BIOMATERIALS IN ORTHOPAEDICS

Lecture 3

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LEARNING OBJECTIVES

- Basic concepts and definitions
- Common orthopedic biomaterials and clinical applications
- General tissue implant responses
- Complication associated with biomaterials
- Recent advances

INTRODUCTION

A biomaterial is

- substance / combination of substances (other than a drug)
- Origin: synthetic / natural
- life span : not specified
- Augments / replaces any tissue, organ or function of the body

Bone plate in 1900,earliest successful biomedical implants

Artificial knee joint to alleviate pain and restore functions

BIOMATERIALS CLASSIFICATION

I
- First generation
- Bioinert materials

II
- Second generation
- Bio active and biodegradable materials

III
- Third generation
- Materials designed to stimulate specific responses at molecular level

FIRST GENERATION

- Invented in 1980
- AIM :
  - Same physical properties to match replaced tissue
  - Minimal toxic response to host
  - Bio inert – minimum immune response and foreign body reaction

SECOND GENERATION

- Invented between 1980 and 2000
- AIM
  - ➢ Interact with biological environment
  - ➢ Enhance biological response and tissue surface bonding (BIO ACTIVE)
  - ➢ Undergo progressive degradation with healing and regeneration of tissues (BIODEGRADABLE)

THIRD GENERATION

- Invented in 2002(Hench and polak)
- AIM
  - To stimulate specific cellular response at molecular level
  - Signal and stimulate specific cellular activity

BIOMATERIALS USED IN ORTHOPAEDICS

- Metal and metal alloys
- Ceramics and ceramometallic materials
- Tissue adhesives
- Bone replacement materials
- Carbon materials and composites, polymers

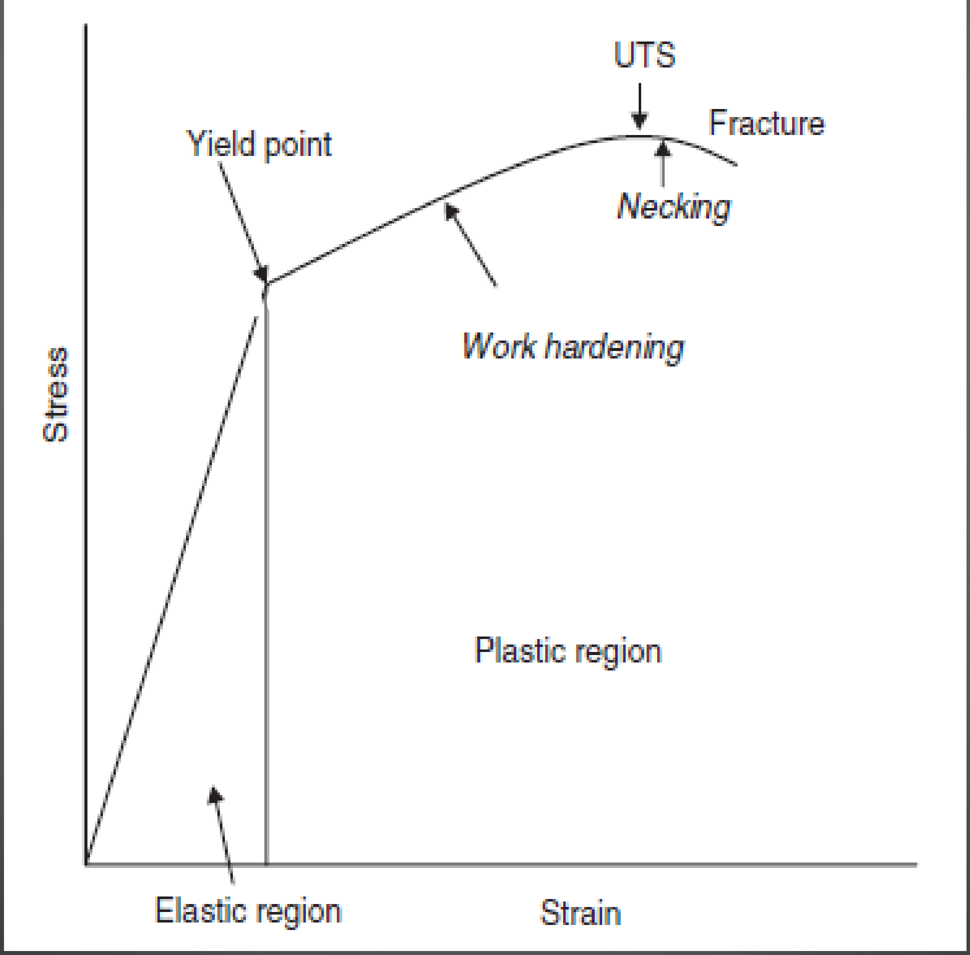
BASIC CONCEPTS & DEFINITIONS

- Force applied will lead to deformation and if continued beyond a certain point will lead to ultimate failure
- The force per unit area----- STRESS and

