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A Review of Ceramics for Biomedical Applications

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Abstract- There is currently an increasing interest in developing sophisticated biomaterials with particular chemical and physical characteristics. These superior materials have to be able to coexist harmoniously with biological settings, like the mouth or other human anatomical areas. Ceramic biomaterials provide a workable answer in terms of mechanical strength, biological functionality, and biocompatibility given these prerequisites. The basic mechanical, chemical, and physical characteristics of the most common ceramic biomaterials and ceramic nanocomposites are discussed in this study, along with a few key applications in biomedical domains like orthopedics, dentistry, and regenerative medicine. Moreover, a thorough examination of biomimetic ceramic scaffold design and fabrication as well as bone-tissue engineering is provided.

Keywords— Biomaterials, Bioceramics, Dentistry, Bone Tissue Engineering, Ceramic Biomaterials.

1. Introduction

The domains of electronics, biology, and medicine are significantly impacted by the field of nanotechnology. Additionally, it brought various novel ideas to the area of medicine, allowing these extensive, multidisciplinary fields to come together. Analytical tools, nanoimaging, nanomaterials and nano-devices, innovative therapies and drug delivery systems, clinical, regulatory, and toxicological difficulties are only a few of the prevalent technical issues that are included in nanomedicine. Among the many types of nanomaterials, cements, coatings, and nanostructured ceramics are being explored for important uses in orthopedic and dental procedures[1]. Biocompatible Ceramics, also known as bioceramics, include of both macro and nano materials mainly used for bone, teeth and other medical applications. Understanding of the potential biomedical applications of ceramic nanomaterials will provide a major insight in to the future developments. It is under this context, this review has been made to enlist the potential biomedical applications of ceramic nanomaterials. Applications of nano technology in several areas of biomedical fields have provided a lot of opportunities and possibilities for the growth of nanomedicine. The major opportunities include superior diagnostic tools and biosensors, improved imaging techniques, innovative therapeutics and technologies to enable tissue regeneration and repair[2]. The long term priorities are found to be in the design of synthetic, bioresponsive systems for intracellular delivery of macromolecular therapeutics (synthetic vectors for gene therapy), and bioresponsive or self-regulated delivery systems including smart nanostructures such as biosensors that are coupled to the therapeutic delivery systems. There is also an urgent need to more clearly articulate and better communicate the potential benefits of Nanomedicine to the budding researchers as a whole[3]. There are increasing challenges within the pharmaceutical industry to locate drugs more efficiently to their disease targets and treat them effectively. The major techniques and tools developed for analysis and diagnostics in the medical field have the potential for wider application. Nanobiomaterials are nanoscale materials utilized for various biological and biomedical applications such as drug and gene delivery, biosensors, bio-imaging, tissue engineering, bio-electronics, and for antimicrobial activities[4]. A variety of Nanobiomaterials are synthesised, characterised and tested to find out their potentialities by global scientific communities, during the last four decades. A substantial amount of work has been carried out in the field of nanobiomaterials. The types of nanobiomaterials synthesized, produced and used are very highly heterogeneous with reference to their physical, chemical, biological and engineering properties. They pose not only many challenges in their design and development, but also provide ample opportunities to use them in several of the modern applications. Huge repositories of literature collections are available on the synthesis and characterisation aspects[5]. Nanobiomaterials include a wide range of nanoscale fine particles and devices that are fabricated with a prime focus on biological and biomedical applications.

2. Characteristics of Ceramic Nanobiomaterials

Ceramics are compounds between metallic and non-metallic elements; they are most frequently oxides, phosphates, nitrides, and carbides. There are wide range of ceramic materials like clay minerals, cement, and glass used for various applications[6]. These materials are typically insulative to electricity and heat, and are highly resistant to harsh chemical environments than metals and polymers. With regard to their mechanical behaviour, ceramics are very hard and brittle. At nanoscale also, ceramic materials exhibit higher hardness, excellent heat and corrosion resistance, and electrical insulation properties. Typical examples include china clay, firebricks, cements and glass[7]. In addition to these properties, Fine Ceramics (also known as "advanced ceramics") have many advanced mechanical, electrical, electronic, magnetic, optical, chemical and biochemical characteristics. One of the major field of application of bioceramics is tissue generation. The major parameters considered to optimize the biomaterials for tissue generation include, a) Structural Components (physical, mechanical and chemical properties) and b) Biochemical Components (immobilized signals, diffusable signals, and living components)[8]. The bioceramics have good biocompatibility, osteo conductivity, osteoinductivity, biodegradability resorbability, and hydrophilicity. Yet another major field of application of bioceramic is clinical dentistry.

