

Bioceramic in Dental Implants: A Review

Gaurav P. Jayaswal, S. P. Dange, A. N. Khalikar

© Indian Prosthodontic Society

Biomaterials are non-drug substance suitable for inclusion in system which augment or replace the function of bodily tissue or organ. Orthopedic and dental applications represent approximately 55% of the total biomaterials market. Changes in biologic responses and device design have been the direct result of advances in material science. Bioceramics fulfill a unique function as biomedical materials. Bioceramics are non-toxic and bioinert, bioactive or bioresorbable. Bioceramics continue to be vital for bone repair and uncemented implant fixation with recent advances in its composition and coating technology.

Keywords: Biomaterials, Hydroxyapatite, Zirconia

Introduction

An implant is defined as a medical device made from one or more biomaterials that is intentionally placed within the body, either totally or partially buried beneath an epithelial surface. Biomaterials by definition is a non-drug substance suitable for inclusion in system which augment or replace the function of bodily tissue or organ. From as early as a century ago artificial material and device have been developed to a point where they can replace various component of the human body.

There are three terms in which a biomaterial may be described in or classified into representing the tissues responses. These are bioinert, bioresorbable and bioactive, which are well covered in range of literature. More effective means of affixing hard tissue implants for augmentation or replacement involves three elements: the material system, the biologic profile and device design. Changes in biologic

responses and device design have been the direct result of advances in material science.

Bioceramics primarily have provided the research and dental clinical professionals with new substances of interest for over last 2 decades. Various formulations of these materials have been conceived on the basis of their chemical similarity to bone.

Bioceramics

Bioceramics have structural function as joint or tissue replacement, can be used as coatings to improve the biocompatibility of metal implants and can function as resorbable lattices which provide temporary structures and a framework that is dissolved, replaced as the body rebuilds tissue. The thermal and chemical stability of ceramics, their high strength, wear resistance and durability all contribute to making ceramics good candidate material for surgical implants.

Bioceramics are non-toxic can be bioinert, bioactive that is durable material which can undergo interfacial interactions with surrounding tissue, they can be also biodegradable, soluble or resorbable. Sugar and proteins can bind to ceramics. Blood vessels for example can penetrate some ceramic prosthetics and bone materials can eventually begin to replace them. Bioceramics fulfill a unique function as biomedical materials.

G. P. Jayaswal ✉ • S. P. Dange • A. N. Khalikar
Department of Prosthodontics,
Government Dental College and Hospital,
Aurangabad, India

e-mail: drgpjayaswal@gmail.com

History of Bioceramics

Firstly widely evaluated bioceramic was common plaster of paris ($\text{CaSO}_4, \text{H}_2\text{O}$).

Dressman published first report on use of plaster of paris to repair bone defect in 1892.

First successful use of tricalcium phosphate was reported in 1920. The interest of invention of bioceramics was developed in 1960s by work of Hulbert and coworkers. While interest reach plateau in 1970 and early 1980s [1].

The modern era of bioceramic was traced by Smith's successful study of ceramic bone substitute named Cerosium in 1963, Cerosium is composed of porous aluminate ceramic impregnated with a epoxy resin.

The use of bioceramics in human surgery began in 1980s. First commercially available hydroxyapatite coated implants were seen in 1980s.

In 1997 Chevalier and coworkers reported that the coefficient of friction between alumina and zirconia is very low. The most devastating historical event was the introduction of 'TH-Zirconia' implants in 1998. It has been reported that over 400,000 Zirconia hip joint femoral heads have been implanted since 1985 until 2001.

Bioceramics are available as

- Microspheres
- Thin layers or coatings on a metallic implants
- Porous networks
- Composites with a polymer component
- Large well polished surface.

Types of Bioceramics

Bioceramics can be categorized according to there tissue response as [2]:

- Bioactive - Bioglass/glass ceramic
- Bioresorbable - Calcium phosphate
- Bioinert - Alumina, zirconia, carbon.

Functions of Bioceramics

Bioceramics satisfy needs as diverse as follows:

- They have low co-efficient of friction for lubricating surfaces in joint prostheses
- Can be placed on surfaces on heart valves that avoid blood clotting
- They act as a material that stimulate bone growth.

