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BIOACTIVE COATINGS AND THE SAFETY OF USING METAL IMPLANTS

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Abstract: Metal implants are commonly used in implant practice due to their very good mechanical properties and low cost of production. Unfortunately, these materials do not have sufficient biological activity, and their long-term exposure to human body fluids can cause corrosion and release toxic ions. Bioactive coatings on metal implants enable bone growth at the implant site. Moreover, ions of biogenic elements and active ingredients are released from their surface in a controlled manner, which prevent inflammation, bacterial growth, or the formation of blood clots. In addition, the bioactive coating creates a tight barrier between the metal implant and body tissues, providing the implants with a non-corrosive environment. This article describes an important issue of the safety of using metal implants and implants with a bioactive coating. The paper presents the characteristics of selected bioactive coatings, their mechanism of action, and application techniques. Particular attention was paid to the use of bioglasses and glass-crystalline materials for bioactive coatings.
Keywords: metal implants, bioactive coatings, surface modifications, biocompatibility, bioceramics

1. INTRODUCION

The first mentions of implants appear in the history of ancient Egypt and pre-Columbian American cultures, but their most intensive development has taken place recently. The huge interest in biomaterials is related to the extension of human life and the increasing requirements for its quality (Dudek, 2009; Saini et al., 2015). Musculoskeletal injuries are among the most common injuries, and a large part of them results from the high incidence of osteoporosis, which in Poland affects every third woman and every fifth man (Pawlikowska-Łagód et al., 2016). Expectations towards orthopedic implants are growing along with the demand for this type of implants, therefore today's implantology has precise tools and a huge variety of implants that enable the reconstruction of damaged tissues and improvement of the functioning of the body. Bone cements, joint prostheses for knee and hip arthroplasty, and numerous devices stabilizing reconstructed bone fractures are commonly used (Sergi et al., 2020).

One of the biggest problems associated with biomaterial implantation is the risk of infection (IAIs). The effects of infections may include improper or complete lack of bone fragments, skin or mucous membrane infections, and even a general systemic reaction, which results in prolonged hospitalization, reimplantation, and reduced quality of life for the patient. Implant-associated infections are very common and account for about 60-70% of all hospital infections, which generates huge costs. It is estimated that treating a post-implantation infection is 5 times more expensive than treating other hospital infections (Ul Haq and Krukiewicz, 2023). In the case of metal orthopedic implants, as much as 20% of implant failures are related to aseptic loosening of the implant (Bormann et al., 2020). Research on related orthopaedic issues was conducted by Wojnar et al. (2019) and Jasiewicz et al. (2021).
Metal implants are known for their very good mechanical strength and crack resistance. Unfortunately, they do not create a sufficiently durable connection with the bone and surrounding soft tissues. This is mainly due to the smooth surface of metal implants, which is an ideal substrate for the development of infections. For this reason, implants of this type are unstable in the environment of physiological fluids and corrode. Corrosion of metal implants is inevitable in the environment of human tissues and has serious consequences, i.e. loss of biocompatibility and mechanical integrity of the implant with the bone and carcinogenic and genotoxic effects on the human body. Additionally, smooth implant surfaces favour the adhesion of pathogens, their colonization and the formation of a biofilm. It is considered that the surface of implants is not only a substrate for colonization by pathogens but also determines the quality of the host's cellular response (Su et al., 2019). An interesting surface refinement is coating it with special coatings (Radek, 2009; Radek and Antoszewski, 2009), with special friction properties (Radek et al., 2021) as well as using special cutting techniques (Radek et al., 2020). Such processing techniques significantly affect corrosion resistance (Scendo et al., 2012; Scendo et al., 2013). Regardless, the elements require careful strength (Wrońska et al., 2019; Krysiak et al., 2020; Drach et al., 2021) and fatigue (Mazur et al., 2021; Bogdanowicz et al., 2023) analysis. Due to the large share of experimental and clinical studies, it is necessary to use appropriate quality control (Czerwińska et al., 2020) and statistical (Dwornicka and Pietraszek, 2018; Radek et al., 2023) techniques.
The above-mentioned problems are the reason for the need to search for modern bioactive coatings for metal implants, which will increase the biointegration of implants, provide corrosion resistance and reduce the risk of developing peri-implant infections.