3. Applications of Ceramic Nanobiomaterials

(i) Calcium Phosphate (CaP)- Calcium plays a very important role in the body. It is necessary for normal functioning of nerves, cells, muscles, and bones. If there is not enough calcium in the blood, then the body will take calcium from bones, thereby weakening bones. Tooth enamel is composed of almost ninety percent hydroxyapatite[9]. Its solubility in cold water is 2 mg / 100 cc. Calcium Orthophosphates have very useful properties and show several major biomedical applications. Regardless of the composition, all calcium phosphates are osteoconductive[10]. Bone, which is similar to other calcified tissues, is an intimate composite of the organic (collagen and noncollagenous proteins) and inorganic or mineral phases.

(ii) Tri-Calcium Phosphate- Tricalcium phosphate (TCP) is one of the most common and important members of the calcium phosphate family of minerals, which are made of calcium cations with different phosphate anions such as orthophosphates, metaphosphates or pyrophosphates[11]. TCP is practically insoluble in water; insoluble in ethanol, soluble in dilute hydrochloric and nitric acid. It has three crystalline polymorphs α, α' and β. The α and α' states are formed at high temperatures. The α-tricalcium phosphate (α-TCP, α-Ca3(PO4)2) is receiving growing attention as a raw material for several injectable hydraulic bone cements, biodegradable bioceramics and composites for bone repair[12]. Tricalcium phosphate materials mostly behave like osteoconductive materials, which permits bone growth on their surface or into pores, channels, or pipes. It is a resorbable phase. Calcium phosphate exhibits some good properties to support bone growth[13]. The major field of applications are a) bone implant and replacement applications and b) tissue engineering.

(iii) Hydroxy-Apatite (HAP)- Hydroxyapatite (HAP) has been widely used as a biocompatible ceramic in many areas of medicine, but mainly for contact with bone tissue, due to its resemblance to mineral bone. HAP has exceptional biocompatibility and bioactivity properties with respect to bone cells and tissues[14]. As a result of excellent favorable osteoconductive and bioactive properties, it is widely preferred as the biomaterial of choice in both dentistry and orthopaedics. The hydroxyapatite has a few favorable bioactive and osteoconductive properties which help in rapid bone formation, with a strong biological fixation to bony tissues. It also has very low mechanical strength and fracture toughness, which is an obstacle to its applications in load-bearing areas.

(iv) TCP+HAP- TCP and HA are used together since they both have bioactiveness and resorbability. Pure HA or TCP are not osteoinductive. Sintered hydroxyapatite-tricalcium phosphate (HA-TCP) ceramic material has more biomedical applications[15].

(v) Si Substituted HAP- Silicon (Si) substitution in the crystal structures of calcium phosphate (CaP) ceramics such as hydroxyapatite (HAP) and tricalcium phosphate (TCP) generates materials with superior biological performance. Silica is an essential trace element required for healthy bone and connective tissues. It influences the biological activity of CaP materials by modifying material properties[16]. Silica has direct effects on the physiological processes in the skeletal tissue. The two main applications of silica-based materials in medicine and biotechnology are seen in bone repairing devices and for drug delivery systems.

4. Properties of Bioceramic Materials

(i) Physical and Chemical Properties of Ceramics - The term "ceramic" (from the Greek word κεραμικό: "keramikò," which means "burnt stuff"), a word that is also found in ancient texts, indicates any heat-treated material derived from clayey raw materials through a process called firing[17]. Generally speaking, ceramics are inorganic materials consisting of metallic and non-metallic components chemically bonded together by means of ionic or prevalently ionic bonds with a variable degree of covalent character. Their properties essentially depend on the type of these bonds and on the type of plexus that shapes the microstructure of the respective material[18]. They can be both crystalline and non-crystalline, and the structure in which a crystalline phase is dispersed in a non-crystalline one is very common. A ceramic material can typically be identified as a member of one of these categories: glasses, structural clays, whitewares, refractories, abrasives, cements, or advanced ceramics. The main characteristics of ceramic materials are high stiffness and strength, great hardness, insulating behavior, and resistance to high temperatures, wear, and chemical degradation, and in fact most bioceramics are not reactive within the living body. Their low toughness and therefore great fragility is a major issue.

