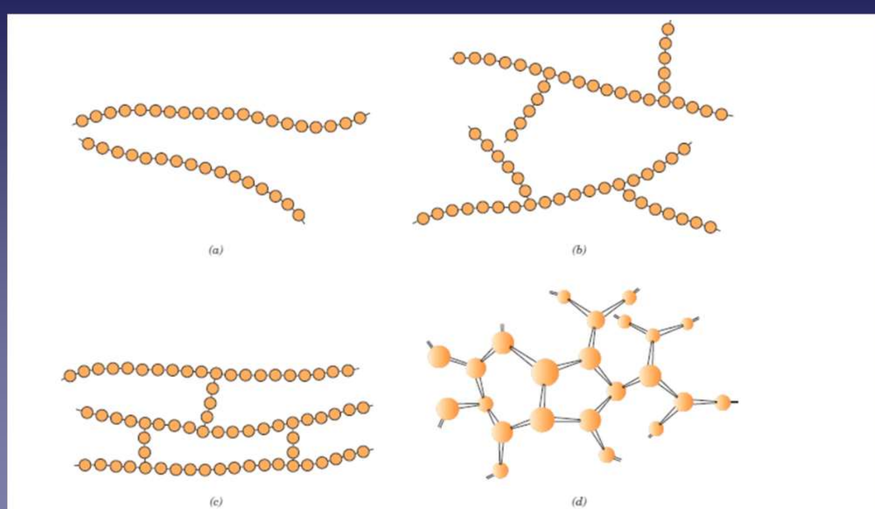


Figure 14.7 Schematic representations of (a) linear, (b) branched, (c) crosslinked, and (d) network (three-dimensional) molecular structures. Circles designate individual repeat units.

Mechanical Properties of Polymers

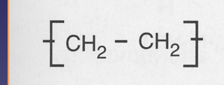
Polymer	σ_{UTS} (MPa)	E (GPa)	Ductility ε_f (%)	Poisson's Ratio
Polyethylene	7-40	0.1-1.4	1000-15	0.46
Polypropylene	20-35	0.7-1.2	500-10	-
Polystyrene	14-83	1.4-4	60-1	0.35
Polyester	55	2	300-5	0.38
Polyamide (nylon)	55-83	1.4-2.8	200-60	0.32-0.40

Polymer in THA: Replace Cartilage

FIGURE II.5.6.10 Examples of the three types of bearing couples used in modern TJA. From top to bottom: metal-on-polymer, ceramic-on-ceramic, and metal-on-metal (Lineage™ line from Wright Medical Technology, Inc. Arlington, TN, USA).

Polymers in Medicine

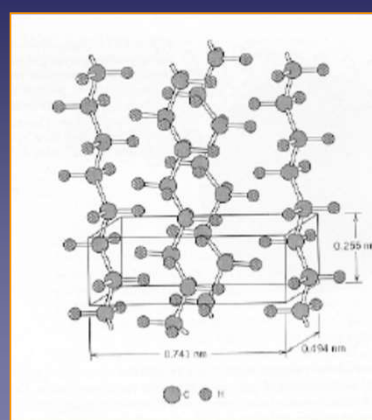
- **Polyethylene (PE, HDPE, UHMWPE)**
  - HDPE and UHMWPE are used clinically
  - Linear polymer chain
  - Synthesized via addition polymerization
  - Crosslinked via Gamma radiation (2.5-5.0 Mrad)
  - heat treated to reduce residual free radicals
  - T_m = 130-136ºC
  - Applications
    - Acetabular component of hip and knee prostheses
    - Artifical Cartilage



Polyethylene (PE)

Polymer: Crystal Structure

- **Polyethylene**
  - orthorhombic crystal structure
  - Bi-functional monomer unit, with two reactive bonds through which the chain is propagated
  - Ribbon like chains folded in lamellae of about 10nm in thickness
  - Lattice parameters:
    - a≠b≠c, α=β=ɣ=90º, a=0.494 nm, b=0.741 nm, c=0.255 nm,
    - <C-C = 109.5º, conserved thorough out the backbone



Polyethylene: Crystal Structure

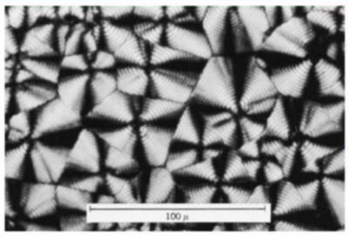
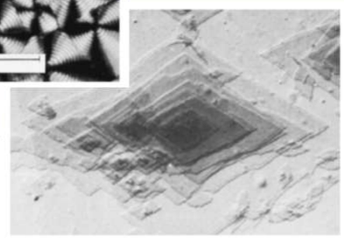


Figure 14.14 A transmission photomicrograph (using cross-polarized light) showing the spherulite structure of polyethylene. Linear boundaries form between adjacent spherulites, and within each spherulite appears a Maltese cross. 525×. (Courtesy F. P. Price, General Electric Company.)



Doremus, B. W. Roberts, and D. Turnbull (Editors), *Growth and Perfection of Crystals*. General Electric Company and John Wiley & Sons, Inc., 1958, p. 498.]

