Modern Possibilities and Prospects of Nanotechnology in Dentistry

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Abstract

Objective. Nanotechnology is spreading among all areas of life, from everyday devices to medicine. The concept of nanotechnology argues that not only can new physical and chemical properties of materials be discovered, but also the new potential of nanostructures when reduced to the nanoscale. The growing interest in the application of nanomaterials in dentistry contributes to the proliferation of the range of nanomaterials used by specialists. The purpose of this review of information sources was to analyze the prospects for the use of nanomaterials in dentistry. **Methods**. We used the bibliographic semantic method of research, for which we analyzed electronic databases of primary literature sources Scopus, Web of Science, Research Gate, PubMed, MDPI, and MedLine. English-language scientific articles published after 2017 were taken into consideration. **Results**. According to the results of a search study among modern information primary sources, nanotechnology improves the preventive properties of oral care products, improves the structural-mechanical and aesthetic properties of composite mixtures for dentistry, overcomes the problems of the clinical application of dental implants. Despite the prospects of nanotechnology applications in medicine in general and dentistry in particular, the existing economic and technological problems require a thorough solution for further implementation of nanostructures.

Scientific novelty. For the first time, the analysis of modern trends in the application of nanotechnology in dentistry is carried out and the peculiarities of materials are highlighted, the problems and prospects of nanostructures implementation in modern dental implantology are given, physical, chemical, mechanical, and antibacterial properties of nanomaterials are evaluated. The effect of nanomaterials on the microbial adhesion of the tooth or implant surface is described.

Practical significance. The presented publication can become a scientific basis for the solution of urgent problems hindering the introduction of nanotechnology into dental practice.

Conclusions. Thus, the use of nanostructures opens up great opportunities for the treatment of a wide range of diseases, not only of dental nature but also in medicine in general.

Keywords:
nanotechnology, dentistry, composites, implants, endodontics.

1. Introduction

Over the past 30 years, there has been a growing scientific and practical interest in nanotechnology. This discipline has rapidly spread to all fields of human activity, including medicine. Given that the size of nanostructures does not exceed 100 nm, medical nanomaterials solve patient problems on the atomic and molecular scale [1].

The rationale behind the use of nanotechnology has several reasons. First, as particle sizes change, their surface energy per gram of material changes, which, in turn, changes the physical and chemical properties. One of the most simplified applications, in this case, is the dissolution of hydrophobic substances and thus the delivery of most of the drug to human bodily fluids. Secondly, the addition of nanoparticles to dental composites improves the mechanical properties of the mixture, extreme wear resistance, and better aesthetic effect of the materials. The literature primary sources describe recent research in the field of active nanostructures for therapeutic or prophylactic dental applications [2]. With this in mind, the purpose of this review of information sources was to analyze the prospects for the use of nanomaterials in dentistry. To achieve the objectives, the following tasks had to be carried out: to analyze the dynamics of nanotechnology development; to establish the specifics of nanotechnology applications in medicine and dentistry; to determine the main types of nanostructures used for the prevention and treatment of dental and gum diseases and dental implantology; to analyze current problems and prospects of nanotechnology in the dentistry industry.

2. The methodology

To identify relevant information, we used a bibliographic semantic method of research, for which we analyzed electronic databases of primary literature sources Scopus, Web of Science, Research Gate, PubMed, MDPI, MedLine. English-language scientific articles published after 2017 were taken into consideration.

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3. Results and discussion

3.1 History of nanotechnology development. Introduction of nanotechnology in the medical industry

One of the most promising scientific applications of the 21st century is the prospecting, observation, measurement, manipulation, collection, quality control, and production of nanomaterials. According to the definition formulated by the National Nanotechnology Initiative of the United States, nanotechnology should be understood as technologies with sizes ranging from 1 to 100 nm, whose unique properties open up prospects for practical applications from the chemical, physical, and biological branches of medicine or electronics [3].