(ii) Mechanical Properties of Ceramics- Regarding the essential mechanical properties of ceramics, these include (i) low resis tance to tensile loads, (ii) high hardness due to the internal microstructure characterized by strong ionic or covalent bonds, and (iii) minor or negligible plasticity resulting in low fracture toughness and resistance to shock loads[19]. Different from metal alloys, which exhibit a ductile behavior, the main disadvantage of ceramic materials is their susceptibility to brittle fracture, even in the presence of very low energy absorption. Even if they are brittle, ceramics have greater hardness and elasticity values than metals. At room temperature, in both crystalline and non-crystalline ceramics, when undergoing tensile stresses fractures are observed before any plastic deformation occurs, and this effect also leads to poor fatigue resistance[20]. The brittleness consists of the formation and propagation of cracks in a direction perpendicular to the applied load. In crystalline ceramics, cracks develop both transgranularly, i.e., through grains, and along certain crystallographic planes presenting high atomic density[21]. These weak responses occur because at micro-scales a wide variety of imperfections of different size and geometry exists, such as internal.

5. Ceramic Materials for Biomedical Applications

(i) Bioceramics for General Applications- The science of ceramics is developing rapidly, as ceramics can be porous or glassy and hence can have many applications in medicine and biotechnology. They are widely used in dental and orthopedic applications for wound healing and tissue engineering when non-metallic inorganic materials are required[22]. Bioceramics can be designed to mimic the mechanical properties of the surrounding tissues, and this can improve the long-term stability of the implant. For biomedical applications, these materials can also be used for the fabrication of all-ceramic prosthetic components and can be distinguished according to their glass-content structure in (i) mainly glass, (ii) glass mass filled with other particles, and (iii) polycrystalline. These biomaterials can be crystalline (sapphire), polycrystalline (alumina, hydroxyapatite), glass–ceramic (Ceravital), and composite. As described in the following sections, bioactive and bioresorbable ceramic materials are currently employed to repair and reconstruct diseased or damaged parts of the musculoskeletal system by inserting customized supporting structures called biomimetic scaffolds" in the fracture site[23]. Obviously, the choice of the correct bioceramic depends on the site of application.

(ii) Advanced Bioceramics- Over time, engineers have tried to improve ceramic materials in order to give them ultra-specialized properties through the development of composite micro- and nano systems. A composite material is defined as a heterogeneous combination of two or more distinct materials presenting a finite interface between them. Ceramic nanocompos ites constitute an emerging research field aiming to further improve specific properties of bioceramics and to offer new opportunities for the treatment of a wide range of biomedical issues[24]. Nanocomposites are a class of composites in which one or more dimensions of the reinforcing phase is in the nanometer range (1 nm = 10 Å), typically up to 100 nm. The characteristic trait of nanocomposite materials is their ability to combine properties and functionalities that are out of reach for traditional materials. By incorporating nanoparticles into a ceramic matrix (e.g., by adding organic molecules, carbonnanotubes, graphene, nanoscale ceramics, proteins, or even DNA to bioceramics or bioglasses), it is possible to create materials with improved mechanical strength, biocompatibility, and osteoconductivity. Ceramic nanocomposites have been developed for a wide range of biomedical applications, including bone replacement or repair and drug delivery[25]. In dentistry and tissue engineering, the architecture of a custom-built nanocomposite material should allow the tissues to self-organize within the organism. In clinical applications, nanocomposite ceramic materials must exhibit adequate mechanical properties, including compressive strength, stiffness, fracture toughness, and fatigue resistance, as well as biocompatibility.