  Deformation is known as STRAIN

STRESS-STRAIN CURVE

Young's modulus of elasticity



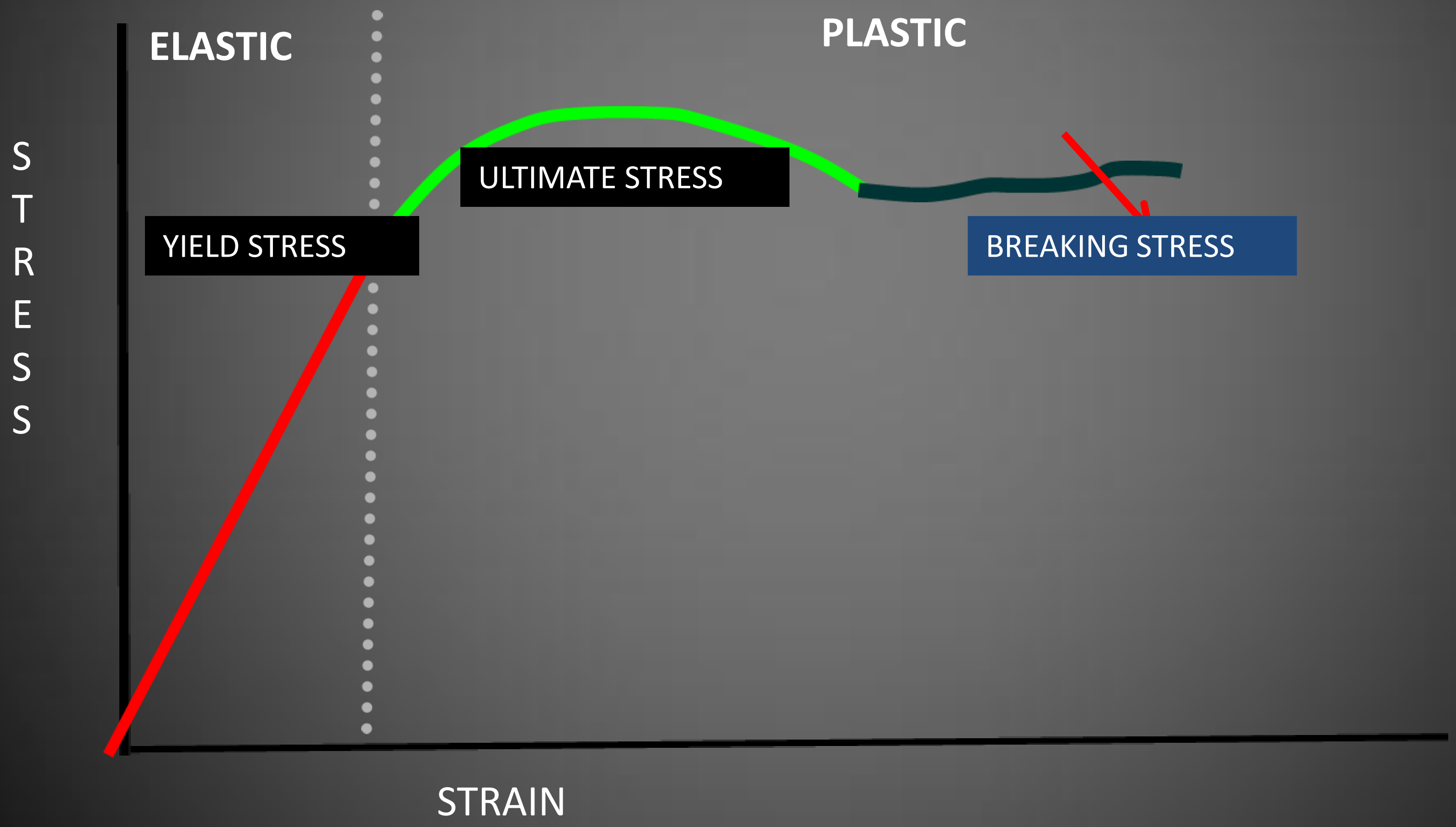
DEFINITIONS

- **TENSILE STRENGTH/ ULTIMATE TENSILE STRENGTH** –
  The maximum stress on the curve *before* breakage

- **YIELD STRESS-**
  Point at which elastic behaviour changes to plastic Behaviour

- **BREAKING STRESS**
  Point at which the substance fails/brakes

- **FATIGUE FAILURE**: The failure of a material with repetitive loading at stress levels below the ultimate tensile strength

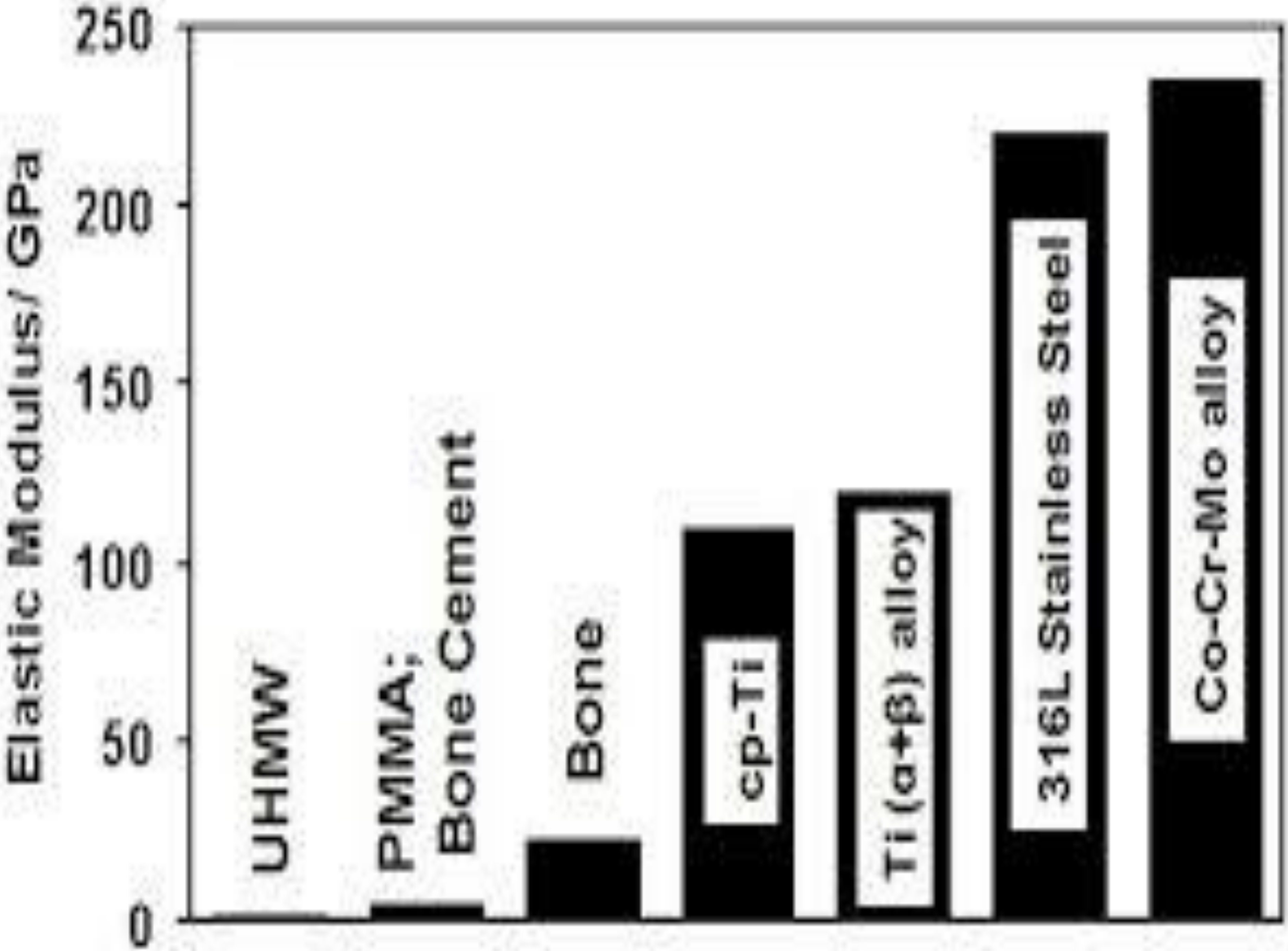

ELASTIC
PLASTIC
S
T
R
E
S
S
ULTIMATE STRESS
YIELD STRESS
BREAKING STRESS
STRAIN

DEFINITIONS

- STRENGTH: The degree of resistance to deformation of a material
  - Strong if it has a high tensile strength
- TOUGHNESS: Amount of energy per unit volume that a material can absorb before failure
- DUCTILITY/ BRITTLENESS- The amount by which a *material deforms* (i.e. the strain that occurs) before it breaks.
- HOOKE'S LAW → Stress α Strain produced
  - The material behaves like a spring

