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The development and functions of silver in water purification and disease control

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Abstract

The use of silver to control putrefaction of liquids and as a mitigate to the incursion and spread of disease can be traced to ancient times. In recent decades, studies have revealed the biochemical reactions of ionic silver that result in the inactivation of bacteria, fungi, protozoa, spirochetes, viruses, etc. not protected by proteinaceous membranes. The unique chemisorption of atomic oxygen on the surface of silver in both gaseous and aqueous media combined with freedom of movement of oxygen throughout the crystal lattice of the silver provides a reservoir of oxygen and thus sets silver apart in its catalytic activity. Studies have revealed that bulk silver in an oxygen-charged aqueous media will catalyze the complete destructive oxidation of microorganisms. However, the broad use of silver as a powerful clinical tool is still in the future because its full range of activity remains to be elucidated.

Keywords: Silver; Oxygen; Sanitation; Microorganisms; Bacteria; Water; Disease

1. Introduction

It has been said that the use of silver may be linked to man's earliest attempts to improve his environment. But only recently has it become known that silver may react with microorganisms by any or all three of the following mechanisms:

(1) Destruction of microorganisms by oxidation catalyzed by silver,

(2) Disruption of electron transfer in bacteria by monovalent silver, and/or preventing the unwinding of DNA in viruses with the substitution of hydrogen ions by monovalent silver, and

(3) Destruction of bacteria and viruses by bivalent and trivalent silver.

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2. Silver, the oxidation catalyst

Among all the metals, silver is unique in its behavior with oxygen. Molecular oxygen in the air is adsorbed onto the surface of silver as atomic oxygen, and because atomic oxygen fits into the octahedral holes of silver, oxygen accumulates within the bulk of silver [1]. This stored oxygen significantly contributes to the catalytic oxidative power of silver. When pure silver is melted in air it absorbs about ten times its volume, or 0.3% of its weight in oxygen. On cooling to a few degrees above solidification, it abruptly releases much of its oxygen in a dramatic phenomenon known in the industry as ''spit''.

The catalytic power of silver to markedly accelerate oxidation reactions has been known

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at least since 1908 when the gaseous conversion of methanol to produce formaldehyde was disclosed in the German Patent No. 228,687. Today some 23 000 000 troy ounces of silver are in the operating inventory for the chemical process industry worldwide used to convert methanol to formaldehyde, and ethylene to ethylene oxide, which synthesis has been thoroughly elucidated [2].

It was not until 1986 that USA Patent No. 4,608,247 was issued to cover the catalytic action of silver in an aqueous media for the sanitation of water [3]. Atomic oxygen adsorbed on the surface of the silver instantaneously oxidizes organic material on contact.

The use of a silver membrane to produce atomic oxygen to evaluate the oxidative degradation of organic materials in space was developed by Outlaw [1]. He found that atomic oxygen had an almost perfect fit in the octahedral holes of gold, silver, and copper. However, in gold the electron cloud of oxygen tends to be repelled by the lattice electrons of the gold atoms and this blocks its movement through the holes. Copper, on the other hand, forms the oxide providing an impassable barrier. Silver offers so little repulsion to oxygen that only a small amount of thermal energy is required to readily move the atomic oxygen through the silver lattice [4].

3. Epidemiological background of silver

The use of silver vessels to keep liquids pure longer has been known since ancient times. Cyrus the Great, King of Persia (550–529 B.C.), who established a board of health and a medical dispensary for his citizens, had water drawn from a designated stream then "boiled, and very many four wheeled wagons drawn by mules carry it in silver vessels, following the king whithersoever he goes at any time" [5]. Since ancient times silver vessels have been used in Mexico, the world's major producer of silver, to keep water and milk sweet.

Pliny the Elder, in his great work, *Natural History*, (78 A.D.) reports in Book XXXIII, Section XXXV, that the slag of silver "... has healing properties as an ingredient in plasters, being extremely effective in causing wounds to close up..." [6].

In 1884, F. Crede, observing a relationship between 20% and 79% of children in various institutions of the blind and the presence of maternal venereal disease, introduced the 1% silver nitrate solution prophylaxis for the eyes of newborns. Following its introduction, the incidence of gonococcal ophthalmia neonatorum dropped to about 0.2%. His prophylaxis became a state regulation in most countries throughout the world [7].