2. METAL IMPLANTS

2.1. Properties of metallic materials intended for implants

A metallic material can be used for biomedical applications if it has sufficient corrosion resistance and low production cost. Additionally, such a material should guarantee an even distribution of stresses throughout the implant. Another condition is to ensure minimal movement at the implant-bone interface, which can damage each of these structures separately or both. Metallic material intended for orthopedic implants should also have high tensile and compressive strength as well as high yield strength and fatigue strength, because implants are exposed to cyclic loads, the consequence of which may be brittle fracture (Davis et al., 2022).

2.2. Classification of metal biomaterials

Metal biomaterials can be classified as follows (Bormann et al., 2020):

- Stainless steels
- Cobalt, chromium and molybdenum alloys
- Titanium and its alloys
- Magnesium alloys
- Precious metal alloys

Stainless steel and cobalt-based alloys are economical, very durable materials with sufficient mechanical properties. Titanium has low density and high corrosion resistance, for this reason it is the most commonly used material in trauma and orthopedic surgery. Magnesium-based alloys are used due to their high biocompatibility and good mechanical strength. Platinum and gold are used for very expensive bioimplants, which are chemically inert and have high corrosion resistance (Davis et al., 2022).

The basic type of metallic material for implant applications is stainless steel (SS) type AISI 316L. The chromium present in this steel (10.5% by weight) forms a passive layer of chromium oxide and protects the implant surface from corrosion. Carbon (min. 0.03% by weight) increases mechanical properties, in particular fracture resistance, corrosion resistance and tribological properties of implants. The ability of SS to transfer loads makes them a suitable material for orthopedic implants. Pitting corrosion and the release of nickel and chromium ions from the surface result in an allergic reaction of the body and cause ~90% of implants made of SS class 316L to lose their properties. SS has a modulus of elasticity (200 GPa) that is higher than the modulus of human bone (10–30 GPa), which causes a high stress shielding effect at the tissue-implant interface and leads to implant failure. Stainless steel is mainly used to produce screws, sutures, bone plates, steel threads and bone pins that are used to stabilize fractures. (Mosas et al., 2022).

Co-based alloys exhibit better corrosion resistance, wear resistance and mechanical properties than SS. In vivo and in vitro tests have shown that their level of biocompatibility is sufficient to be used for the production of hip, knee and shoulder joint implants and for the treatment of broken bone epiphyses. The most commonly used cobalt alloy is Co-Cr-Mo due to its unique combination of strength and ductility. Co-Cr-Mo alloy exhibits better modulus of elasticity, density and stiffness than other alloys and is a material dedicated to permanent implant fixation procedures because it retains its properties for a long time after implantation. The elements included in its composition (Ni, Mo and Cr) are toxic to the human body if released from the metal surface into the body fluid during corrosion, and can lead to skin diseases, liver, kidney, blood cell and lung damage (Garcia-Mendez et al., 2021).

Pure titanium and its alloys (Ti-6Al-4V, Ti-6Al-7Nb, Ti-5Al-6Nb and Ti-13Nb-13Zr) are highly regarded in the field of implantology due to their biocompatibility, low density and suitable mechanical properties. All titanium alloys show improved mechanical properties and greater biocompatibility compared to pure titanium. The Ti-6Al-4V alloy is most commonly used because it guarantees excellent corrosion resistance, biocompatibility, formability, structural stability and the best weight-to-strength ratio. It is used in the production of heart valves, dental prostheses, artificial joints and bone substitutes. Vanadium and aluminum are present in titanium alloys, which in the form of oxide vanadium (IV), vanadate (V) and aluminum (Al^{3+}) ions are toxic to the body. The Ti-13Nb-13Zr alloy does not contain these elements and, as studies have shown, has better