(iii) Bioceramics for Dentistry Applications- The fundamental property of ceramic materials for dentistry is their compatibility with biological tissues. In recent decades, bioceramics such as alumina, zirconia, SiAlON, bioglasses, and hydroxyapatite (Ca10(PO4)6(OH)2) have been studied for dentistry applications. Porcelain, zirconium oxide, and single-crystal sapphire are already being used on a large scale for orthodontic issues[26]. The main disadvantages of modern osteoplastic devices made of bioceramics are the fragile behavior and the low resistance to tensile or bending forces. They are not osteoinductive except for bioactive glass, and bioabsorption is generally unpredictable. Indeed, TCP and synthetic HA are not bioresorbable in the short term, whereas bioactive glass is rapidly absorbed. In many dentistry applications, a glass mixture is usually crystallized by employing alumina, zirconia, magnesium spinel (MgAl2O4), and other compounds in the forms of powders or crystals. By imposing a controlled heat treatment, commonly known as ceramification or devitrification, the final result is obtained[27]. When crystals are used, composite materials known as interpenetrating phase composites (IPC) can be formed. They are constituted by two phases (crystals and glass) that are interconnected and constantly expand inside each other without generating a chemical bond. The production of these IPCs takes place in two stages. Initially, the ceramic is sintered to form a porous core consisting of alumina- or magnesium-spinel (MgAl2O4) crystals or alumina and zirconia in a ratio of 70/30[28]. The molten glass is then filtered through a porous mesh, and after this phase it fills all pores and gaps of a precise shape. In this way, a high-strength frame is created on which a special dental porcelain (i.e., an aesthetic coating) is deposited and fired. In the event that oxides are added in the form of powder, a specific ceramic material called glass–ceramic is formed. Commonly used reinforcing particles are mainly lithium-disilicate crystals.

(iv) Bioceramics for Bone-Tissue Engineering- Bone-tissue engineering is a multidisciplinary activity that implements mechanical design principles in biomedical applications, primarily aiming at realizing volumetric and porous structures commonly known as biomimetic scaffolds[29]. These elements are implanted in patients' bodies to promote and guide bone-tissue regeneration in cases where large bone defects are present that cannot heal spontaneously. From a physiological point of view, it is important to point out the fact that cells can only randomly migrate to form two dimensional layers, without any control of the shape to reconstruct to regenerate a damaged bone region[30]. Therefore, opportunely designed porous scaffolds act as biocompatible extracellular matrices, since they are engineered to support colonies of undifferentiated stem cells and to promote their differentiation and proliferation in a controlled way. The general properties required to realize an optimal biomimetic scaffold for bone tissue regeneration are (a) appropriate mechanical strength and stiffness to support the differentiating cells in load bearing during healing phases; (b) adequate surface properties to enable cell adhesion, differentiation, and osteointegration; (c) optimized topology and interconnectivity between pores to ensure cell migration, vascularization of the structure, and waste-material removal; (d) [31] biocompatibility, intended as the capability of avoiding inflammatory or toxic responses in the implantation sites; (e) biodegradability, consisting of the process of being degraded and absorbed in a precise time period by the physiological environment of the implant; and (f) ease of fabrication into several shapes and dimensional scales.

6. Conclusion

Numerous biological domains have benefited from the applications of nanotechnology, which present a wealth of potential and prospects for the development of nanomedicine. A vast array of ceramic materials, including glass, cement, clay minerals, and minerals, are utilized in different applications. Biocompatible ceramics, sometimes referred to as bioceramics, are mostly utilized in dental and other medical applications for bone. The bioceramics have favorable properties such as hydrophilicity, biodegradability, resorbability, osteoconductivity, and osteoinductivity. Calcium phosphate (CaP), Tri-Calcium Phosphate (TCP), Hydroxy Apatite (HAP), TCP+HAP, Si-substituted HAP, Calcium Sulphate, and Carbonate are among the often utilized ceramic nanobiomaterials. Ceramic polymer composites, zirconia ceramics, alumina ceramics, titania-based ceramics, bioactive glasses, and bioactive glass ceramics. All of these have been shown to have several applications in the fields of nanomedicine, orthopedics, dentistry, bone regeneration, tissue formation, and other biomedical processes involving the human body. Ceramic nanobiomaterials offer great potential in all commercial uses of nanotechnology and have outstanding applicability in a number of health and medical fields.

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