

THE ROLE OF BIO CERAMICS IN MODERN DENTISTRY: FROM EARLY INNOVATIONS TO FUTURE DIRECTIONS

Diana Hanu¹, Sorina Mihaela Solomon^{1*}, Sorina Paduraru³, Lorena Roman⁴, Ioana
Rudnic¹, Gianina Iovan²

¹"Gr. T. Popa" U.M.Ph. - Iași, Romania, Faculty of Dentistry, Department of Periodontology

²"Gr. T. Popa" U.M.Ph. - Iași, Romania, Faculty of Dentistry, Discipline of Cariology and
Restorative Odontotherapy

³"Clinica Stomatologică Dentesse

⁴"Cabinet Dentar Târgu Frumos

Corresponding authors; Sorina Mihaela Solomon *e-mail: sorina.solomon@umfiasi.ro*

ABSTRACT

The use of bioceramics in modern dentistry has significantly evolved, offering enhanced clinical outcomes in various procedures. This article reviews the development and application of bioceramic materials, focusing on their biocompatibility, ability to stimulate tissue regeneration, and chemical stability. Notable materials such as Mineral Trioxide Aggregate (MTA) and Biodentine are highlighted for their role in endodontic treatments and bone regeneration. The paper also discusses innovations in the synthesis and functionalization of bioceramics, including doping with various elements and the integration of nanotechnology, which have led to advancements such as faster setting times and improved antimicrobial properties. Furthermore, the article provides a historical perspective on the transition from early bioceramics to bioactive materials like hydroxyapatite, emphasizing their impact on implantology and bone tissue regeneration. The future directions of bioceramics, including their potential in regenerative medicine and the development of materials with enhanced antimicrobial activity, are explored.

Key words: bioceramic materials, biodentine, hydroxyapatite, MTA

1.INTRODUCTION

In the field of dental medicine, bioceramic materials have gained increasing popularity due to their ability to optimize clinical outcomes in various dental procedures. These materials are particularly valued for their superior properties, including excellent biocompatibility, the ability to stimulate the mineralization process, and chemical stability in the oral environment (Dong *et al.*, 2023).

Over the years, technological advancements have enabled the improvement of these materials, offering more efficient options for conventional treatments, particularly in the field of restorative dentistry. Bioceramic materials are especially significant

in biomedical research due to their diverse applications in the regeneration of hard tissues (bone and dental tissues) and in controlled drug delivery (Velard *et al.*, 2021). They are distinguished by their high biocompatibility, ability to facilitate biological integration, and excellent mechanical properties, which allow them to function effectively as scaffolds for new tissue generation (Han *et al.*, 2024).

Recently, research efforts have focused on the development of innovative techniques for the synthesis and functionalization of bioceramics, with the aim of enhancing their regenerative capabilities and expanding their applicability across various medical fields (Velard *et al.*, 2021).

II. THE IMPORTANCE OF BIOCERAMIC MATERIALS IN DENTISTRY

Bioceramic materials have become an essential component of modern dentistry, providing advanced solutions for a wide range of clinical procedures. Biomaterials such as Mineral Trioxide Aggregate (MTA) and Biodentine are renowned for their superior biocompatibility. Not only do they integrate excellently with dental and bone tissues, but they also have the ability to stimulate their regeneration (Dong *et al.*, 2023). Bioceramics are bioactive, meaning they interact with bodily fluids to form a chemical bond with bone and dentin, thus promoting efficient healing (Dong *et al.*, 2023). These materials are widely used in various clinical procedures, including root canal obturation, the treatment of root perforations, apexification, and regenerative treatments. In addition, bioceramics play a significant role in guided bone regeneration (GBR) treatments, contributing substantially to the bone reconstruction required for dental implants (Abbas *et al.*, 2021).

Recent research has focused on enhancing the properties of bioceramic materials through doping with various elements and the use of nanomaterials (Sprio *et al.*, 2023). These advancements have led to the development of bioceramics with shorter setting times, reduced solubility, and increased antimicrobial activity. Additionally, 3D printing technologies have been integrated into the fabrication process of bioceramics, facilitating the customization of dental treatments (Cai *et al.*, 2023).