mechanical properties, ductility, good structural stability, higher wear resistance, lower modulus of elasticity and better corrosion resistance (Mosas et al., 2022).
Magnesium is a valuable biogenic element, and in a physiological environment containing oxides it corrodes very quickly, which is why it has become a biodegradable and biocompatible material used for implants. Mg and its alloys have low density, a modulus of elasticity close to that of bone, lightness, biocompatibility and excellent mechanical properties. Metal implants that are biodegradable allow you to avoid expensive and dangerous revision surgeries, the purpose of which is to remove the implants after healing. The modulus of elasticity of magnesium implants and human bone are similar, which leads to reduced stress shielding at the implant-bone interface and better matching of both structures. Currently, efforts are being made to alloy magnesium with other elements in such a way as to reduce the cytotoxicity of the material to zero (Mosas et al., 2022). A major problem with these implants is their too rapid degradation (corrosion) in physiological conditions. Rapid corrosion causes implant failure and rapid release of by-products, i.e. gas hydrogen (Rau et al., 2016).

2.3. Use of metal implants - dangers

Under physiological conditions, durable and long-lasting metal implants can lose their properties and release dangerous ions or contaminants into the patient's blood plasma. Corrosion of metal implants in the environment of human tissues is a natural process, and as corrosion products, oxide layers such as chromium or titanium oxide can form, which are uniform, dense and thus protective passive layers. All kinds of minor scratches that may occur during normal life and depletion of sliding layers associated with cyclic use of implant surfaces can cause the release of ions and an increase in their concentration in the blood. As mentioned, ions can trigger an unwanted biological reaction, as their presence can trigger anaphylactic reactions, and excess ions can accumulate in organs in the form of solid particles, which permanently impair their function and lead to failure. In addition, heavy metal ions have a carcinogenic and genotoxic effect on all human tissue cells (Bormann et al., 2020). It should be emphasized that metal implants are not fully biocompatible with the human body, and incomplete attachment of the implant to the tissue disrupts the functioning of the tissues in the area of the implant, which results in pain, discomfort and inflammation. The use of metal implants carries a high risk of infection and extended healing time, and often also rejection of the graft, therefore the development and use of bioactive coatings on metal implants is a very important aspect (Ul Haq and Krukiewicz, 2023).

3. BIOACTIVE COATINGS

3.1. The role of bioactive coatings

Bioactive coatings enable the metal prosthesis to adapt to the implant site, e.g. the bone cavity. Proper biointegration of the prosthesis prevents the formation of connective tissue at the implant-bone interface and greatly reduces the risk of inflammation, irritation and tissue damage at the implant site (Sergi et al., 2020). Bioactive coatings provide osteoconductive, osteoinductive and osteogenic properties to metal implants. Osteoconductivity is the specific ability of a biomaterial to physically support the process of forming the bone extracellular matrix and stimulate cell adhesion and proliferation. Osteoinductivity is the ability to induce the differentiation of mesenchymal stem cells into osteoblasts. Osteogenic properties are demonstrated by a material that provides minerals and enables calcification of the collagen matrix that forms the substrate for new bone (Kędzia et al., 2023). Bioactive coatings are designed to: ensure effective and accelerated healing, prevent and minimize the risk of postoperative complications and contribute to the longevity of the implant-tissue connection. Such coatings should guarantee corrosion resistance to metal implants and provide the necessary anti-inflammatory and antimicrobial properties (Goodman et al., 2013). Figure 1 (Fig. 1.) shows the role of bioactive coatings in improving the safety of metal implants.

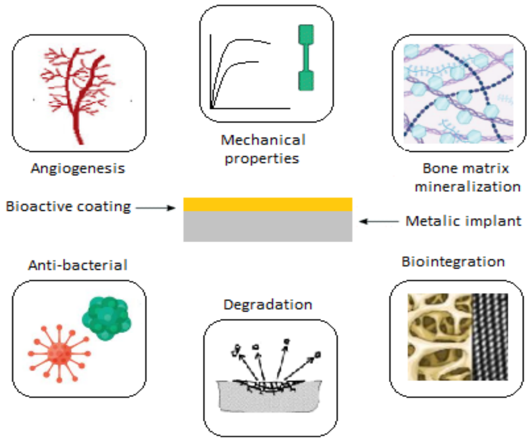

Fig. 1. The role of bioactive coatings in improving the safety of metal implants (source: Nilawar et al., 2021)