BONE BIOMECHANICS

- *Anisotropic:*
  - elastic modulus depends on direction of loading
  - weakest in shear> tension> compression
- *viscoelastic*:
  - stress-strain characteristics depend on the rate of loading
- WOLF’S LAW:
  - Bone remodelling occurs along the line of stress
- Bone density changes with age, disease, use and disuse



Elastic Modulus/ GPa
250
200
150
100
50
0
UHMW
PMMA;
Bone Cement
Bone
cp-Ti
Ti (α+β) alloy
316L Stainless Steel
Co-Cr-Mo alloy

CLINICAL APPLICATIONS OF ORTHOPAEDIC IMPLANTS

- Osteosynthesis
- Joint replacements
- Nonconventional modular tumor implants
- Spine implants

IDEAL IMPLANT MATERIAL

- Chemically inert
- Non-toxic to the body
- Great strength
- High fatigue resistance
- Low Elastic Modulus
- Absolutely corrosion-proof
- Good wear resistance
- Inexpensive

COMMON IMPLANT MATERIALS IN ORTHOPAEDICS

Metal Alloys:

- stainless steel
- Titanium alloys
- Cobalt chrome alloys

Nonmetals:

- Ceramics & Bioactive glasses
- Polymers (Bone cement, polyethylene)

STAINLESS STEEL

COMPOSITION:

- Iron (62.97%)
- Chromium (18%)
- Nickel (16%)
- Molybdenum (3%)
- Carbon (0.03%)

- The form used commonly is 316L (3% molybdenum, 16% nickel & L = Low carbon content)

STAINLESS STEEL

ADVANTAGES

- ✓ Relatively ductile
- ✓ Biocompatible
- ✓ Relatively cheap
- ✓ Reasonable corrosion resistance
- ✓ STRONG

DISADVANTAGES:

- ➢ Poor wear resistance
- ➢ *High Young's modulus* – 200 G Pascals (10× that of bone)
- ➢ stress shielding of surrounding bone and bone resorption

- Used in plates, screws, IM nails, external fixators

COBALT CHROME ALLOYS

- Contains primarily cobalt (30-60%)
- Chromium (20-30%) added to improve corrosion resistance
- Minor amounts of carbon, nickel and molybdenum added(ASTM F75 Vitallium)

COBALT CHROME ALLOYS

Advantages:

- Excellent resistance to corrosion
- Excellent long-term biocompatibility
- Strength (very strong)

Disadvantages:

- Very high Young's modulus
- Risk of stress shielding
- Expensive

USES

- Usually for bearing surfaces
- THR
- Metal-on-metal devices.

THR IMPLANT BEARING SURFACES

Metal-on-polyethylene

Metal-on-metal

TITANIUM ALLOYS

- Contains:
  - Titanium (89%)
  - Aluminium (6%)
  - Vanadium (4%)
  - Others (1%)
- Most commonly orthopaedic titanium alloy is *TITANIUM 64 (Ti-6Al-4v)*

TITANIUM ALLOYS

- ADVANTAGES:
  - Corrosion resistant
  - Excellent biocompatibility
  - Ductile
  - Fatigue resistant
  - Low Young's modulus
  - MR scan compatibly
  - osseointegration

- Useful in Int fixators , plates, vertebral spacers,IM nails etc.

- DISADANTAGES:
  - poor wear characteristics
  - Systemic toxicity – vanadium
  - Relatively expensive


BoneCare CE1293 372.102 Thole
BoneCare CE1293 372.101 Thole

YOUNG'S MODULUS AND DENSITY OF COMMON BIOMATERIALS

MATERIAL	YOUNG'S MODULUS (GPa)	DENSITY (g/cm^3)
Cancellous bone	0.5-1.5	-
UHMWPE	1.2	-
PMMA bone cement	2.2	-
Cortical bone	7-30	2.0
Titanium alloy	110	4.4
Stainless steel	190	8.0
Cobalt chrome	210	8.5

COMPARISON OF METAL ALLOYS

ALLOY	Young's modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)
Stainless Steel 316L	190	500	750
Titanium 64	110	800	900
Cobalt chrome F562	230	1000	1200

BIOACTIVE IMPLANTS

- Coating of implant with a bioactive ceramic (HA and BGs).
  - ✓ electrophoretic deposition
  - ✓ plasma spraying,
  - ✓ radio frequency or ionic ray sputtering,
  - ✓ laser ablation or hot isostatic pressure
- All are not cost effective

HA COATED IMPLANTS

CERAMICS

- Compounds of metallic elements e.g Aluminium bound ionically or covalently with nonmetallic elements
- Common ceramics include:
  - Alumina (aluminium oxide)
  - Silica (silicon oxide)
  - Zirconia (Zirconium oxide)
  - Hydroxyapatite (HA)

CERAMICS

Ceramics are refractory polycrystalline compounds

- Usually inorganic
- Highly inert
- Hard and brittle
- High compressive strength
- Generally good electric and thermal insulators
- Good aesthetic appearance

Types of bioceramics:

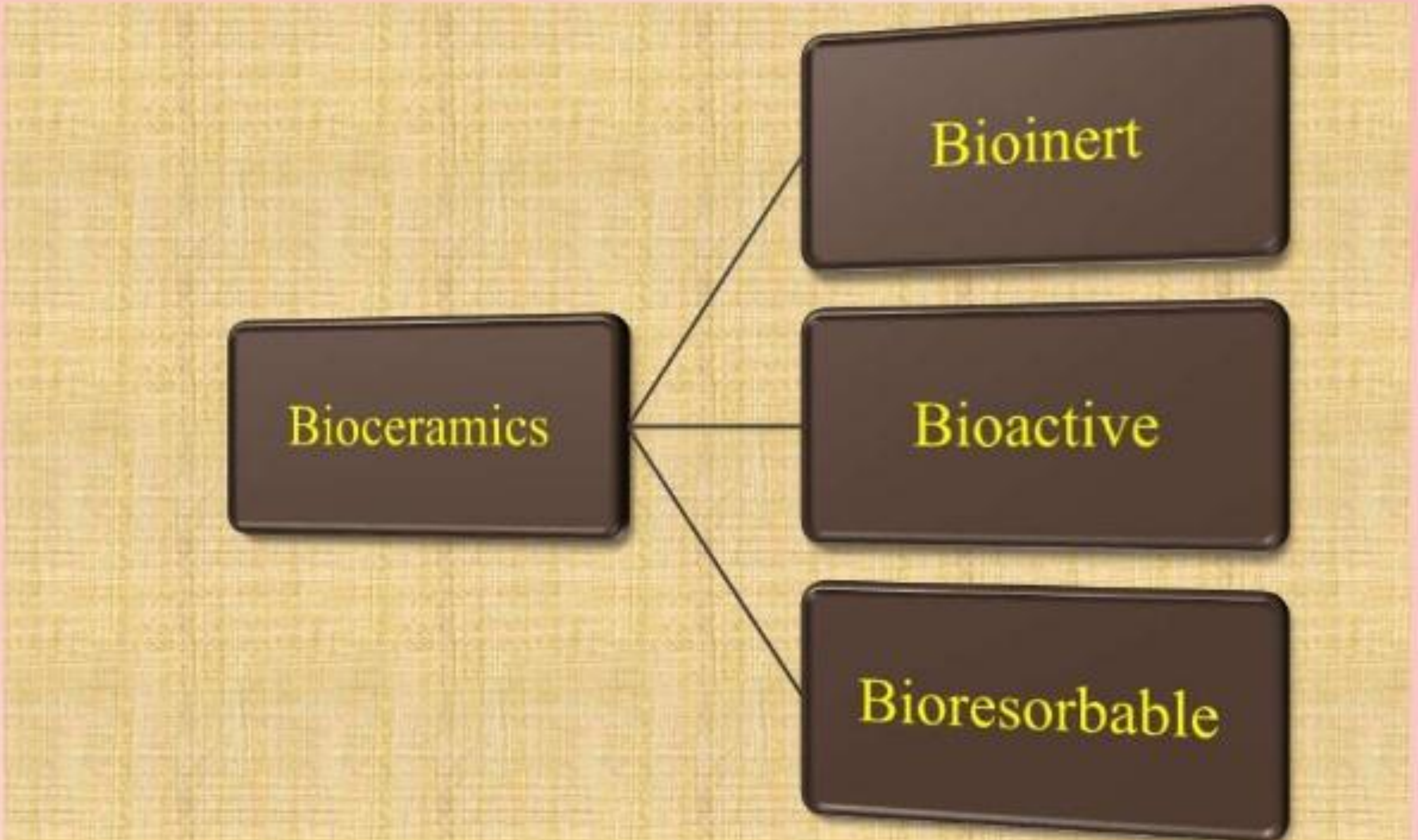


TABLE 1.3. Ceramics Used in Biomedical Applications

Ceramic	Chemical Formula	Comment
Alumina	Al_2O_3	Bioinert
Zirconia	ZrO_2	
Pyrolytic carbon		
Bioglass	$Na_2OCaOP_2O_3{-}SiO$	Bioactive
Hydroxyapatite (sintered at high temperature)	$Ca_{10}(PO_4)_6(OH)_2$	
Hydroxyapatite (sintered at low temperature)	$Ca_{10}(PO_4)_6(OH)_2$	Biodegradable
Tricalcium phosphate	$Ca_3(PO_4)_2$	

ALUMINA(INERT CERAMICS)

APPLICATIONS:

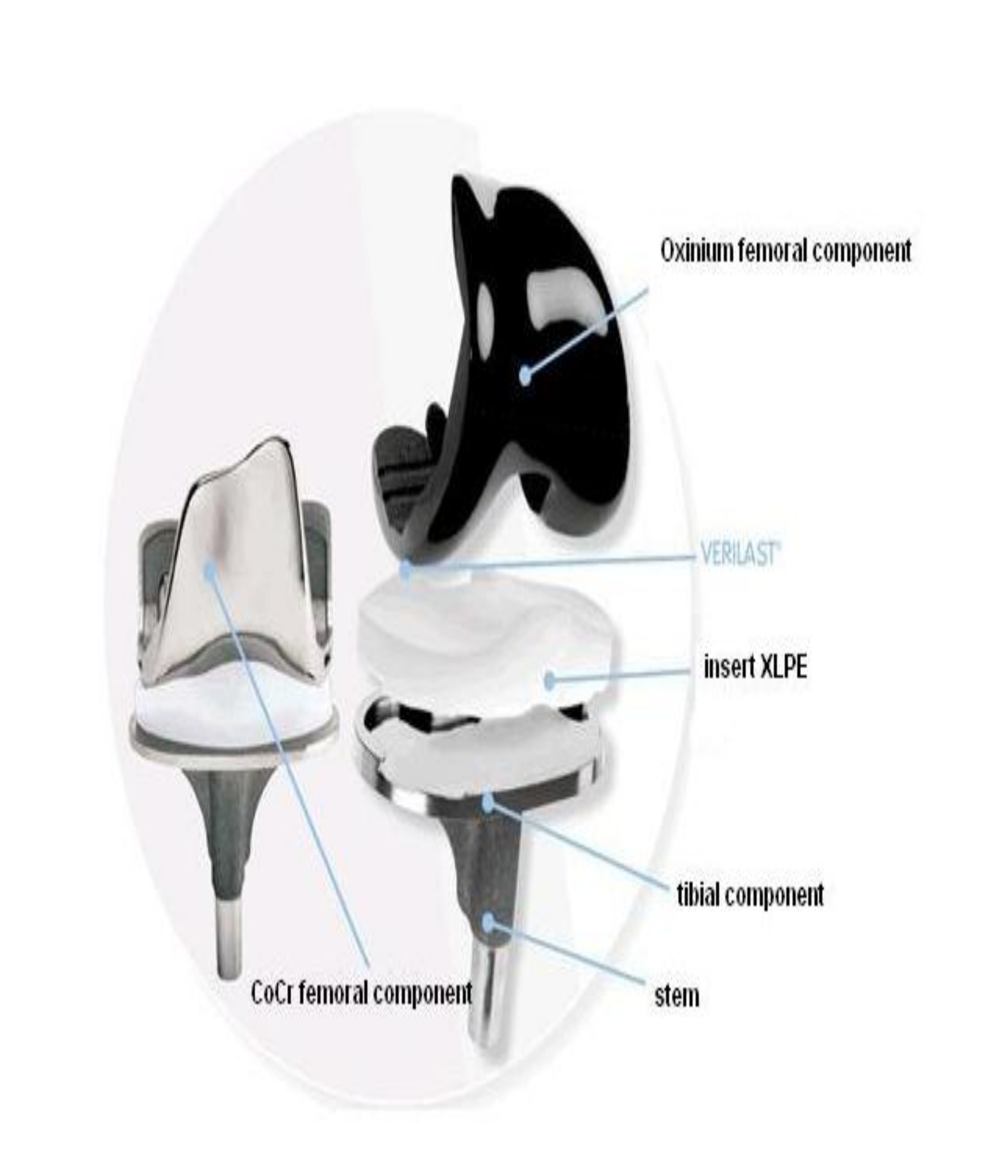
- femoral head
- bone screws and plates
- porous coatings for femoral stems
- porous spacers (specifically in revision surgery)
- knee prosthesis