III. THE HISTORY AND EVOLUTION OF BIOCERAMIC MATERIALS

Bioceramic materials represent a crucial field in the development of medical solutions,

with a history spanning several decades and characterized by constant innovations that have fundamentally transformed clinical applications.

III.1. The First Uses of Bioceramics

The history of bioceramic materials begins in the 1960s, a period when ceramics were introduced into medical applications due to their corrosion resistance, biocompatibility, and superior mechanical properties (Hench *et al.*, 1973). Aluminum oxide (alumina) was one of the first widely used bioceramic materials. Due to its hardness and chemical stability, alumina was used in the production of joint prostheses, such as femoral heads for hip replacements (Boutin *et al.*, 1988). These implants demonstrated that ceramic materials could perform excellently in biological environments, paving the way for their use in other orthopedic and dental applications (Christel *et al.*, 1988).

III.2. The Transition to Bioactive Materials

In the 1970s, research shifted towards the development of bioactive materials that not only were well-tolerated by the body but also actively interacted with biological tissues to stimulate their regeneration. Hydroxyapatite, a calcium phosphate that mimics the mineral composition of bone, became one of the most important bioactive materials. Hydroxyapatite was used in dental and orthopedic implants due to its ability to promote osteoconductivity and support the formation of new bone tissue. This material played a crucial role in the development of modern implantology, providing a foundation for the osseointegration of implants and significantly reducing the risk of rejection (Hench, 1991).

III.3. Innovations of the 1980s and 1990s

Technological advancements in the 1980s and 1990s led to the development of bioceramic materials with significantly

improved properties. A remarkable example is bioactive glass (Bioglass), which was designed to stimulate the regeneration of bone and other hard tissues. Bioglass revolutionized the field of tissue regeneration through its ability to form a chemical bond with bone tissue and release therapeutic ions that promote cell growth (Hench *et al.*, 1984). These innovations enabled the use of bioceramics not only in orthopedics but also in other medical fields, such as reconstructive surgery and craniofacial treatments (Hench *et al.*, 1982).

III.4. Recent Developments and the Future of Bioceramics

In the past two decades, research has focused on optimizing the properties of bioceramics through doping with various elements and the use of nanotechnology. These advancements have led to the creation of bioceramics with specific properties, such as enhanced antimicrobial activity, reduced setting times, and controlled solubility. For

example, doping hydroxyapatite with strontium or magnesium ions has been investigated to improve bone healing rates and reduce the risk of post-operative infections (Bose *et al.*, 2020). Additionally, the use of nanomaterials has enabled the development of bioceramics with nanometric structures that promote cellular interactions and accelerate tissue regeneration processes (John *et al.*, 2023). Furthermore, by combining bioceramics with stem cells, researchers are exploring the potential to create functional tissue structures that can replace damaged or lost tissues, opening new pathways for regenerative medicine (Fei *et al.*, 2023). Another future aspect is the enhancement of the antimicrobial properties of bioceramics, which will help reduce implant-associated infections. Recent research has focused on doping bioceramics with metal ions such as silver or copper, which can provide long-term antibacterial protection without compromising the material's biocompatibility (Hao *et al.*, 2024).

IV. CLASSIFICATION OF BIOCERAMIC MATERIALS

IV.1. Classification Based on Chemical Composition

The chemical composition of a bioceramic material largely determines its physical, chemical, and biological properties. For example, oxide-based materials, such as alumina, are known for their hardness and chemical stability, while calcium phosphates, such as hydroxyapatite, are notable for their biocompatibility and resorbability (Kumar *et al.*, 2022). By classifying materials based on their chemical composition, researchers can select the appropriate material according to the specific requirements of medical applications. Understanding the chemical composition of

bioceramic materials allows for the optimization of synthesis and manufacturing processes, thereby ensuring the production of high-quality products. For instance, in order to achieve the desired density and structure during the sintering of ceramic oxides, precise control of the applied temperature and pressure is required (Song *et al.*, 2023). By investigating various combinations of chemical elements and crystal structures, researchers can develop materials with enhanced properties, tailored to the emerging demands of the medical sector. Thus, this classification not only supports the current uses of bioceramics but also paves the way for new discoveries and innovative applications in the future.