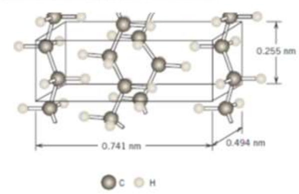


Figure 14.10 Arrangement of molecular chains in a unit cell for polyethylene. (Adapted from C. W. Bunn, *Chemical Crystallography*, Oxford University Press, Oxford, 1945, p. 233.)

Orthorhombic

Polymers in THA: Acetabular Cup

- Charnley: PTFE (1950) to UHMWPE (1962)
- UHMWPE (100-250k mers, MW~4M g/mol)
  - Structurally long chains of PE
  - Aligned chains joined by VW forces
  - Low coefficient of friction, self lubrication
  - Susceptible to oxidation
  - Leading to increased wear and reduced fatigue resistance
  - Wear products (>10^9/yr, 1-10microns)

- 1998: highly crosslinked UHMWPE – Gamma or e-beam along with heat treatment
- 2007: Anti-oxidant doped UHMWPE –Vitamin E
- Vitamin E neutralized free radicals in polymer formed or left over from sterilization by radiation

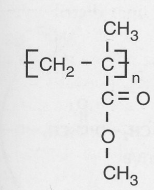
Polymers in Medicine

- **Polyethylene (PE)**
  - Advantages
    - Low coefficient of friction (.15-0.20 dry on SSL)
    - Resistance to lipid adsorption
    - Relatively strong at high density
    - Highest abrasion resistance
    - Highest impact strength
    - Lightweight (0.94 g/cm^3)
    - Economical
  - Disadvantages
    - Wear products nonbiocompatible
    - Non-biodegradable

BIOMET

Polymers in Medicine

- **Polymethylmethacrylate (PMMA)**
  - Oldest polymer in service
  - Hydrophobic linear chain polymer
  - Synthesized via free radical polymerization
  - Applications
    - Intraocular Lens
    - Hard contact lenses
    - Bone cement

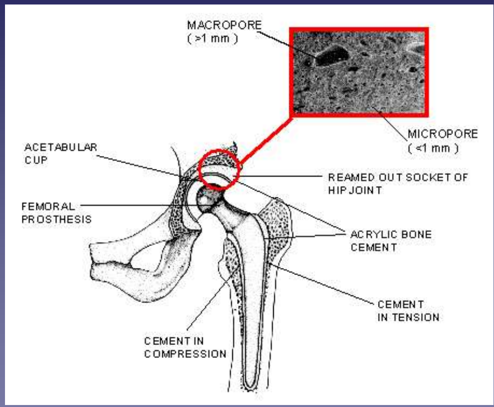


Poly(methyl-methacrylate) (PMMA)

Stryker SIMPLEX® PMMA Cement

Polymers in THA: PMMA Cement

FIGURE II.5.6.9 Examples of cemented and non-cemented stems showing the plug and centralizer used with a cemented stem. (Picture courtesy of Zimmer, Inc.)



To Cement or not to Cement?

Polymers in Medicine

- Polymethylmethacrylate (PMMA)
  - Advantages
    - Good optical properties
    - Relatively biocompatible
  - Disadvantages
    - Exothermic reaction during polymerization
    - Toxic monomer if degraded

BIOMET
COBALT™ HV BONE CEMENT
Radiopaque Bone Cement

Polymers used in Intraocular Lens Implants

Healthy | Cataract | IOL

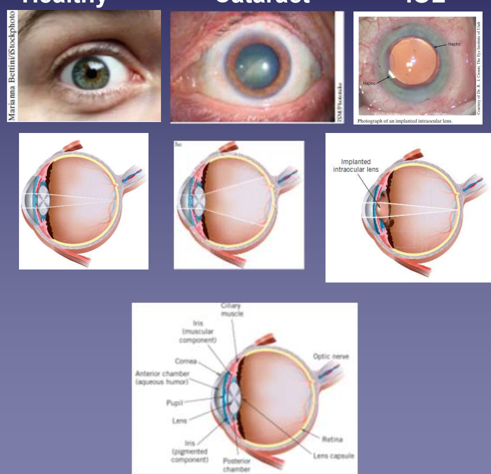


Table CS5.1 Names, Types, and Characteristics of Intraocular Lenses

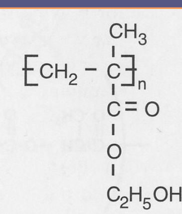
Manufacturer	*Product Name*	*Type of IOL*	*Biomaterial/Features*
Bausch & Lomb	Crystalens	Multifocal (single-focus accommodating)	Biosil (solid silicone)
Alcon	AcrySof IQ Monofocal	Monofocal	Phenylethyl acrylate–phenylethyl methacrylate crosslinked copolymer
	AcrySof IQ ReSTORE	Multifocal	Acrylate–methacrylate copolymer, apodized (tapered diffractive steps)
	AcrySof IQ Aspheric	Aspheric	Hydrophobic acrylate–methacrylate copolymer
	AcrySof IQ Toric	Monofocal, toric, aspheric	Hydrophobic acrylate–methacrylate copolymer
Abbott Medical Optics	ReZoom	Multifocal	High-index acrylic, PMMA haptics, multifocality achieved by a series of rings
	Tecnis Multifocal 1-Piece	Multifocal, aspheric	Hydrophobic acrylic, multifocality achieved by a series of rings
	Tecnis Multifocal 3-Piece	Multifocal, aspheric	Hydrophobic acrylic, PMMA haptics, multifocality achieved by a series of rings
	Tecnis Acrylic	Aspheric	Hydrophobic acrylic, PMMA haptics
	Tecnis CL Silicone	Aspheric	SLM-2 Silicone, PMMA haptics
Staar Surgical	NanoFLEX Collamer	Aspheric	Collagen/poly-HEMA copolymer; single-piece
	Afinity Collamer	Aspheric	Collagen/poly-HEMA copolymer; three-piece
	Elastimide	Aspheric	Silicone, aspheric, 3-piece, polyimide haptics
	Elastic	Aspheric	Silicone, single-piece
	Toric	Toric	Silicone, single-piece

