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Role of Nanotechnology in Prosthodontics: a review

Duggineni Sreenivasulu[1], N. Simhachalam Reddy[1], J Lakshmi Sowjanya[2,*]

[1]Professor, Department of Prosthodontics, G Pulla Reddy Dental College, Kurnool, Andhra Pradesh, India.
[2]Postgraduate student, Department of Prosthodontics, G Pulla Reddy Dental College, Kurnool, Andhra Pradesh, India.

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*Correspondence

J Lakshmi Sowjanya

Postgraduate Student,
G Pulla Reddy Dental College,
Kurnool, Andhra Pradesh, India.
E-mail: sowjanyajinka96@gmail.com
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Abstract

In the present-day context, a considerable portion of the population faces the challenge of edentulism. Various treatment approaches, including both fixed and removable prostheses, are available for restoring missing teeth. Noteworthy progress has recently been observed in the characteristics of commonly used dental materials, attributed to the emergence of nanotechnology. This technological advancement has significantly contributed to improving the outcomes of dental treatments. Nanotechnology represents a multidisciplinary domain that amalgamates principles from both the arts and sciences, involving the manipulation of structures and functional materials at a minuscule scale. This field leverages various physical and chemical methodologies to operate at dimensions where sizes of particles, typically ranging from 1 to 100 nanometers, give rise to what is termed as Nanoparticles. The integration of nanoparticles in dentistry, particularly within dental materials such as ceramics, acrylic resin, tissue conditioners, and denture adhesives, has exhibited a discernible positive impact on their inherent properties. This review predominantly delves into an exploration of diverse applications of nanoparticles within the realm of dentistry, with a specific emphasis on their role in prosthodontics.

Keywords: Nanotechnology, Nanoparticles, Carbon nanotubes.

1. Introduction

Prosthodontics, a specialized branch of dentistry, is dedicated to the restoration of missing teeth and correction of facial defects using artificial prostheses. The increasing emphasis on oral health and elevated standards of living have amplified the recognition of prosthodontics [1-4]. Human curiosity has consistently driven scientific innovation, and contemporary science, heavily influenced by technology and the practical application of scientific knowledge, has significantly shaped our lifestyle [5].

A recent groundbreaking development in this regard is "Nanotechnology." The term "Nano" is of Greek origin, signifying "Dwarf." Nanotechnology is a discipline that combines the art and science of manipulating structures and functional materials at an exceptionally small scale, employing various physical and chemical methods. Nanoparticles, particles ranging between 1-100nm, play a pivotal role in this field. Nanotechnology imposes three technological prerequisites: development at the atomic, molecular, or macro levels within the 1-100nm size range; creation and utilization of structures, devices, and systems exhibiting novel properties and functions due to their minute size and the capacity to manipulate at the atomic or molecular scale [6]. Nano dentistry, a subdivision of nanotechnology, is defined as the scientific approach to maintaining oral health through the application of nanomaterials.

In recent years, the escalating interest in nanomaterials has been driven by their distinctive structures and properties. A noteworthy development in pharmaceutical research within the realm of nanotechnology has emerged, particularly in the context of its application to dental materials. Nanotechnology, being an exceedingly diverse and multidisciplinary field, has spurred the growth of a specialized domain within dentistry known as "Nano dentistry." The advent of nano dentistry has contributed to advancements in oral health and hygiene through the utilization of nanomaterials [7].

Nanoparticles exhibit enhanced efficiency when linked with bulk materials, and various types such as nanotubes, nanopores, nanodots, nanowires, nanobelts, nanorods, nanospheres, and nano capsules have found applications in dentistry. In the realm of inorganic nanoparticles, structures characterized by substantial reactivity and favorable properties due to their diminutive sizes have garnered significant attention, particularly in biological and pharmaceutical applications.

Recent studies have demonstrated that specifically engineered metal oxide nanoparticles not only exhibit robust mechanical strength but also possess notable antimicrobial activity. Among inorganic substances, silver has historically served as an antimicrobial agent, utilized since ancient times for the treatment of infections and the preservation of substances [8].