Bioactive

Bioglasses/Glass Ceramics

Since discovery of the bioglasses, which bond to living tissue by Hench and Wilson, various kinds of bioactive glasses and glass ceramics with different functions such as high mechanical strength and fast setting ability have been developed. The glasses that have been investigated for implantation are primarily based on silica (SiO_2), which may contain small amounts of other crystalline phases.

Since the discovery of stable $\text{SiO}_2\text{-Na}_2\text{O-CaO}$ ceramic formulations several thousand years ago, most silicate ceramics used by man have an SiO_2 content of 65 wt% or more. These $\text{SiO}_2\text{-Na}_2\text{O-CaO}$ ceramics are more commonly called glass. These 65% silica glass are bioinert, also they are weak and shatter easily.

The first bioactive glass was invented in 1971 [3]. Composition of 45S5 Bioglass is 45% SiO_2 , 24.5% CaO , 24.5% Na_2O , unfortunately it is very weak and brittle. The addition of 6% P_2O_5 by weight makes the glass extremely bioactive. Hench, and Vrouwenvelder et al. suggested that bioglass® 45S5 has greater osteoblastic activity as compared to hydroxyapatite. Li et al. prepared glass ceramics with differing degrees of crystallinity and found that the amount of glassy phase remaining directly influences the formation of an apatite layer, with total inhibition when the glassy phase constituted less than about 5 wt%.

Bio-Resorbable

Hydroxyapatite

Synthetic hydroxyapatite $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ was accepted as a potential biomaterial that forms a strong chemical bond with bone *in vivo* [4]. It was initially used for repair of residual ridge resorption in 1970s and was firstly declared as successful implant material in 1988 at North America.

Hydroxyapatite is chemically similar to the mineral component of bones and hard tissues in mammals. It is one of few materials that are classed as bioactive.

Properties

- The ability to integrate in bone structures and support bone in growth, without breaking down or dissolving (i.e. it is bioactive)
- Hydroxyapatite is a thermally unstable compound, decomposing at temperature from about 800–1,200°C depending on its stoichiometry
- It does not have the mechanical strength to enable it to succeed in long-term load bearing applications

- Hydroxyapatite is having calcium to phosphorus ratio of 1.67.

Applications

- Coatings of hydroxyapatite are often applied to metallic implants to alter the surface properties. To date, the only commercially accepted method of applying hydroxyapatite coatings to metallic implants is plasma spraying
- Hydroxyapatite may be employed in forms such as powders, porous blocks or beads to fill bone defects or voids. The bone filler will provide a scaffold and encourage the rapid filling of the void by naturally forming bone and provides an alternative to bone grafts.

Advantages of Hydroxyapatite

It is rapidly integrated into the human body. Perhaps its most interesting property is that, hydroxyapatite will bond to bone forming indistinguishable unions.

Disadvantages of Hydroxyapatite

However, poor mechanical properties (in particular fatigue properties) mean that hydroxyapatite cannot be used in bulk form for load bearing applications.

Calcium Phosphate

It is classified as resorbable bioceramic. It was first commercially available as implant material in 1980s. The benefit of calcium phosphate bioceramic is that the dissolution product can be readily assimilated by the human body.

Calcium Phosphate Compounds

Amorphous calcium phosphate (ACP)

Dicalcium phosphate (DCP) CaHPO_4

Tricalcium phosphate (α -TCP) $\text{Ca}_3(\text{PO}_4)_2$

Pentacalcium hydroxyapatite (HAp) $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$

Tetracalcium Phosphate monoxide (TTCP) $\text{Ca}_4\text{O}(\text{PO}_4)_2$.

Solubility of Calcium Phosphate Compound

$\text{ACP} > \text{DCP} > \text{TTCP} > \alpha\text{-TCP} > \beta\text{-TCP} \gg \text{HAp}$

The relative insolubility of hydroxyapatite compared to other calcium phosphate phases is not surprising as it is the only stable calcium phosphate compound at pH above 4.2. Below this, dicalcium phosphate dehydrate is the stable compound [5]. It is not uncommon for unstable

calcium phosphate to dissolve and reprecipitate as the stable compound at a given pH. Under normal physiologic condition of pH 7.2 Hydroxyapatite is the stable calcium phosphate compound. This may drop to as low as 5.5 in the region of tissue damage, although this would eventually return to pH 7.2 over a period of time. Even under these conditions Hydroxyapatite is still the stable phase.