ZIRCONIA(ZrO_2)

- Obtained from the mineral zircon(Zr)

APPLICATION:

- femoral head
- artificial knee
- bone screws and plates
- favored over UHMWPE due to superior wear resistance



CERAMICS

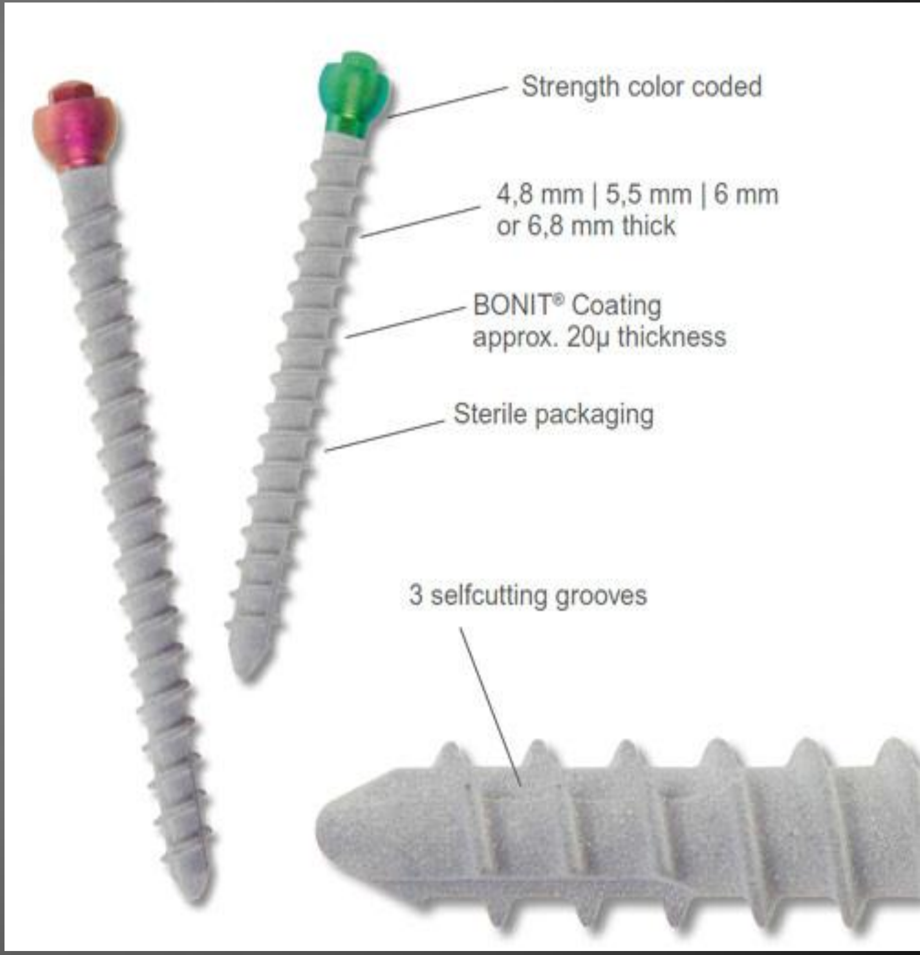
ADVANTAGES

- ✓ Chemically inert & insoluble
- ✓ Best biocompatibility
- ✓ Very strong
- ✓ Osteoconductive
- ✓ Low wear resistance

DISADVANTAGES

- ✓ Brittleness
- ✓ Very difficult to process – high melting point
- ✓ Very expensive
- ✓ High young's modulus
- ✓ Low tensile strength
- ✓ Poor crack resistance

HA COATED SCREWS



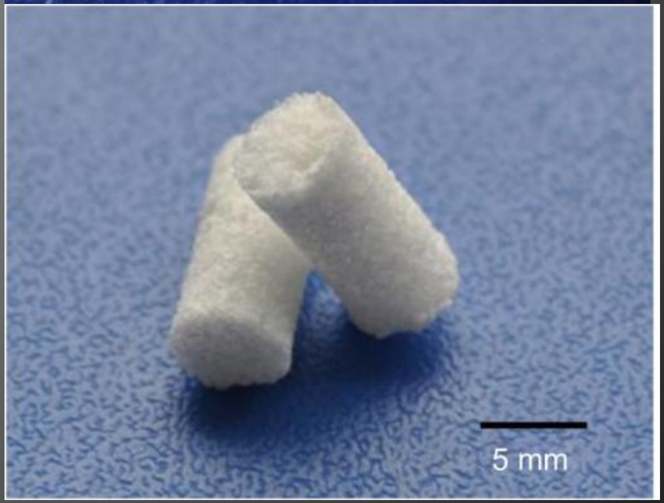
BEARING SURFACES

Ceramic-on-polyethylene

Ceramic-on-ceramic

BIOACTIVE CERAMICS

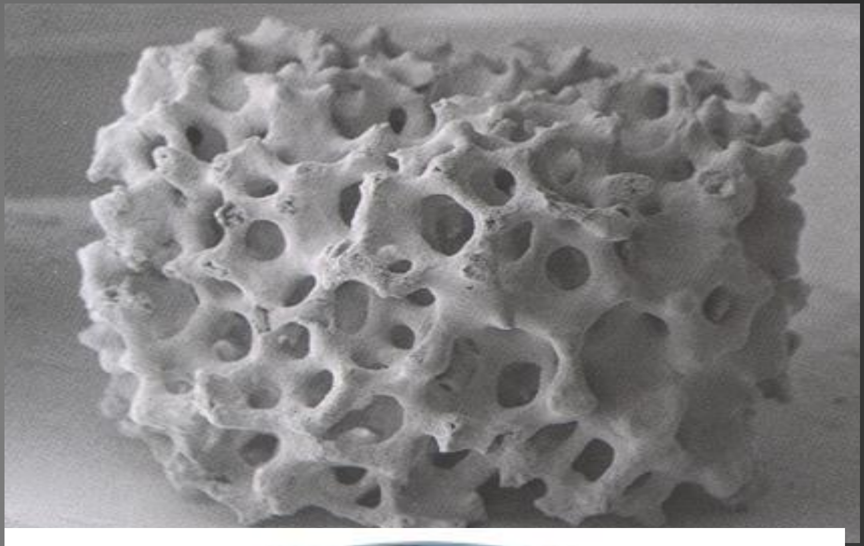
- Bio glass–ceramics
- calcium phosphates (CaPs)
- Silicon incorporated cements and ceramics
- Not used in high load bearing devices due to low tensile strength and toughness



