NANOMATERIALS AND COATINGS WITH ANTIMICROBIAL PROPERTIES

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Contents

Summary

The chapter describes the existing experience of antimicrobial materials use in medicine, hygiene and cosmetics, applications of antibacterial textile materials, biocidal lacquer coatings on the basis of principles and methods of nanotechnology and nanomaterials.

The necessity of development and manufacture of new effective biocompatible nanomaterials and coatings with antimicrobial, bactericidal properties that is connected with the increase in microbial infections, their influence on human community, development of the antibiotic resistance in microorganisms is highlighted. The promising direction of development and application of nanocompositions based on harmless biocompatible sorption materials - natural and synthetic polymers, mineral

clays, use of biologically active metals, ions of metals (silver, copper, zinc) for modification (intercalation) of these structures is considered.

High efficiency and perspective of the use of nanosystems based on montmorillonite (a natural clay mineral) intercalated by biometal ions for antibacterial processing of textile products, natural and artificial leather, nonwoven materials, medical polymers, orthopedic products, hygienic and cosmetic products, for giving antimicrobial and fungicidal properties to paint and varnish materials is shown.

1. Introduction

The human society co-exists and constantly interacts with other world - the world of microorganisms. The modern life is characterized by objective growth in number of infections. Goods, equipment, clothes, materials used in household and manufacture are a subject to influence of microorganisms.

Researches show that the isolates from telephone tubes, counters of supermarkets and cafe, handles and armrests of seats in hospitals contain a considerable quantity of bacteria potentially dangerous to humans. Essential growth of surgical and postoperative infections worldwide is noted irrespective of economic development of the countries.

Many factors and indicators of infection activation are a subject to revision because of changing relations between the agent and its host organism. There are the microorganisms resistant to the majority of antibiotics and antiseptics; the ways of transmission and duration of their existence in a macroorganism are transformed.

Inherently, there are general biological reasons, which are based on changed immunological resistance (resistibility) of a human body. The reasons connected with technical progress, various structural changes of human life and, partly, development of medicine and pharmacology influence this.

Therefore, in connection with the phenomenon of antibiotic resistance development in microorganisms, the necessity of expansion of spectrum of effective bactericidal preparations, manufacture and use of biocompatible nanomaterials and coatings with antimicrobial, bactericidal properties are of high priority; in this connection, nanotechnological principles and methods are used.

We shall consider the most interesting and promising offers on application of antimicrobial nanomaterials in medical polymers, sanitary means and cosmetics, use of antibacterial textile and nonwoven materials, biocidal paintwork materials and coatings.

We lay special emphasis on application of advanced nanocompositions based on biocompatible sorption materials - natural and synthetic polymers, mineral clays (layered inorganic structures), on use of biologically active metals, ions of metals (silver, copper, zinc) for modification (intercalation) of these structures.

The examples of self-organizing nanosystems development on the basis of harmless natural montmorillonite clays are presented. As a result of ionic exchange, a nanoparticle of this natural structure is capable to liberate an exchangeable metal cation, for example, silver, to the environment, being simultaneously an enterosorbent that is capable to absorb the waste products of pathogenic microorganisms.

On basis of the given nanosystems, the following is developed:

- antimicrobial finishing of textile materials and products with nanosystems based on intercalated clays in the silver form;
- antimicrobial paintwork materials comprising nanosystems based on intercalated clays in the silver and/or copper, zinc forms;
- antimicrobial medical polymeric composite materials containing nanoparticles of intercalated clays in the silver and/or copper forms as fillings;
- medical cosmetics containing nanosystems based on intercalated clays in the silver form.

2. Application of Nanostructures and Biologically Active Metals

Antimicrobial, bactericidal properties of biologically active metals - biometals (silver, copper, zinc, etc.) - in the form of salts, complexes, colloid particles, "silver" water are known to humans for a long time.

Modern scientists from the USA, for example, offer new complex antibacterial and antiviral nanosystems on the basis of metal oxides or intermetallic oxide compounds, such as TiO_2, ZrO_2, SnO_2, ZnO and SiO_2. These compounds are functionalized by organic or organometallic molecular structures capable to connect ions of the transition biometals, such as Ag^+ and Cu^{++}.

Such antibacterial and antiviral nanosystems can be used for manufacturing of medicinal and nonmedicinal means, dermatological compounds and creams, for bactericidal modification of surfaces and coatings in living quarters, industrial and specialized premises.