Source: Manufacturers' data sheets.

Biomaterial: Polymers

- **Polyhydroxyethylmethacrylate (PHEMA)**
  - Hydrogel material: permeable
  - Water content similar to living tissue (58% in ACUVUE®)
  - Relatively Inert and non-degradable
  - Used as contact lenses

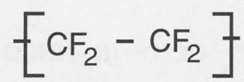
HEMA/ MA UV blocker



Poly (2-hydroxyethyl-methacrylate) poly(HEMA)

Polymers in Medicine

- **Polytetrafluoroethylene (PTFE, Teflon)**
- **Similar to PE, except H is replaced by F**
  - Synthesized via condensation polymerization
  - T_m = 327ºC



Polytetrafluoroethylene (PTFE)

Polymers in Medicine

- **PTFE: Applications**
  - Cardiovascular grafts
    - Artificial blood vessel
    - Coatings for metallic devices
  - Orthopedic soft tissue replacements
    - Ligaments
    - Tendons

Edwards Lifespan ePTFE

Polymers in Medicine

- PTFE
  - Advantages
    - Low coefficient of friction - lubrication
    - Chemically stable
    - Anti-adhesion surface (hydrophobic)
  - Disadvantages
    - Poor fatigue strength - Wear products
    - Difficult to process
      - Non-reactive thermally and chemically
    - Expensive

Polymers in Medicine

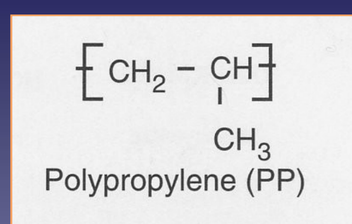
- PTFE + hexafluoropropylene (FEP-Teflon)
  - hexafluoropropylene
    - Added to increase processibility
    - Melting pt at 265ºC vs. 327ºC for PTFE
    - Still Chemically stable
    - Maintains low friction coefficient

Polymers in Medicine

- **Polyethylene Glycol (PEG)**
  - Water soluble, waxy polymer
  - Photopolymerizable hydrogel
  - Used in cosmetic industry
  - Used in drug delivery
  - Used to graft onto material surface and form non-fouling surfaces

Biomaterial: Polymers

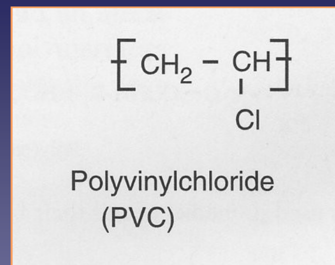
- **Polypropylene (PP)**
  - High rigidity and good chemical resistance
  - Relatively high tensile strength
  - Improved resistance to stress cracking when compared to PE
  - Used as surgical mesh, onlays in hernia repair



Ethicon PROLENE® Hernia System

Biomaterial: Polymers

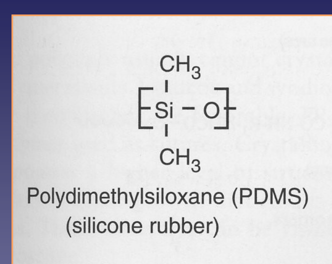
- **Polyvinyl Chloride (PVC)**
  - Derived from mineral oil, natural gas
  - 25% of all medical plastics (Baxter)
  - Used as tubing in biomedical application
    - Blood transfusion
    - Dialyses
  - Brittle
    - only used as a non-permanent biomaterials

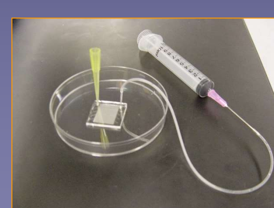


Baxter

Biomaterial: Polymers

- **Polymethylsiloxane (PDMS)**
  - Silicone oxygen backbone
  - Properties are relatively insensitive to temperature
  - Highly flexible material
  - Used as insulator coating for pacemakers, catheters
  - Used in micropatterning & microfluidics (BIOMEMS)

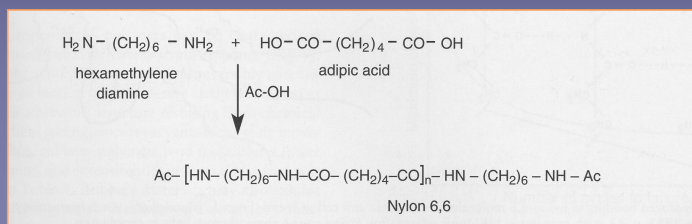




Biomaterial: Polymers

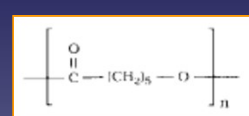
- **Polyamides (Nylon)**
  - **Highly elastic material**
  - **Flexible and durable**
  - **More hydrophobic than PU**
  - **Used as sutures, catheters and soft tissue replacement grafts**