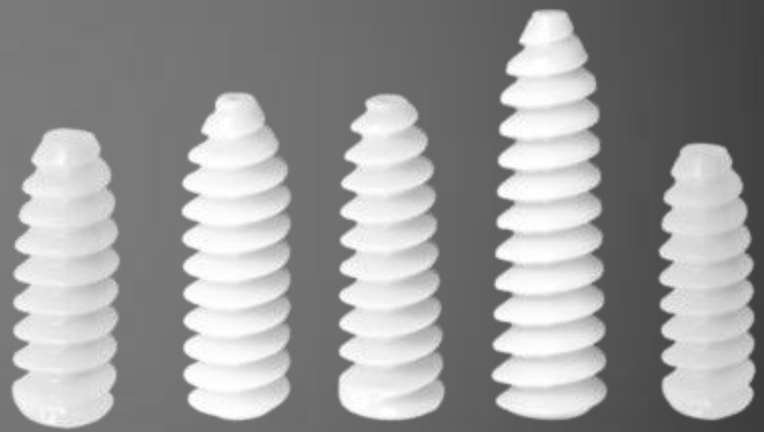
BIODEGRADABLE CERAMICS(CALCIUM PHOSPHATE)

Uses

- repair material for bone damaged trauma or disease
- void filling after resection of bone   tumours
- repair and fusion of vertebrae
- repair of herniated disks
- repair of maxillofacial and dental defects
- drug-delivery

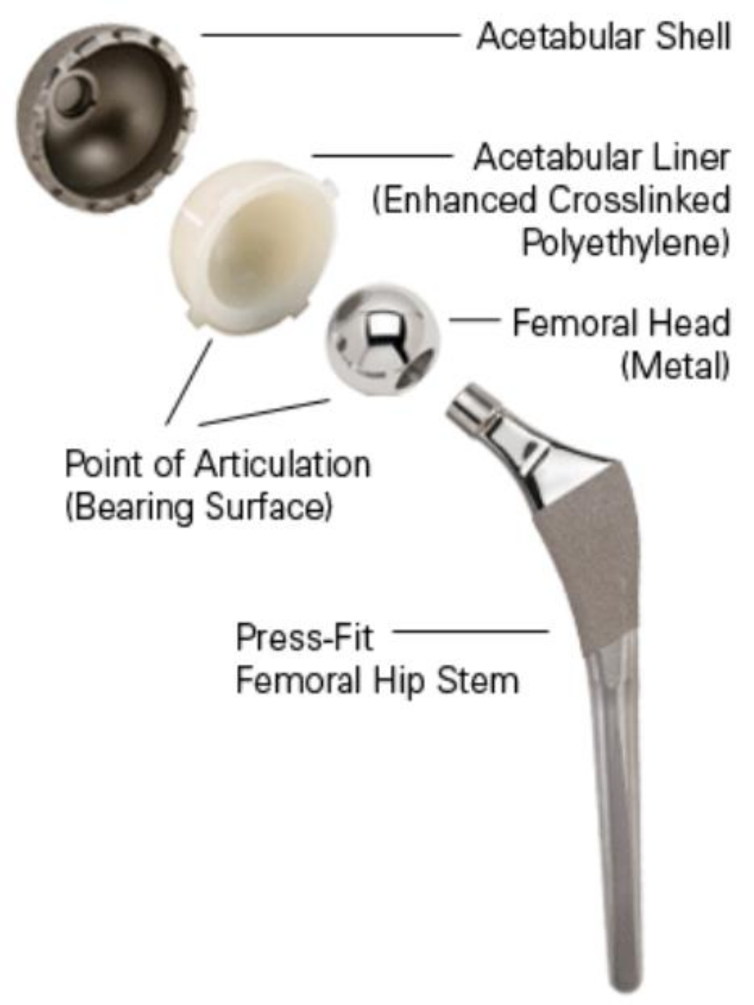


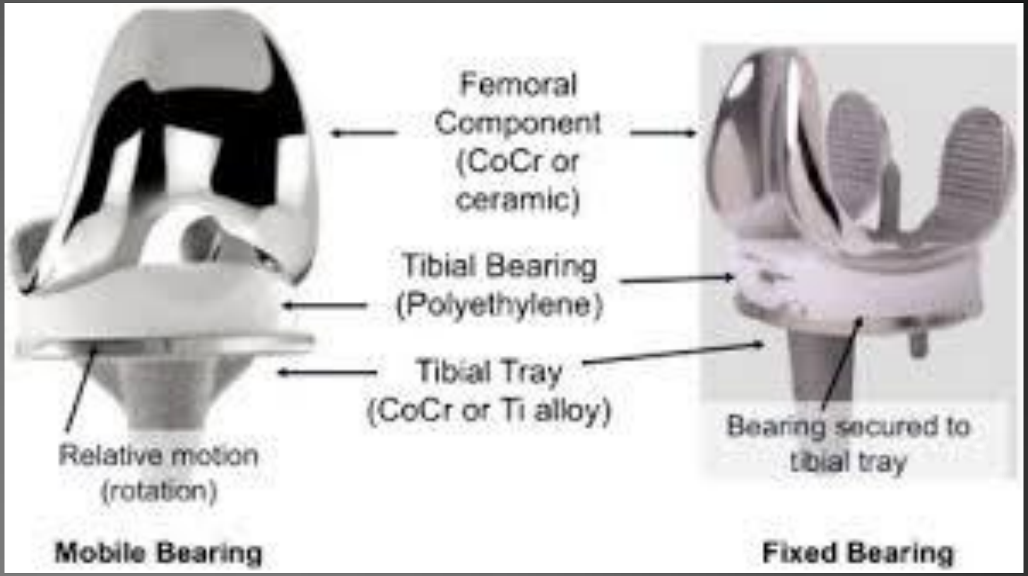
CALCIUM PHOSPHATE



POLYMERS

- Consists of many repeating units of a basic sequence (monomer)
- Used extensively in orthopaedics
- Most commonly used are:
  - Polymethylmethacrylate (PMMA, Bone cement)
  - Ultrahigh Molecular Weight Polyethylene (UHMWPE)


Acetabular Shell
Acetabular Liner
(Enhanced Crosslinked
Polyethylene)
Femoral Head
(Metal)
Point of Articulation
(Bearing Surface)
Press-Fit
Femoral Hip Stem


Femoral
Component
(CoCr or
ceramic)
Tibial Bearing
(Polyethylene)
Tibial Tray
(CoCr or Ti alloy)
Relative motion
(rotation)
Bearing secured to
tibial tray
Mobile Bearing
Fixed Bearing

PMMA

The powder contains:

- PMMA copolymer
- Barium or Zirconium oxide (radio-opacifier)
- Benzoyl peroxide (catalyst)

Clinically relevant stages of cement reaction:

- DOUGH TIME – 2to 3 mins
- WORKING TIME – 5 to 8 mins
- SETTING TIME – 8 to 10 mins