The concept of nanotechnology was first introduced by the American physicist Richard Feynman in 1959. Almost 26 years later, in 1985, a group of scientists (R. Curl, G. Kroto, and R. Smalley) found that carbon can also exist in the form of very stable spheres, fullerenes, or buckyballs. A few years later, in 1991, a new member of the fullerene family was discovered - empty graphite tubes or carbon nanotubes, which due to their strength and flexibility have potential applications in the construction industry, as well as for energy storage, in catalytic reactions and as electronic molecular. components [3, 4].

At the beginning of the 21st century, in 2004, the so-called carbon dots (C-dots) were discovered during the purification of single-walled carbon nanotubes, and it was decided to refer them to a new class of carbon nanomaterials. Due to their affordability, low toxicity, and high biocompatibility, C-dots have found wide application in medicine as materials for analytical studies and drug delivery systems. In addition, the optical properties of carbon dots determine their use in completing photoelectric spaces and nanoprobes. The discovery of graphene in the same year led to the application of carbon-based nanomaterials in almost all branches of science and technology [1].

A number of publications in the last ten years describe the successful application of nanotechnology in biological research, diagnostics, and molecular imaging, highlighting the potential of nanomaterials and nanoscience for human body examination and therapy of pathological conditions [1-4].

The group of nanopharmaceuticals includes materials for targeted drug delivery, tools for regenerative medicine, nanoparticles with antibacterial activity, and functional structures that are used to detect biological markers (nanobiochips, nanobiosensors, nanoelectrodes). Unlike their macroscopic counterparts, nanoscale materials have unique properties that maximize the therapeutic activity of drugs and minimize unwanted side effects [1, 2]. Despite the assertion of critics that nanotechnology in medicine has failed to meet the initial hopes for targeted drug delivery, this is not the only pharmacological parameter by which to evaluate the success of nanomedicine [5].

Scientific research in the field of nano-oncology devoted to the targeted bombardment of the tumor site with cytotoxic agents and targeted delivery of active pharmacotherapeutic compounds allowed to increase the anti-tumor activity of traditional chemotherapeutic agents with simultaneous reduction of their toxic effects on the patient body, as well as to stimulate autophagy processes and affect the condition of cancer patients [6].

Thus, the issue of the application of nanotechnology in various industries, especially in medicine, does not lose its relevance [1]. Modern nanotechnology in medicine is not only passive carriers of active pharmaceutical ingredients. Starting from the development of therapeutic drug delivery and absorption enhancement systems, lipid systems, liposomes, and micelles approved by the FDA, today's range of nanomaterials for medicine includes biosensor systems, tissue engineering materials, systems with controlled drug release, the latest formulations with unique properties, and fibers with specific structural, chemical, mechanical, magnetic, electrical and biological properties [7].

3.2 Relevance of Innovation in Dental Practice

According to the literature, research in the field of nanotechnology has at one time contributed to revolutionary solutions in various areas of human endeavor, particularly in the field of health care. Like every other branch of medicine, dentistry is experiencing constant technological and material development. The science and practice of dentistry has undergone tremendous change over the past decade, primarily due to the introduction of technological and scientific innovations to the profession. The growing need of the population to maintain a healthy mouth has led to active exploratory biotechnological and biomedical research and advances. For example, the revolutionary polymerase chain reaction method is used in dentistry to detect periodontal cariesogenic pathogens, microorganisms in endodontic infections, viruses present in host cells, useful markers in the diagnosis and prognosis of certain types of oral cancer, and for quantification purposes.].

Thanks to the Genome Project, a framework for the diagnosis and treatment of diseases of the jaw joints, periodontal and dental tissues has been established [9]. At the same time, it turned out that despite the achievements of the last ten years in the field of dentistry, no synthetic macromaterial can fully meet the needs of both patients and doctors, mainly because of its sensitivity to environmental factors. With this in mind, scientists have faced the pressing problem of applying advanced technologies to the treatment of oral diseases, which still requires a timely solution [8].

