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Review of Literature on Bioceramics

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ABSTRACT

There are two major type of bioceramics, namely bioactive and bioinert ceramics.10 The bioactive ceramics include hydroxyapatite (HAp), tricalcium phosphate (TCP), glass ionomer cement (GIC) and bioglass.13,14,15,16,17 When these types of bioceramic are used as bone substitutes, the bone is directly chemically bonded to the material. However, these materials are mechanically weak and unsuitable for use in stress bearing areas. Alumina and zirconia are classified as bioinert ceramics which are tough and strong.13,15,16 When such ceramics are implanted as a bone substitute they become surrounded by a fibrous tissue capsule which prevents direct bonding of the material to bone. Repeated stimulation by stress and tension at the interface leads to the growth of connective tissue, which increases the risk of loosening between the bone and ceramic implant.

KEYWORDS:

INTRODUCTION

The potential of ceramics as biomaterials relies upon their compatibility with the physiological environment. Bioceramics are defined as ceramic biomaterials designed to achieve a specific physiological response when used as a material of construction for prosthetic devices or artificial internal organs.

The first ceramics to be used as prosthetic materials were mainly alumina, titania and mixtures of calcia and alumina.

Bioceramics are classified into three sub-groups, based upon their chemical reactivity in a physiological environment, 1) bioinert such as ZrO_2 and Al_2O_3, 2) bioactive such as HAp and Bioglasses and 3) resorbable such as tricalcium phosphate (TCP).

1. Bioinert Materials

Inert bioceramics or non-toxic inactive bioceramics undergo little or no chemical change during long-term exposure to the physiological environment .Bone response to bioinert ceramics involves the formation of a very thin of fibrous membrane, several micrometers or less, surrounding the implant material.

1.1 Alumina

One of the most widely employed bioinert ceramics is alumina (Al_2O_3). The first use of aluminas for implants in orthopaedics and dentistry was in the

Although the aluminas currently available perform satisfactorily,

1.2 Zirconia

Zirconia is also classified as a bioinert ceramic and is noteworthy for its high strength and toughness. Zirconia has three crystal phases: monoclinic, tetragonal, and cubic. Through this phase transformation, zirconia has been shown to have a high fracture toughness. In addition, zirconia has demonstrated better wear resistance than alumina

2. Bioactive Materials

In bioactive or non-toxic active bioceramics, the composition is designed such that the surface undergoes a selective chemical reaction with the physiological environment, resulting in a chemical bond between tissue and the implant surface.The bonded interface protects the implant material from further deterioration with time.

2.1 Bioglass

The first man-made materials which were found to bond to living bone were glasses in system Na_2O-CaO-SiO_2-$P2O_5$. These were discovered by Hench. The bioglass material seems to enhance bone-implant interface development and bonding when implanted in bone.

2.2 Glass Ionomer Cement

Glass ionomer cement (GIC) was orginally developed by Wilson and Kent [22] in 1969 Recently Brook[22] in his in vivo and in vitro study has confirmed that GICs showed a favourable biological response as potential bone substitutes, when compared to HAp and TCP ceramics.

2.3 Calcium phosphates

Although the mineral is similar to hydroxyapatite (HAp), it is poorly crystalline in structure and contains a wide range of calcium phosphate phases, including TCP, The favourable response of the calcium phosphate ceramics, despite variations in the chemical composition and material structure, is attributable to their being mainly composed of calcium and phosphate ions.[81,82] Some of the synthetic calcium phosphates are briefly described below and HAp is

a) Hydroxyapatite (HAp)

HAp with the chemical composition $Ca_{10}(PO_4)_6(OH)_2$ has been extensively study as a bone substitute. when sintered at high temperatures of up to 1250 ^oC, was initially believed to be non-resorbable. However, it is currently generally accepted that degradation of HAp can occur to a certain extent. LeGeros, et alreported that the bioactivity of HAp may be related to its dissolution rate.

b) Fluorapatite (FA)

Fluorapatite $Ca_{10}(PO_4)_6(F)_2$ exhibits the same structure as HAp, the only difference being that the hydroxyl. It would therefore be more suitable than HAp for high temperature processes such as plasma spraying, which was confirmed by Dhert.

c) Tricalcium phosphate (whitlockite).

Tricalcium phosphate $Ca_3(PO_4)_2$ (TCP), together with HAp, is one of the most widely investigated calcium phosphate ceramics. TCP can be found in two forms, -TCP and the more stable -TCP. Both forms have been reported to exhibit relatively high dissolution properties.

d) Tetracalcium phosphate.