Thus a 2500-year history of the use of silver for water purification and disease control has been established with no reports of toxic reactions to the hundreds of millions of children and adults exposed to it. During World War II, however, it was discovered that when severe injuries to the skull were repaired by the use of a silver plate, a toxic reaction resulted. The fact that toxicity to nerve cells in the brain and the spinal column had never been previously observed was due to the blood-brain barrier, a cellular membrane which blocks the entry of heavy metals into this domain. This mechanical barrier effectively blocks silver from the one area of the body where it would be toxic.

In addition to the blood-brain barrier, there are in the blood metallothioneins, ubiquitous proteins found in all life. They were first characterized in 1957 as having the property of binding metals in metal-thiolate-cluster structures to transport, store, and detoxify essential and nonessential trace metals that may enter the body [8]. The coordination chemistry which binds metals into these thiolate-cluster complexes is unusual. Essentially the metallothioneins remove heavy metals by forming bridging bonds incorporating two metal atoms or by terminal bonds. Metallothioneins circumscribe the treatment of internal diseases by silver ions.

Thus the epidemiological history of silver has established its non-toxicity in normal use. And there has been no evidence of carcinogenic activity [9].

4. Destructive oxidation catalyzed by silver

The atomic oxygen adsorbed onto the surface of silver exposed to aqueous media readily reacts with pairs of sulfhydryl (–S–H) groups on the surface of bacteria or viruses by replacing the hydrogen atoms (as water) resulting in the coupling of the sulfur atoms to form an R–S–S–R bond which completely blocks respiration and electron transfer.

4.1. The fountainhead system

The catalytic cartridge developed by Heinig [3], contains a layer of silver microcrystals deposited on 14 to 18 mesh alpha-alumina having a surface area of about 250 square inches per gram. The bed of alumina is about five inches deep and is surrounded by a copper sheath. During operation, some silver and copper are made soluble by galvanic action and circulated in the swimming pool providing the pool with the bactericidal properties of silver and the algicidal properties of copper. In his system, no electric current is applied [10].

Heinig showed that lightly-bound nascent oxygen on the microcrystals of silver (with a binding energy of only 40 kcal/mol) readily oxidizes bacteria or viruses, resulting in complete disintegration. It also oxidizes other organic and inorganic material, forming relatively stable peroxides that continue to sanitize the water downstream. His experiments with ozone gas additions showed bacteria and viruses being torn apart, the silver acting purely as an extremely efficient oxidative catalyst.

Laboratory tests by Heinig and participating third-party commercial laboratories have demonstrated an instantaneous 99% kill rate, with complete removal of *E. coli* in 2.0 to 2.5 seconds in the catalytic cartridge. Heinig conducted one experiment in which he intentionally depleted oxygen from the water to less than 1 ppm; the result was a substantial increase in the survival rate of the test bacteria, Table 1. The catalytic cartridge oxidizes not only bacteria and viruses but also inorganic compounds into peroxides providing further sanitation downstream.

5. Disruptive reactions by monovalent silver

Monovalent silver ions have an affinity for sulfhydryl groups exposed on bacteria or viruses. The resulting stable –S–Ag group inhibits hydrogen transfer: their energy transfer system. An unpublished study using tagged silver showed that silver was not present within the bacteria's cell, only on the surface –S–H groups. In the case of mammalian cells, there was no action because sulfhydryl groups are not exposed.

The medicinal value of silver has long been recognized. Silver nitrate is referenced in a Roman pharmacopoeia of 69 B.C. The nitrate,

Table 1
Single-pass kill study, using *E. coli* in an activated medium passing through a Fountainhead Silver-on-alumina catalytic cartridge

	Plate counts (colony forming units)			
Dilution	Initial count	Before oxygen enhancement (1)	After oxygen enhancement (2)	After oxygen depletion (3)
1:1000	> 300	17	2	75
1:10000	42	0	0	5

From an inhouse report, Fountainhead Technologies, Inc. (Providence, RI, USA).
(1) Untreated water containing 3.2 ppm oxygen.
(2) Water saturated with oxygen. At 24°C the saturation point for oxygen is 8.5 ppm.
(3) Dissolved oxygen intentionally depleted to less than 1 ppm.

however, is corrosive to tissue and draws chloride ions out of the body fluids, acting as a chlorine sink. Thus, the search has been to discover less corrosive silver compounds, for example silver thiosulfate.