A. Oxides

Oxide-based bioceramic materials, such as alumina (Al_2O_3) and zirconium dioxide (ZrO_2), are known for their exceptional hardness and wear resistance. Alumina, for example, is one of the hardest ceramic materials, making it ideal for use in components subjected to intense friction, such as prosthetic joints. It is also chemically stable, meaning it does not react with biological fluids and does not cause adverse reactions in the body, thus ensuring high biocompatibility (Lin *et al.*, 2021).

Zirconium is recognized for its toughness and exceptional fracture resistance, which makes it particularly valuable in the manufacture of dental prostheses and orthopedic implants, where superior mechanical properties are required. Additionally, zirconium dioxide exhibits high thermal stability, making it ideal for use in applications involving exposure to high temperatures (Khalifa *et al.*, 2021). In dental implantology, zirconium dioxide is specifically chosen for implants due to its superior aesthetic appearance and excellent compatibility with gingival tissues (Singh *et al.*, 2023).

B. Calcium Phosphates

Among the most commonly used types of calcium phosphates in biomedicine are hydroxyapatite, tricalcium phosphate, and octacalcium phosphate. Hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) is the best-known and most widely used bioceramic material due to its composition, which closely resembles the natural mineral found in bone (Alkaron *et al.*, 2024). Tricalcium phosphate is valued for its rapid resorption in the body, making it ideal for applications where rapid bone tissue regeneration is required (Lu *et al.*, 2021). Although less stable, octacalcium phosphate offers controllable resorption, making it useful in specific applications where this

characteristic is essential (Drevet *et al.*, 2023). Calcium phosphate is known for its exceptional biocompatibility and ability to promote osteoconduction, a process by which bone cells grow on the surface of an implant (Jin *et al.*, 2023). These compounds form a strong chemical bond with natural bone, facilitating the integration of implants into bone tissue (Vaiani *et al.*, 2023). In addition to their biocompatibility, calcium phosphates are resorbable, meaning the material can gradually be absorbed and replaced by natural bone. This property is particularly valuable in bone reconstruction procedures, such as craniofacial surgery and the repair of bone defects (Mishchenko *et al.*, 2023).

C. Silicates

Silicate-based bioceramic materials represent a crucial category of biomaterials in modern medicine due to their distinct properties, such as bioactivity, biocompatibility, and the ability to stimulate tissue regeneration (Singh *et al.*, 2022). Materials like bioglass have become fundamental in clinical applications, particularly in orthopedics and dentistry, due to their ability to effectively interact with biological tissues (Jafari *et al.*, 2022).

Bioglass is renowned for its ability to form a hydroxyapatite layer on its surface when in contact with bodily fluids, thus facilitating integration with natural bone (Jafari *et al.*, 2022). This characteristic is crucial in the use of silicate in dental and orthopedic implants, where establishing a strong bond between the implant and the host bone is essential. In dentistry, bioglass is used for bone grafts and in dental cements due to its ability to stimulate bone regeneration and prevent bacterial colonization (Skallevoid *et al.*, 2019).

D. Carbides and Nitrides

Carbides and nitrides, such as silicon carbide and titanium nitride, are distinguished by their extreme hardness, ability to withstand high

temperatures, and chemical stability (Khan *et al.*, 2024). These characteristics make them ideal for applications requiring the support of high mechanical loads or operation in harsh environmental conditions (Sinha *et al.*, 2023). Bioceramic materials based on carbides and nitrides are used in a wide range of clinical applications, particularly in orthopedics and dentistry. In dental medicine, titanium nitride is frequently used as a coating for dental implants and surgical instruments (Liu *et al.*, 2023). This not only enhances biocompatibility but also provides superior resistance to wear and corrosion, significantly extending the lifespan of dental implants (Guo *et al.*, 2023).