Researchers from Canada and the USA offered the technology of encapsulation of nanosized Ag salt crystals into polymeric coatings (for example, microfibers). Dimensions of such nanoparticles ranges from 20 to 150 nanometers. The process of encapsulation should be optimized for stable and long bactericidal effect, as well as for safety of coatings for humans. Cytotoxicity tests show that the coatings obtained are nontoxic for humans.

Researches carried out in China showed a possibility of coating of the surface of paper products (fibers of the paper) by zinc oxide (ZnO) nanoparticles with the help of ultrasound. This technology allows receiving paper products with antibacterial properties (wall-paper, packing, hygienic napkins, etc.)

Russian researches and practice show that nanocompositions based on modification of biocompatible sorption materials - natural and synthetic polymers, mineral clays (layered inorganic structures) by biometal ions are the processable, effective and safe medicinal form of biometals.

Sorption materials can be presented in the form of powders, fibrous products, sponges. It is possible to impart antimicrobial properties and ability to affect the enzymatic clearing of a wound surface (that is important for medical practice) to the sorption materials.

Preventive, hygienic and medical products prepared on their basis are less toxic than salts and silver and copper complexes, and in many cases they are more effective and processable than corresponding silver salts, colloid silver preparations or "silver" water. For example, in preparations of "silver" water, effect of Ag^+ is partially inactivated due to formation of colloid particles or complexes with impurities dissolved in water.

Forms of argentiferous preparations applied now in the form of colloid solutions and gels are effective at stages of treatment of the infected wounds where suppression of pathogenic flora is a priority. At the subsequent stages, it becomes important to remove products of tissue disintegration and/or to accelerate the wound healing processes.

Sorption materials modified by biometal ions have such properties. So, for example, the layered structure of montmorillonite (mineral clay) provides channels for moisture leaking from skin and wound and its immobilization in montmorillonite that swells perfectly in liquid.

Influence of Silver Ions on Microbial Cell

The founder of scientific studying of the mechanism of silver effect on microbial cell is the Swiss botanist Carl von Nägeli who in 1880th has established that interaction not the metal itself, but its ions with cells of microorganisms cause their destruction. He named this phenomenon oligodynamia (from Greek «oligos» - small, traced, and «dynamos» - effect, i.e. effect of traces). The scientist proved that silver shows oligodynamic effect only in the dissolved (ionized) form. Afterwards, these data have been confirmed by other researchers as well.

The German scientist Vinzent, comparing the activity of some metals, has established that silver has the strongest bactericidal effect, copper and gold – a weaker one. Russian professors of medicine S. S. Botkin and A. P. Vinogradov have explained this fact as the dependence of biological properties of microelements on their position in the Mendeleev periodic system.

So, diphtheria bacillus died on a silver plate in three days, on copper plate - in six days, on gold plate – in eight days. Staphylococcus died on silver in two days, on copper - in three, on gold - in nine days. Typhoid bacillus died on silver and copper in 18 hours, on gold - in six - seven days.

A big contribution to studying of antimicrobial properties of silver water, its application for disinfecting of drinking water and foodstuff was made by Soviet academician L.A. Kulskij. His experiments and later works of other researchers proved that it is the metal ions and their dissociated compounds (the substances capable to dissociate to ions in water) what cause destruction of microorganisms. In all cases, in bactericidal effect, the degree of activity of silver is the more marked the more is the concentration of ions of silver.

When comparing antimicrobial properties of ionic silver and other preparations, it was revealed that bactericidal effect of ionic silver is 1750 times stronger than the effect of carbolic acid and 3,5 times stronger than the effect of mercuric chloride and lime chloride. In addition, the spectrum of antimicrobial activity of silver is much wider than that of many antibiotics and sulfonamides, and its bactericidal effect is created by the minimum doses of the substance.

In this connection, V. S. Bryzgunov and co-authors, scientists of Kazan Medical Institute (Russia), revealed that silver demonstrates more powerful antimicrobial effect than penicillin, biomycin and other antibiotics, and it has a pernicious effect on antibiotic-resistant strains of bacteria.

Silver ions have various antimicrobial effects - from bactericidal (ability to kill microorganisms) to bacteriostatic (ability to impede the reproduction of microorganisms) on *Staphylococcus aureus*, *Proteus vulgaris*, *Pseudomonas aeruginosa* and *Escherichia coli*, which represent special interest for clinical physicians. In respect of *Staphylococcus aureus* and the majority of cocci, sometimes their effect considerably surpasses the effect of antibiotics in the intensity.