3.2. Properties and modifications of implant surfaces

It should be noted that the implant surface is the place where all important interactions between the biomaterial and living tissue take place. The implant surface is characterized by a number of properties that determine the quality of the human body's cellular response. It is believed that the wettability of the implant surface determines the adhesion of cells and proteins responsible for the production of growth factors - superhydrophilic surfaces and wetted superhydrophobic surfaces provide very good adhesion (Liang et al., 2023). Surface chemistry is a factor to which osteoblasts and microorganisms are very sensitive to changes. By introducing surface modification, e.g. in the form of fluorine, cell adhesion is increased, osteointegration is accelerated at the early stage of healing and the rapid growth of new tissue near the implant is stimulated (Damiati et al., 2018). The optimal coating thickness increases corrosion resistance and improves the quality of implant-bone contact. In the case of the oxide layer formed on the surface of a metal implant, it has the ability to regenerate after its disruption (Sergi et al., 2020). The morphology of the implant surface determines the functioning of cells in contact with it. Roughness participates in osseointegration, bone engagement and the healing process and improves bone biomechanics because it increases mechanical retention and provides proper stress distribution (Nguyen et al., 2024). The allowable roughness is 0.2 μm and is dictated by the size of pathogens that could colonize it (Damiati et al., 2018).

Mechanical modifications are carried out to obtain a rough surface, improve adhesion, bonding and obtain better biomineralization. Chemical modifications of metal surfaces can be obtained using physicochemical adsorption, covalent bonds of molecules or by surface functionalization with peptides. These effects can be obtained using, for example, anodization, oxidation, biochemical functionalization, acid/base treatment, chemical evaporation and the sol-gel method. Chemical modifications in the form of active molecules have a positive effect on cell signaling. Physical modifications are most often spraying coatings or rearrangement of coating atoms with ion implantation obtained using plasma and gas phase deposition, ion implantation, thermal oxidation or laser irradiation. Such modifications positively affect osteoblast activity, their proliferation, differentiation and osteoconductivity (Damiati et al., 2018). Initially, the coatings were deposited directly without surface preparation, but recent studies indicate the need to deposit the coatings on a properly prepared, rough metallic substrate, which at the same time becomes an element involved in the formation of the coating (Nilawar et al., 2021).

The physical, chemical and mechanical properties of the surface can be changed, among others, by (Damiati et al., 2018):

- applying an additional layer to the surface,
- changing the surface structure by exposing it to physical or chemical factors, i.e. plasma deposition or acid-chemical treatment,
- introducing surface modifications due to the action of mechanical factors, i.e. mechanical abrasion (SMAT).

Manipulation of the phase composition of the coating, the type and concentration of incorporated biogenic element ions, the use of different processing parameters or deposition techniques allow the production of coatings with the desired properties for specific biomedical applications (Su et al., 2019).

The currently used coating techniques include: 3D printing, electrospinning, electrophoretic deposition, dip coating, drop casting, sol–gel deposition, biomimetic deposition, spray coating, physical vapor deposition, chemical vapor deposition, layer-by-layer assembly, and titanium- and nanotube-based anodizing (Kravanja and Finšgar, 2022).

4. TYPES OF BIOACTIVE COATINGS

There are three main types of coatings used on metal implants (Damiati et al., 2018):

- Organic coatings (polymers, biomimetic and bioinspired films, e.g., natural cell environment components)
- Inorganic coatings (HAp, calcium phosphate (CaP), titanium oxide (TiO2), bioglasses, bioceramics)
- Organic-inorganic coatings

In order for a coating to be used clinically, it must meet a number of stringent requirements, such as strong adhesion to the substrate, sufficient mechanical integrity, minimal cytotoxicity at the local and systemic level, no genotoxicity, optimal amount and kinetics of release of the medicinal or biological substance from the coating matrix, the possibility of using the coating with a broad spectrum of antibiotics. Other technical requirements for bioactive coatings include: small thickness, easy and low-cost production, long durability, the possibility of using conventional sterilization methods without the risk of damaging the coating structure and deactivating the applied medicinal agents (Goodman et al., 2013).