IV.2. Classification Based on Biocompatibility

Bioceramic materials are used in a wide range of interventions, from dental implants and artificial joints to bone regeneration and medical devices (Dong *et al.*, 2023). However, the long-term success of any clinical application largely depends on the biocompatibility of the material used (Vaiani *et al.*, 2023). Bioceramic materials are commonly classified into three main categories based on their biocompatibility: bioinert, bioactive, and bioresorbable. Each category has unique characteristics that make them suitable for specific clinical applications (Bedir *et al.*, 2023).

A. Bioinert Bioceramics

These materials are frequently used in dental implants and other prosthetic procedures due to their durability, chemical stability, and compatibility with biological tissues (Wu *et al.*, 2023). To ensure both functionality and patient comfort, selecting the appropriate material is essential, as this is fundamental to the long-term success of dental treatments (Reza *et al.*, 2020).

In the field of dentistry, aluminum oxide and zirconia are among the most common bioinert

bioceramics, primarily used for dental implants and restorations. Due to its exceptional resistance to wear and corrosion, aluminum oxide is frequently used in dental implant components and other prosthetic applications. Although not as popular as other materials like titanium, it remains a viable option for durable dental restorations (Khaohoen *et al.*, 2023). Zirconia is an increasingly utilized material in dentistry, standing out for its high fracture resistance and excellent aesthetic properties (Kang *et al.*, 2024). In dentistry, bioinert bioceramics play a crucial role in ensuring efficient integration and long-term durability of dental implants and restorations (Zafar *et al.*, 2020).

B. Bioactive Bioceramics

Hydroxyapatite is a type of calcium phosphate, having a chemical composition similar to the main mineral of human bone (Fiume *et al.*, 2021). Due to its property to stimulate osteoconductivity, hydroxyapatite is frequently used in dental implants and bone grafts, promoting bone formation around these structures (Kumar *et al.*, 2022).

Another essential material in dentistry is bioactive glass, known for its ability to chemically bond to bone (Kaou *et al.*, 2023). When it comes into contact with body fluids, bioactive glass triggers chemical reactions that lead to the appearance of a layer of hydroxyapatite on its surface. This layer facilitates the integration of the implant into the bone and promotes bone regeneration (Andualem *et al.*, 2022).

C. Resorbable Bioceramics

Resorbable bioceramics are an essential type of bioceramic materials used in dentistry, characterized by their ability to gradually decompose in the body and be replaced by newly formed biological tissue (Knabe *et al.*, 2023). These materials provide a temporary solution that supports the healing and regeneration process, frequently used in bone grafts and other reconstructive procedures

(Verbist *et al.*, 2024). Among the most commonly used resorbable bioceramics in dentistry are calcium phosphate and tricalcium phosphate (Jasser *et al.*, 2021).

Chemically, calcium phosphate is similar to the natural mineral found in bone, allowing it to be broken down and replaced with new bone over time. It is used to fill bone defects or stimulate regeneration in areas affected by bone loss (Jin *et al.*, 2023). Tricalcium phosphate is another type of resorbable material commonly used in dentistry. It is known for its controlled resorption rate, which can be tailored to meet clinical needs. This material is employed in bone grafts and bone augmentation procedures, with the aim of promoting bone regeneration without leaving long-term foreign residues in the body (Aoki *et al.*, 2024).

IV.3. Classification Based on Clinical Applications

Bioceramic materials are used in direct interaction with human tissues, making their biocompatibility critically important. For instance, materials used in endodontic treatments must be non-toxic and should not induce inflammatory reactions, ensuring patient safety and long-term treatment success (Zakrzewski *et al.*, 2021). This approach minimizes the risks of rejection and postoperative complications, promoting the optimal integration of materials into the patient's biological structure. Each clinical application requires selecting materials with specific mechanical properties tailored to the functional demands of the treatment. For example, dental crowns and bridges must be made from materials capable of withstanding intense masticatory forces, such as zirconia or glass-based ceramics (Lagunov *et al.*, 2024). Bioceramic materials used in dental restorations, such as veneers and crowns, must accurately mimic the shade, translucency, and brightness of the patient's natural teeth (Remm, 2022). The classification of materials based on aesthetic characteristics allows the selection of those that offer superior visual

performance, ensuring an aesthetic result that aligns with patient expectations and significantly contributes to their satisfaction (Yair *et al.*, 2020). Classifying bioceramic materials based on their clinical applications in dentistry not only optimizes the selection of the appropriate material for each specific type of treatment but also ensures their biocompatibility, durability, aesthetics, and efficiency.

