Copper Oxide Impregnated Textiles with Potent Biocidal Activities

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Abstract

Impregnation or coating of cotton and polyester fibers with cationic copper endows them with potent broad-spectrum anti-bacterial, anti-viral, anti-fungal and anti-mite properties (FASEB Journal 2004,18:1728-30). This durable platform technology enables the mass production of woven and non-woven fabrics, such as sheets, pillow covers, gowns, socks, air filters, mattress-covers, carpets, etc. without the need of altering any industrial procedures or machinery, but only the introduction of copper oxide-treated fibers. The biocidal properties of fabrics containing 3-10% copper-impregnated fibers are permanent, are not affected by extreme washing conditions, and do not interfere with the manipulation of the final products (e.g. color, press, etc.). In this manuscript we describe data showing that i) anti-fungal socks containing 10% (weight/weight) copper impregnated fibers alleviate athlete's foot; ii) antimicrobial fabrics (sheets) containing 10% (weight/weight) copper impregnated fibers decrease bacterial colonization in a clinical setting, and iii) these products do not have skin sensitizing properties or any other adverse effects. Taken together, our results demonstrate the wide preventive and curative potential of copper oxide-impregnated apparel products.

Keywords: copper oxide, biocidal, anti-bacterial, athlete's foot, nosocomial infections.

INTRODUCTION

Metal ions have been used for centuries to disinfect fluids, solids and tissues [1;2]. The ancient Greeks of the pre-Christian era of Hypocrates (400 BC) were the first to discover the sanitizing power of copper. They prescribed copper for pulmonary diseases and for purifying drinking water. The Celts produced whisky in copper vessels in Scotland around 800 AD and this practice has continued to the present day. Gangajal is stored in copper utensils in every Hindu household due to copper's anti-fouling and bacteriostatic properties. Copper strips were nailed to ship's hulls by the early Phoenicians to inhibit fouling, as cleaner vessels were faster and more maneuverable.

By the 18th century, copper had come into wide clinical use in the western world, being employed for the treatment of mental disorders and afflictions of the lungs. Early American pioneers moving west across the continent put silver and copper coins in large wooden water casks to provide them with safe drinking water for their long voyage. In the Second World War, Japanese soldiers put pieces of copper in their water bottles to help prevent dysentery. Copper sulphate is highly prized by some inhabitants of Africa and Asia for healing sores and skin diseases. NASA first designed an ionization copper-silver sterilizing system for its Apollo flights. Today copper is used as a water purifier, algaecide, fungicide, nematocide, molluscicide, and as an anti-bacterial and anti-fouling agent [3-7]. Copper is considered safe to humans, as demonstrated by the widespread and prolonged use of copper intrauterine devices (IUDs) by women [8;9]. In contrast to the low sensitivity of human tissue (skin or other) to copper [10], microorganisms are extremely susceptible to copper.

INTRODUCING COPPER OXIDE INTO FIBERS

Utilizing the properties of copper, two durable platform technologies were developed: the first one plates cotton fibers with copper oxide and the second one impregnates polyester, polypropylene, polyethylene, polyurethane, polyolefin, or nylon fibers with copper oxide.

Briefly, cotton fibers are plated as follows: cationic copper (a mix of Cu^{2+} and Cu^{1+}) is bound to cellulose-based fibers. Cotton, rayon/viscose, and fibers such as Lyocel by Tencel are treated with an electroless plating process, which includes the following steps: a) fibers having a diameter of about 11-13 micrometers are soaked for 5 seconds in 1% $SnCl_2$, pH 3.5 at room temperature; b) the fibers are then soaked for 5 seconds in $PdCl_2$, pH 4 at room temperature, producing activated fibers; and c) the activated cellulose based fibers are then exposed to formaldehyde, $CuSO_4$ and polyethylene glycol at pH 9. After about 5 minutes the fibers are plated with cationic copper (Cu(II) and Cu(I)). Finally, the fibers are dried and run through a textile carding machine which separates and aligns them.

Impregnation of copper into the various synthetic fibers mentioned above is achieved by adding a cupric oxide powder to the polymers during the master batch preparation stage. The master batch can be made in the industrially accepted concentrations and added to the polymeric slurry the same way any other master batch would be added such as for pigmentation, etc. The copper oxide doped master batch is designed in such a way as to allow fiber extrusion in the normal production systems. The fibers can be cut into short staple or produced in filament form and texturized, if so desired. As in the case of the plated fibers above, the product yielded is a fiber that can be introduced at the blending stage of yarn production or directly into a woven or knit product so that no manufacturing processes are changed.