Silver thiosulfate incorporated in a complex encapsulated in silica gel microspheres was developed by Ueda [11]. The silica gel slowly releases the silver, providing a long-term presence of silver without being immediately precipitated by any nearby chlorides and long-lasting bactericidal action. It is planned to apply this material to the surface of plastic consumer products to prevent the harboring of disease organisms left by infected users. Ueda has shown that the complex has positive bactericidal action against a variety of disease-causing bacteria such as *E. coli* and *S. aureus*, as well as HIV-1103 [11].

5.1. Silver organic compounds

The combination of silver with an antibiotic compound was explored by Fox. His silver salt of sulfadiazine has proved to be a most efficacious topical compound for reducing the development of early burn-wound sepsis [12]. He found this combination to be at least 50 times more active than sulfadiazine alone. It avoids the corrosive effects of silver nitrate and its tendency to remove chloride ions from the body. Silver sulfadiazine inhibits infection over extended periods of time allowing dermal structures to grow unimpeded by bacteria, spread across the burn, and heal the area spontaneously (and painlessly) without the need for a skin graft. Silver sulfadiazine has become the treatment of choice for burn wound therapy.

Silver sulfadiazine, unlike silver nitrate, is active against both gram positive and gram negative organisms, fungi, and protozoa, including mouse malaria. It is also topically effective against viruses such as herpes, and sexually transmitted diseases such as genital herpes, gonorrhoea, trichomonas, and *Treponema pallidia*. It also inhibits the colony formation of *Staphylococcus, Streptococcus, Pseudomonas*, etc. [13].

Some bacteria appear to develop a resistance to silver compounds. This was noted within a few years of the introduction of silver sulfadiazine by Fox. Among the early cases of bacterial resistance to silver was that reported by McHugh et al. [14] who studied 13 strains of *S. typhimurium* not all of which were resistant to silver sulfadiazine nor did the resistant strain transfer its resistance to the other strains. Those studying this problem have found resistance to be unstable and difficult to transfer from one strain to another. A list of bacteria evidencing resistance to silver compounds is given by Clement and Jarrett [15].

Continuing research at Columbia University includes determining the efficacy of silver quinolones which when added to silver sulfadiazine will inhibit the generation of bacteria resistant to silver compounds [16].

5.2. Viruses

There is no comprehensive study of viruses inactivated by silver. Viruses are basically pure DNA or RNA with a protein-like coating and no cell membrane. For viruses with sulfhydryl terminuses, the reaction to silver would be similar to that of bacteria. In one study, Fox showed that silver sulfadiazine causes direct inactivation of herpes simplex and vesicular stomatitis (viruses that affect the eyes) [17].

5.3. Binding with DNA

Studies by Fox of *Pseudomonus aeruginosa* with sublethal concentrations of silver sulfadiazine revealed that up to 12% of the silver was located in the DNA fraction, 3% of silver was in the RNA fraction, less than 0.5% in the lipid fraction and the remainder in its proteins and polysaccharides, Fig. 1 [18]. When silver bonds with DNA, the resulting complex is not unwound [19]. However, by treating the complex with chlorides, bromides, cyanides, etc which

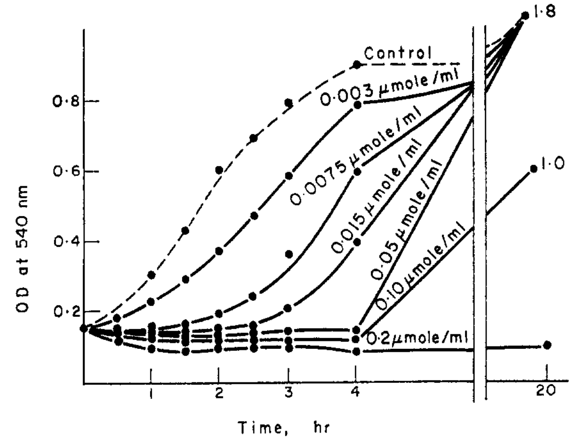

Fig. 1. Effect of silver sulfadiazine (AgSD) on the growth of *P. aeruginosa*. Early log phase cultures at an O.D. of 0.15 were added to tubes containing the concentrations of AgSD. These were incubated at 37°C on a shaker and the O.D. was measured hourly and after 20 hours. Drug concentrations of 0.10 μmol/ml or below were bacteriostatic; the concentration of 0.2 μmol was bactericidal. Reprinted with permission from *Biochemical Pharmacology*, Vol. 22, p. 2393 [18].

remove the silver, regeneration of the native DNA takes place and its function is restored.