Fostalon 5000



Biomaterial: Polymers

- **Poly-ε-Caprolactone (PCL)**
  - **Aliphatic polyester synthesized in the 1930s**
  - **Semicrystalline Polymer (T_m = 60ºC)**
  - **Degraded by hydrolysis and micro-organisms**
  - **Autocatalyzed by the carboxylic acid end groups**
  - **Forms carbon dioxide and water as products**
  - **Lower degradation rate than poly-α-hydroxyesters**
  - **Used as Capronor™**
    - **Transdermal contraceptive device**
    - **Implanted for up to 1 year**

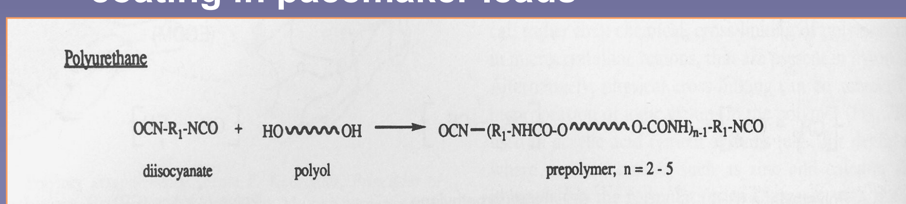


Polymers in Medicine

- Co-Polymers
  - Polyurethanes
  - Polyhydroxethylmethacrylate (pHEMA)
  - Polyesters (PGA, PLA,PLGA)

Biomaterial: Polymers

- Polyurethanes (PU)
  - Block copolymers (hard and soft blocks)
  - Blood biocompatible
  - Good fatigue properties
  - Used as tape, insulator coating in pacemaker leads



Implantable cardioverter defibrillators (ICDs)

- ICDS for treating tachyarrhythmia
- Polyurethan-coated ICD leads
- Medtronics Sprint Quattro™ 6944
  - Steroid eluding for reduced inflammation at the tissue-electrode interface
  - Silicone insulation with PU overlay for smooth lead passage
  - Electrode composition
    - Platinum/Iridium with porous Titanium Nitride coating

Medtronic

Biodegradable: Definitions

- Bioerodible: Degrade by hydrolysis
- Bioresorbable: Degrade by cellular activity
- Biodegradable: Degrade by enzymatic activity

Terms usually used <u>interchangeably</u> now

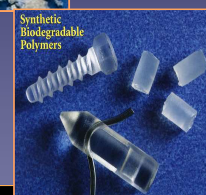
Bioerosion: the most general term

- Physical erosion: dissociation, dissolution
- Chemical erosion: hydrolysis (backbone & side chain)
- Enzymatic erosion: enzymatic hydrolysis and conversion
- Bacterial erosion: specific bacterial degradation

From K Leong Lecture Notes

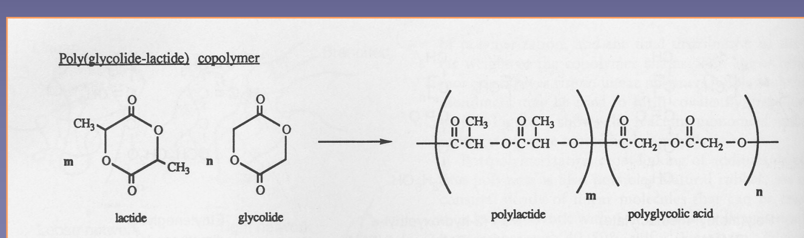
Polymers in Medicine

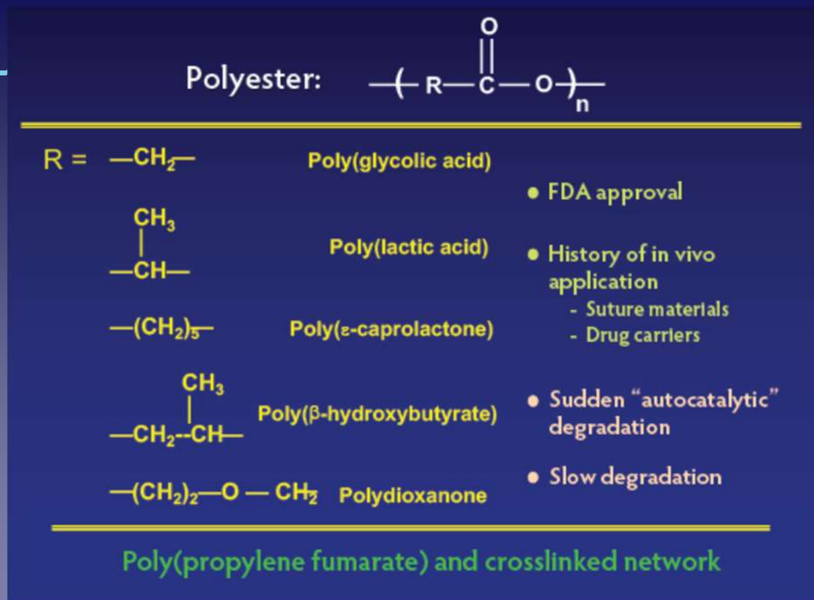
- **Poly-α-hydroxyesters**
  - **Applications**
    - **Cardiovascular grafts – heart valve**
    - **Orthopedic – fixation devices, sutures**
    - **Drug Delivery**
    - **Tissue Engineering applications**