PMMA (BONE CEMENT)

- Mainly used to fix prosthesis in place can also be used as void fillers
- Available as liquid and powder
- The liquid contains:
  - The monomer N,N-dimethyltoluidine (the accelerator)
  - Hydroquinone (the inhibitor)

ADVANTAGES

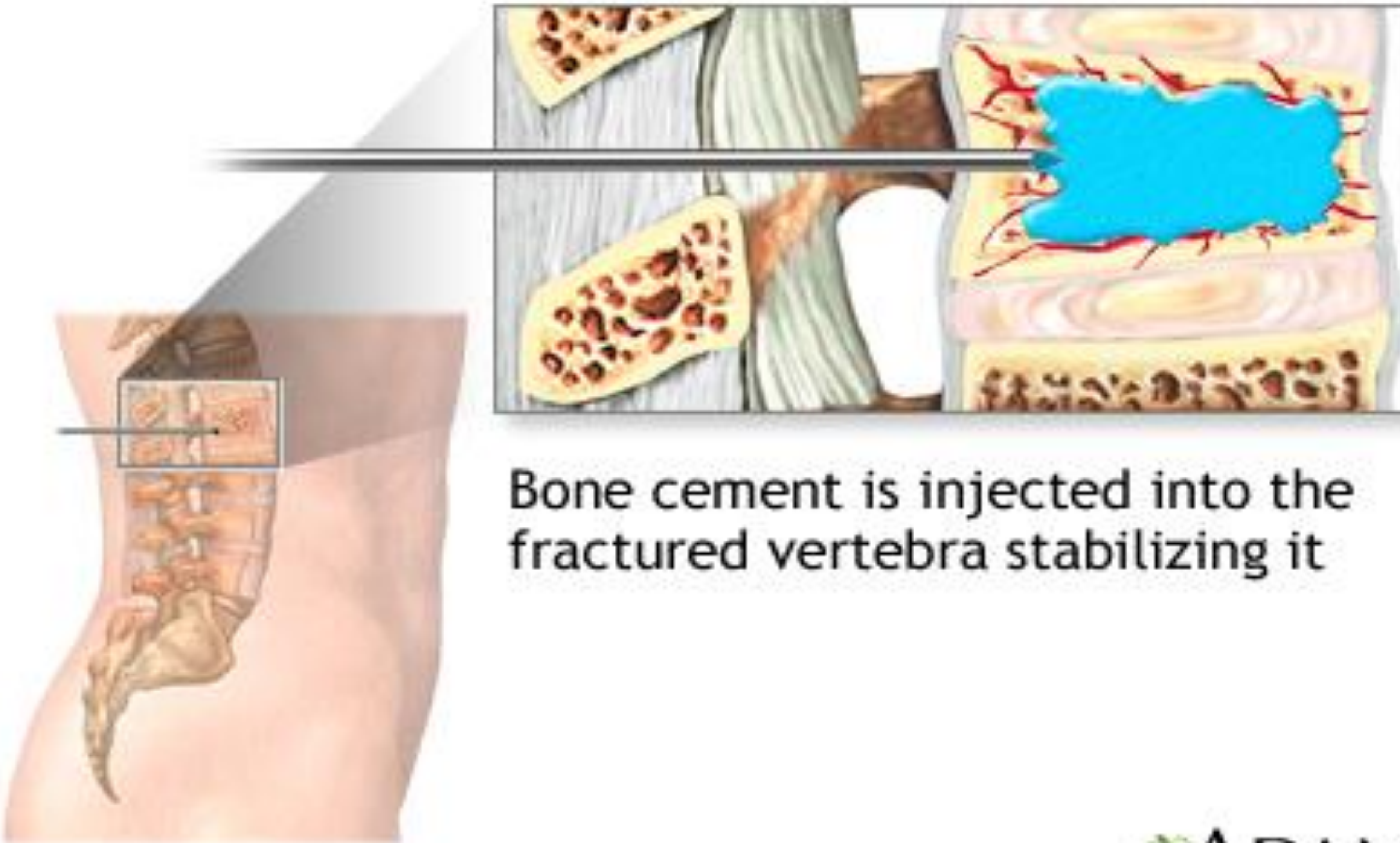
- Tough
- Ductile
- Resilient
- Resistant to wear

USES:

-It provides an excellent primary fixation of the prosthesis

DISADVANTAGES

- Susceptible to abrasion
- Wear usually caused by third body inclusions
- Thermoplastic (may be altered by extreme temperatures)
- weaker than bone in tension



Bone cement is injected into the fractured vertebra stabilizing it

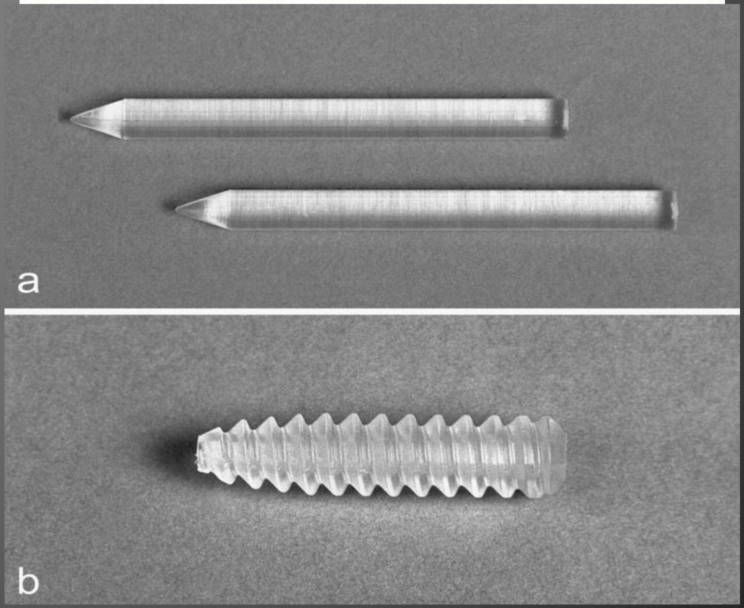
A.D.A.M.