Bioinert

Alumina

Alumina is a highly inert material and resistant to most corrosive environments, including the highly dynamic environment that is the human body. Under physiological conditions, it is also extremely unreactive and is classed as nearly inert. It was firstly used as implant material in 1970s.

However, the body does recognize it as a foreign material and does attempt to isolate it by forming a layer of non-adherent fibrous tissue around the implant where possible.

Properties of alumina bioceramic

- High degree of chemical inertness under physiological condition
- Excellent wear resistance
- Ability to be polished to a high surface finish
- Excellent hardness.

Manufacturing of Alumina

Most of the aluminium oxide produced commercially is obtained by the calcination of aluminium hydroxide (frequently termed alumina trihydrate or ATH) [6]. The aluminium hydroxide is virtually all made by the Bayer process. This involves the digestion of bauxite in caustic soda and the subsequent precipitation of aluminium hydroxide by the addition of fine seed crystals of aluminium hydroxide.

Phases of alumina

Aluminium oxide exists in many forms, α , χ , η , δ , κ , θ , γ , ρ ; these arise during the heat treatment of aluminium hydroxide or aluminium oxy hydroxide. The most thermodynamically stable form is α -aluminium oxide.

Applications

- Articulating surfaces in joint replacements
- Bone spacers
- Dental applications.

Alumina has been used in dental applications. Specifically, it has been used for tooth replacements. In many of these cases single crystal alumina or sapphire is used. However, this is declining in popularity, being replaced by other materials such as dental porcelains.

Zirconia

It was successfully used as implant material in 1960s. The biological response of bone to zirconia ceramics has been reported to be similar to the response generally observed for alumina. Compared to alumina, partially stabilized zirconia (PSZ) has higher flexural strength, fracture toughness and high Weibull modulus (which equates to better reliability), as well as lower Young's modulus and the ability to be polished to a superior surface finish [7].

Zirconia ceramic implants somehow have had a controversial history regarding their phase metastability, degradation in water lubricants in simulation studies and influence on friction and wear phenomena.

There have been some concerns regarding this degradation phenomenon associated with the tetragonal-to-monoclinic phase transformation under the long-term aqueous condition such as *in vivo*. One of the current manufacturers of zirconia implants has improved the conventional zirconia, leading to the increased strength and the high resistance to the phase transformation. In addition, it was reported in implant testing that the polyethylene wear against the improved zirconia implant is lower than that against the Co-Cr implant. When articulated with highly cross-linked polyethylene, not only zirconia implants but also Co-Cr implants showed very low wear rates. However, because zirconia is more scratch-resistant than Co-Cr, it would be more suitable implant for the long-term clinical use.

Yttrium Stabilized Tetragonal Polycrystalline Zirconia

Yttrium stabilized tetragonal polycrystalline zirconia (Y-TZP) has a fine grain size and offers the best mechanical properties. Low temperature degradation of TZP is known to occur as a result of the spontaneous phase transformation of the tetragonal zirconia to monoclinic phase during ageing at 130–300°C possibly within water environment. It has been reported that this degradation leads to a decrease in strength due to the formation of microcracks and accompanying phase transformation.

Zirconia/Alumina Composite Biomaterials

Recently degradation free new zirconia-alumina composites have been reported; TZP/alumina composite (80% TZP of [90 mol% ZrO₂ - 6 mol% Y₂O₃ - 4 mol% Nb₂O₅ composition]

and 20% Al₂O₃. Another potential composite comprised of 70 vol% TZP (stabilized with 10 mol% CeO₂), and 30 vol% Al₂O₃ and 0.05 mol% TiO₂ is currently being investigated in Japan.

Pyrolytic Carbon

Pyrolytic carbon is commonly used in artificial heart valves and has been the most popular material for this application for the last 30 years. Properties that make this material suitable for this application include, good strength, wear resistance, durability and most importantly thromboresistance, or the ability to resist blood clotting. Pyrolytic carbon is also used for small orthopedic joints such as fingers and spinal inserts.