These copper oxide plated or impregnated synthetic fibers possess broad-spectrum biocidal properties – they are anti-bacterial, anti-fungal, anti-viral and kill dust mites [11]. Moreover, animal studies demonstrated that these fibers do not possess skin sensitization properties [11].

STUDIES CONDUCTED WITH COPPER OXIDE CONTAINING FABRICS

In view of the biocidal properties of copper oxide treated fibers [11], these fibers were introduced into fabric production. The following section describes constructions, contents, and manufacturing processes of several of the different fabrics whose biocidal properties are shown in Table 1. The final content of the copper-oxide containing fibers may have been different from that described in the following section, as specified in Table 1.

1. Cellulose based fabrics: two different configurations were used for these fabrics.

   Configuration #1:

      Fabric construction and content: Base fabric - 50% cotton, 50% polyester warp; fill - 90% cotton/10% Tencel copper plated fibers. The construction was similar to a standard T180 used in the sheeting industry and the finished fabric weight was about 150 grams per square meter. The fabrics were dyed a medium blue shade.

      Manufacturing process: A Tencel staple of 1.4 denier in a 38 millimeter length was treated through an oxidation reduction process for the plating of a cationic species of copper. Fibers were then mixed by weight in a 90% cotton/10% treated fiber blend. Yarns with the treated fibers were only placed in the fill of the fabric. The fabric was woven, dyed using a direct dye method, and finished by conventional methods.

   Configuration #2: Fabrics only used for mite testing.

      Fabric construction and content: Base fabric - 100% cotton greige cloth that was bleached and prepared for printing. The construction was similar to a standard T180 used in the sheeting industry and the finished fabric weight was about 160 grams per square meter.

      Manufacturing process: The full width fabric was first treated to create nucleation sites on its surface through soaking in a chemical formula with a pH of 4. The fabric was then dried and placed on a suspension roll similar to that used for velvet fabric storage to allow a small space between each layer of the fabrics. While on its tube, the entire fabric roll was then placed in a vat in an upright position. The chelated copper solution with the reductant was added to the vat. The reaction was complete after about four minutes, at which time the fully plated fabric was removed from the roll and thoroughly dried.

2. Polyester/Cotton blended fabrics:

      Fabric construction and content: A T180 fabric was made using a 50% cotton/50% polyester warp and a 40% polyester/10% Cupron treated polyester/50% cotton fill.

Manufacturing process: A staple fiber containing 1% copper oxide by weight was created through a conventional process, whereby the copper oxide was in a master batch added to the slurry of the polyester. This polyester fiber was then blended with cotton to form a 90% cotton/10% Cupron treated polyester yarn. These yarns were only used in the fill.

3. Polyester and nylon based fabrics:

Fabric construction and contents: These fibers are classified as 100% polyester and 100% nylon. In all cases, the fiber was extruded with a master batch let down of 1% to yield a 70 denier 68 filament yarn. The yarns were then 2-plyed to form a 140 denier yarn. The fabrics were then knit on a 168 needle circular machine. The fabrics were not dyed but were washed before testing to remove any extraneous substances on their surface.

4. Polypropylene based fabrics:

This refers to a spun bond non-woven fabric created for the disposable market. The fabrics were made in two versions: 25 grams per square meter and 13.5 grams per square meter. In each case the load down from the master batch was 3% by weight of copper master batch to slurry. No difference in biological efficacy was observed between the 13.5 gram version and the 25 gram version.

The following Table shows representative data of the biocidal properties of several of these fabrics against several pathogens.

Table 1: Biocidal properties of copper-oxide impregnated fabrics

Type of Copper Treated Fiber	Percent of Copper Treated Fibers in Fabric (weight/weight)	Type of Organism Tested*	Name of Organism Tested	Time of Exposure	Percent Reduction of Organism Titer	Organism Related Maladies
Plated Cellulose	10	Gram + bacteria	*Staphylococcus aureus*	1 hour	>99.8	Systemic and skin infections
	10	Gram + bacteria	Methicillin Resistant *Staphylococcus aureus* (MRSA)	1 hour	>99.5	Hospital acquired infections
	10	Gram + bacteria	Vancomycin Resistant *Enterococci* (VRE)	1 hour	99.5	Hospital acquired infections
	10	Gram - bacteria	*Escherichia coli*	1 hour	>99.9	Food poisoning

