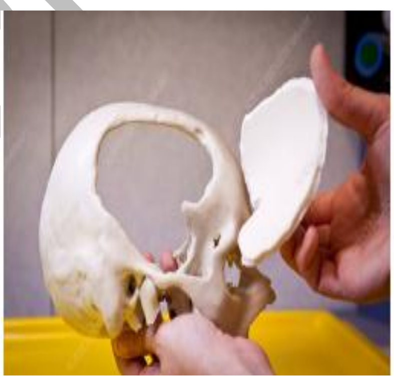
Chapter Five

Bio-ceramics



Chapter Five BIOCERAMICS

Bio-ceramics

Ceramics are used for the repair and restoration of diseased or damaged parts of the musculo-skeletal system.

Bio-ceramics may be:

1- Bioinert like Alumina (Al_2O_3), Zirconia (ZrO_2);

2- Resorbable like tri-calcium phosphate (TCP);

3- Bioactive like Hydroxyapatite, bioactive glasses, and glass-ceramics;

4- Porous for tissue in-growth (hydroxyapatite-coated metals, alumina) of the jaw bone.

Applications include: Replacement for hips, knees, teeth, tendons and ligaments, and repair for periodontal disease, maxillofacial reconstruction, augmentation and stabilization, spinal fusion and bone fillers after tumor surgery.

Carbon coatings are thrombo-resistant and are used for prosthetic heart valves.

Types of Bio-ceramics – Tissue Attachment

The mechanism of tissue attachment is directly related to the type of tissue response at the implant interface. No material implanted in living tissues is inert; all materials elicit a response from living tissues.

Four types of response allow different means of achieving attachment of prostheses to the musculo-skeletal system.

The types of implant-tissue response are:

a- If the material is toxic, the surrounding tissue dies;

b- the material is nontoxic and biologically inactive (nearly inert), a fibrous tissue of variable thickness forms;

c- If the material is nontoxic and biologically active (bioactive), an interfacial bond forms;

d- If the material is nontoxic and dissolves, the surrounding tissue replaces it.

The attachment mechanisms with examples are summarized below:

Type of Bioceramic	Type of Attachment	Example
1	Dense, nonporous, nearly inert ceramics attach to bone-growth into surface irregularities by cementing the device into the tissues, or by pressing fitting into a defect (termed **Morphology Fixation**).	Al_2O_3 (single crystal and polycrystalline)
2	For porous inert implants bone ingrowth occurs, which mechanically attaches the bone to the material (termed **Biological Fixation**)	Al_2O_3 (porous polycrystalline) hydroxyapetite-coated porous metals
3	Dense, nonporous, surface-reactive ceramics and glass-ceramics attach directly by chemical bonding with the bone (termed **Bioactive Fixation**)	Bioactive glasses Bioactive glass-ceramics Hysdroxyapetite
4	Dense, nonporous (or porous), resorbable ceramics are designed to be slowly replaced by bone.	Calcium sulphate (Plaster of Paris) Tricalcium phosphate, Calcium phosphate salts

Nearly Inert Crystalline Bioceramics

Inert refers to materials that are essentially stable with little or no tissue reactivity when implanted within the living organism.

When a biomaterial is nearly inert (type1) and the interface is not chemically or biologically bonded, there is relative movement and progressive development of a non-adherent fibrous capsule in both soft and hard tissues. Movement at the biomaterial-tissue interface eventually leads to deterioration in function of the implant or the tissue at the interface or both.

Bone at an interface with type1, nearly inert, implant is very often structurally weak because of disease, localized death of bone, or stress shielding when higher elastic modules of the implant prevents the bone from being loaded properly. Most notable among the nearly inert ceramics are alumina and special forms of carbon and silicon.

High density high purity (>99.5%) alumina (α-Al_2O_3) was the first bioceramic widely used clinically. It is used in load-bearing hip prostheses and dental implants, because of its combination of excellent corrosion resistance, good biocompatibility, and high wear resistance, and high strength.

Although some dental implants are single-crystal sapphire, most alumina devices are very-fine-grained polycrystalline α-Al_2O_3. A very small amount of magnesia (<0.5%) is used as an aid to sintering and to limit grain growth during sintering.