UHMWPE

- A polymer of ethylene with MW of 2-6million
- Used for acetabular cups in THR prostheses and tibial components in TKR
- Metal on polyethylene has high success rate in bearing surface in THR
- Osteolysis produced due to polyethylene wear debris causes aseptic loosening
- Increases polymer chain cross-linking which improves wear characteristics

BIODEGRADABLE POLYMERS

- Polyglycolic acid, Polylactic acid, copolymers
- As stiffness of polymer decreases, stiffness of callus increases
- Hardware removal not necessary (reduces morbidity and cost)



CARBON FIBRES

APPLICATIONS:

- Total hip replacement
- Internal fixation for various fractures
- Spine surgeries

DISADVANTAGES:

- Release of carbon debris in to surrounding medium





TISSUE ADHESIVES

PROPERTIES OF TISSUE ADHESIVES:

- Moderately viscous (spread easily)
- Ability to degrade at a appropriate rate
- Biocompability

Commonly used tissue adhesives are

- fibrin gel,albumim,cyanoacrylates and mucopolysaccharides

GENERAL TISSUE-IMPLANT RESPONSES

- All implant materials elicit some response from the host
- The response occurs at tissue-implant interface
- Response depend on many factors;
  - Type of tissue/organ;
  - Mechanical load
  - Amount of motion
  - Composition of the implant
  - Age of patient

TISSUE-IMPLANT RESPONSES

BIOMATERIAL

TOXIC

DEATH OF SURROUNDING TISSUES

NON TOXIC

BIODEGRADABLE

DISSOLUTION OF MATERIAL

BIO ACTIVE

INTERFACIAL BOND FORMATION

BIO INERT

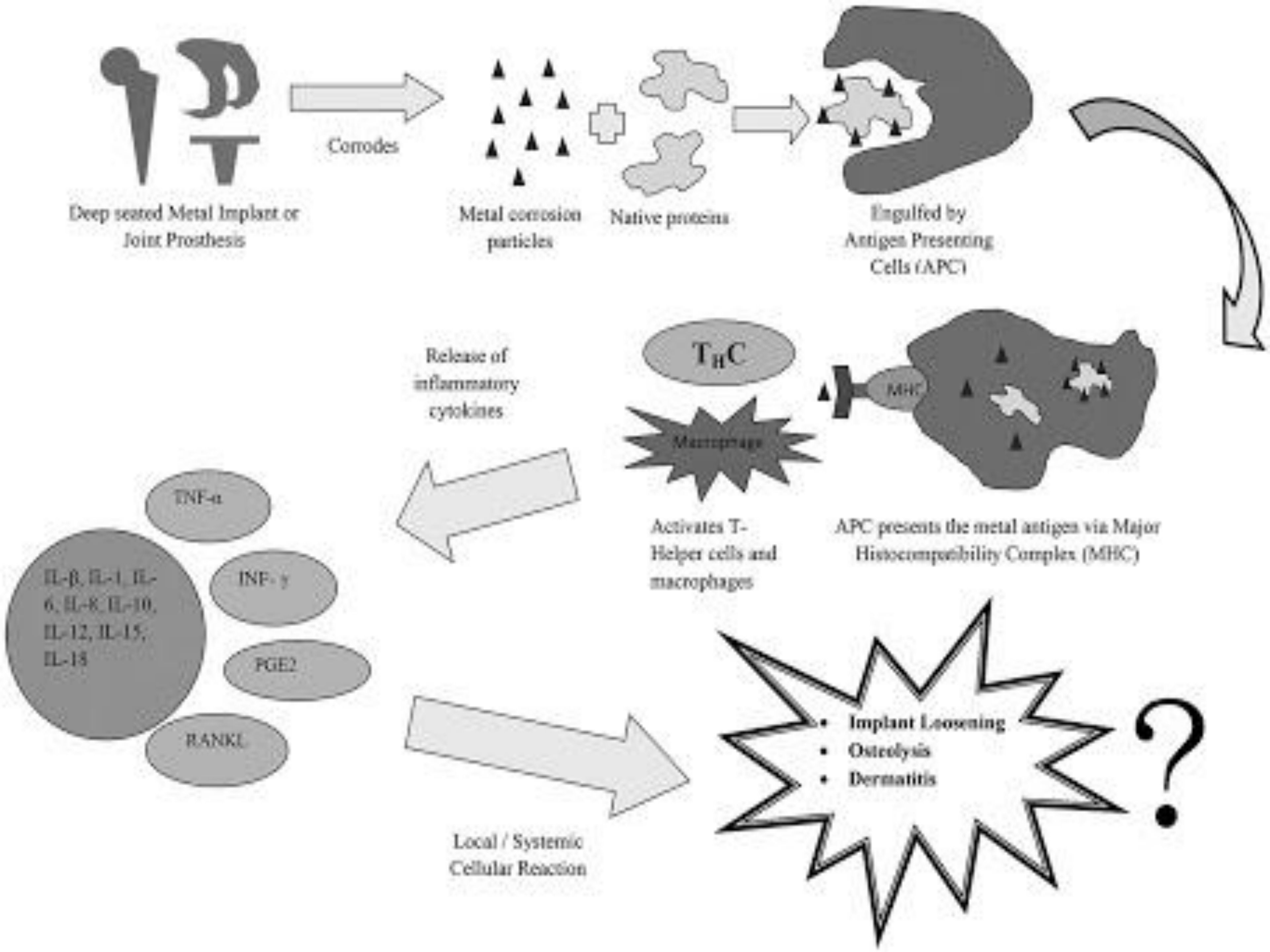
FIBROUS ENCAPSULATION

COMPLICATIONS

- Aseptic Loosening:
  - Caused by osteolysis from body's reaction to wear debris
- Stress Shielding:
  - Implant prevents bone from being properly loaded
- Corrosion:
  - Reaction of the implant with its environment resulting in its degradation to oxides/hydroxides

COMPLICATIONS

- Infection
- Metal hypersensitivity
- Manufacturing errors
- VARIOUS FACTORS CONTRIBUTE TO IMPLANT FAILURE


Corrodes
Deep seated Metal Implant or
Joint Prosthesis
Metal corrosion
particles
Native proteins
Engulfed by
Antigen Presenting
Cells (APC)
T_HC
MHC
Macrophage
Release of
inflammatory
cytokines
Activates T-
Helper cells and
macrophages
APC presents the metal antigen via Major
Histocompatibility Complex (MHC)
TNF-α
IL-β, IL-1, IL-
6, IL-8, IL-10,
IL-12, IL-15,
IL-18
INF- γ
PGE2
RANKL
Implant Loosening
Osteolysis
Dermatitis
?
Local / Systemic
Cellular Reaction

RECENT ADVANCES

- Aim is to use materials with mechanical properties that match those of the bone
- Modifications to existing materials to minimize harmful effects
  - Ex; nickel-free metal alloys
- Possibility of use of anti-cytokine in the prevention of osteolysis around implants
- Antibacterial implant

RECENT ADVANCES

- **Porous tantalum** is also being successfully used clinically in several orthopaedic applications.
  - high volumetric porosity,
  - low elastic modulus
  - good frictional characteristics
- Ideal candidate for weight-bearing applications such as total joint arthroplasty

CONCLUSION

- Adequate knowledge of implant materials is an essential platform to making best choices for the patient
- Promising and satisfying results from use of existing implant materials
- Advances in biomedical engineering will go a long way in helping the orthopedic surgeon
- The search is on…