A. Bioceramics Used in Implantology

Dental implantology is recognized as one of the most advanced and effective methods for restoring lost teeth, and bioceramic materials play a crucial role in ensuring the success of this procedure. These materials are preferred due to their remarkable properties, such as biocompatibility, osteoconductivity, osteoinductivity, and resistance to degradation in biological environments (Surana *et al.*, 2024). These characteristics make them ideal for use in implantology, contributing to the optimal integration of implants into bone tissue and ensuring the long-term durability of treatments (Hameed *et al.*, 2021). Bioceramic materials, such as hydroxyapatite and calcium phosphates, are among the most commonly used in implantology (Fiume *et al.*, 2021). Hydroxyapatite, due to its chemical composition resembling that of the mineral components of human bone, has an exceptional capacity to integrate with the surrounding bone tissue, ensuring a solid anchoring of the implant (Ielo *et al.*, 2022). In addition to hydroxyapatite, calcium phosphates such as tricalcium phosphate are used to stimulate bone regeneration (Sascha *et al.*, 2024). These materials are osteoconductive, facilitating the formation of new bone on the surface of the implant (Roca-Millan *et al.*, 2022). Furthermore, they are biodegradable, being gradually resorbed by the body and replaced with new bone, which integrates seamlessly into the structure of the maxillary or mandibular bone (Bohner *et al.*, 2020).

B. Bioceramics Used in Dental Restorations

Bioceramic materials have become a central element in dental restorations due to their advanced properties, including biocompatibility, durability, and the ability to integrate effectively with natural dental tissues (Suhag, 2024). Zirconia-based ceramics, particularly in the form of zirconium oxide (ZrO₂), are among the most widely used bioceramic materials in dental restorations due to their remarkable combination of mechanical and aesthetic properties. Zirconia offers exceptional hardness and high fracture resistance, making it ideal for extensive restorations such as crowns and dental bridges (Han *et al.*, 2024).

Glass ceramics, such as those based on silicon dioxide (SiO₂), are heavily used in aesthetic dental restorations due to their transparency and ability to closely mimic the natural appearance of teeth (Al-Johani *et al.*, 2024). The optical properties of these ceramics allow for excellent aesthetic integration, providing high-quality results in dental restorations (Almohammed *et al.*, 2022).

Glass-based ceramics also demonstrate excellent biocompatibility, being well-tolerated by gingival tissues, thus minimizing the risk of inflammation or other postoperative complications (Baino *et al.*, 2021). Moreover, these materials exhibit superior adhesion to dental structures, ensuring an effective seal that prevents bacterial infiltration and reduces the risk of secondary caries (Venturini *et al.*, 2020). Feldspathic ceramics, one of the oldest and most commonly used bioceramics in dentistry, are appreciated for their outstanding aesthetics (Talibi *et al.*, 2022). These materials are primarily used for veneers and dental crowns due to their ability to precisely replicate the color and translucency of natural teeth (Sean *et al.*, 2020). While more fragile than other bioceramic materials, feldspathic ceramics offer superior aesthetic outcomes,

faithfully recreating the appearance of dental enamel (Talibi *et al.*, 2022).

C. Bioceramics Used in Endodontic Treatments

Mineral Trioxide Aggregate (MTA) is a cutting-edge bioceramic material in endodontics, introduced in the early 1990s and quickly adopted due to its superior biocompatibility and ability to create a hard barrier between the root canal and periradicular tissues (Eskandar *et al.*, 2023). MTA is applied in various endodontic procedures, such as sealing root perforations, retrograde fillings in apicoectomies, and direct pulp capping (Pushpalatha *et al.*, 2022). A major advantage is its ability to stimulate tissue regeneration, encouraging the formation of new dental cementum and effectively sealing the root canal to prevent bacterial infiltration (Naved *et al.*, 2024).