Strength, fatigue resistance, and fracture toughness of polycrystalline α-Al_2O_3 are a function of grain size and percentage of sintering aid, i.e. purity. Alumina with an average grain size of <4µm and >99.7% purity exhibits good flexural strength and excellent compressive strength.

Low wear rates have led to wide-spread use of alumina non-cemented cups, press fitted into the acetabulum (socket) of the hip. The cups are stabilized by bone growth into grooves or round pegs. The mating femoral ball surface is also of alumina, which is bonded to a metallic stem. Though long-term results in general have been excellent, it is essential that the age of the patient, nature of the disease of joint, and bioceramics of the repair be considered carefully before any prosthesis is used.

Porous Ceramics

The concept behind nearly inert, micro-porous bioceramics (type2) is the ingrowths of tissue into pores on the surface or throughout the implant. The increased interfacial area between the implant and the tissues result in an increased inertial resistance to movement of the device in the tissue. The interface is established by the living tissue in the pores. This method of attachment is often termed biological fixation. It is capable of with standing more complex stress states than type1 implants, which achieve only morphological fixation.

The limitation associated with type2 porous implants is that, for tissue to remain viable and healthy, it is necessary for the pores to be greater than 100 to 150μm in diameter. The large interfacial area required for the porosity is due to the need to provide a blood supply to the ingrown connective tissue. Vascular tissue does not appear in pores, which measure less than 100μm. If micro-movement occurs at the interface of a porous implant, tissue is damaged, the blood supply may be cut off, tissue dies, inflammation ensues and the interfacial stability can be destroyed.

inert porous ceramics can provide a functional implant.

pore sizes exceed 100μm, Porous ceramic surfaces can also be prepared by mixing soluble metal or salt particles into the surface. The pore size and structure are determined by the size and shape of the soluble particles that are subsequently removed with a suitable etchant.

The porous surface layer produced by this technique is an integral part of the underlying dense ceramic phase. Materials, such as alumina, may also be made porous by using a suitable foaming agent that evolves gases during heating.

Porous materials are weaker than the equivalent bulk form. As the porosity increases, the strength of the material decreases rapidly. Much surface area is also exposed, so that the effects of the environment on decreasing the strength become much more important than for dense nonporous materials.

$$\sigma = \sigma_\circ \; e^{-C\rho}$$

Where σ is strength;
σ_o is strength at zero porosity (Nonporous);
c is a constant;
and ρ is porosity.

Bioactive Glasses and Glass-Ceramics

Another approach to the solution of the problems of interfacial attachment is the use of bioactive materials (type3). The concept of bioactive materials is intermediate between resorbable and bioinert.

Certain compositions of glasses, ceramics, glass-ceramics, and composites have been shown to bond to bone. These materials are also called bioactive ceramics.

Some, even more specialized compositions of bioactive glasses, will bond to soft tissues as well as bone. A common characteristic of such bioactive materials is a modification of the surface that occurs upon implantation. The surface forms a biologically active hydroxycarbonate apatite (HCA) layer, which provides the bonding interface with tissues. The HCA phase that forms on bioactive implants has the same chemical structure as the mineral phase in bone, and is therefore responsible for interfacial bonding.

Several other compositions have developed that are bioactive, as tabulated below:

Component	45S5 Bioglass	KGC Ceravital	A/W Glass-ceramic
SiO_2	45	46.2	34.2
P_2O_5	6	-	16.3
CaO	24.5	20.2	44.9
$Ca(PO_3)_2$	-	25.5	-
CaF_2	-	-	0.5
MgO	-	2.9	4.6
Na_2O	24.5	4.8	-
Structure	Glass and glass-ceramic	Glass-Ceramic	Glass-Ceramic

Many bioactive silica glasses are based upon the formula (called 45S5), which signifies 45wt% SiO_2, S as the network former, and a 5 to 1 molar ratio of CaO/ P_2O_5 45S5 glass implants have been used successfully for replacement of ear bones and maintenance of the jaw bone for denture wearers for up to eight years, with nearly 90% retention ratio.

