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Bioceramics in Hip and Knee Implants

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Abstract

Bioceramics are the ceramics that are usually composed of zirconia, alumina, hydroxyapatite, tricalcium phosphate, bioglass, etc., Bioceramics are used in various biomedical applications because of positive interactions with human tissues. Medicine, dentistry, surgery, and tissue engineering are different field that use bioceramics to initiate potential treatment choices to reinforce the conventional dental and medical practices. Gradually, bioceramics have been established for usage in numerous applications including hip and knee replacement, cardiovascular valve replacements, dental restorations, and implants. Interestingly, bioceramics is gaining wide attention especially for hip and knee implants due to their ability to repair and reconstruct damaged or diseased parts of Musculo-skeletal system. Both synthetic and natural bioceramics are promising as prompt to strongly bind to bone and emerge as a substitute to other metal implants. The major objective of bioceramic research was the dormancy to prevent biological rejection and interaction of foreign body with functional biomaterials within the body. Currently, bioceramic materials casted for repairing and reconstruction of soft and hard tissues can be classified based on composition, structure and properties. The bioinert ceramics are the ones categorized as zirconia and alumina, glass-ceramics and bioglass, and calcium phosphates-based materials that are bioresorbable. Various properties of bioceramic properties and recent clinical trials are also contemplated as an update. On the basis of rigorous requirements in the field of clinical application, developing advanced functional bioceramics for tissue engineering are considered as future prospect. Thus, current review discusses on various biomedical applications of bioceramics, but majorly focuses on role of different bioceramics in hip and knee replacement.

Keywords: *Bioceramics, implants, biomedical applications, Hip and knee replacement, tissue engineering.*

1.0 Introduction

The bioceramics belongs to the category of biomaterials, that are utilized to treat, repair, augment, or replace diseased or damaged hard tissue present in the body. Since many years, titanium and its alloy (Ti-6Al-4V), are widely used as dental and orthopaedic implant materials. However, owing to higher strength and elastic modulus compared to human bones, stress-shielding effect lead to loosening of implant and failure will be of high concern in the long run. Failure of implant devices due to implant-related infections is also a critical issue. There are two important factors on which the success of any implant depends; (a) tissue response to the implant and (b) materials behaviour after implantation. Overall success and long-term life of the metal implants is greatly affected by non-ideal osseointegration and implant-related infections necessitating revision surgery resulting in high economic and social impact[8]. Thus, there is a high need to develop biocompatible implants to address these issues and for overall success and long-term life.

Owing to many properties that can overcome the limitations of the metal implants, bioceramics are emerging as the most

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suitable materials for medical implants. During the 18th century, Porcelain was the first bioceramic material that was used for the treatment of the crown. In the 19th century Plaster of Paris was used for treatment of dental disorders. Application of bioceramics in the medical field was enlarged in the 20th century[29]. Moderate degradation, significant biocompatibility, high mechanical strength and good osseointegration with host tissue have made bioceramics excellent choice of materials for medical implants. Bioceramics are user friendly and biocompatible substitutes for medical implantation, due to their important properties such as low heat conductance, high melting temperatures and difficult to shear plastically[5]. In addition, due to their biological safety, bioceramics have gained wide acceptance in the medical industry.

2.0 Classification

Bioceramics are categorized based on various criteria such as origin, composition, crystallinity and tissue response[14]. Table 1 and Figure 1 brief the overall classification of bioceramics. These ceramics are obtained either naturally or artificially synthesized using sandblasting[16], Ultraviolet (UV) light treatment[31], Coating[26], Precipitation/Calcination (Sobczak, et al., 2009), Biofunctionalization (Ruoslahti, et al., 1987), Emulsion[21], Sol–gel[21], Hydrothermal[21], Selective infiltration etching[1], Hydrolysis (Sobczak, et al., 2009), Polishing[17], Laser treatment[25], Conventional method (Affatato, et al., 2012).