Very little information is available for $Ca_4(PO_4)_2O$ (TTCP) as a bone substitute material. Similar interface morphologies as that with HAp were observed when TTCP was implanted in bone tissue.

Bioinert Zirconia

With its very high melting point (2680 15 ^oC), and stability in both oxidising and reducing atmospheres, zirconia has attracted an ever increasing interest from both the theoretical scientists and practical and clinical researchers. Currently, zirconium oxide ceramics are mostly used for refractory applications.

Bioactive Hydroxyapatite and its clinical applications

1 Structure and composition

Hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$ crystallises into a hexagonal structure, its theoretical density is 3.156 gcm^{-3}, lighter than metallic implants

2 Thermal Stability of HAp

HAp with various degrees of porosity and different strengths have been produced, using powder press, hot press, hot isostatic press and slip cast techniques. In the former process HAp loses hydroxyl groups during heating and transforms to oxyhydroxyapatite $Ca_{10}(PO_4)_6O$ as follows:

$Ca_{10}(PO_4)_6(OH)_2 Ca_{10}(PO_4)_6(OH)_{2-2x}\ O_{x(\ )x} + x\ H_2O$ (1)

Where ( ) is a vacancy, x1.

In the latter process Locardi et al.[131] have reported that the HAp decomposes into -TCP or -TCP and tetra calcium phosphate when the sintering temperature is more than 1125^{o}C according to the formula:

$Ca_{10}(PO_4)_6(OH)_2 2Ca_3\ (PO_4)_2 + Ca_4P_2O_9 + H_2O$ (2)

3 Forms of Hydroxyapatite

Particulate HAp

This consists of small particles of HAp between 0.5 to 2.0 mm,[134] which are used for alveolar ridge augmentation and the restoration of periodontal defects.

This material may be produced by sublimation of naphthalene pore formers or decomposition of hydrogen peroxide. The porous material can be used to replace parts of the skeleton which are not loaded or loaded mainly in compression.

4 Mechanical Properties of HAp Ceramics

The Young's modules of natural bone is the lowest of the four materials, whereas its fracture toughness, K_{1c} , has the highest value. This is due to the fact that natural bone is a composite of HAp and collagen.

Table 1: Comparison between bone and bioceramics

Parameters	Bone	HAp	ZrO_2	Al_2O_3
$_f$ (MPa)	140	100	1000	400
K_{1c}(MPa.m$^{1/2}$)	6	1	8	4
E(GPa)	18	100	200	400

Hydroxyapatite implant materials are limited in their mechanical properties. Like most bioactive ceramics, these materials are brittle, have low impact resistance, and relatively low tensile strength and toughness. Therefore, these ceramics, are poorly suited for load-bearing situations in which considerable bending or torsional forces would be brought to bear on the implant

Table.2: Comparison of the mechanical properties of HAp ceramic with those currently used metallic materials.

Material	Elastic Modulus (GPa)	Tensile Strength (MPa)	Density (g/cm^3)
Stainless steel	200	550	7.9
Co-Cr-Mo	240	700	8.5
Titanium	100	450	4.5
Ti6Ai4V	110	900	4.5
TypeIII Gold alloy	90	840	15.5
HAp ceramics	100	100	3.156
Cortical bone	18	140	0.7 (dry)

. In contrast, With et al. found a decrease in 3-point bending strength under wet conditions, the strength under wet conditions being 24 MPa lower than that under dry conditions. They also observed a similar tendency in fracture toughness; with K_{1c} of their toughest HAp being 1.0 MPam$^{1/2}$ under dry conditions, while the value under wet conditions is 0.75 MPam$^{1/2}$. As mechanical behavior is sensitive to test methods, there is some argument concering the discrepancy.

5 Biological Response of HAp

Hydroxyapatite, is perhaps the most biocompatible substances known for use in bone replacement. It is not toxic and can become completely integrated with natural bone . With natural bone cementing mechanisms a bond strength of 50-60 MPa can achieved between the bone and a HAp implant, whereas other materials like titanium show a bond strength of only 0.6 MPa. Protein adsorption onto implant materials may also be of importance for the bond formation. Implantation studies have shown the presence of an electron dense layer at the interface between hydroxyapatite and bone. This layer was continuous with the lamina limitans of the surrounding bone, and was composed of both organic and inorganic material.

6 Biodegradation of Calcium Phosphates.

Biodegradation refers to the gradual breakdown of a material mediated by specific biological activity, while bioresorption is the process of removal by cellular activity and/or dissolution of a material in a biological environment.