3.3 Application of nanotechnology in dentistry

Literature primary sources indicate that nanotechnology may become the necessary basis for creating modern dental materials and improving oral diagnostic and treatment methods [8]. First of all, the active improvement of technologies and therapeutic approaches concerns the methods of primary and secondary prevention of dental diseases. It is known that the preventive direction today is no less important than the therapeutic, so the main method of "preventive" dentistry is an adequate and complete oral hygiene [6].

3.4 Nanotechnology innovations in oral care products

The introduction of nanotechnology in the above case can meet the need for functional oral hygiene items and products. For example, oral care products "Sesderma Dentyses Perio" (Spain) contain liposomes of active pharmaceutical ingredients, which provides better permeability to the tissues and a more pronounced antiseptic, cleansing, and antimicrobial effect. After all, as stated in [10], dental caries and periodontal disease are some of the most common infectious diseases in the world. Scientists consider Streptococcus mutans to be a factor in tooth and gum disease, mainly because of its ability to possess several high-affinity surface adhesins that allow colonization even in the absence of sucrose [11]. Preclinical trials have confirmed that the introduction of silver nanoparticles in dental cleaners and oral rinse or irrigation fluids led to a reduction in the growth rate of S. mutans. In addition, silver nanoparticles are used by toothbrush manufacturers for aseptic treatment of the bristles, which with long-term use has resulted in a reduction of toothbrush bristle degradation, a decrease in the number of viable streptococci and lactobacilli in saliva, a decrease in plaque formation index and improved condition. use of toothbrushes with chlorhexidine bristle treatment [5, 12]

Manufacturers of oral care products add not only noble metal nanoparticles to toothpastes but also zinc or titanium. It has been proven that an excess of zinc, for example, slows the process of periodontal disease development through its effect on collagen metabolism in tissues. Titanium nanotubes combined with hydrogen peroxide, along with their antibacterial properties, help break down the chemical bonds of dark tooth enamel pigments, which in turn increases the effectiveness of teeth whitening in professional or home settings [13]. One of the negative consequences of this procedure can be hypersensitivity of the teeth to external stimuli. To minimize the patient's discomfort, specialists use preparations with hydroxyapatite nanoparticles in the composition. This material is used in the treatment of the deep stage of caries for the prevention of demineralization of dental tissues, as well as in the manufacture of dental implants [14].

Toothpaste containing nanostructured calcium carbonate for gentle teeth whitening at home are under development, as well as oral care products containing sodium phosphate nanoparticles, which in in vitro studies showed the ability to reduce the symptoms of tooth hypersensitivity after the whitening procedure. Toothpastes with amino acid complexes stimulate the synthesis of peptides from the tissue with specific activity, regulate the metabolic processes in periodontal tissues and reduce inflammation. The introduction of clay nanocoloid into toothpastes reduces the adhesion of Pseudomonas aeruginosa colonies on the surface of teeth [15].

Thus, one of the most relevant ways to introduce nanotechnology into the production of oral care products is the search for so-called "smart" materials that, unlike their "passive" counterparts, enhance the preventive properties of products and meet the needs of consumers [1, 5].

3.5 Introduction of nanotechnology to endodontics

In recent years, the quality of endodontic treatment has received considerable attention from dental professionals. Despite the progress of recent years in the treatment of dental and periodontal diseases, complications leading to tooth loss and the need for surgical intervention remain an important and timely problem [15]. One of the reasons for poor quality endodontic treatment is related to ignoring the functional and morphological relationship between the tooth and periodontal tissues, the treatment of existing pathology without monitoring the surrounding tissues, and the presence of foci of not only beneficial but also aggressive microbes in the bacterial plaque. The latter aspect is complicated by the low level of awareness of patients regarding proper oral hygiene and the lack of timely preventive examinations. In addition, endodontic treatment on a plane with an extremely small size involves a large number of complex manipulations, which are difficult to control visually. However, knowledge of objective complications that are likely to occur during the endodontic intervention, as well as ways to prevent them, can be the basis for preserving tooth function and patient health [16].