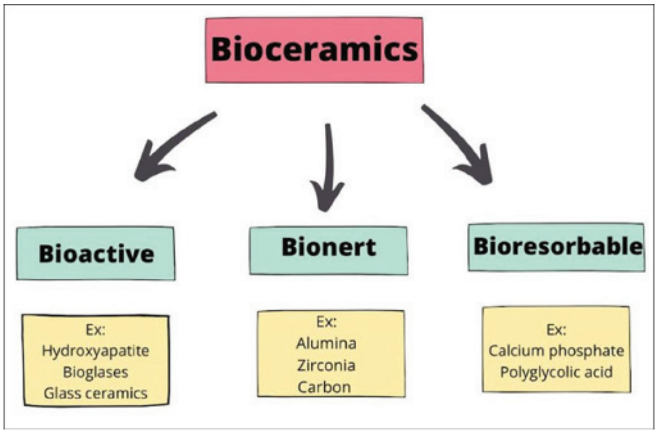

Figure 1: Classification of bioceramics

3.0 Properties of Bioceramics

During the selection of a suitable bioceramic, the material has to be checked for desirable properties satisfying the purpose.

3.1 Mechanical properties

Bioceramic should have high wear resistance, elastic modulus and fatigue strength. Bioceramics such as Al_2O_3 and YSZ (yttria-stabilized zirconia) are utilized for hip joint prostheses due to their enhanced mechanical properties, bioinert nature, and wear resistive nature. But the major issue for the non-success of hip joint implant is sudden impact of the material due to lower mechanical characteristics including young's modulus, fracture toughness and hardness[34]. These numerous mechanical properties of bio ceramics are mentioned in the Table 2.

3.2 Biological properties

3.2.1 Biocompatibility

The material used as a bioceramic must be biocompatible, non-toxic, non-combustible[38], demonstrated biocompatibility of ZrO_2 bio ceramic for umbilical vein endothelial cell lines via haemolysis and cytotoxicity assays.

3.2.2 Antibacterial activity

The bioceramic material used must possess long lasting antibacterial property[18]. But due to absence of osseointegration property of the metal alloys implants, there was restriction in their attachment with the bone tissues biologically and also, metal ions were released leading to adverse effects on the health of the patient[2].

3.3 Physicochemical properties

3.3.1 Durability

Bioceramic constituents should be durable and long lasting to receive advantages such as improved bond strength. Fatigue behaviour is one of the notable characteristics of bioceramic that helps in long-term usage[32].

3.3.2 Radiopacity

Sufficient radiopacity of a bio ceramic material ensures it is differentiated from an adjacent anatomical structure, like jaw bone or dental tissue[40].

3.3.3 Short setting time

For a bioceramic to set, there should be requirement of moisture content. Shorter setting time help in tight sealing of bioceramic with the desirable part of the body whereas, longer setting time might result in struggle with respect to mixture maintenance[22].

4.0 Most Commonly used Bioceramics as Implants

Bioceramics have various applications in medical fields inclusive of orthopedics and dentistry as shown in the