Polymers in Medicine

- **Poly-α-hydroxyesters**
  - **Polyglycolic acid (PGA)**
  - **Polylactic acid (PLA, D or L or D,L)**
  - **Polylactic-co-glycolic acid (PLGA)**
  - **Synthesized via condensation polymerization**





From Prof. K. Leong

Polymers in Medicine

- Poly-α-hydroxyesters (PGA, PLA, PLGA)
  - Random or block co-polymer
  - Surface energy depend on LA:GA ratio
    - PLA – hydrophobic
    - PGA – hydrophilic
  - Degradation products
    - Lactic acid and/or glycolic acid
    - Acidic degradation products pH <4.0
    - Process via the normal metabolic cycles

Surface versus Bulk Degradation

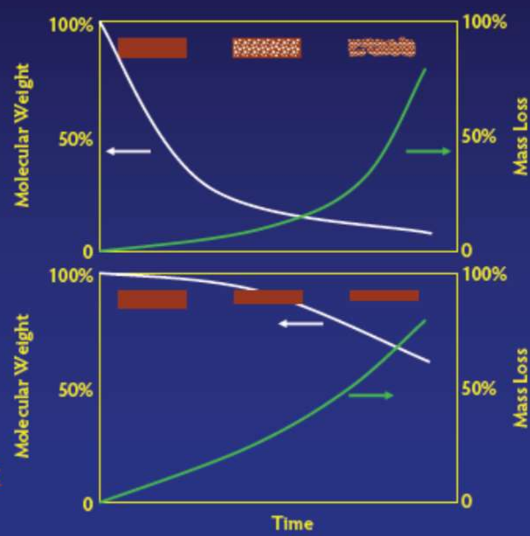
Bulk Degradation

$R_{H2O\ penetration} >> R_{cleavage}$

Surface Degradation

$R_{H2O\ penetration} << R_{cleavage}$

Geometry Dependent



From Prof. K. Leong

Biodegradable Polymers: Thermal

Polymer[a]	M_w	T_g(°C)	T_m(°C)	T_d(°C)	H_f(Jg^{-1})	X_c(%)[b]
Poly(ortho esters)						
t-CDM:1,6-HD = 35:65 [1a]	99 700	55	-	358	Amorphous	
t-CDM:1,6-HD = 70:30 [1b]	101 000	84	-	362	Amorphous	
t-CDM:1,6-HD = 90:10 [1c]	131 000	95	-	338	Amorphous	
Poly(glycolic acid) [2]	50 000	35	210	254	71	52
Poly(lactic acids) [3]						
L-PLA	50 000	54	170	242	41	30
L-PLA	100 000	58	159	235	20	15
L-PLA	300 000	59	178	255	39	29
D,L-PLA	21 000	50	-	255	Amorphous	
D,L-PLA	107 000	51	-	254	Amorphous	
D,L-PLA	550 000	53	-	255	Amorphous	
Poly(β-hydroxybutyrate) [4]						
Homopolymer (0 mol% HV) [4a]	370 000	1	171	252	51	-
Copolymer (7 mol% HV) [4b]	450 000	−1	160	243	32	-
Copolymer (11 mol% HV) [4c]	529 000	2	145	235	12	-
Copolymer (22 mol% HV) [4d]	227 000	−5	137	251	7	-
Poly(ε-caprolactone) [5]	44 000	−62	57	350	34	-
Polyanhydrides						
Poly(CPP-SA-ISO anhydride) [6]	31 000	-	46	297	1.2	-
Poly(SA-HDA anhydride) [7]	142 000	-	49	292	2.5	-
Poly(trimethylene carbonate) [8]	48 000	−15	-	261	Amorphous	
Polyiminocarbonates						
Poly(BPA-iminocarbonate) [10]	105 000	69	-	135	Amorphous	
Poly(DTH-iminocarbonate) [11][c]	101 000	55	-	138	Amorphous	

[a] Numbers in square brackets refer to the structures provided in the text.
[b] X_c was calculated from H_f, based on a calibration value of 72.3 J/g determined for PGA with a crystallinity of 52% (Reference 55).
[c] DTH: Dat-Tyr-Hex.