The introduction of new materials, high-precision instruments, and the latest technologies into endodontic practice has accelerated positive trends and improved treatment efficiency. From the very beginning, the relevance of nanomaterials was not in doubt, mainly due to the difficulty of maintaining sterility in the surgical area.

Today, a wide range of nanoparticles such as bioactive glass, zirconium dioxide, chitosan, hydroxyapatite, silver particles, zinc oxide, etc. are used in dental materials for endodontic treatment. The increased variety of nanomaterials has improved the mechanical properties of the therapeutic mixtures and prolonged the durability of their application. Considering that biofilm from bacterial plaque is the cause of complications in endodontic treatment, the introduction of nanotechnology has contributed to improving the bactericidal properties of dental materials and had a positive effect on the regeneration of oral tissues [17].

A variety of forms of nanomaterials - nanotubes, rods, wires - has opened up possibilities for use in various forms of dental intervention [3, 5, 18]. For endodontic treatment, nanotechnology is used in silers, obturations, composites, materials for root repair, disinfectants, coating of surgical instruments, and as part of medications to accelerate pulp regeneration. Considering the above, nanoparticles can be included in sealant, obturation material, intracanal medication, and irrigation solutions to achieve the desired results [19, 20].

From the physicochemical point of view, the characteristics of nanoscale dental materials and conventional materials for endodontic treatment have several differences. Firstly, the large usable surface area of nanomaterials leads to an increased interaction potential with biomolecules, forming the so-called “corona” [21]. In addition, catalytic processes on the surface of the nanomaterial change not only physical and chemical but also electronic properties. Scientists [19] suggest that the nanoscale can affect the magnetization of particles, which can be successfully used in clinical practice. This example alone shows that if research on nanomaterials continues, the potential for their use may be much greater than originally thought.

One of the main manipulations during endodontic treatment is the irrigation of root canals. As a rule, such chemicals as chlorhexidine, ethylenediaminetetraacetic acid, and sodium hypochlorite are used for this purpose. The use of such active oxidants facilitates the physical removal of materials from the root canal and the introduction of chemicals for antimicrobial action, demineralization, tissue dissolution, bleaching, deodorization, and control of bleeding in the area, but has several drawbacks: cytotoxicity, damage to healthy tissue due to accidental extrusion beyond the apical opening, low ability to dissolve biofilm in the root canal dentine In contrast to the known components of irrigants, chitosan nanoparticles have demonstrated In addition, the low toxicity to eukaryotic cells allows the use of irrigation fluid with nanoparticles for the final flushing of root canals [22].

3.6 Prospects for nanoparticles in composite dental materials

The use of nanoparticles in dental composites can be justified primarily from an aesthetic point of view since their introduction into composite mixtures increases the transparency and wear resistance of the latter and improves the final result [6]. On the other hand, the addition of nanoparticles to a composite material may lead to a complication of the technological process, since nanoparticles have an extremely high surface area and hence a high surface charge/gram of powder, which may lead to strong and almost constant particle agglomeration during placement and curing of the material, or even loss and unsatisfactory achievement of the desired properties, such as cracking or failure of the filling after curing [23].

One of the most sought-after materials for composite compounds is hydroxyapatite, which is a mineral natural form of calcium apatite. Due to its high biocompatibility with dentin (tooth enamel is 96% composed of this mineral), such composite mixtures quickly integrate into tooth cavities with supporting connective tissue, so they can be used in a variety of forms for endodontic intervention: coatings, powders, mixtures for filling [24].