Prosthodontics primarily involves the restoration of dental structures through the application of artificial substitutes, known as prostheses. These prostheses can manifest as fixed, removable, maxillofacial, or implant-based solutions. Given their consistent interaction with oral tissues and saliva, the properties and biological compatibility of prostheses in dentistry are subject to considerable scrutiny. In the domain of Implantology, nanomaterials have exhibited notable regenerative effects on both hard and soft tissues surrounding implant sites. The capacity to stimulate tissue regeneration introduces a paradigm shift, potentially replacing implanted biodegradable materials and offering novel insights into tissue regeneration. Within prosthodontic dentistry, the integration of nanomaterials extends to various components, including ceramics, porcelains, restorative metals, acrylic resins, composites, dental adhesive systems, dental cement, and implants. The reduction of these materials to smaller sizes has resulted in heightened strength, durability, and overall efficacy [9]. This article primarily delves into diverse applications of nanotechnology within the field of dentistry, with a specific emphasis on its role in prosthodontics.

2. History [10]

Dr. Richard Phillips Feynman is credited with the discovery of nanotechnology, a term initially introduced by Taniguchi in 1974. The widespread acknowledgment of this field was propelled by Eric Drexler in 1986 through his influential book, "Engines of Creation." Filtek™ Supreme, developed by 3M ESPE, is considered one of the first commercially developed dental nanocomposites. Introduced in 2002, it marked a significant advancement in dental materials, incorporating nanotechnology for improved performance.

3. Classification of nanomaterials

The general classification of nanomaterials is [11]

3.1 Organic nanomaterials

3.1.1 Polymer based nanomaterials: They are non-toxic and have nanosphere or nano-capsule shapes, which can be easily activated. Polymer-based nanomaterials are nanoscale materials composed primarily of polymers or macromolecules. They have gained significant attention in various fields, including dentistry, due to their versatility, biocompatibility, and tunable properties. In dentistry, polymer-based nanomaterials find applications in drug delivery, restorative dentistry, and tissue engineering. Polymer-based nanomaterials used in dentistry are polymer nanoparticles (poly(lactic-co-glycolic acid) (PLGA) or chitosan), polymeric nanofibers (poly(lactic acid) (PLA) or poly(caprolactone) (PCL), etc.), polymeric nanocomposites (hydroxyapatite nanoparticles), polymeric hydrogels, polymeric micelles and polymeric nanocarriers.

3.1.2 Lipid-based nanomaterials: These nanomaterials are size between 10 to 1000 nm and used in bio-medical application. They have solid core made of lipophilic molecules and the surfactants on the outer aspect. Lipid-based nanomaterials are nanoscale materials composed primarily of lipids, which are naturally occurring organic molecules that include fats, oils, and phospholipids. These materials have gained significant attention in various fields, including dentistry, due to their biocompatibility, versatility, and ability to encapsulate and deliver therapeutic agents. In dentistry, lipid-based nanomaterials find applications in drug delivery, oral care, and tissue regeneration. The Lipid-based nanomaterials are liposomes, solid lipid nanoparticles (SLNs), Nanolipid carriers, lipid-based hydrogels, lipid nanoparticles for local anasthesia, lipid-based nanoparticles for dental imaging.

3.1.3 Carbon based nanomaterials: Carbon-based nanomaterials are typically considered a subcategory of nanomaterials and are often referred to as "organic nanomaterials." These materials are composed primarily of carbon atoms and may also contain other elements such as hydrogen, nitrogen, or oxygen. They include various structures like carbon nanotubes, fullerenes, graphene, and carbon dots.

Organic nanomaterials encompass a broader range of nanomaterials that are carbon-based and contain organic (carbon-containing) compounds. Carbon-based nanomaterials are an important subset of organic nanomaterials due to their unique properties and applications, but the category of organic nanomaterials can also include non-carbon-based organic compounds in nanoscale structures.

3.2 Inorganic nanomaterials

3.2.1 Metal: They are derived from precursors of metal.

3.2.2 Metal oxide nanomaterials: Metal oxide nanomaterials are synthesized because of higher reactivity and effec¬tiveness like Cerium Oxide (CeO_2), Zinc Oxide (ZnO), Alu-minium Oxide (Al_2O_3), Titanium Oxide (TiO_2), Magnetite (Fe_3O_4), Iron Oxide (Fe_2O_3), and Silicon Dioxide (SiO_2) [12,13,14].