	10	Fungi	*Candida albicans*	2 hours	>99	Athlete's foot; opportunistic infections
	10	Virus	Human Immunodeficiency Virus Type 1 (HIV-1)	20 minutes	>99.9	AIDS
	20	Mite	*Dermatophagoides farinae*	46 days	100	Allergies, Asthma
	100	Mite	*Dermatophagoides farinae*	5 days	100	Allergies, Asthma
Polyester	3	Gram + bacteria	*Staphylococcus aureus*	4 hours	>99.9	Systemic and skin infections
	5	Fungi	*Candida albicans*	2 hours	>99.9	Athlete's foot; opportunistic infections
	10	Gram + bacteria	*Listeria*	1 hour	>99.8	Food poisoning
	10	Gram - bacteria	*Salmonella*	2 hours	>98.5	Food poisoning
	10	Gram - bacteria	*Escherichia coli*	1 hour	>99.9	Food poisoning
	10	Virus	Cytomegalovirus (CMV)	20 minutes	>99.9	Mononucleosis-like syndrome
	10	Virus	HIV-1	20 minutes	>99.9	AIDS
Polypropylene	3	Gram + bacteria	*Staphylococcus aureus*	4 hours	>99.9	Systemic and skin infections
	3	Gram - bacteria	*Escherichia coli*	4 hours	>99.9	Food poisoning
	3	Fungi	*Candida albicans*	4 hours	>98.7	Athlete's foot; opportunistic infections
	3	Virus	HIV-1	20 minutes	>99.9	AIDS
Nylon	10	Gram + bacteria	*Staphylococcus aureus*	2 hours	>99.9	Systemic and skin infections
	10	Gram - bacteria	*Escherichia coli*	1 hour	>99.9	Food poisoning
	10	Fungi	*Candida albicans*	2 hours	>99.9	Athlete's foot; opportunistic infections
	10	Virus	HIV-1	20 minutes	>99.9	AIDS

*The American Association of Textile Chemists and Colorists (AATCC) Test Method 100-1993 was used to determine the biocidal properties of the fabrics against the bacteria and fungi tested. The initial bacterial or fungal inoculum used varied between $1x10^5$ to $4x10^6$ colony forming units (cfu)/sample. These tests were carried out by independent laboratories: AminoLab Laboratory Services, Weizmann Industrial Park, Nes Ziona 79400, Israel, and Hy Laboratories Ltd., Park

Tamar, Rehovot 76325, Israel. The experiments with the mites were conducted under a subcontract agreement by Dr. Kosta Y. Muncuoglu from the Department of Parasitology, Hebrew University-Hadassah Medical School, Jerusalem 91120, Israel. The CMV testing was done at the Ben Gurion University by Dr. Shemer-Avni, and the HIV-1 testing was done in Cupron Biosafety Viral Laboratory. For detailed experimental protocols, please see Ref 11. The results shown are representative examples of at least 2 similar experiments per fabric per organism.

Studies were then conducted with socks containing polyester fibers impregnated with copper oxide (Fig 1), and sheets containing cotton copper oxide-plated fibers (Fig 2), as described below.