The features of nanohydroxyapatite are not only its high bioactivity and affinity for bone apatite but also its high ion-exchange capacity. For the most part, such physical and chemical properties can be explained by the size and morphological structure of the molecules, as well as the type and quantitative ratio of ions in the crystal lattice, which affects the ability of its hexagonal system to crystallize. Features of a crystal structure allow nanohydroxyapatite to stand the raised pressure at the laying of composite materials, promote remineralization by sedimentation of ions of calcium and phosphorus, improve biomechanical properties of a dental mix, strengthen the structure, and increase the durability of a tooth tissue [25]. In in vitro studies, it was proved that nanohydroxyapatite molecules can induce nerve regeneration: a correlation was observed between the time of nerve inflammation and an increase in mitochondrial activity in neurons affected by hydroxyapatite nanoparticles. It was also proved that the addition of nanohydroxyapatite to chitosan frameworks activates the regulation of collagen mRNA and integrin subunits together with myosins, increases bone marrow stem cell proliferation in comparison with molecular hydroxyapatite [26, 27].

Other studies of this type have shown that nanohydroxyapatite is used to improve the bioactive properties and reinforce polymer meshes [2, 5]. In addition, the addition of nanohydroxyapatite improves cell spreading and adhesion [17]. Bone reconstruction and periodontal regeneration are also performed by introducing the mentioned bioactive materials that make up the matrix of the whole process. However, despite its various advantages, hydroxyapatite has poor mechanical properties and therefore cannot be used for load-bearing applications. To improve the characteristics of nanohydroxyapatite, it can be strengthened with elements such as metal ions. It has been confirmed that several characteristics can be affected by this action, including a reduction in the biodegradation rate. Nanocomposite dental mixtures reinforced with nanohydroxyapatite improve the mechanical stiffness and biological activity of the material. Besides, thanks to unique properties nanohydroxyapatite can be effective at such procedures, as the increase of defects of periodontal bone or alveolar process, and also at the restoration of a part of a tooth [28].

In the 1960s, a composite material called "bioactive glass" was obtained that consisted of specifically defined proportions: sodium oxide, calcium oxide, phosphorus oxide, and silicon dioxide. Today, this material is widely used in modern dentistry for dental restoration due to its ability to bind to bone [19].

In addition to its basic characteristics, bioactive glass has regenerative and antimicrobial properties. Its structure allows to build up new bone tissue directly on the composite material, which becomes possible due to the similar chemical composition of bioactive glass, human bone, and dental dentin. In addition, bioactive glass has been proven effective in remineralizing dentin by precipitating nanoparticles due to their solubility upon contact of the composite dental mixture with blood plasma or saline solution. As a consequence, there is a crystallization process of apatite hydroxycarbonate nanoparticles at the interface between the glass and the dental tissue, and, due to the hydrophilic properties of the bioactive glass nanomaterial and the spread of moisture to the walls of the dentinal channels, more effective sealing of the dentin, compared with standard composite dentistry.

Bioactive glass also possesses antibacterial properties, mainly due to its high pH and consequently its ability to release calcium and phosphorus ions as well as its osmotic effects. Thus, when the bioactive glass comes in contact with water, there is a process of dissolution and release of calcium and phosphorus ions, leading to an increase in pH. In turn, the released calcium and phosphorus ions initiate mineralization on the surface of the bacterial cell wall. An increase in osmotic pressure of at least 1% inhibits the growth of microbial strains and biofilm on the tooth surface [19].

The addition of zirconia nanoparticles to composite compounds improves the parameters of strength, resistance to compression, and mechanical resistance of the materials compared to composites containing silica- and barium-based micro- and macromolecules [18, 22].