Polymer Mechanical Properties

Polymer[a]	M_w	Tensile strength (MPa)	Tensile modulus (MPa)	Flexural modulus[b] (MPa)	Elongation Yield (%)	Elongation Break (%)
Poly(ortho esters)						
t-CDM:1,6-HD – 35:65 [1a]	99 700	20	820	950	4.1	220
t-CDM:1,6-HD = 70:30 [1b]	101 000	19	800	1000	4.1	180
t-CDM:1,6-HD = 90:10 [1c]	131 700	27	1150	1250	3.4	7.0
Poly(glycolic acid) [2]	50 000	N/A	N/A	N/A	N/A	N/A
Poly(lactic acids) [3]						
L-PLA	50 000	28	1200	1400	3.7	6.0
L-PLA	100 000	50	2700	3000	2.6	3.3
L-PLA	300 000	48	3000	3250	1.8	2.0
D,L-PLA	21 000	N/A	N/A	N/A	N/A	N/A
D,L-PLA	107 000	29	1900	1950	4.0	6.0
D,L-PLA	550 000	35	2400	2350	3.5	5.0
Poly(β-hydroxybutyrate) [4]						
Homopolymer (0 mol% HV) [4a]	370 000	36	2500	2850	2.2	2.5
Copolymer (7 mol% HV) [4b]	450 000	24	1400	1600	2.3	2.8
Copolymer (11 mol% HV) [4c]	529 000	20	1100	1300	5.5	17
Copolymer (22 mol% HV) [4d]	227 000	16	620	750	8.5	36
Poly(ε-caprolactone) [5]	44 000	16	400	500	7.0	80
Polyanhydrides						
Poly(CPP-SA-ISO anhydride) [6]	31 000	N/A	N/A	N/A	N/A	N/A
Poly(SA HDA anhydride) [7]	142 000	4	45	N/A	14	85
Poly(trimethylene carbonate) [8]	48 000	0.5	3	N/A	20	160
Polyiminocarbonates						
Poly(BPA-iminocarbonate) [10]	105 000	50	2150	2400	3.5	4.0
Poly(DTH-iminocarbonate) [11][c]	101 000	40	1630	N/A	3.5	7.0

Mechanical Properties of PLA

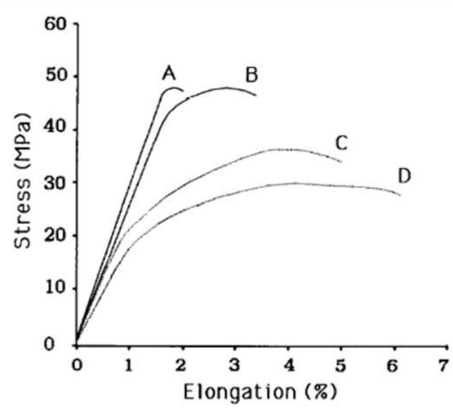
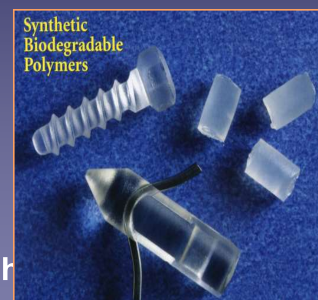


Figure 3 Stress–strain curves for various samples of PLA. Curves A and B were obtained from samples of poly(L-lactic acid) with mol wt of (A) 300 000 and (B) 100 000. The curves indicate mostly elastic deformation. Curves C and D were obtained from poly(D,L-lactic acid) with mol wt of (C) 550 000 and (D) 107 000. These curves show both elastic and plastic deformation.

Polymers in Medicine

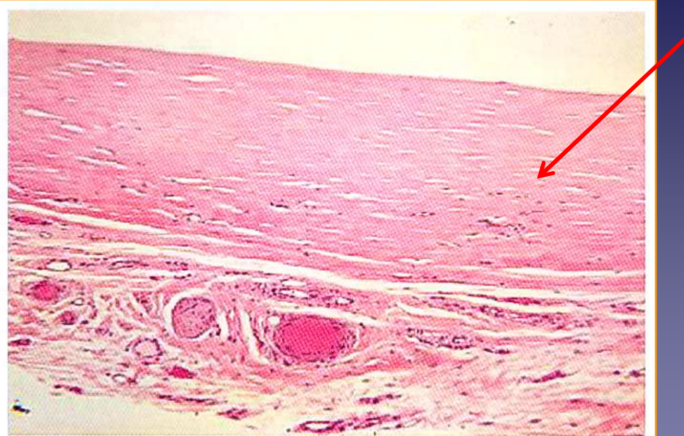
- **PLA, PGA, PLGA**
  - Sutures: PGA (Dexon™), PLLGA 10/90 (Vicryl®),
  - Advantages
    - Biodegradable
    - Biocompatible
    - Found in FDA – approved devices
  - Disadvantages
    - Acidic degradation products may be toxic at h
      - Implantation site (vasculature, transport)
    - Relatively weak mechanical properties



Polymer in THA: Replace Cartilage and Improve Fixation

FIGURE II.5.6.9 Examples of cemented and non-cemented stems showing the plug and centralizer used with a cemented stem. (Picture courtesy of Zimmer, Inc.)

Inert vs. Bioactive: Fibrous Capsule



Chapter 4.2, Fig. 9 Fibrous capsule composed of dense, compacted collagen. This fibrous capsule had formed around a Mediport catheter reservoir. Loose connective tissue with small arteries, veins, and a nerve is identified below the acellular fibrous capsule.

