Dental Implants: Modern Materials and Methods of Their Surface Modification: A Narrative Review

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Abstract

Dental implant technologies offer an effective solution to replace missing teeth and meet patients' aesthetic and functional requirements. This review provides an overview of the modern materials used in dental implants and the surface modification techniques used, focusing on their importance in enhancing biocompatibility and osseointegration. A comprehensive overview of materials such as metals (e.g. titanium and its alloys), ceramics (e.g. zirconia), and polymers (e.g. PEEK) provided, detailing their mechanical properties, biocompatibility, and applications. In addition, the review discusses different surface modification methods, including roughness enhancement and bioactive coatings, which play a critical role in improving implant stability and enhancing osseointegration. The findings emphasize the importance of selecting appropriate materials and using advanced surface treatments to improve dental implant performance, ultimately leading to better patient outcomes and satisfaction. Further research is needed to refine these methods and address the challenges associated with each type of material.

Keywords: Dental implants, materials, surface modification, Implant integration.

1. Introduction

Implants have been used to support dentures for many decades. Recently, they have received significant attention for their ability to meet the aesthetic and functional needs of patients. Dental implants have become a popular treatment option for replacing individual or entire missing teeth [1]. According to statistics, approximately 3.5 billion people worldwide suffer from oral diseases, which is approximately 45% of the world's population [2]. In addition, there are more than 350 million cases of tooth loss worldwide, which is approximately 6.82% [3]. The number of patients suffering from such problems will increase as the average age of the population increases [4].

In Saudi Arabia, dental caries is a major cause of tooth loss. The prevalence of dental caries is estimated to range from 24% to 70%, and the prevalence of periodontal disease is estimated to range from 30% to 50%, leading to tooth loss. In addition, accidents and injuries are a direct cause of tooth loss [5,6]. Dental implants are an alternative for people who have lost one or more teeth due to trauma, gum infection, or any other cause of tooth loss [7]. They are considered one of the most important alternatives in the current era to replace damaged and missing teeth, as dental implants closely resemble the shape and function of natural teeth as well as the color of the crown of adjacent teeth, which gives an aesthetic appearance, and enhances oral health and protects the gums and jawbone loss, among others [8].

The technological advancements used in dental implants, the increase in tooth loss cases worldwide, and the increasing demand for cosmetic dentistry have led to an increase in the demand for dental implants. It is estimated that the dental implant market may reach $18.42 billion by 2030 [9]. The progress of dental implants depends on a detailed study of the interaction of implants with surrounding tissues and methods of stimulating bone formation around the implants. This has been proven by the increasing number of scientific articles presenting the results of studies on the effect of the chemical composition of the dental implant material on oral and gum health, and the method of modifying its surface on the main properties of dental implants [3]. According to many basic and applied studies, the main materials used in dental implants are stainless steel, titanium and its alloys, zirconium alloys, tantalum and its alloys, and other materials. The great diversity of dental implants based on chemical composition and surface modification technology indicates that it is necessary to reach the optimal material selection for manufacturing implants [8,10,11].

Therefore, this study aims to analyze the different current materials used in dental implants at present, and to find ways to improve their performance properties by modifying the implant surface.

Classification of dental implants

Dental implants are classified according to their placement into (gingival, subperiosteal, osseous, intraosseous, interdental, or composite implants). According to the nature of contact between the implant material and the host body (negatively bonded implants, neutrally bonded implants, positively neutrally bonded implants, cross-linked positively bonded implants). Moreover, according to the shape (flat or hairline implants, cylindrical implants, needle implants, etc.) [1,12].

Dental implant materials.

There are a variety of materials used to make dental implants, some of which have been in use for thousands of years. There are a variety of materials used in the manufacture of dental implants, some of which have been in use for thousands of years. Some implants are made of gold or platinum, as well as alloys of these metals. More recently, tungsten, zirconium, and carbon composites have been tried. Stainless steels and cobalt chromium alloys are the most used materials for dental implants, due to their acceptable physical properties, good mechanical properties, and acceptable morphological compatibility. However, pure titanium or titanium alloys have become widely used due to their biocompatible properties with oral tissues. Currently, the focus is on coating the implants with tricalcium phosphate or hydroxyapatite to provide an effective viscous surface that stimulates bone growth [13].

According to the chemical properties and biological responses of dental implants, the three most important categories used in dental implants are metals, ceramics, and polymers [14].