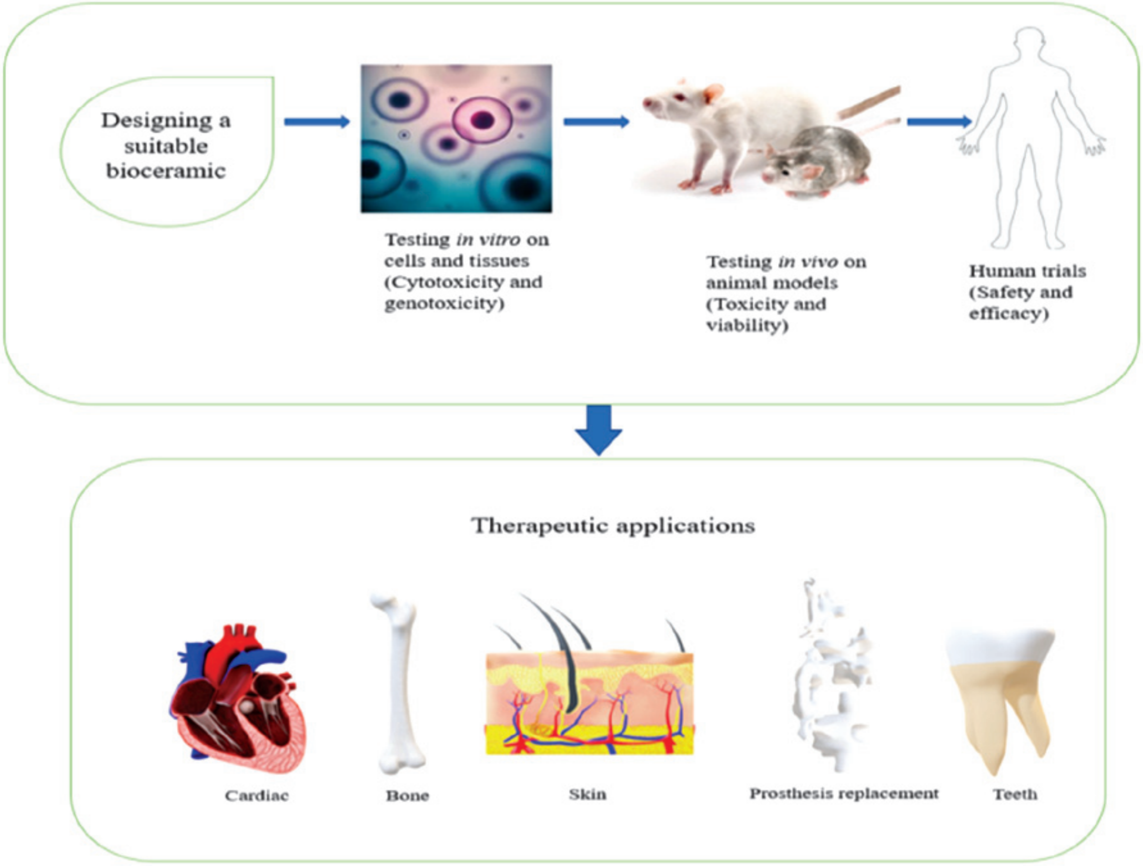

Figure 2: Various applications of Bioceramics

Figure 2. The medical applications of bioceramics include replacement for hips, knees, tendons, ligaments, tendons, dental, alveolar ridge augmentation, maxillofacial reconstruction as well as stabilization of bony dental arches.

4.1 Bioglass

Bioactive glass is a material that can replace damaged tissues and promote tissue regeneration. It is also a good promising candidate for the integration of metal implants[35]. Bioglass composites are commonly used as coating materials due to their various properties such as mechanical strength, bioactivity, and surface functionality[12].

The biocompatibility of bioglass was noted when it comes in contact with the body tissues. Ions leave the implant surface's glass material complex to enter the body whereas hydrogen forms a network with silicon during glass coating once it leaves[13]. If the material for implant was not biocompatible, then the body might reject material considering it to be a foreign entity. Hence, the implant material can be used for a prolonged duration. Due to these interactions, bioactive glass was used in orthopedic and dental applications[36].

4.2 Calcium phosphate-based bioceramics

The calcium containing cation (Ca^{2+}) along with orthophosphate (PO_4^{3-}), metaphosphate (PO_3^{-}) or pyrophosphate ($P_2O_7^{"4}$) anions are considered to be calcium phosphate. It is majorly found in tooth enamel and bone[11]. By coating calcium phosphate on surface of stem, bonding of bone-bone takes place resulting in the osteoconduction of implant formed during the technique of interface bioactive bone cement (IBBC)[9]. These materials can also be used as bone fillers and bone replacers in oral surgery. According to[4], calcium phosphate materials were used in osteonecrotic cells present in the body for encouraging bone growth.

When the hip joints are provided with a load of thrice the body weight, then the load encountered will be about ten times the body weight. This might result in stress indulging daily activities such as sitting, standing, walking, stretching and jogging. Hence, the bioceramic material used must be durable under various conditions[4]. Few examples of calcium phosphate based bioceramics are â-TCP (â-ticalcium phosphate) used as a bone substituent, in dentistry, and as calcium phosphate bone cements[33] and Amorphous calcium

Table 1: Categorization of Bioceramics based on various criteria

Criteria	Types	Examples
Origin	1. Natural 2. Synthetic	1. Bones, Teeth, Biogenic silica, Natural pearls. 2. Hydroxyapatite (HA), Calcium phosphate-based materials, Bioglass.
Composition	1. Carbon based 2. Zirconium based 3. Calcium phosphate based 4. Aluminum based 5. Silica based	1. Vitreous carbon, Graphite 2. Cubic zirconia, Zircon, Tetragonal zirconia 3. Fluorapatite, Biphasic calcium phosphate, HA. 4. Aluminosilicates, Alumina. 5. Tricalcium silicate
Crystallinity	1. Crystalline 2. Amorphous	1. HA, Zirconia, Aluminosilicates, Fluorapatite 2. Bioglass, Amorphous calcium phosphate.
Tissue response	1. Bioactive 2. Bioinert	1. HA, Bioglass, Calcium phosphate-based materials. 2. Glassy carbon, Alumina.