There is evidence for unequal sensitivity of different pathogenic and not pathogenic organisms to silver. It is revealed that the pathogenic microflora is more sensitive to silver ions than not pathogenic microbes. Relying on this fact, Russian physician Yu. P. Mironenko developed in 1971 a way of treatment of dysbacteriosis of different origin with the help of silver solution (concentration of 500 mkg/l) using the method of cavity electrophoresis, thus reaching long-lasting therapeutic effect.

Some researchers established that silver ions possess an evident ability to inactivate variolovaccine virus, flu virus strains A-1 and B, some entero- and adenoviruses, and also to inhibit the AIDS virus and have good therapeutic effect while treating the Marburg disease, viral enteritis and distemper. In addition, the advantage of colloid silver therapy is revealed in comparison with the standard therapy.

However, the experiment of the physician L. V. Grigorieva shows that full inactivation of colibacteriophage N163, Coxsackie virus serotypes A-5, A-7, and A-14 requires a higher concentration of silver (from 500 to 5000 mkg/l) than for *Escherichia*, *Salmonella*, *Shigella* and other intestinal bacteria (from 100 to 200 mkg/l).

Among the numerous theories explaining the mechanism of effect of silver on microorganisms, the most generally adopted is the adsorptive theory, according to which the cell loses viability as a result of interaction of electrostatic forces arising between cells of bacteria carrying a negative charge and positively charged ions of silver in the course of adsorption of silver by a bacterial cell.

Some researchers give special value to physical and chemical processes. In particular, to oxidation of bacterial protoplasm and its destruction by oxygen dissolved in water, where silver plays a catalyst role.

There are the data about formation of complexes of nucleic acids with heavy metals, which broke stability of DNA and, accordingly, viability of bacteria.

There is also an opinion that silver has no direct influence on DNA, but acts indirectly, by increasing quantity of intracellular free radicals, which reduce concentration of intracellular active compounds of oxygen. Moreover, there is also a hypothesis that one of the factors of wide antimicrobial effects of silver ions is the inhibition of the transmembrane transport Na^{+} and Ca^{++} caused by silver.

Thus, in the light of modern data, the mechanism of effect of silver on microbial cell consists in the following. Silver ions that have a protective function, are sorbed by cell wall. The cell remains viable, but some functions, for example, division (bacteriostatic effect), are thus impaired. As soon as silver is sorbed on the surface of microbal cell, it penetrates the cell and inhibits enzymes of the respiratory chain, and also separates the process of oxidation and the process of oxidative phosphorylation in microbial cells; therefore, the cell dies.

Silver reacts with bacterial cellular membrane that consists of special fibers (peptidoglycanes) connected by amino acids for maintenance of mechanical durability and stability. Ag interacts with external peptidoglycanes, blocking their ability to transfer oxygen into bacterial cell, what leads to its "suffocation". Effect of silver ions is specific not in respect of infection (as in the case of antibiotics), but in respect of their ability to affect the cell structure. Because cells of mammals have a membrane of absolutely different type (containing no peptidoglycanes) as compared to bacteria, ions Ag^{+} affect them in no way.

Modern use of ions of silver may be illustrated by the following example. “Eurasian chemical market” informs that a British manufacturer of packaging "M&H Plastics" (Beccles, county Suffolk) developed an antimicrobial additive for packaging materials. Application of silver ions provides protection against *Escherichia coli*, *Staphylococcus aureus*, Salmonella and some kinds of molds. Silver ions are located on the surface of packaging. Penetrating the bacterial organism, silver ions impede cell wall closing in penetration sites, impairing metabolism of the bacterium and interfering with such processes as respiration and cell division. The antimicrobial effect lasts during the service period of packaging. Silver ions do not affect the structure of packaged product in any way. The antimicrobial additive can be used in the manufacture of packaging of personal hygiene products and pharmaceutical preparations.

Biocompatible Sorption Materials

As it was mentioned above, sorption materials - natural and synthetic polymers (collagen, gelatin, polysaccharides, etc.), mineral clays can be effective carriers of biometal ions. A promising choice is application of a mineral structure – montmorillonite.

Montmorillonite is the basic component of bentonitic clays. Bentonite is a clay containing not less than 70 % of a mineral of montmorillonite group. Montmorillonite is a fine-grained layered aluminum silicate carrying an extra negative charge because of nonstoichiometric replacements of cations of crystal lattice, which compensates exchange cations located in the interlayer space. This determines high hydrophylic properties of bentonite.

The formula of montmorillonite is: (Ca, Na...) (Mg, Al, Fe) $_2$ [(Si, Al) $_4O_{10}$] $(OH)_2 \cdot nH_2O$.