Silver nanoparticles have found their application in medicine, in particular in dental practice, mainly due to its antimicrobial, anti-inflammatory, and optical properties. In addition, the inert nature of silver makes it an indispensable metal used in endodontic manipulations. In contact with the biological fluid, there is an ionization process, as a result of which silver nanoparticles become reactive towards the proteins of the tissue wall of microorganisms. The silver atoms change the structure of the cell walls and lead to the death of the bacteria. Antimicrobial and anti-adhesive properties of silver nanoparticles against Enterococcus faecalis, Candida albicans, and Pseudomonas aeruginosa have been clinically proven. These studies confirm the effectiveness of silver nanoparticles as an adjunct to endodontic treatment for root canal disinfection or to inhibit biofilm formation [30]. In addition, in the composition of the root canal washing solution silver nanoparticles increase the antibacterial effect when mixed with a solution of ethylenediaminetetraacetic acid by 17% and contribute to better removal of the biofilm layer during endodontic manipulations [31].

Zinc oxide nanoparticles are widely used to enrich composite mixtures. By improving the diffusion of the material and hermetic filling of the root canal cavity the risk of microbial invasion is reduced, because the cause of endodontic infection is often the adhesion of bacteria and biofilm formation on the materials for canal filling - gutta-percha [32]. One way to combat microbial biofilm formation is to use aggressive disinfectant solutions for irrigation, but even with this approach, the antimicrobial resistance of modern sealants is retained for a maximum of 1 week after bonding. However, the treatment of dentin canals with zinc oxide nanoparticles or a mixture of zinc oxide and cesium sulfide reduces the adhesion of Enterococcus faecalis and decreases the number of gram-positive microorganisms [22]. The bactericidal mechanism of action of zinc oxide nanoparticles is realized through electrostatic interaction with the bacterial cell membrane, since nanoparticles carry a positive charge, while the bacterial membrane carries a negative one. As a result, the permeability through the cell membrane is disturbed, which leads to the death of the bacteria [33].

A promising area of enrichment of composite dental mixtures with nanoparticles is the study of exosomes. Exosomes are bioactive organoids secreted by cells into the intercellular medium. The size of exosomes ranges from 30 to 100 nm. The main function of exosomes is to participate in intercellular communication. The delivery of bioactive exosome molecules from one cell to another causes them to participate in various processes, such as cell regeneration or the formation of new cells. In addition, exosomes are involved in information transfer during inflammatory processes in the human body[34]. Scientists are studying the prospect of using exosomes to accelerate the regeneration of dental pulp. It has been proven that the use of a dental composite containing dental pulp stem cells as an exosome promotes a regenerative effect, mainly due to the activity of exosomes and, as a consequence, pro-angiogenic activity [5, 30]. Exosomes isolated from human deciduous tooth cells in in vitro studies promote osteogenic regeneration. Moreover, the addition of exosomes improves the synthesis of osteocalcin, osteonectin, and type I collagen. As a consequence, dental composites with exosome nanoparticles promote better bone regeneration, making them a promising raw material for future dental regeneration procedures [35].

Nanomodified graphene due to the variety of properties has found application in several areas of medicine, including dentistry. Graphene nanoplate shows antimicrobial properties due to the sharp edges of the flakes of hybridized atoms that pierce the soft cell walls of bacteria, which leads to their death. These results suggest that Streptococcus mutans, responsible for the development of human caries, can be fought in this way. Graphene used as a coating on a titanium implant has the potential to improve osseointegration properties, accelerate tissue healing and inhibit microbial growth. It was proved that graphene combined with silver nanoparticles has more pronounced antibacterial properties with less cytotoxic effect on soft tissue and bone compared to sodium hypochlorite. This makes graphene a promising material for the irrigation of infected root canals in the future, tissue engineering, fabrication of dental implants, as well as in the fields of endodontics, periodontics, and conservative dentistry.

In addition to root canal irrigation, nanomodified graphene is a promising material for use in endodontics. This compound can be added to bioactive cements such as Biodentine. The effect of graphene in this case is to reduce the setting time of the cement by reducing the induction and accelerating the hydration process. The combination of graphene with other biomaterials can expand its clinical use in dental practice due to its biocompatibility and antibacterial properties [19, 36].