Bioactive Materials

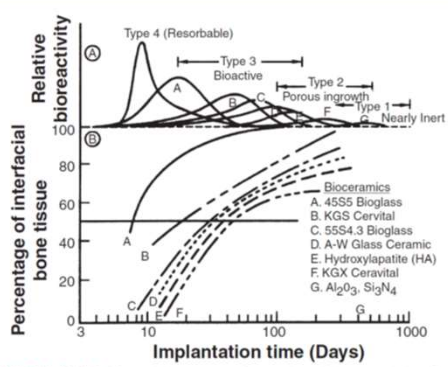


FIGURE I.2.4.1 Bioactivity spectra for various bioceramic implants: (A) Relative rate of bioreactivity; (B) Time-dependence of formation of bone bonding at an implant interface.

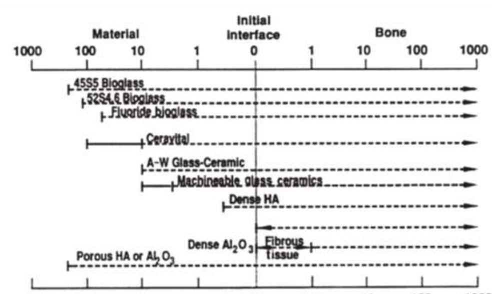


FIGURE I.2.4.2 Comparison of interfacial thickness (μm) of reaction layer of bioactive implants of fibrous tissue of inactive bioceramics in bone.

Bioactive Glass

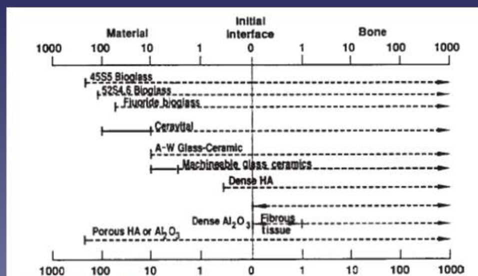


FIGURE I.2.4.2 Comparison of interfacial thickness (μm) of reaction layer of bioactive implants of fibrous tissue of inactive bioceramics in bone.

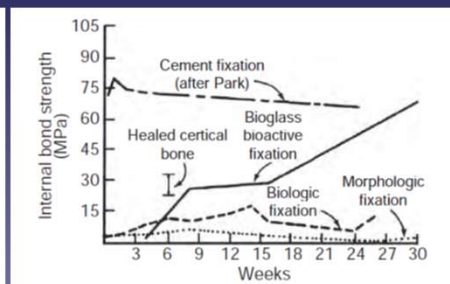
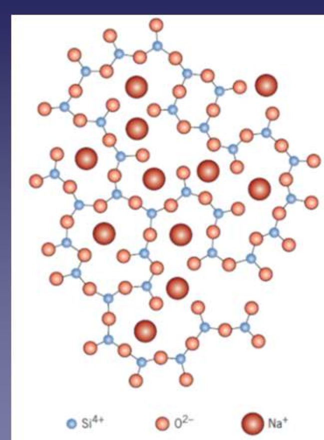


FIGURE I.2.4.7 Time dependence of interfacial bond strength of various fixation systems in bone. (After Hench, 1987.)

- Light micrograph of a 45S5 Bioglass® implant (BG) bonded to rat bone (B) after 1 year
- Bone cells (O) in conjunction with the hydroxylcarbonate apatite layer (Ca-P) formed on top of the silica gel (S). (Hench et al, 1982)

Bioactive Glasses

- **Composition and Structure**
  - SiO_2, Na_2O, CaO, P_2O_5
  - Less than 60% SiO_2
  - High network former content
    - Na_2O, CaO
  - High CaO/P_2O_5 ratio
  - Example: 45S5 bioactive glass (CaO/P_2O_5 =5)
    - 45% SiO_2, 24.5% Na_2O, 24.5% CaO, 6% P_2O_5



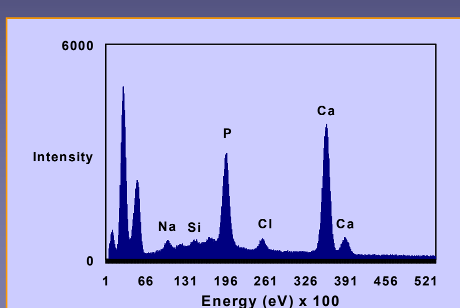
Silica Structure, Callister, 5th Ed, 2000

Bioactivity

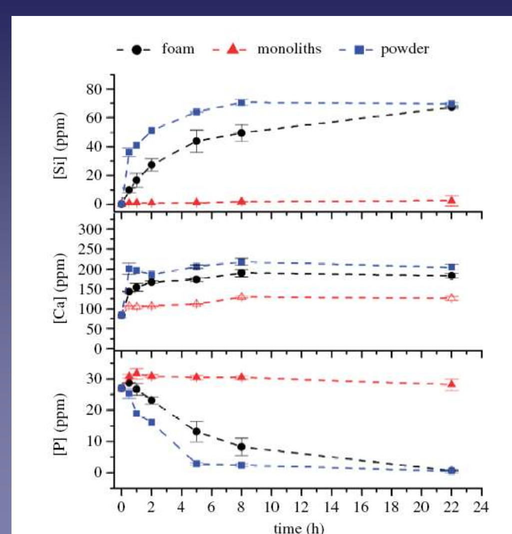
- **Osteointegration**
  - Chemical integration between bone and implant
  - Example: bioactive glass
- **Osteoconduction**
  - Materials that provide a scaffold for bone-forming cells and subsequent bone formation
    - Interconnecting porosity for cell and vascular ingrowth
  - Example: hydroxyapatite
- **Osteoinduction**
  - Materials that have a capacity to induce bone
    - Recruit stem cells
    - Induce proliferation and differentiation
  - Example: demineralized bone matrix