Table 2: The mechanical properties of bio ceramics (Kokubo, 2008)

Bioceramic	Elastic modulus (GPa)	Hardness (GPa)	Poisson's ratio	Flexural strength (MPa)	Fracture toughness (MPa m1/2)
Hydroxyapatite	80–110	500 (HV)	-	115–120	1.0
Glass infiltrated Zirconia	240 (9)	11 (0.9)	0.26	476 (50)	4.9 (0.36)
Glass-infiltrated Alumina	265 (10)	11 (1.1)	0.25	440 (50)	3.6 (0.26)
Alumina	400	2300(HV)	-	595	5-6
Feldspathic Porcelain	64	-	0.21	95 (20)	0.9
Pressable Ceramic	65 (1.5)	6.5 (0.4)	-	106 (17)	1.2 (0.14)

phosphates (ACP) considered as anticarcinogenic or remineralizing agents and their ability to liberate phosphate, calcium or other ions confer on the property of osteoinduction[30].

4.3 Hydroxyapetite (HAp)

The advantage of using HAp in bone implantation is its biodegradable nature, biocompatibility, non-inflammatory, non-toxic and increased immune response[19]. In human bone, hydroxyapatite is a mineral of calcium phosphate and it is used as fabrication material of bone void plaster and bone development[3].

The different applications of HAp include spacers to the defected bones, filler into bone defects, treatment of acetabula with severe bone damage and bone defects, and bioactive bone cement. Natural bond between the host tissue and the implant is created by HAp-coated implants. For better integration with the host tissue, the HAp coating is applied on implants for cement less Total Hip arthroplasty (THA), hence reducing the time of healing[6].

4.4 Zirconia-based bio ceramics

These ceramics have major applications in dental implants and hip replacement. Yttrium, the chemical element with symbol Y is used for aging resistance and so the Yttria Tetragonal Zirconia Polycrystal (YTZP) is formed. This is six times harder than stainless steel and is a bioinert material. YTZP has other characteristics such as high resistance to high temperature, chemical stability, colour similar to tooth structure, electrically neutral, high affinity for bone tissue, low thermal conductivity, fracture toughness, high thermal shock resistance, high strength, absence of an oncogenic effect, biocompatibility, exhibiting minimal ion release in comparison with metallic implants, and noncarcinogenic property.

In 1980s, Zirconia was initiated in orthopaedics as a replacement for alumina due to higher fracture toughness and mechanical strength. The use of 3Y-TZP for hips and other joint replacements, particularly the hip femoral head was recommended due to these properties. This material is considered for dentistry due to the characteristic features such as biocompatibility, mechanical strength, and low