Metals in Dental Implants

Metals are the primary choice for dental implants due to their excellent mechanical properties. Titanium, especially titanium alloys such as Ti-6Al-4V, are widely used in this field, as they offer good corrosion resistance and high biocompatibility properties, making them the standard in dental implants [16,17]. However, some components of these alloys, such as vanadium and aluminum, raise concerns about toxicity, which has prompted researchers to develop new low-strength alloys containing non-toxic elements such as nickel, tantalum, and zirconium. These new alloys exhibit a hardness range of 55 to 85 GPa, which is much lower than conventional alloys, but still higher than the hardness of bone [10,18]. Among other metals used, 316L stainless steel is a popular choice for the manufacture of bone screws and plates due to its strength and reasonable cost. However, its corrosion resistance is not comparable to that of titanium, making it less suitable for dental implants. Cobalt-chromium alloys are also traditional options, used to make partial dentures, but in some cases, they show poor performance when in contact with bone [19].

Tantalum has proven its effectiveness as a dental implant material in recent studies, showing promising results in achieving synergy with bone, which enhances bone growth during healing periods. Tantalum has high corrosion resistance, and despite not containing threads, it achieved stability similar to that of conventional implants [20].

Research shows that titanium alloys and alternative alloys such as tantalum show good biocompatibility, which supports their use in dental implants. However, challenges related to toxicity and hardness require further research to determine the optimal materials for use in different clinical contexts [21]. Overall, metals offer a variety of options that may enhance dental implant outcomes, making them an active area of research and development in biomedicine.

Ceramics in Dental Implants

Ceramic materials are a promising option in the field of dental implants due to their unique properties such as high corrosion resistance, excellent biocompatibility, and good aesthetic appearance. Ceramic materials used in implants mainly include aluminum oxide (Al2O3), silicon carbide (Si3N4), and zirconia. These materials are characterized by their high hardness and strength, making them suitable for withstanding the stress resulting from chewing functions [22]. Aluminum oxide, for example, shows great corrosion resistance and good mechanical properties, but suffers from lower flexural strength compared to metals. However, aluminum oxide and zirconia show positive cellular interactions, as their surfaces are characterized by their biocompatibility, which promotes cell adhesion. Studies indicate that treating the ceramic surface with the enzyme alkaline phosphatase increases the adhesion of bone cells, which enhances the osseointegration process [23].

Silicon carbide is another interesting option, as it shows increased hardness and high strength, in addition to positive biological properties. Studies have shown that silicon carbide implants exhibit good biostability and excellent osseointegration after the healing period, making them a strong candidate for use in dental implants [22,24]. However, challenges remain regarding dynamic endurance, as repeated stress can lead to microfractures in ceramics. For example, studies have shown that the combination of zirconia with alumina can improve fracture resistance, enhancing the durability of implants [25]. With their aesthetic and mechanical properties, ceramic materials offer an attractive alternative to conventional metals in dental implants. However, further clinical research is needed to determine their optimal applications in various clinical situations, reflecting the importance of continuing to explore and develop new materials in this field [26].

Polymers in Dental Implants

Polymers are an innovative option in the field of dental implants, combining good mechanical properties with biocompatibility, making them suitable for use as implant materials. Among the most widely used polymers is polyether ether ketone (PEEK), which has strong mechanical properties, in addition to its excellent chemical resistance. PEEK is an ideal choice as it does not show any shadows on X-rays, making it ideal for medical applications [27].

Polymers have an elasticity close to that of bone tissue, which reduces mechanical stress on the bone surrounding the implant. Studies show that adding carbon particles to PEEK can enhance its strength and elasticity, making it more compatible with bones [28]. Research has also shown that PEEK is superior in adhesion to bone and periodontal cells compared to metals such as titanium, due to its increased surface wettability [29].

Despite the many benefits, there are challenges regarding the rate of bone fusion with polymers. Although PEEK shows good biocompatibility, it may be less Osseo integrating than titanium [30]. To improve this fusion, surface treatment to improve wetting and adhesion properties, such as sand made with aluminum particles or laser modification, has been suggested, which increases the effectiveness of polymers as implant materials [31,32]. Furthermore, polymer composites, such as carbon fibre-reinforced PEEK, have been studied and show superior mechanical performance in high stress environments. Studies suggest that the bond strength at the bone interface with these materials can be similar to that of hydroxyapatite-doped titanium, which enhances their effectiveness in implantation [33].

In conclusion, polymers show great potential in improving dental implant outcomes, but further clinical research is needed to determine when and how they should be optimally used, emphasizing the importance of continued innovation in this field.

Other Materials for Dental Implants

In addition to metals, ceramics, and polymers, a variety of other materials have been explored as potential options for dental implants. These include composites, biomaterials, and some natural materials, each of which has unique properties that make them suitable in specific contexts.

1. Composites: which combine metals with ceramics or polymers, are a promising option for dental implants. These materials are designed to take advantage of the properties of each component, enhancing strength, flexibility, and biocompatibility. For example, hydroxyapatite has been combined with ceramics such as alumina and zirconia to form strong, biocompatible composites. These composites have shown good results in terms of osseointegration and wear resistance, making them ideal choices for dental applications [34].