3.2.3 Ceramic nanomaterials: These are inorganic non-metallic materials obtained by heating and cooling process and they have wide application in prosthodontic dentistry.

3.2.4 Semiconductor nanomaterials: The properties of semiconductor nanomaterials are in between metals and non-metals, and they are widely used in electronic devices.

4. Classification of nanoparticles [15]

Nanoparticles are classified based on various criteria. Firstly, they are categorized according to their origin, distinguishing between natural and artificial nanoparticles. Secondly, their dimensions play a pivotal role in classification, with zero-dimensional representing nano-sized particles, one-dimensional as nanorods, and two-dimensional as thin films. Lastly, the structural configuration further refines the classification, encompassing carbon-based nanoparticles, metal nanoparticles, dendrimers, and composite resin nanoparticles. This multifaceted classification system enables a comprehensive understanding of the diverse nature of nanoparticles in terms of their origin, dimensions, and structural composition.

5. Ultra structural classification of nanoparticles [16]

The ultrastructural classification of nanoparticles encompasses distinct categories, including nanorods, nanowires, and nanotubes (Figure 1). Nanorods are characterized by their elongated shape, featuring a cylindrical or rod-like structure. Nanowires, on the other hand, exhibit a slender and elongated form with a high aspect ratio, resembling tiny wires. Nanotubes, as the name suggests, are hollow cylindrical structures with diameters at the nanoscale. This ultrastructural classification provides a nuanced perspective on the diverse geometries and characteristics exhibited by nanoparticles, offering valuable insights into their unique properties and potential applications.

6. Approaches in nanotechnology

Various methodologies are employed in the generation of nano-sized particles, encompassing the bottoms-up technique, top-down technique, and the functional technique. Unlike the former two, the functional technique diverges from the conventional production methods of nano-sized particles. Instead, it focuses on creating nanoparticles with precise functionalities, emphasizing the tailored design and specific attributes of the nanoparticles to meet targeted objectives.

6.1 Top-down approach

Top-down fabrication involves the reduction of large materials to the nanoscale, leading to the emergence of distinct properties that render them suitable for diverse applications. This reduction in size results in an increased surface area-to-volume ratio, enhancing the materials' characteristics. The technique is employed in various applications, such as Pit & fissure sealants, Bone targeting Nano carriers, and other related products. Dental procedures utilizing this approach encompass Nanocomposites, Nano Light-Curing Glass Ionomer Restorative, Nano Impression Materials, Nano-Composite Denture Teeth, Nanosolutions, Nanoencapsulation, Plasma Laser application, Prosthetic Implants, Nano needles, and Bone replacement materials (Figure 2) [17].

6.2 Bottom-up approach:

The bottom-up nanomanufacturing approach involves constructing products by assembling small components into more intricate structures. This technique is applied in various dental procedures, including local anesthesia, hypersensitivity curing procedures, nanorobotic dentifrice, nano toothpaste, cosmetic interventions, orthodontic procedures, photosensitizers and their carriers, oral cancer diagnosis, complete tooth replacement procedures, tooth renaturalization methods, cancer treatment in the oral cavity, biomimetic dental processes, regeneration methods primarily in endodontics, and nanoterminators (Figure 2) [18].

6.3 Wet nanotechnology

Wet nanotechnology involves the examination and manipulation of biological systems predominantly found in aqueous environments. This encompasses a comprehensive study of elements within living organisms, such as genetic materials, membranes, enzymes, and nano-sized cellular components. The emphasis is on understanding and harnessing the intricate structures and functions of these components within the context of a water-based environment. This branch of nanotechnology explores the unique properties and behaviors of biological entities at the nanoscale, with potential applications in various fields, including medicine, biology, and environmental science.