For disinfection of root canals during endodontic manipulations, nanopolymeric materials are actively used, in particular: quaternary ammonium polyethylene, which has antimicrobial activity in relation to both Gram-positive and Gram-negative bacteria. Application of the composite with the addition of quaternary ammonium polyethylene reduces the viability of Enterococcus faecalis in the root canals. This increases the effectiveness of endodontic intervention and reduces the risk of complications and the development of inflammatory infections in the deep tissues. Strengthening nanopolymer composites with zinc oxide particles contributes to the mechanical strengthening of the root dentin, sealing the root canals by releasing calcium phosphate and filling the microcracks and micro cavities inside the tooth [37].

3.7 Prospects for nanoparticles in composite dental materials

In recent years, the use of dental implants has gained widespread popularity, which, unlike dentures, has a more positive impact on the quality of life of patients [5, 20]. The production of various biocompatible components, materials, and technical frameworks can expand the range of biological-based dental implants. Despite the advances in dental implantology, the problems of maintaining proper asepsis, osseointegration of the implant, and minimizing side effects remain relevant. Dental implants are usually used as a substitute for missing teeth that the patient has lost due to decay, gum inflammation, root canal infection, mechanical damage, etc. Even though the replacement of missing teeth with dental implants is a difficult and often expensive alternative, dental implantology remains a sought-after and promising field of oral manipulation [37]. In addition, endodontic treatment can lead to a decrease in the mineral tissue of the tooth (tooth loss) and, consequently, weakening of the tooth. As a result of the processes that occur, a decrease in the total amount of tooth tissue makes it difficult to recover from surgery. One of the ways to maintain the core materials of the tooth is to build up the core with the help of modern epoxy-based implant composites. Enhancing the mechanical function of epoxy resins is impossible without the use of nanoparticles [17].

The quality of an implant can be assessed by three specific aspects, such as physicochemical, topographical, and mechanical characteristics. These characteristics are closely correlated with each other and any improvement or deterioration of them can affect other indicators of dental success [20, 22, 37].

Different types of materials are used for dental implants: ceramics, cobalt-chromium alloys, gold, copper, titanium alloy, or iridium-platinum alloy. Metal dental implants have been used for a long time; however, the lack of osseointegration effect, easy infection, and mechanical properties are the main drawbacks of such materials. The trend in recent decades shows that titanium alloy is one of the most popular implant materials [17, 21].

An important problem in implantology is considered to be osseointegration - a special kind of fixation of a dental implant into the bone tissue. This special type of fixation implies that the structures of the jaw bone are connected to the implant structure as a result of bone-like substance formation without an intermediate layer of connective tissue, such as a cartilage layer or fibrous tissue formation. The problem with osseointegration is that not all dental composites for implants involve the formation of the necessary bone-like structures. Thus, although the bone begins to grow on dental implants containing titanium nanoparticles, over time this growth slows down and is practically not observed [22, 27, 30]. Ceramic sprayed treatment of implants improves the rate of osseointegration. In addition, ceramics or ceramic glass are highly transparent due to optical compatibility between the vitreous matrix and the crystalline phase, minimizing internal light scattering [28]. Since the osseointegration of an implant is directly related to its peripheral tissue and its interaction with the surrounding area and surrounding tissues, the establishment of a nanostructured surface implant can promote osseointegration, mainly through the ability of osteoconductive nanoparticles to induce a chemical bond with a bone fixation for implants [33]. Modifying the implant surface using the antibacterial properties of nanomaterials can also reduce the likelihood of infection due to biofilm formation and certainly improve clinical outcomes of dental interventions [19, 29].

The surface structure plays an equally important role in dental implants. The advantage of nanomaterials is the ability to form surfaces with controlled topography, which allows to develop of the most comfortable implant surface with the expected tissue integration properties. Various processing techniques derived from the electronics industry, such as lithography, ion implantation, anodization, and radiofrequency plasma treatment, can be applied to dental implant surfaces to obtain controlled features on the nanometer scale [36, 38].