Bioactive Glasses

- **Properties**
  - Osteoinductive, osteoconductive, osteointegrative



EDX Analysis of Ca-P Layer Formation on PLGA-BG Composite

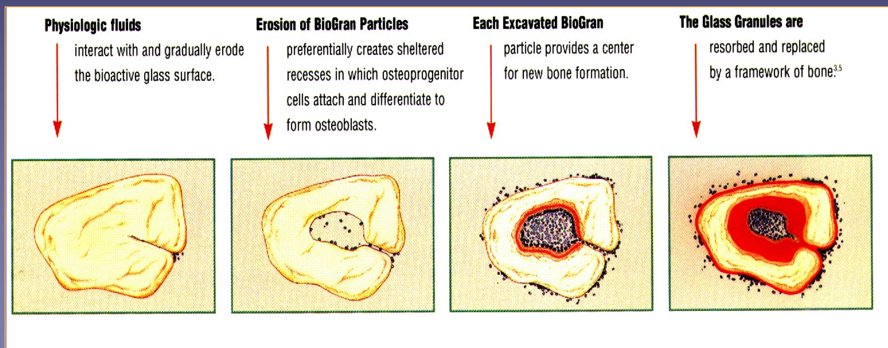


Dissolution Profiles, Jones et al, 2006

In Vivo Bioactivity

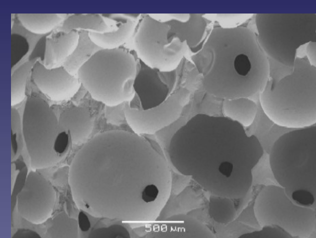
Applications

BIOGRAN® - bone/dental filler, 300-355 μm, Orthovita, Melvern, PA
Dental and orthopedic applications



Bioactive Glasses

- Advantages
  - Can elicit targeted cell response (bioactivity)
  - Tissue-material interface formation (biomimetic)
- Disadvantages
  - Dissolution products
  - Poor mechanical properties



BG Foam, SEM, Jones et al, 2006

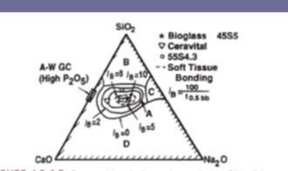


FIGURE I.2.4.5 Compositional dependence (in wt.%) of bone bonding and soft tissue bonding of bioactive glasses and glass-ceramics. All compositions in region A have a constant 6 wt.% of P_2O_5. A-W glass ceramic has higher P_2O_5 content (see Table I.2.4.5 for details). I_B, Index of bioactivity.

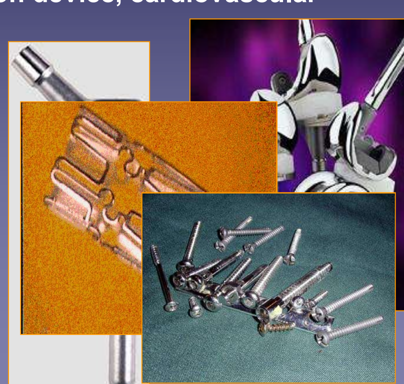
Classes of Bioceramics

- Bioinert Ceramics
- Bioactive Ceramics
- Bioresorbable Ceramics
  - Degrade gradually and allow for replacement by host tissue
    - Calcium phosphate ceramics
      - Tricalcium phosphate
      - Hydroxyapatite

Biomaterials: Metals

Applications

Load bearing conditions
Joint replacement
Fixation device, cardiovascular



Advantages

Controllable design
Biocompatible
Blood-compatible

Limitations

Stress Shielding
Corrosion
Fatigue and wear
Lifetime

BIOMATERIALS: Ceramics

Applications

- Load bearing conditions
- Joint replacement
- Orthopedic/Dental

Advantages

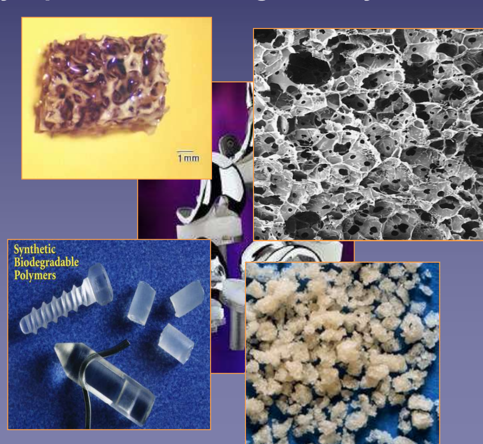
- Controllable design
- Biocompatible/Inert
- Lubrication
- Biomimetic
- Bioactive

Limitations

- Stress Shielding
- Low fracture toughness

BIOMATERIALS: Polymers

- Polyesters - sutures
- Polyanhydrides-drug delivery
- Polycaprolactone – drug delivery



Advantages

- Controllable design
- Biocompatible
- Biodegradable

Limitations

- Mismatch in properties
- Degradation products