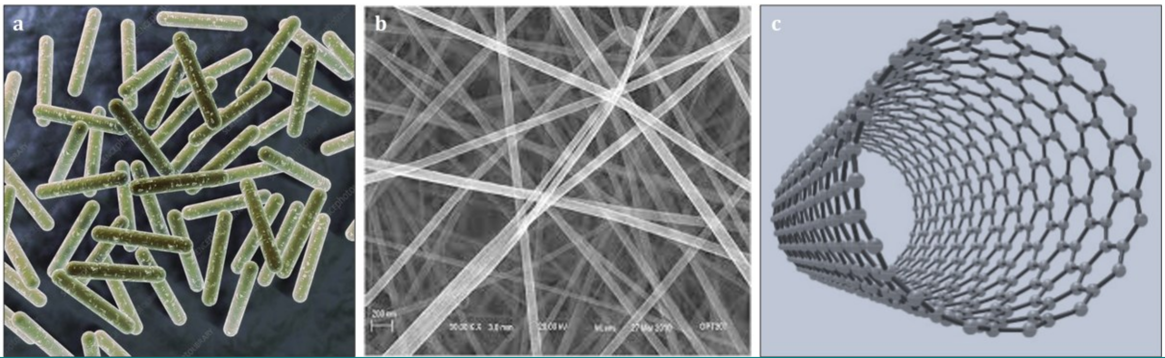

Figure 1. Structural classification of nanoparticles. Where a. Nanorods, b. Nanowires and c. Nanotubes.

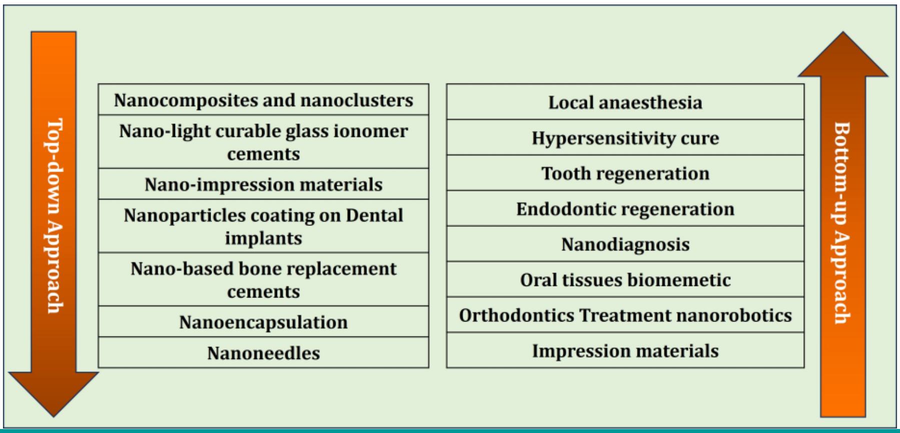

Figure 2. Top-down & Bottom-up approaches in nanotechnology

6.4 Dry nanotechnology

Dry nanotechnology is rooted in surface science and physical chemistry, with a primary focus on the controlled fabrication of structures within materials like carbon, silicon, and other organic substances. Unlike wet nanotechnology, which deals with biological systems in aqueous environments, dry nanotechnology centers on non-biological materials and the precise manipulation of their properties at the nanoscale. This approach involves techniques that are often based on physical and chemical principles to engineer structures and devices with specific functionalities. Applications of dry nanotechnology span various industries, including electronics, materials science, and nanoelectromechanical systems (NEMS).

6.5 Computational nanotechnology

Computational nanotechnology facilitates the modelling and simulation of intricate structures at the nanometer scale. The utilization of computational tools is crucial in predicting and analyzing the behavior of materials and devices at this minute level. The power of computation plays a pivotal role in the success of nanotechnology by enabling researchers to simulate and understand the properties and interactions of nanoscale structures. Through computational approaches, scientists can explore the behavior of materials, predict their properties, and design novel structures with specific functionalities. This predictive and analytical capability is essential for advancing research and innovation in the field of nanotechnology.