The ability of nanomaterials for implant fabrication to facilitate the release of therapeutic agents, in particular antibacterial drugs, at the site of insertion deserves special attention by dental specialists. This aspect is important because during the first 48 hours after immersion saliva proteins envelop the implant surface, form a biofilm, and cause the growth of colonies of pathogenic or conditionally pathogenic strains (Fusobacterium nucleatum, Aggregatibacter actinomycetes). In the case of complications of such colonization, peri-implantitis - inflammation of the bone tissue surrounding the implant - may develop [33]. Local application of antibiotics after biofilm formation does not give the desired therapeutic effect, so synergistic antibacterial functions of dental implants made with titanium-modified nanomaterials are necessary to prevent bacterial colonization and normal implant functioning. At the same time, it was found experimentally that heat-treated titanium oxide with a diameter of 80 nm has a more pronounced antibacterial effect compared to other nanoscale analogs [12, 19, 30].

The biocompatibility and corrosion resistance of zirconium nanoparticles make it suitable for dental implants. In addition, it was found that positively charged zirconium ions interact with negatively charged bacterial membranes and cause the death of the latter. As a rule, zirconium elements are used in the form of nanotubes and nanocylinders, sometimes as an alloy with titanium [18].

To enhance the antibacterial functions, the composite mixture for implant fabrication can be enriched with silver or copper nanoparticles [30, 31].

It should be noted that the application of various strategies and directions of nanoengineering to solve the key issues of dental practice is relevant and promising, but the issues of the impact on the patient's body over time, clinical implementation of nanoengineering projects, optimization of nano-topography of implants, as well as the organization of dentistry on an industrial scale still remain unsolved The main drawbacks of working with nanomaterials to date are time consumption of manufacturing composite mixes or implants [2, 16, 37].

3.8 Problems of implementing nanotechnology in dental practice

The potential of nanomaterials for health care applications is not in doubt. However, to date, a number of unresolved problems hamper the introduction of nanotechnology in practical dentistry [7, 8].

The issue of the environmental impact of nanostructure production arises since the properties of such materials differ from macromolecules, so their utilization and recycling may occur by a different mechanism [2, 3].

The complexities of manufacturing dental composites with nanoparticles lead to an increase in the cost of the technological process and, consequently, the cost of the finished product [17, 30, 32].

Ethical problems primarily concern the biocompatibility of dental nanomaterials with the patient's body, bioregulation of nanoparticle functions, and, as a consequence, patient safety [35, 36].

Of course, the goal of pharmaceutical companies is to increase the level of product quality while reducing the cost of production, including the time required to find and develop new substances. Nanotechnology in this context can revolutionize the pharmaceutical industry, improve the effect of drugs by moving to a new level of interaction with cell organelles [1]. However, without addressing the issues of funding, availability of nanomaterials, time for development, and finding affordable equipment, nanotechnology remains virtually unavailable to most patients.

4. Conclusions

Nanoengineering of dentistry is a promising direction to improve the biological activity and mechanical functions of conventional materials for endodontic manipulations, treatment of caries and periodontitis, as well as mixtures for dental implants. The article considers the basic materials for composite mixtures and highlights their features, presents the problems and prospects of implementing nanostructures in modern dental implantology, evaluates the physical, chemical, mechanical, and antibacterial properties of nanomaterials based on titanium or alloys, graphene, bioactive glass, silver, etc. The effect of nanomaterials on the microbial adhesion of the surface of teeth or implants is described.

Thus, the use of nanostructures opens up great opportunities for the treatment of a wide range of diseases, not only dental but also in medicine in general. However, until the problem of the cost of synthesis of such materials and optimization of the composite technology is solved, nanostructures cannot find proper clinical application.

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