Bioactive glass with macro-porous structure has the properties of layer surface areas, which are favorable for bone integration.

They are designed to degrade gradually over a period of time and be replaced by the natural host tissue. This leads to a very thin or nonexistent interfacial thickness. This is the optimal solution to the problem of biomaterials if the requirements of strength and short-term performance can be met. Natural tissues can repair themselves and are gradually replaced throughout life by a continual turnover of cell population. As we grow older, the replacement of cells and tissues is slower and less efficient, which is why parts "wear out", unfortunately sum faster than others. Thus resorbable biomaterials are based on the same principles of repair which have evolved over millions of years.

One of the unique advantages of the resorbable ceramic is that its initial poresize can be small, thereby possessing high mechanical strength compared to the strength of more porous substances.

Calcium Phosphate Ceramics

Different phases of calcium phosphate ceramics are used depending upon whether a resorbable or bioactive material is desired. These include dicalcium phosphate ($CaHPO_4$) and hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$ [HA].

Applications include dental implants, skin treatments, gum treatment, jawbone reconstruction, orthopedics, facial surgery, ear, nose and throat repair, and spinal surgery.

The mechanical behavior of calcium phosphate ceramics strongly influences their application as implants. Tensile and compressive strength and fatigue resistance depend on the total volume of porosity. Because HA implant have low reliability under tensile load, such calcium phosphate bioceramics can only be used as powders, or as small, unloaded implants with reinforcing metal posts, coatings on metal implants, low-bonded porous implants where bone growth acts as a reinforcing phase and as the bioactive phase in a composite.

Calcium phosphate (CaP) biomaterials are available in various physical forms (particles or blocks; dense or porous). One of their main characteristics is their porosity. The ideal pore size for bioceramic is similar to that of spongy bone.

Macroprosity (pore size >50μm) is intentionally introduced into the material by adding volatile substances or porogens (naphthalene, sugar, hydrogen peroxide, polymer beads, fibers, etc) before sintering at high temperatures.

Microporosity is formed when the volatile materials are released.

Microporosity is related to pore size <10μm. Microporosity is the result of the sintering process, where the sintering temperature and time are critical parameters.

Composites and Coatings

One of the primary restrictions on clinical use of bioceramics is the uncertain lifetime under the complex stress states, slow crack growth, and cyclic fatigue that arise in many clinical applications.

The table below shows the characteristics of those composites:
Matrix Reinforcing Phase
Type1: Nearly inert Composites
Polyethylene Carbon fiber
Poly(methyl methacrylate) Carbon fiber
Carbon SiC
Epoxy resin Alumina/ stainless steel
Type 2: Porous ingrowth composites
Coral HA yoniopora DL polylactic acid
Type3: Bioactive Composites
Bioglass Stainless steel fibers
Bioglass Titanium fibers
Collagen HA
Polyethylene HA
Poly(methyl methacrylate) Phosphate-silicate-apatite glass fiber
A/W glass-ceramic Transformation-toughened ZrO_2
Type4: Resorbable composite
Polyhydroxybuturate HA
PLA/PGA HA
PLA/PGA PLA/PGA fibers
PLA is poly(lactic acid)
PGA is poly(glycalic acid)

Implant materials with similar mechanical properties should be the goal when bone is to be replaced. Because of the anisotropic deformation and fracture characteristics of cortical bone, which is itself a composite of compliant collagen fibrils and brittle HCA crystals, the Young's modulus (E) varies between about 7 to 25GPa. The critical strain intensity increases from as low as $600Jm^{-2}$ to as much as $5000J\ m^{-2}$ depending on orientation, age, and test conditions.
Most bioceramics are much stiffer than bone, many exhibit poor fracture toughness. Consequently, one approach to achieve properties analogous to bone is to stiffen a compliant biocompatible synthetic polymer, such as PE with a higher modulus ceramic second phase, such as HA powders. The effect is to increase Young's modulus from1 to 8GPa and to decrease the strain to failure from >90% to 3% as the volume fraction of HA increases to 0.5.
Thus, the mechanical properties of the PE-HA composite are close to or

superior to those of bone.