HAp dissolves far less readily than TCP. For example, when HAp and TCP preparations, known to be pure and dense. The surface area of the ceramic is also important in determining the rate of bioresorption. High density ceramics possess a much smaller surface area than porous ceramics and will have a reduced tendency to undergo bioresorption; whether they are composed of HAp, TCP or some combination of the two.

7. Clinical Applications of HAp

Alveolar ridge augmentation:

HAp is the most popular material used at present but does not fulfil all the above criteria. Dense particulate HAp has come into wide use for augmentation of atrophic mandibular and maxillary alveolar ridges. Improved denture stability and retention have been achieved, and patients have reported greater wearing comfort and overall satisfaction with their dentures. However, a variety of problems such as periodontal disease, ankylosis with concurrent root resorption, caries, and prohibitive cost due to endodotic therapy limit the usefulness of these two procedures and neither have come into widespread clinical use.

Repair of periodontal lesions

Particulate HAp and TCP are both used as an aid in the repair of periodontal osseous lesions. Such osseous defects are a major complicating factor in periodontal disease. Dense HAp ceramic particles can be used as effective space fillers and so can reduce the amount of osseous and fibrous tissue ingrowth needed to fill the bony defects.

8. Methods of Overcoming the limitations of HAp

HAp is mechanically weak and unsuitable for use in stress bearing areas. Two approaches have been taken to overcome this problem.

Coatings :

One of the most promising applications of calcium phosphate technology revolves around the use of HAp coatings on conventional metallic prostheses. In the case of major orthopaedic appliances such as total hips and knees, a strongly adherent HAp coating on the metallic devices could obviate the need for methyl methacrylate bone cement, which has proved to be the limiting factor in long-term survival of such devices. However, all commonly used coating techniques depend on mechanical adhesion (rather than a chemical bond) to the underlying metal which makes this metal-HAp interface the weakest point of the system. Composites:

The second approach is to produce HAp/Ceramic composite with better mechanical properties with HAp, such as ZrO_2-HAp, Ti-HAp, Al_2O_3-HAp composites. The even distribution of the apatite phase as islets in a strong matrix may contribute to mineralization and direct bone apposition onto this type of ceramic composite.[18,19,20]

Ceramic Composites

The objective of research concerned with structural ceramics is the generation of materials having high reliability. To achieve this objective, there are two fundamentally different approaches: flaw control and toughening. The latter has emerged more recently, and has the obvious advantage that appreciable processing and postprocessing damage can be tolerated without compromising the structural reliability.

Composite materials which combine the properties of a ceramic matix and ceramic reinforcement or aggregate phase, otherwise known as ceramic matrix composites, are the subject of intense research interest. With careful processing improved strength and toughness can be

obtained when compared to unreinforced ceramics. Composite such as zirconia toughened Al_2O_3 (ZTA), TiC-Al_2O_3 and SiC-Al_2O_3 are currently used as wear resistant bearings and cutting tools. A variety of ceramic composites are been explored for medical applications e.g. ZrO_2-HAp, Ti-HAp, Al_2O_3-HAp composites.

. The strength of the composite increased with increasing zirconia content. This bioceramic exhibited extremely high bending strength (400-1000 MPa) for 30-80 vol. % zirconia. The bioactivity of these zirconia toughened glass-ceramic composites was evaluated by their bond strength to living bones, and it was found that the bond strength of composite containing 30 vol. % zirconia was as high as that of the glass-ceramic.

Several researcher have reported[12,21-25] on hydroxyapatite-zirconia composites with different volume ratio of zirconia particles. Most of these works reflect the difficulties of retaining the HAp and ZrO_2 phases in the composites due to difference in densification temperature (e.g. HAp start to densify at 1250 ^oC, whereas ZrO_2 start to densify at 1400 ^oC), and decomposition of HAp at 1400 ^oC into TCP. As a consequence the desirable initial phases cannot be preserved in the composites unless expensive high technology processing at temperatures as low as 1250 ^oC is used.

Ducheyne, P et al.[17] produced HAp/ZrO_2 composites using hot isostatic pressing (HIP) at 800-1150 ^oC at 100 MPa for 2 hours. No phase change was found in zirconia nor in the HAp phase. The strength and the toughness achieved were respectively 190 MPa and 2.3 MPa.$m^{1/2}$. These value were approximately 20% and 100% higher than the corresponding value for hydroxyapatite ceramics without zirconia. Wu, J-M. et al.[18] also used HIPing (1225 ^oC at 160 MPa for 1 hour) to produce HAp/ZrO_2 composite that has excellent fatigue resistance in addition to high strength, but they did not characterised the fired composite.

Conclusion

Thus the possible benefits of a high strength, high toughness, bioactive HAp/zirconia have not as yet been fully explored.

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