Mechanism of Bioactive Materials to Bond with Bone

Local pH changes near the bioglass/calcium phosphate/hydroxyapatite surface causes sodium, calcium and phosphate ions to be dissolved from it. At the same time, hydrogen ions from the local tissue fluids replace the lost sodium in the bioglass.

At the surface a silica rich gel forms because of selective dissolution of elements that are lost from the surface including an abundance of silica. This silicon depletion is followed by the migration of calcium and phosphate ions into silica gel surface from within both the bioglass and the tissue fluids, to form calcium phosphate layer.

Once the sufficient concentration of phosphorus is present at the surface osteoblast begin to proliferate, thereby producing collagen fibrils that become incorporated into the calcium phosphate gel and are anchored by the calcium phosphate crystals. This strong bonding layer is 100–200 microm thick, which is roughly 100 times the thickness of comparable layer formed by hydroxyapatite [8].

New Developments in Bioceramic Implant Materials

Bioceramics have been the cornerstone of strategies for bone repair and uncemented implant fixation for more than 2 decades. An important feature of these materials is that they form a carbonate apatite layer on their surface following implantation.

The success of bioceramic implants and coatings is evident from their increasing use. These have shown the powerful ability of these materials to bond to bone and provide a substrate for, and in some cases stimulate, bone formation. They are also relatively easy to synthesize from

simple chemicals, they are stable and can be prepared in a number of formats.

Hydroxyapatite coated joint replacements perform well compared with the cemented alternatives. In addition, in the modern age of developments in tissue engineering and molecular approaches to the promotion of tissue repair, research using these materials continues apace. There is now a new range of bioceramic-based materials and material coatings, they will improve the efficacy and extend the application range of bioceramics in bone.

Silicon Substitution

An important development in the ability to manipulate calcium phosphate ceramics was the synthesis of phase pure hydroxyapatite by carefully controlling the reaction conditions. Prior to this, the hydroxyapatite-based ceramics, both natural and synthetic, could be characterized, but were often a mixture of phases, for example, hydroxyapatite, β -tricalcium phosphate and calcium oxide are three separate phases that could be present in a preparation; substitution of phosphate and hydroxyl residues could also be present.

This non-uniformity meant that the beneficial properties of a particular implant material could not be definitely ascribed to any particular component. Phase purity has allowed controlled substitution of ions into the hydroxyapatite lattice and their effect can therefore be carefully assessed. It is known that the main ion-substitution in bone mineral is carbonate and this increases its solubility. However the most useful substitution determined so far is silicon.

Silicon substitution produced improved osteo-conductivity following implantation and has led to the development of macroporous silicon-substituted hydroxyapatite implants. New substitution with for example carbonate or yttrium ions and different levels of

substitution may lead to further improvements in bioactivity of hydroxyapatite.

Summary

Bioceramics fulfill a unique function as biomedical materials. The development of biomaterials and manufacturing techniques has broadened the diversity of application within the human body. They have provided the research and dental clinical professionals with new substances of interest for over 20 years.

Bioceramics have a bright future. This is not only in the devices currently used, which will continue to perform well in bone. The promise lies in new formulations with innovative methods of application of these materials to implant surfaces.

References

1. Hench LL (1991) Bioceramics: from concept to clinic. *Journal of the American Ceramic Society* 74(7):1487–1510
2. Heness G, Ben-Nissan B (2004) Innovative Bioceramics. *Materials forum* 27:104–114
3. Hawley, Gessner G (1981) *The Condensed Chemical Dictionary*, Tenth Edition, p 185
4. www.AZoM.com
5. John FK (1986) Calcium phosphate coatings for dental implants. *Dent Clin North Am* 30(1):1
6. Cordingley R, Kohan L, Ben-Nissan B, Pezzotti G (2003) *Journal of the Australasian Ceramic Society* 39(1):20–28
7. Dr. Owen (1995) Standard Ph.D Thesis, “Application of Transformation-Toughened Zirconia Ceramics as Bioceramics”, University of New South Wales, Australia
8. Guéhenec L Le, Layrolle P, Daculsi G (2004) A review of bioceramics and fibrin sealant, *European cells and materials* 8:1–11