Biomaterials that meet these criteria and are used for bioactive coatings are primarily: hydroxyapatite (HAp), calcium phosphate bioceramics (CaP), bioactive glasses and bioactive glass-crystalline materials.

4.1. Calcium phosphate bioceramics (HAp, CaP)

Hydroxyapatite is a commonly used material for bioactive coatings of metal implants, which is most often applied by plasma spraying. Due to the similarity of HAp to the

inorganic part of bone and high osteointegration, non-toxicity, this bioceramic has also become the basis for numerous bioactive antibacterial coatings, in which silver, strontium and zinc ions are incorporated. A major problem with HAp coatings is their stability, which depends on the presence of a highly crystalline HAp phase. As shown by numerous clinical studies, HAp coatings very often delaminate and are chemically unstable, which ultimately causes implant rejection (Rios-Pimentel et al., 2023).
Similarly to HAp, calcium phosphate bioceramics are very often used for metal implant coatings, mainly due to their similarity to the inorganic component of bone. CaP has very good osteoconductive properties, allows for the adhesion of osteoblast cells and numerous proteins, and its degree of biointegration can be regulated by producing coatings with appropriate roughness and porosity. The degree of bioactivity of CaP is very high and varies depending on the type of calcium phosphates due to existing differences in solubility, crystallinity, mechanical properties and ion release kinetics (Xiao et al., 2020). The osteointegration process in the case of CaP coatings is caused by a decrease in pH in the implant environment, which initiates the degradation process of the surface coating and the release of Ca^{2+} and PO_4^{3-} ions (Fig. 2).

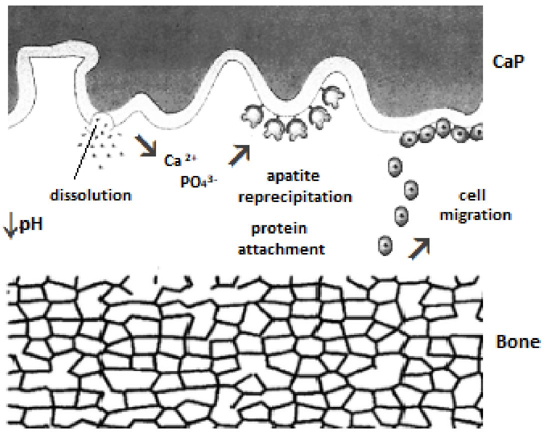

Fig. 2. Osteointegration process on the example of a bioactive CaP coating
(source: Cunningham et al., 2009)

Ions affect the behaviour of osteoblast cells and can precipitate again as apatite and participate in collagen synthesis (Cunningham et al. 2009). Most often, biocompatible CaP coatings are applied using vapor deposition, while plasma spraying is used to obtain thick coatings from high-temperature phases such as tricalcium phosphate (TCP) or tetracalcium phosphate (TTCP). The latest approach is the use of biomimetic precipitation, which mimics the biomineralization process of natural CaP in a simulated physiological environment at low temperature. Unfortunately, this method is time-consuming and requires activation treatment to accelerate apatite nucleation on the surface of the metal implant. Due to the low mechanical strength of CaP, composite coatings are produced on its basis reinforced with collagen or polymers, which are also characterized by better adhesive and biological properties (Su et al., 2019).