7. Applications of nanotechnology in various fields

Nanopharmaceuticals find diverse applications encompassing cancer treatment, antiviral agents, arteriosclerosis, lung disease, diabetes, gene therapy, tissue engineering, and tissue cell repair. Nanodevices, specializing in the delivery of diagnostic and therapeutic agents, are classified into three potent molecular technologies. The integration of nanoscale materials and devices is pivotal in advanced diagnostics and biosensors, targeted drug delivery, and the development of smart drugs. This convergence facilitates molecular medicine through genomics, proteomics, and artificial biorobotics, such as microbial robots. Additionally, molecular machines and medical nanorobots play a vital role in immediate microbial diagnosis, treatment, and the enhancement of physiological functions [19].

8. Application of nanoparticles in prosthodontics

Nanoparticles have got numerous applications in the medicine and dentistry [20]. They include,

8.1 Impression Materials

An impression serves as a negative replica of teeth or associated structures, and in prosthodontics, various materials are employed for this purpose, including rigid materials, reversible hydrocolloids, irreversible hydrocolloid materials, and elastomeric impression materials. Nano fillers, incorporated into polyvinylsiloxanes, enhance the hydrophilic properties of the material, leading to improved flow and fewer voids at the margin [21]. The introduction of silver nanoparticles (80-100nm) to alginates imparts antimicrobial activity [22]. ZnO-NP (30-40nm) and CuO-NP (20-95nm) exhibit significant antimicrobial activity against oral microorganisms, such as S. mutans, P. intermedia, and P. gingivalis, enhancing flow characteristics [23]. Chitosan, a hydrophilic polysaccharide derived from chitin, is antibacterial, biocompatible, non-toxic, biodegradable, and possesses various additional properties [24]. Titanium dioxide nanoparticles (7-25nm) are added for antimicrobial effects against Candida Albicans, Staphylococcus aureus, Pseudomonas aeruginosa, Escherichia coli, and lactobacillus acidophilus [25].

8.2 Acrylic Resin

The significance of acrylic resins in dentistry is evident, as they are extensively utilized in the fabrication of temporary prosthetics, base materials, provisional prosthesis, dentures, and orthodontic removable appliances such as retainers and functional devices. These resins typically comprise methacrylates, notably poly methyl methacrylate (PMMA), along with additional copolymers. However, a notable challenge faced by both patients and dentists with these removable acrylic appliances is their susceptibility to plaque accumulation due to surface porosities and food-retentive configurations, thereby promoting bacterial activity from cariogenic oral flora.

To address these issues, various nanoparticles have been introduced as additives to biomaterials, demonstrating antimicrobial properties. For instance, the incorporation of titanium dioxide nanoparticles has been observed to induce antimicrobial effects [26]. Similarly, the inclusion of nanoparticles like silver, platinum, titanium, and iron has shown improvements in flexural strength, antimicrobial properties, surface hydrophobicity, viscoelasticity, and reductions in porosity and biomolecular adherence [27].

Reinforcing carbon nanotubes has been found to decrease polymerization shrinkage and enhance mechanical properties, owing to their honeycomb-shaped carbon atoms with sizes ranging from 10 to 100 nm, multilayered and incorporated into PMMA [28]. Additionally, the incorporation of zirconium dioxide nanoparticles (8-10nm) to heat-cured PMMA has resulted in increased abrasion resistance, tensile and fatigue strength, as well as reductions in water sorption, solubility, and porosity [29].

8.3 Tissue Conditioners

Tissue conditioners are frequently employed to ensure sufficient retention in cases of resorbed residual tissues, aiming to prevent damage to the denture-bearing area resulting from injury or trauma caused by poorly fitting dentures. While the maintenance of tissue-conditioned prostheses involves cleaning through chemical and mechanical methods, these agents may pose a disadvantage by potentially causing significant damage to the prosthesis's antimicrobial properties. The incorporation of silver nanoparticles, characterized by wound bio-burden reduction and anti-inflammatory properties, offers a solution. The nanoscale nature of silver particles results in an increased surface-to-volume ratio. Positively charged silver particles interact with negatively charged bacterial cells, effectively reducing the microbial count. Hence, the addition of silver nanoparticles to tissue conditioners serves as a strategy to address this concern [30].