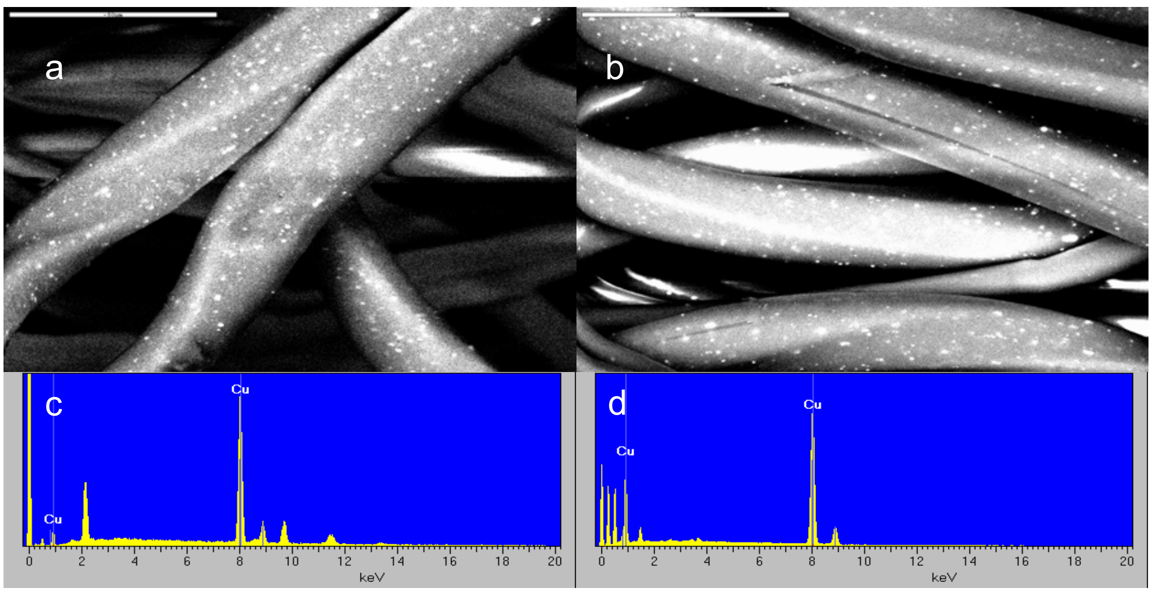

Fig 1. Scanning electron microscopy (SEM) of the polyester copper oxide impregnated fibers in the tested socks before washing (a) and after 75 washings (b). The fabrics were washed with Tide with no bleach in a Kenmore washer at 140ºF using a normal cycle protocol for a 4 lbs. load. The fabrics were tumble dried. The white dots are copper oxide, as determined by X-ray photoelectron spectrum analysis (c and d).

Fig 2. Mixture of cotton copper oxide plated fibers and untreated fibers as observed by SEM.

The percent of copper on the surface of the polyester fibers was ~ 4%. Significantly, even after 75 washes of the socks, the amount of copper on the surface of the fibers remained similar (~4%, Fig 1b). Minor loss of copper oxide, without loss of biocidal efficacy, occurred in the cotton copper oxide-plated fibers following 100 washes [11]. The final percent of copper-impregnated fibers in the socks and in the sheets was 10% (w/w).

Athlete's Foot Study

One hundred individuals suffering from athlete's foot (*tinea pedis*) were given socks containing 10% copper-impregnated fibers (hereafter referred to as copper-socks). The individuals were asked to wear the copper-socks on a daily basis. During this period the individuals did not receive any anti-fungal treatment and their feet were monitored by a podiatrist.

All one hundred individuals suffering from athlete's foot reported the disappearance of the burning and itching, which may accompany the fungal infection, within 1-3 days of wearing the socks. In acute infections, the blistering and fissures, characteristic of this fungal infection, began disappearing within 2-6 days of using the socks, and the skin returned to normal. In individuals who had chronic and severe athlete's foot infections for years, improvement of the athlete's foot condition occurred within days of wearing the copper-socks (Fig 3). In some individuals, like patient number 3 in Figure 3, complete return of the skin to a normal appearance occurred within 1 to 2 months. None of the one hundred individuals reported any adverse effects while using the copper-socks.

Fig 3. Athlete's foot infection at Day 0 and after wearing socks containing 10% copper-impregnated fibers in three representative examples of individuals suffering from athlete's foot infections. (Patient 1 – acute infection; Patients 2 and 3 – chronic infections).

Bacterial Colonization Study

Thirty patients internalized in a General Internal Hospital Ward, aged 30-75, with different diseases, necessitating in-patient treatment, non-relevant to this study, were chosen arbitrarily to participate in the study. Following their informed consent, the patients slept overnight on regular sheets and then overnight on sheets containing 90% regular cotton fibers and 10% copper-impregnated fibers (hereafter referred to as copper-sheets). Bacterial swabs samples were taken from both sheets in the areas where the feet were placed. The overall bacterial load per swab was determined by standard routine bacteriology growth assays in the Microbiology Hospital Department. Additionally to these 30 patients, 70 other patients slept overnight on the copper-fabrics. Each of these 100 patients was examined by a specialist in allergy and clinical immunology, a dermatologist and an internist in order to determine any possible unwanted effects caused by the sheets, such as skin sensitizations.

As depicted in Figure 4, there was statistically significant lower bacteria colonization on copper-sheets than on regular sheets. While the number of bacteria on the regular sheets under the feet of the 30 patients examined after overnight sleeping was 21909 ± 3134 cfu/ml (mean ± standard error), the number of bacteria on the copper-sheets was almost half on average after overnight sleeping (13182 ± 2863 cfu/ml).