4.2. Bioactive glasses (BG) and glass-crystalline biomaterials

Bioglasses are considered to be biodegradable materials with the highest degree of bioactivity and constitute an alternative to HAp or CaP bioceramics coatings. A major advantage of bioglasses is the possibility of modifying their chemical composition and

introducing biogenic elements into their structure (Sergi et al., 2020). For example, the addition of strontium and magnesium improves the rate of bone growth and stimulates angiogenesis (Bellucci and Cannillo, 2018). A common feature of bioactive glasses is the formation of a strong bond with bone tissue, and in the case of some compositions even with soft tissues. The degradation process of bioglasses is accompanied by the release of ions (including biogenic dopant ions), the formation of carbonate hydroxyapatite (HCA) and bone growth, and thus increased implant integration. The rate of degradation of bioactive glasses depends on their composition and the pH of the environment, therefore it is possible to adjust the rate of degradation to the rate of tissue regeneration (Al-Harbi et al., 2021). Bioglass coatings allow for a large degree of control over the corrosion of metal implants, provided that their composition is selected to create coatings with long-term chemical stability (Rau et al., 2016).
There are three basic groups of bioactive glasses: silicate glasses, phosphate glasses, and borate glasses. Silicate-based glasses are highly bioactive and are commonly used in implantology, while phosphate- and borate-based glasses exhibit a very high dissolution rate and are mainly used in drug delivery systems (Sergi et al., 2020).

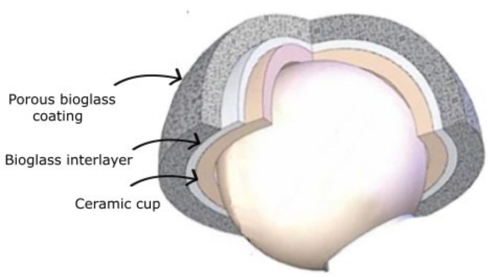

Fig. 3. Multilayer structure of the acetabular component (source: Kaou et al., 2023)

Figure 3 (Fig. 3) details the structure of the layered coating covering the acetabulum of the hip joint. Clinical studies indicate the efficacy of bioglass-coated implants in hip arthroplasty and dental implantology. BG-coated implants in these applications achieve high survival rates and wear resistance (Liang et al., 2023).
Bioglass intended for metal implant coatings should have several important features, including: osteointegration, good matching of the thermal expansion coefficients of the glass and the metal substrate, which will ensure strong adhesion of the coating to the implant and the ability to locally and controlled release of therapeutic and antibacterial ions. The most common cause of cracks and exfoliation of the surface of the bioglass coating is too large a discrepancy in the values of the thermal expansion coefficients of the glass and the substrate and too thick a layer of the applied coating (Fernandes et al., 2018; Sergi et al., 2020; Kaou et al., 2023). Numerous studies show that in the case of covering titanium dental implants with bioglass, the difference in the thermal expansion coefficients is too large to be long-lasting. An existing and effective solution is to replace Na_2O and CaO oxides with K_2O and MgO oxides (Al-Harbi et al., 2021). Bioglass-based coating technologies struggle with problems at the level of poor adhesion of the coating to the implant surface, the occurrence of undesirable phase transformations, changes in coating properties and the presence of impurities. The choice of coating technique is determined not only by the nature of the bioglass but also by the use of the implant, which determines a number of features, i.e. shape or size, and additionally requires meeting a

number of rigorous conditions regarding the microstructure and thickness of the coating, its roughness, porosity and stability (Sergi et al., 2020).

Pretreatment of the metal substrate before applying the bioglass coating allows for obtaining the appropriate roughness and better adhesion of the coating to the substrate, and additionally improves corrosion resistance and osteointegration of the entire system. Sandblasting combined with acid etching is most often used to obtain a microporous structure. For titanium implants, chemical and heat treatment is performed, the task of which is to create a passive titanium oxide layer, which significantly increases the stability of the implant. In order to obtain a uniform, porous and rough titanium oxide layer, microarc oxidation is increasingly used. Cleaning the substrate with distilled water, acetone or ethanol is also a common practice (Liang et al., 2023).