Fox's studies showed that in general, silver salts of antibiotic compounds provide superior antibiotic performance. Also that the combination of the two is especially superior as regards blocking the development of resistant bacteria.

6. Two water purification systems using metallic silver

Silver vessels have been used since ancient times to keep water, wine, and vinegar from putrefaction. Metallic silver is said to dissolve in water in about 10^{-5} g/l which is toxic to *E. coli* and *Bacillus typhosus*, both of which can cause virulent diseases [20]. The catalytic oxidation by the metallic silver in the walls of the container as well as reaction with the dissolved monovalent silver ion probably contributes to the bactericidal effect of silver vessels.

6.1. The Katadyn system

Marketed by Katadyn Products, Inc., Switzerland, for over 50 years, the Katadyn filter uses 0.28% by weight of metallic silver in a ceramic fired to provide a pore diameter of 0.2 micrometers [21]. This pore size mechanically filters out living organisms. Bacteria that might squeeze into the pores meet pure silver with its adsorbed oxygen atoms and are destroyed. Because viruses can be smaller, and their destruction by silver cannot be assured, Katadyn does not guarantee elimination of viruses.

6.2. The Ionics system

Developed at the Johns Hopkins University some 50 years ago, the product of Ionics, Inc. (Bridgeville, PA, USA) contains somewhat over 1% by weight of metallic silver deposited on activated carbon. Because carbon and silver form a mild galvanic couple, the catalytic activity of silver is supplemented by some dissolution that provides silver sanitation throughout the carbon filter, preventing buildup of bacteria. Activated carbon has the additional benefit of adsorbing organic compounds such as the cancer-inducing trihalomethanes which may be generated by chlorine treatment in municipal water treatment systems [22].

7. Bivalent and trivalent silver

X-ray spectroscopy and neutron diffraction analysis revealed that the unit cell of silver peroxide, a black oxide long marketed as AgO, actually consists of: 2 Ag(I), 2 Ag(III) and 4 oxygen atoms (Ag_4O_4). In acid, the interaction between the silver ions results in silver (I) being oxidized to silver (II) and the silver (III) being reduced to silver (II). This reaction long masked the actual valence of the silver atoms in silver peroxide.

Antelman [23] observed that when the reproductive rates of an organism are high as in the case of bacteria with their exposed sulfhydryl and amino sites, this action will attract oxidation by the silver ions (III) and the organism will be oxidized. On the other hand, if the reproductive rates of a pathogen are slow, the ionic crystals of the compound are not attracted to them. His research indicates that in an aqueous medium the peroxide (Ag III) works about 240 times as fast as Ag(I), and is up to 200 times more effective a disinfectant than Ag (I) compounds or metallic silver. The pharmaceutical potential of the tetraoxide is now being subjected to a wide variety of trials, for example in Central America, curing patients with otherwise terminal cases of amoebic dysentery.

8. Electrically driven silver ions

8.1. Clinical applications

Extensive study by Becker [24] showed electrically driven silver ions overcome a critical problem in the treatment of serious bone infections. It is the lack of an adequate circulatory system in bone that makes treatment of bone infections with conventional blood-carried antibiotics ineffective. A silver impregnated nylon fabric soaked in saline solution placed over the depths of the wound and charged with a potential of about 0.9 volt promoted complete healing of the bone and its surrounding tissues. Reported was the positive healing experience with some 75 patients, proving the efficacy of the technique. Further, his experience in healing severe wounds in the skin showed the general efficacy of the technique and the lack of any side effects.

During the silver-ion treatment of patients, Becker noted that the copious exudate which appeared in the wound area was accompanied by a constant decline in bacterial count. Microscopic examination showed the exudate to be composed of a large number of primitive cells resembling a variety of primitive bone marrow type cells. With the appearance of the exudate, a dramatic increase in healing rate by a factor of at least two was observed. Further examination revealed that a process of de-differentiation had occurred; that is, the mammalian fibroblast cells had reverted to the primitive stem cells. With the silver-ion technique it was now possible to do open bone grafts. In the case of skin, grafts are not necessary because the silver ions eliminate the bacteria that would otherwise impede the cell-by-cell reconstruction of the original [25].