Coatings

A biometric coating, which has reached a significant level of clinical application, is the use of HA as a coating on porous metal surfaces for fixation of orthopedic prostheses. This approach combines biological and bioactive fixation. Though a wide range of methods have been used to apply the coating, plasma spray coating is usually preferred. The table below lists the bioceramic coatings:

Substrate	Coating
316L stainless steel	Pyrolytic carbon
316L stainless steel	45S5 bioglass
316L stainless steel	αAl_2O_3-HA-TiN
316L stainless steel	HA
Co-Cr alloy	45S5 bioglass
Co-Cr alloy	HA
Ti-6Al-4V alloy	45S5 bioglass
Ti-6Al-4V alloy	HA
Ti-6Al-4V alloy	Al_2O_3
Ti-6Al-4V alloy	HA/ABS glass[ABS is alkali borosilicate glass]

1- Carbon

The medical use of pyrolytic carbon coatings on metal substrates were used in heart surgery. The first time the low-temperature isotropic (LTI) carbon coatings were used in humans was a prosthetic heart valve.

Almost all commonly used prosthetic heart valves today have LTI carbon coatings through the use of these bioceramic-in-heart valves.

Three types of Carbon are used in biomedical devices:

1- Low temperature Isotropic (LTI);

2- Ultra low Temperature Isotropic (ULTI);

3- Glassy Carbons.

The LIT, ULTI and glassy carbon are sub-crystalline forms and represent a lower degree of crystal perfection.

High density LTI carbons are the strongest bulk forms of carbon and their strength can further be increased by adding silicon.

ULTI carbon can also be produced with high densities and strength, but it is available only as a thin coating (0.1 to 1μm) of pure carbon.

Glassy carbon is inherently a low density material and, as such, is weak. Its strength cannot be increased through processing.

2- Hydroxyapatite (HA)

A second bioceramic coating which has reached a significant level of clinical applications is the use of HA as a coating on porous metal surfaces for fixation of orthopedic prostheses.

Resorption or biodegradation of calcium phosphate ceramic is caused by:

(i) Physiochemical dissolution, which depends on the solubility product of the material and local pH of its environment;

(ii) Physical disintegration into small particles due to preferential chemical attack of grain boundaries;

(iii) Biological factors, such as phagocytosis, which causes a decrease in local pH.

The rate of biodegradation increases as:

(a) Surface area increases;

(b) Crystallinity increases;

(c) Crystal perfection decreases;

(d) Crystal and grain size decrease;

(e) Ionic substitutions of

CO^{+} ,Mg^{++} , Sr^{-} in HA take place.

Natural Composites

Natural occurring composites are within us all. On the macroscale, soft and hard tissues are formed from a complex structural array of organic fibers and matrix. Soft tissues are formed from elastic (elastin) and non-elastic fibers (collagen) with a cellular matrix between the fibers. Biological structures, such as tendon, linking muscles to bone, are low in elastin.

Hard Tissues

The two most important naturally occurring forms of bone required for structural stability are termed cancellous (spongy bone) and cortical. Spongy bone is a sponge-like structure, which approximates to an isotropic material. Cortical bone is highly anisotropic with reinforcing structures .

All hard tissues are formed from the four basic phases, shown below. The relative fractions of each phase vary between bone types and conditions. The relative percentages of mass for a typical cortical bone are included.

Organic- Collagen Fiber 16%

Mineral – Hydroxyapatite (HA) $[Ca_{10}(PO_4)_2(OH)_2]$ 60%

Ground substance 2%

Water 23%

The collagen fibers provide the framework and architecture of bone, with the

HA particles located between the fibers. The ground substance is formed from proteins, polysaccharides, and musco-polysacharides, which acts as a cement, filling the spaces between collagen fibers and HA mineral.

Synthetic Bone Grafting Materials

These materials must be:

1- Biocompatible with host tissues, i.e.
a- non-toxic;
b- non-allergic;
c- non-carcinogenic;
d- non-inflammatory
2- Able to stimulate bone induction;
3- Resorbable following replacement by bone;
4- Radio-opaque;
5- Capable of withstanding sterilization
6- Inexpensive and stable to variation of temperature and humidity;
7- It has sufficient porosity to allow bone conduction and growth.