The most commonly used technique for applying bioglass to flat implant surfaces is plasma spraying. Various flame and plasma spraying techniques (HVSFS, SPS and SPPS) allow for the application of coatings with variable particle size (Pawlowski, 2009). The following techniques are used to apply thin and well-adhered coatings: physical vapor deposition (PVD), pulsed laser deposition (PLD) and pulsed electrodeposition (PED). Sol-gel and electrophoretic deposition techniques enable coating substrates with complex shapes and building multilayer coatings while maintaining control over the thickness of the applied layers. Changing the electrophoretic deposition parameters allows for regulating the density and uniformity of the coatings. The advantage of the sol-gel technique is the application of bioglass coatings of almost any composition at low temperatures. Enameling is one of the simplest and cheapest methods, but unfortunately it requires high temperature, which very often introduces defects and unwanted changes to the structure of the metal substrate (Sergi et al., 2020). Using magnetron sputtering (RF-MS), uniform coatings with adjustable thickness, high purity and adhesion are obtained. This method works well for large working areas (Liang et al., 2023).

The biggest challenge for bioactive coatings from bioglass is the selection of the bioglass composition, application technique and its parameters. It is believed that the appropriate chemical composition of bioglass can facilitate the coating application process, increase their adhesion and reduce the failure rate of coatings (Gomez-Vega et al., 2000). A major challenge is to obtain bioglasses with a wide processing window, which would create completely amorphous and bioactive coatings, when applied by thermal spraying. One of the solutions is the addition of MgO and SrO oxides, which increase the crystallization temperature of bioglasses, to the bioglass composition and obtain bioglasses that do not devitrify during heat treatment (Bellucci and Cannillo, 2018).

An increasingly common practice is to enrich the structure of bioglasses with ions with antibacterial activity. One of the more well-known examples is the use of silver ions, which causes a significant bacteriostatic effect without any consequences for the adhesion and proliferation of fibroblast cells (Chouirfa et al., 2019).

Recently, several innovative composite coatings with the participation of bioglass particles have been designed. The combination of bioactive glasses with metal oxides such as TiO_2, Al_2O_3, ZrO_2 or 2D materials such as graphene and its derivatives improve corrosion resistance and antibacterial activity without losing the bioactivity of the obtained composites (Nikolova and Apostolova, 2022). Composite coatings based on bioglass and vitamin D3 for titanium implants for osteoporotic fractures have achieved increased biocompatibility, improved hydrophilicity and good corrosion resistance (Negut et al., 2023). Thin coatings made of bioglass, HAp and β-TCP simultaneously enriched with

copper improved compressive strength, osteointegration and asepsis of titanium implants (Przybilla et al., 2023). Dual drug-loaded BG-Al composite coatings increased bone-binding capacity of the implant and showed great potential in treating postoperative infections (Bargavi et al., 2022). Composite coatings with chitosan and bioglass increased cell adhesion and showed higher proliferation rate (Liang et al., 2023).
Glass-crystal biomaterials based on bioglass are characterized by high biological reactivity and very good mechanical properties, exceeding the parent glass in terms of hardness, flexural strength and fracture resistance (Montazerian and Zanotto, 2016). The most commonly used technique for applying coatings based on glass crystal biomaterials is enameling (Sergi et al., 2020). The latest studies concern ceramic coatings based on CaO-MgO-SiO_2 bioglass, which allowed the formation of new bone directly in contact with the bone marrow (Zhang et al., 2019).

5. CONCLUSION

The use of bioactive coatings has significantly improved the effectiveness and safety of implants in the treatment of bone defects but has not eliminated the problem of infections and the complications that follow them. Analyses conducted by hospitals, clinics and numerous medical journals clearly state that the use of coatings with antimicrobial agents is effective and reduces the number of cases of peri-implant infections and further complications. The study broadly discusses the problems of metal implants that appear at the time of their implantation in the human body. The impact of the implant surface on the risk of infection and the dangers associated with the corrosion process of metal implants are emphasized. Such significant problems are a great motivation to create bioactive coatings, which should ensure high biointegration, corrosion resistance, accelerate healing and contribute to the longevity of implants, reducing the risk of inflammation and tissue damage. The discussed bioactive materials used for metal implant coatings are osteoconductive, osteoinductive and osteogenic, but they are not ideal. There are a number of issues concerning bioactive coatings that engineers struggle with during their production and application. Due to differences in cell behaviour in vitro and in vivo, all of the discussed biomaterials require further clinical testing to be safely used in surgical practice.

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