2. Biomaterials: such as collagen and biofibers, are natural materials that interact well with living tissue. Collagen, a protein found naturally in the body, has been used to develop dental implants that promote bone growth and regeneration. These materials represent a new direction in implant design that can contribute to improved osseointegration and reduced risk of implant rejection [35].

3. Natural materials: Some natural materials such as animal bone (e.g., processed bone) and shellfish extracted materials are used as options for dental implants. These materials have high biocompatibility and provide a supportive structure that can enhance the osseointegration process. Research suggests that the use of these materials can improve implant outcomes, especially in cases requiring bone regeneration [36].

4. Laser-processed materials: Advanced processing techniques such as laser processing are used to improve the surface of implants, which enhances osseointegration properties. Surface improvements can increase the surface area of the implant, facilitating bone cell adhesion and improving the healing process. These techniques are an important tool for improving the effectiveness of materials used in implants [37].

There are many options available in the field of dental implants, allowing the materials used to be customized according to the patient’s needs and implant conditions. These materials need further research to determine the effectiveness of each in different clinical contexts, but they represent a promising future for improving dental implant outcomes.

Implant Surface Modification

According to Albrechtson and colleagues (1986), the criteria for the success of dental implants depend mainly on the following [38].

- Stability of the dental implant and its non-movement upon clinical examination.
- The absence of any radiographic transparency around the dental implant upon radiographic examination.
- The vertical radiographic bone loss does not exceed 0.2 mm per year, after one year of the dental implant being exposed to functional strength.

- Absence of the following clinical signs and symptoms after implant loading: Infection, Movement, and Numbness

Dental implant failure is classified as follows [39]:

- Primary failure occurs within the first three months of the implant's life and is caused by the surgical techniques used.

- Failure occurring within one year is due to compensatory causes and is associated with poor occlusal loading.

- Late failure: occurs within 3-5 years, usually due to plaque and poor oral hygiene.

Osseointegration and biocompatibility are the most important operational properties of dental implants, since the surface of the dental implant is in direct contact with tissues and bones. Therefore, modification of the surface of dental implants is of great importance and plays an important role in the success of dental implants.

Methods of surface modification of dental implants are divided according to the main effect on the surface into mechanical, physical, chemical, and biochemical. In addation, they are classified according to the effect of surface modification of implants on their functional properties into:

1. methods that aim to change the roughness of the surface of implants to improve their integration.

2. methods that form protective and/or bioactive layers on implants to improve their corrosion resistance, biocompatibility, biomechanical stability, antibacterial properties and promote bone tissue regeneration.

The requirements for biocompatibility and effective attachment of implants to body tissues can be effectively met using materials with rough surfaces, allowing for strong bonding with living tissue. Two primary methods of interaction between the implant and tissue are mechanical attachment through tissue ingrowth into the implant pores and chemical attachment via interaction with the implant's structural components [40].

Smooth, polished (3S) implants have a reduced contact area with body tissues and are fixed using the double-shell technique, facilitating removal without damaging surrounding tissues, which highlights the superior osseointegration of rough-surfaced implants [41]. Common methods for modifying the implant surface microgeometry include anodic oxidation, acid/alkaline etching, hydrogen peroxide treatment, and various coating techniques such as sol-gel and chemical deposition, along with mechanical treatments like sandblasting and laser ablation. Surface roughness significantly impacts cell adhesion, with fibroblasts and epithelial cells adhering better to smooth surfaces, while osteoblast proliferation is enhanced on moderately rough surfaces. Recent trends in surface modifications focus on applying functional coatings to improve implant integration and combat infections that may lead to implant rejection [42]. Research indicates that calcium phosphate (CaP) compounds promote stronger bonds with bone tissue compared to uncoated titanium implants. Additionally, bio surface modifications using growth factors and antibacterial agents are being explored [43].

However, analysis of numerous studies reveals no consensus on the optimal surface modification method for dental implants. Enhancing the effectiveness of dental implants requires a multifaceted approach involving the selection of suitable materials, manufacturing technologies, and surface modifications, including the development of porous structures and bioactive properties [44,45].

2. Conclusion

The current review indicates the diversity and multiplicity of promising materials used in dental implants. However, the selection of modern materials used in dental implants lacks systematic and organized methods based on diverse clinical cases, which calls for an integrated approach of the type of material used, manufacturing technology, and effective surface modification methods to meet the needs of patients and improve the quality of dental implants. Moreover, multiple techniques should be combined to create a suitable surface structure and form bio-coatings to modify the surface of dental implants and enhance integration with the bone. Modern manufacturing techniques and technology have provided dental implants with graded properties, which contribute to reducing movement problems and bacterial contamination. The development of dental implant technology requires a joint effort in research, development, and clinical applications, with a focus on improving material selection, enhancing manufacturing processes, and improving surface properties to ensure better patient outcomes.

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