Becker's treatment is now ongoing at the Mountain Medical Specialties (Demorest, GA, USA). With the silver ion treatment, the physician need only clean the wound, place a silver dressing on it and start an electric current flowing with a small battery. Then the patient is shown how to take care of the wound and the patient is sent home. Once a week the patient comes in for check up and new dressings if necessary. Within a month the wound has healed and silver treatment may no longer be necessary. Within 3 to 6 months the darker skin begins to disappear, and when the darkness disappears, the location of the wound cannot be found [26]. The treatment has achieved exceptional success with the restoration of skin and function on severely burned hands and fingers where grafts result in unsatisfactory function and lack of normal sensation. The skin is regenerated in all of its complex tissue morphology even including the fingerprint [27].

8.2. Swimming pool applications

The search for a swimming pool sanitation system that could be used by those allergic to chlorine was the force behind the development of a silver–copper ion generator with minimal or no chlorine. Tens of thousands of swimming pools in Europe and the United States have used electrically driven silver–copper ion systems to provide satisfactory sanitation for decades. The swimming pool industry, to answer questions of product efficacy, developed a consensus standard for copper–silver ion purification systems with minimal chlorine [28].

Gerba showed that with this system, adequate sanitation could be achieved. For example, Fig. 2 shows that beginning with about 1 000 000

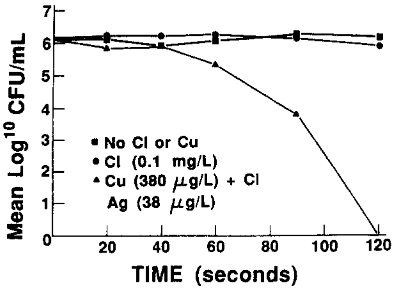

Fig. 2. Combined effect of chlorine, copper, and silver on the survival of *E. coli* in tapwater. Square indicator: control; circle indicator: chlorine 100 ppb; triangle indicator: copper 380 ppb + silver 38 ppb + chlorine 100 ppb. Reprinted with permission from *CRC Critical Reviews in Environmental Control* [29].

colony forming units (CFU) of *E. coli* in tapwater, the combination of silver, copper, and greatly reduced amounts of chlorine, the synergistic effect of the silver, copper, and chlorine ions together is far more powerful than the ions individually [29]. Other studies show satisfactory inactivation of other organisms, for example, *Legionella pneumophila* [30] and *Naegleria fowleri* amoebas [31], and poliovirus and Bacteriophage MS-2 [32]. The use of silver–copper systems to inactivate *Legionella pneumophila* is of especial importance in maintenance of air-conditioning cooling towers. Silver and copper ions remain in the water after shut-down, continuing the sanitation of cooling tower water during periods of inactivity during which chlorine would evaporate [30].

The success of silver–copper ion treatment for human use swimming pools has found equivalent value for aquatic animal exhibition pools, for either fresh or sea water. Curators of aquatic animals report far healthier animals with healthier skin, and small scratches and abrasions that under chlorine did not heal well now heal more rapidly; most important, eye problems are markedly reduced [33]. Also fecal coloform bacteria counts are easily maintained far below the maximum limits prescribed by government regulations [34]. In the case of both fresh and sea water, replacement of the water is required less often and the amount of algae normally fouling the pools is significantly reduced.

9. Conclusions

''Exploring the biomedical activity of silver is proving to be one of the most fruitful areas of clinical research,'' said Charles Fox, developer of silver sulfadiazine. ''Silver plays a unique role in its interference in bacterial reproduction.'' [35].

In view of the growing concern over bacteria resistant to antibiotics that have been our mainstay against disease, the availability of a viable alternative clearly needs detailed exploration. Profitable research needs be conducted to answer such questions as:

1. What is the mechanism of silver ions that cause de-differentiation of cells?
2. How many classes of bacteria are inactivated by silver?
3. How many viral structures are inactivated by silver?
4. What diseases can be successfully treated by silver colloids (< 0.2 μm)?

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