Table 3: Biomedical applications of zirconia

	Bio ceramic	Application	Studies conducted	Outcome of the study	Limitation	Reference
1.	Strontium oxide doped Zirconia Toughened Alumina (SrO-ZTA)	Hip-implant	The biological reactions of SrO-ZTA wear debris on the D. melanogaster and mouse myoblast cell line C2C12 model organisms.	After 72 hours of exposure to SrO-ZTA wear debris, the cellular and nuclear morphology of C2C12 mouse myoblast cells is unaltered.	The wear debris derived from the implant can cause severe toxicity by aggregating in the various important organs of the human body	Love, *et al.,* 2005
2.	zirconia toughened alumina (ZTA)	Treatment of osteointegration of ceramic spinal implants.	Osteoconductivity was tested in vitro using a human osteosarcoma cell line (SaOS-2).	To improve the bioactivity of structural ceramic implants laser patterning combined with bio glass/Si_3N_4 filling resulted as a viable tool.	The amount of mineralized hydroxyapatite on the ceramic substrates was increased by adding only bio glass as a filler in the pattern of cylindrical holes. The outcome by adding Si_3N_4 was not mentioned.	Marin, *et al.*, 2018
3.	Alumina and zirconium	Total Hip Arthroplasty (THA)	Osteoarthritis as the major diagnosis, THA surgeries with CoC bearing surfaces are performed.	Mixed ceramic showed less breakage rate than alumina.	The study's main drawback is that it didn't examine how outcomes would change if the femoral or acetabular components were revised.	Nogiwa-Valdez, *et al.*, 2018
4.	zirconia toughened alumina (ZTA)	Hip prosthesis.	ZTA wear morphology, ball-on-disc tribometer, hip joint submodeling, and hip joint wear	For various lubrication and loading conditions, it was discovered that the coefficients of friction (CoF) were high for phosphate buffered saline at 0.42 and low for sesame oil at 0.32.	It can only analyse the wear and friction coefficient up to 10 km.	Piconi,*et al.,* 2016
5.	Oxidized zirconium (OxZr)	In total hip and knee arthroplasty.	Tribological benefits of OxZr relative to CoCr (when arti- \sculated against UHMWPE) have been proven in vitro, \sincluding under abrasive test conditions.	New information about the behaviour of this material in vivo is provided.This work's additional strength comes from comparison with pristine.	There is a lot of evidence that the OxZr ceramic layer is damaged in vivo when it comes into contact with a hard component, like the acetabular shell.	Piconi, *et al.*, 2014
	monolithic Alumina and zirconia-platelet toughened alumina.	Orthopedic implants. Total hip arthroplasties	In comparison to ceramic specimens, XLPE and CoCr MO surfaces had the highest biofilm viability, according to the MTT evaluation of the test materials' surfaces (ZPTA and alumina).	Due to their physicochemical characteristics, ceramic alumina and ZPTA specimens had reduced viability, bacterial adhesion, and biofilm thickness.	In vivo studies would have added much strength to the article	Cogan, *et al.,* 2011

Continued on next page

	Bio ceramic	Application	Studies conducted	Outcome of the study	Limitation	Reference
7.	Zirconia-toughened alumina (ZTA)	Total hip arthroplasties	By using an X-ray diffractometer with a glancing angle, the phase structure of ZrO2 and Ag–ZrO2 composite coatings was examined.	Strong interactions between silver ions and intracellular components affect cellular RNA synthesis, which causes bacterial death.	ZrO_2 coatings have slightly more roughness and grains than silver coatings do.	Nizard, *et al.*, 2008

corrosion potential[25].

Arthroplasties of the hip and knee are typical surgical procedures with great long-term results. These operations are in high demand both in the United States and around the world[20]. The different applications of zirconia in hip implants are listed in Table 3.

4.5 Alumina based bioceramics

Alumina is a biodegradable, biocompatible, bioinert, and bioactive material that has various biomedical application. In 1970s, it was the first ceramic to be used for orthopedic joint prostheses due to its magnificent resistance to wear and creation of polished surfaces (Jayabalan, et al., 2008).

The manufacturing of femoral heads that can be used as substitution to hip implants and wear plates for knee implant require alumina. For substituting hip, alumina femoral head is constructed along with articulating layer[24]. There were two factors considered for successful joint substitution-friction and wear behaviour of the material and quality of implant that was anchorage to the natural tissue (Schwarz, 1973).

4.6 Silica based bioceramics

In the body, Si was discovered at active calcification sites of bones. According to Schwarz, 1973, Si was involved in bone growth and development directly. Tissue regeneration using silicate ceramics is the widely known application over several years. Silicate bio ceramics consists of two important characteristic features – assisting osteogenic differentiation of stem cells by liberating Si-containing products and intensifying regeneration of bone in vivo[39]. These were considered to be supreme substitute for bone graft material that performed as a prototype for bone growth and owned associated porous network such as bone growth and vascularisation. It aided osteogenesis, mortified at a controlled rate and restored by osteoclast action[15].

5.0 Conclusions

Bioceramics, by definition, are the synthetic compounds developed to replace a part or a function of the human body in a safe, reliable, economic, physiologically, and aesthetically acceptable manner. In the recent years, various types of biocompatible ceramics have been developed. The desirable properties of various materials are not only found in the powders but also in the complex structural arrangement of these components. This is a step that has been taken in the direction of creating composite materials that are compatible with the bones. The future of bioceramic materials lies in improving their mechanical properties and the cellular response in implant.

Biomaterials incorporated inside the human body are needed to have specific properties that will ensure that there are no negative interactions with the living tissue in the body. In order to avoid issues such as microbial adhesion and the formation of biofilm, researchers are trying to develop implants using various techniques. Due to their excellent properties, they will be able to improve the surface properties of their implants.

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