8.4 Denture Adhesives

Dental adhesives serve to improve the adhesion and cohesion between distinct substances or between a material and the natural tooth structure. Polymerizable silane is incorporated to augment cohesive strength. To address performance inconsistencies caused by filler particle settling during storage, discrete silane-treated nanoparticles of silica and zirconia, measuring 5-7 nm, have been introduced. Zirconia presents an additional benefit by providing radiopacity to the adhesive [31].

8.5 Dental Ceramics

Nanoceramic denotes a ceramic material characterized by nanoscale dimensions within its microstructure phase. In contrast to conventional ceramics, nanoceramics showcase distinctive attributes such as superior toughness and ductility. These materials possess heightened mechanical properties, including enhanced strength and hardness. While CAD/CAM milled zirconia exhibits superior strength and bending resistance compared to alumina ceramic, there remains a deficiency in toughness [32]. Carbon nanotubes have garnered attention as reinforcement materials due to their exceptional mechanical and electronic properties [33]. Nano-TiO2 ceramics demonstrate notably high toughness [34]. Additionally, nano ZrO2 exhibits increased fracture toughness, rendering it suitable for dental restorations [35]. The addition of silver and platinum nanoparticles increased both the Young's modulus and the fracture toughness of dental porcelain [36].

8.6 Composites

Nano fillers in the size range of 1-100nm have been incorporated into the resin matrix to produce nanocomposites.

8.6.1 Nanomers: These particles are monodispersed, presenting a state of non-aggregation and non-agglomeration. They consist of silica treated with 3-methacryloxy propyltrimethoxysilane (MPTS), a compound pivotal in establishing chemical bonds between the nanomer filler and the resin during the curing process. The incorporation of MPTS contributes to favorable optical properties, superior hardness, elevated flexural strength, and aesthetically pleasing characteristics [37].

8.6.2 Nanoclusters: Nanocluster fillers exhibit a size range spanning from 2 to 20 nm. These fillers are generated through the gentle sintering of nanomeric oxides, resulting in controlled particle size distributions within clusters. Similar to nanomers, nanocluster fillers present advantageous characteristics, while also demonstrating improved rheological properties [38].

8.6.3 Nanohybrid composites: Nanohybrid composites represent a notable advancement in dental materials through the incorporation of pre-polymerized organic fillers into nanomers. This strategic integration contributes to the enhancement of both rheological properties and esthetic features in dental composites [39]. The term "nanohybrid" signifies the combination of nano-sized particles with pre-polymerized organic fillers. The inclusion of nanomers, which are monomer clusters at the nanoscale, allows for improved homogeneity and distribution of the filler within the composite matrix. This meticulous arrangement contributes to enhanced rheological properties, ensuring better flow and adaptation during placement. Additionally, the incorporation of pre-polymerized organic fillers enhances the esthetic qualities of the composite, offering improved color matching and blending with natural tooth structures. The resulting nanohybrid composites thus provide practitioners with materials that exhibit superior handling characteristics and optimal esthetic outcomes in various dental applications.

8.6.4 Tio_2 reinforced resin-based composite: The Tio2 reinforced resin-based composite represents an innovative approach in dental materials, utilizing titanium dioxide nanoparticles as a reinforcing agent. These nanoparticles are treated with organosilane, specifically allyltriethoxysilane (ATES), to enhance the material's microhardness and flexural strength [39]. Titanium dioxide nanoparticles, when treated with ATES, undergo a surface modification that promotes better compatibility and bonding with the resin matrix in the composite. This treatment enhances the interaction between the inorganic filler (TiO_2) and the organic resin, resulting in improved mechanical properties. Microhardness, a measure of material resistance to indentation or penetration, is augmented, signifying enhanced resistance to wear and deformation. The flexural strength, which denotes the material's ability to withstand bending or flexing loads, is also elevated, contributing to the overall durability and structural integrity of the composite.

8.6.5 Nanocomposites with Alumina nanoparticles: Nanocomposites incorporating alumina nanoparticles signify a significant advancement in dental materials, where the inclusion of these nanoparticles has demonstrated notable improvements in hardness, strength, and modulus of elasticity [40]. Alumina nanoparticles, known for their high hardness and mechanical strength, act as reinforcing agents within the composite matrix. When integrated into the nanocomposite, these nanoparticles contribute to enhancing the overall material properties. The increased hardness indicates a greater resistance to deformation or wear, which is a crucial aspect in dental applications where durability is paramount. The improvement in strength suggests enhanced structural integrity, ensuring the composite can withstand mechanical stresses encountered in the oral environment. Additionally, the heightened modulus of elasticity reflects an increased ability of the material to return to its original shape after deformation, contributing to its resilience and performance.