Significantly, no adverse or any other reactions were noted in the 100 patients that slept on the copper-sheets. No skin sensitization or allergic reactions were recorded by the examining physicians

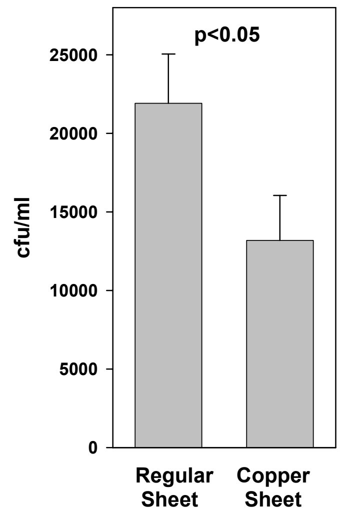

Fig 3. Reduction of bacterial colonization of copper-sheets. The number of bacteria found after overnight sleeping on copper-sheets under the feet of patients was significantly lower than that found under the feet of the same patients after overnight sleep on regular sheets. A paired T-test was conducted, and the statistical difference (p value) is shown.

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DISCUSSION

Permanent or durable binding of inorganic compounds to organic substrates is extremely difficult, especially for mass production processes. By utilizing the properties of copper, an inexpensive platform technology was developed which permanently binds copper to textile fibers from which woven and non-woven fabrics can be produced [11]. The introduction of copper oxide at the early stages of the textile production cycle enables the use of cotton or polyester fibers in many manufacturing processes without altering manufacturing procedures or equipment, allowing for rapid and simple production of fabrics with potent biocidal qualities (e.g. Table 1).

Copper is considered safe to humans, as demonstrated by the widespread and prolonged use by women of copper intrauterine devices (IUDs) [8;9;12]. Animal studies demonstrated that the copper fibers do not possess skin sensitizing properties. In the present study, none of the 100 individuals who used socks containing copper-impregnated fibers to alleviate their athlete's foot conditions reported any negative effects caused by the socks. Furthermore, none of the 100 patients, who slept on sheets containing copper fibers, reported any adverse effects. These findings are in accordance with the very low risk of adverse skin reactions associated with copper [10].

The possibility of introducing copper into fabrics may have significant ramifications. One example is the reduction of nosocomial infections in hospitals. The main sources for contamination are the patient's skin flora, the flora on the hands of medical and nursing staff, and contaminated infusion fluids. However, recently it has been demonstrated that sheets which are in direct contact with a patient's skin and his bacterial flora are an important source of infection [13;14]. Moreover, sheets were significantly more contaminated by patients carrying infection than by non-infected patients ($p<0.01$) [13]. Therefore, use of fabrics that kill microbes in pajamas, sheets, pillow covers, and robes in a hospital setting, may reduce the spread of microorganisms in hospital wards, resulting in a reduction of nosocomial infections.

It is significant to note that healthcare-associated (nosocomial) infection ranks fourth among causes of death in the United States, behind heart disease, cancer and stroke. Nearly two million patients annually contract an infection while hospitalized. Over 90,000 deaths in the US are attributed to these infections each year and one out of four deaths in intensive care units is caused by an infection unrelated to the initial cause of hospitalization. Nosocomial infections is estimated to add $5 billion to US hospital and insurance costs each year [15]. Thus, the use of fabrics with biocidal properties in a hospital setting may not only reduce hospital mortality and morbidity, but may also significantly reduce hospital and insurance costs.

Another possible use of copper fabrics is related to allergies and asthma. It is estimated that 15% of the general population suffer from one or more allergic disorders of which allergic rhinitis is the most common [16]. Allergic rhinitis affects an estimated 20 to 40 million people in the US alone. Similarly, nearly 15 million Americans have asthma, including almost 5 million children. Approximately 5,500 persons die each year from asthma [17]. Dust mites are considered to be an important source of allergen for perennial rhinitis and asthmatic attacks [18]. Thus, elimination of house dust mites in mattresses, quilts, carpets and pillows, would be an important step in improving the quality of life of those suffering from dust-mite related allergies.

Use of copper-impregnated socks by the wider population may also be beneficial in more benign conditions. About 15-20% of the population suffers from *tinea pedis* [19;20]. While there are many clinical presentations of *tinea pedis*, the most common are between the toes and on the soles, heels and sides of the foot. Although this fungal infection is not usually dangerous, it can cause discomfort, may be resistant to treatment, and may spread to other parts of the body or other people. Affected feet can also become secondarily infected by bacteria. As we report here, copper-impregnated socks may be useful in preventing and treating *tinea pedis*. In addition, as the socks kill bacteria, the odor associated with bacterial growth, is eliminated (data not presented).

In conclusion, our study illustrates some of the potential uses of copper-treated textiles in new applications that address medical concerns of the greatest importance. Implementation of even a few of the possible applications of this technology may have a major effect on our lives.

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