While tempering bentonite, the water penetrates the interlayer space of montmorillonite, hydrates its surface and exchange cations that causes swelling of the mineral. After further dilution with water, bentonite forms steady viscous suspension with evident thixotropic properties. Montmorillonite possesses high cation-exchange and adsorptive properties.

Thanks to the properties noted above, bentonite has found wide application as gelling agent and filtration reducer in preparation of drilling agents for sinking of boreholes and passages, as binder in foundry sands and iron-ore pellets, and also as waterproofing and adsorptive material. In agriculture, bentonite is effectively used in manufacture of mixed fodders, as bedding for animals, for soil improvement, and also for clarification of wines and juice. Bentonites with montmorillonite containing mainly exchangable sodium cations have the best technological properties.

Structure of Na-montmorillonite is represented in Figure 1. Elementary plates of clay are charged negatively; counterions Na^+ are necessary for stabilization of the structure.

Metal cations found in montmorillonite can be replaced with other ions of metals through ionic exchange that allows modifying clay by various ions and substances. This process is called intercalation.

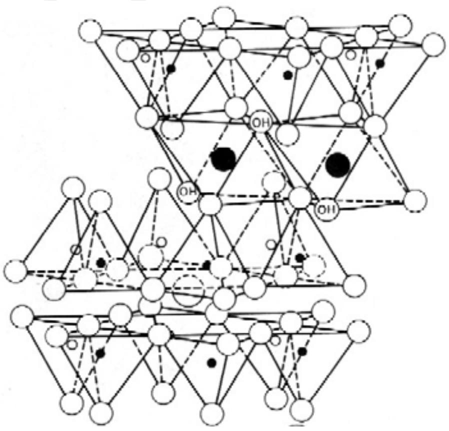

Figure 1. Structure of Na^+-montmorillonite

All clay minerals possess certain capacity of cation exchange. This measure is an important characteristic of a mineral and indicates the quantity of exchange cations (expressed in mg-equivalents) capable to be replaced by cations of other type per 100 g of clay. Montmorillonite possesses the highest capacity of cation exchange among clay minerals (upto 150 meq/100 g).

When using montmorillonite in medical and hygienic practice, paintwork materials and in other purposes, superdispersed montmorillonite powder in various ionic form is obtained. The technology of production of such powders consists of two stages.

The first stage includes replacement of sodium ions in montmorillonite by the corresponding metal ion (Ag, Cu, Zn, Co, Ce, etc.). As a rule, replacement reaction is effected by interaction of the diluted aqueous solution of salt of corresponding metal with suspension of a clay mineral. Then, the received product is filtered, and sodium salts are washed out with the help of deionized water.

At the second stage, the received product is slurried (intensively mixed) in a considerable quantity of water, allow to be defended during some time, and supernatant liquid is decanted. After addition of deionized waters, the deposit is slurried, defended, and decanted again. This process is repeated several times. Nanodispersed product is obtained by filtration of decanted liquid, dried and grinded in planetary mills.

Thus, intercalated montmorillonite is a source of metal ions, figuratively speaking, a “canned clay”. In the case of contact of montmorillonite particles with biological liquids or with normal natural water containing sodium ions, the metal ions liberate from interface clay spaces.

Modified (intercalated) montmorillonite is completely biocompatible material for humans. Calculations and practice show that the content of silver in intercalated clay minerals reaches from 2,0 % to 3,5 % (weight/weight) and the content of copper reaches from 6,0 % to 6,5 % (weight/weight); this ensures effective antimicrobial, bactericidal properties of this nanocomposition.

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Biographical Sketches

Beklemyshev Vyacheslav Ivanovich was born in Tchebarkul' (Russia, Chelyabinsk Region) in 1954. Graduated from the Moscow Physical and Technical Institute in 1977 (physics, physical and quantum electronics).
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Dr. Beklemyshev authored (or co-authored) 82 scientific articles, 95 inventor's certificates and patents. He is a member of the Mendeleev Russian Chemical Society, entered into a reference book "Who is who in Russian chemistry". He is awarded by the Russian medal of honor of the National Society of Inventors and Rationalizers, the orders "*de Chevalier*" and "*Officier*" (Belgium) for active inventive activity.
Now he works at the Institute of Applied Nanotechnologies (Moscow).

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Dr. Makhonin authored (or co-authored) 73 scientific articles, 86 inventor's certificates and patents. He is a member of the Mendeleev Russian Chemical Society, entered into a reference book “Who is who in Russian chemistry”. Makhonin's applied works in the area of nanotechnology are noted by diplomas and medals of the international and Russian exhibitions of innovations, inventions and new technologies.
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