8.6.6 Calcium Phosphate and Calcium Fluoride nanoparticles-based composites: Materials that exhibit the controlled release of calcium phosphate and calcium fluoride have demonstrated the capacity for remineralizing tooth structures, leading to their integration into dental composites. These materials effectively manage the sustained release of calcium (Ca) and phosphate (P) ions through recharge and release mechanisms, earning them the designation of a "smart" material. This intelligent characteristic contributes to inhibiting secondary caries, establishing them as promising components in dental applications [41].

8.7 Dental Cements

Advancements and modifications through the incorporation of nanoparticles as fillers have significantly elevated the properties of dental cements.

Glass ionomer cement enriched with titanium dioxide (TiO_2) nanoparticles, up to 5% w/w, has demonstrated notable improvements in fracture toughness, flexural strength, compressive strength, and antibacterial activity. Additionally, the addition of 5% TiO_2 nanotubes has substantially increased the non-collagenous composition of the extracellular matrix, resulting in enhanced microhardness and fluoride release [42].

Nano light-cure glass ionomer cement, incorporating hydroxyapatite/fluoro-alumino silicate, exhibits enhanced compressive, tensile, and biaxial flexural strength [43].

Glass ionomer cement containing poly quaternary ammonium salt has exhibited remarkable antibacterial activity and elevated strength [44].

Resin-modified glass ionomer, comprising 65% nanofillers, has been utilized for the restoration of primary teeth and small cavities in permanent teeth. The incorporation of silver nanoparticles in resin luting cements has demonstrated a prolonged inhibitory effect [45].

8.8 Dental Implants

The introduction of dental implant therapy stands out as a pivotal advancement in dentistry over the last thirty years. Osseointegration, recognized widely in clinical dentistry, serves as the cornerstone for the success of dental implants. Instances of osseointegration failure can be attributed to factors involving one or more implants, local anatomical considerations, local biological conditions, systemic influences, or functional aspects.

The incorporation of nanostructured hydroxyapatite proves beneficial in enhancing osteoplastic functions, including adhesion, proliferation, and mineralization. Moreover, it facilitates bone formation around the implant, contributing to its overall success [46].

Nanoporous ceramic implant coatings employ an innovative approach to enhance implant properties, involving the anodization of aluminum. This technique entails the creation of a nanoporous aluminum layer atop titanium alloy implants. Nanoporous alumina exhibits potential by enabling the loading of bioactive agents into its porous structure, thereby enhancing cell response and facilitating osseoinductive activity. Additional treatments, such as surface roughening through sandblasting and hydroxyapatite coating, have been applied to improve bone growth [47].

10. Conclusion

In the landscape of modern dentistry, the integration of nanotechnology has revolutionized various facets, from restorative materials to implant therapies. Nanomaterials, such as nano-hydroxyapatite and nanostructured fillers, have demonstrated remarkable enhancements in the mechanical and biological properties of dental composites, contributing to their clinical efficacy and longevity. The development of nanohybrid composites and nanocluster fillers showcases innovative strides in achieving optimal material homogeneity and performance. Moreover, the strategic use of nanoparticles in dental cements has yielded materials with superior strength, fracture toughness, and antibacterial properties, offering promising solutions for diverse clinical applications.

In the realm of implant dentistry, the emphasis on osseointegration as the foundation for success underscores the significance of advancements such as nanoporous ceramic coatings. These coatings, incorporating nanostructured alumina and other bioactive agents, hold potential for improving cell response and fostering osseoinductive activity. The integration of nanotechnology into dental implant therapies marks a significant leap forward, addressing challenges and elevating the overall standard of care in dentistry. As we navigate the future of dental science, the marriage of nanotechnology with traditional practices promises to reshape the landscape, offering innovative solutions and improved patient outcomes.

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