Biodentine is an innovative bioceramic material used in endodontics, designed as a faster and easier-to-handle alternative to MTA (Dong *et al.*, 2023). Its tricalcium silicate-based formula gives it similar properties to MTA, but with a reduced setting time and improved handling (Komabayashi *et al.*, 2020). Biodentine is applied in a variety of endodontic procedures, including root perforation repair, apex sealing, and pulp revascularization (Al-Nazhan *et al.*, 2022).

BioAggregate is an advanced bioceramic material used in endodontics, similar to MTA but with a distinct chemical composition, including oxides of silicon, calcium, and aluminum (Rosas-Díaz *et al.*, 2022). This material is primarily used for retrograde fillings, perforation repairs, and direct pulp capping (Gupta *et al.*, 2021). One of the major advantages of BioAggregate is its ability to form an effective mineral barrier at the root apex, thereby preventing bacterial infiltration and promoting bone regeneration (Wang *et al.*, 2023).

D. Bioceramics Used for Guided Tissue Regeneration

Hydroxyapatite (HA) is one of the most widely used bioceramic materials in guided tissue regeneration procedures due to its chemical similarity to the mineral component of human bone, which grants it remarkable biocompatibility and osteoconductivity (Ielo *et al.*, 2022). HA is available in various forms, including granules, pastes, or blocks, to meet different clinical requirements. In the context of Guided Tissue Regeneration (GTR) and Guided Bone Regeneration (GBR) techniques, hydroxyapatite acts as a temporary scaffold that facilitates the formation of new bone, being progressively resorbed and replaced by natural bone tissue (Mitić *et al.*, 2024). A key advantage of hydroxyapatite is its rapid integration with existing bone, reducing the risk of postoperative complications and accelerating the healing process (Kumar *et al.*, 2022).

Calcium phosphates, including tricalcium

phosphate (TCP) and calcium phosphate ceramics (CPC), are essential bioceramic materials in GTR and GBR due to their osteoconductive and osteoinductive capabilities (Zhang *et al.*, 2022). These materials are resorbable, meaning they are gradually replaced by newly formed bone, harmoniously integrating into the patient's natural bone structure (Alqahtani, 2023). Tricalcium phosphate is often combined with hydroxyapatite to create a material with optimized resorption and osteoconductive rates (Mohd *et al.*, 2022). Bioactive glasses, also known as bioglasses, are another type of bioceramic material used in GTR and GBR (Okereke *et al.*, 2024). One of the major advantages of bioactive glasses is their ability to release ions that stimulate bone and tissue regeneration (Barreto *et al.*, 2023). Additionally, bioactive glasses possess antimicrobial properties, reducing the risk of postoperative infections (Gavinho *et al.*, 2022).

V. CONCLUSIONS

Bioceramics have demonstrated a significant impact in modern dentistry, contributing to improved treatments through their unique properties of biocompatibility and the ability to stimulate tissue regeneration. Materials such as Mineral Trioxide Aggregate (MTA) and Biodentine play an essential role in endodontic procedures and bone regeneration, offering effective solutions for the integration and long-term stability of dental implants. Technological advancements, particularly the integration of nanotechnology and ion doping, have led to important improvements, such as reduced setting times and enhanced antimicrobial activity.

Furthermore, the transition from early bioceramics to bioactive materials, such as hydroxyapatite, has revolutionized implantology and bone regeneration, promoting osteoconductivity and reducing the risk of implant rejection. Recent research opens new avenues in regenerative medicine, exploring the combination of bioceramics with stem cells and the development of materials with superior antimicrobial properties, critical for combating implant-associated infections.

Bioceramics continue to offer promising perspectives for the future of dentistry, improving both clinical outcomes and patient safety.

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