Electrical Augmentation of the Antimicrobial Activity of Silver-Nylon Fabrics

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ABSTRACT: We measured the silver levels produced in *vitro* by three silver-coated fabrics, and the resulting antimicrobial effect on *Pseudomonas aeruginosa, Staphylococcus aureus,* and *Candida albicans.* A significant enhancement of the fabrics' antimicrobial effect was achieved by the passage of weak DC currents, which cause increased liberation of silver ions. The antimicrobial effectiveness of each fabric depended on its textile characteristics. Thus, a silver-coated fabric could potentially serve as an antimicrobial dressing by continuously releasing_ silver ions into a wound either by passive dissociation or through electrical stimulation.

INTRODUCTION

The antiseptic action of silver compounds has long been known (Goodman et al., 1986), but they have not achieved widespread clinical use. Cost, and the absence of reliable and convenient delivery systems for actually applying the silver, are two principal reasons. A possible technique involves coating an inert substrate with silver and placing the composite on the treatment site. The idea is that oligodynamic action -- the passive dissociation of silver from the metallic phase, (Lawrence and Block, 1968) -- would produce a sustained release of silver ion into the wound. Using a substrate of nylon fabric coated with metallic silver, we showed that this phenomenon occurred in *vitro* (Deitch et al., 1983). Silver ions from a silver-nylon composite diffused 2-15 mm and killed or inhibited the growth of bacteria and fungi.

The passive nature of oligodynamic action is a major limitation in contemplated use of silver composites for infection control. The actual amount of silver liberated is determined by the Composite's lability and the chemistry of the wound environment, and thus is not under the clinician's control. To overcome this difficulty we have begun to explore the consequence of the passage of electrical current through silver-nylon composites. If such a composite is made electrically positive (an anode) in an ionically conducting medium, then, according to Faraday's law, silver ions will be liberated in proportion to the magnitude and duration of the current. We therefore studied whether the passage of a weak DC current through the silver-nylon composites would increase their antimicrobial effectiveness.

METHODS

Three silver-nylon fabrics (Swift Textile Metalizing Corporation, Hartford, CT) and pure silver wire were studied (Table 1, Fig. 1). The test system consisted of two 406-ml beakers connected by a salt bridge, and appropriate electronic equipment for applying and monitoring a DC electrical current across the beakers. The material under test (19 cm^2 of the fabrics, 22 cm of 10-mil silver wire) was placed in 50 ml of tryptic soy broth (37°C) in the anodic beaker. The anodic beakers were seeded with 18-hour broth cultures of *Staphylococcus aureus, Pseudomonas aeruginosa,* or *Candida albicans* to produce 1×10^6 or 3×10^4 CFU/ml for the bacteria and fungus respectively. The current was then initiated and aliquots were periodically removed from the anodic beakers for measurement of silver-ion concentration (atomic absorption spectroscopy) and microbial growth (serial pour-plate assays). Silver wire immersed in 50 ml of tryptic soy broth was used as the return electrode in the cathodic beaker. Measurements were made at 0 (with and without the material under study being present in the anodic beaker), 1, and 2 V, which produced currents of 0, 22, and 54µA respectively. All listed microbial levels are the average of at least two measurements.

RESULTS

P. aeruginosa: See Fig. 2. Growth at both 7 and 23 hr was reduced below that of the control (no fabric or wire present in the seeded beaker) by the oligodynamic action of SN. The remaining materials did not have a significant effect as a result of oligodynamic action alone. At 1 V, both SN and 4H reduced the bacterial concentration 5 orders of magnitude below the initial seeded concentration, and 7 orders of

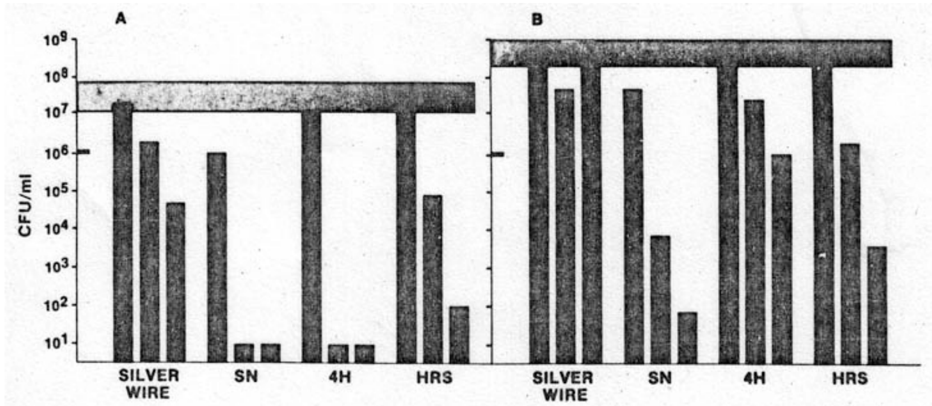

Figure 2. P. aeruginosa concentrations associated with silver wire and silver-nylon fabrics. Cross-hatched region indicates average and SD from control beakers. Index mark at left indicates initial concentration. In each data group the indicated concentrations were associated with (from left to right) 0, 1, 2 V respectively. A, 7 hr; B, 23 hr.

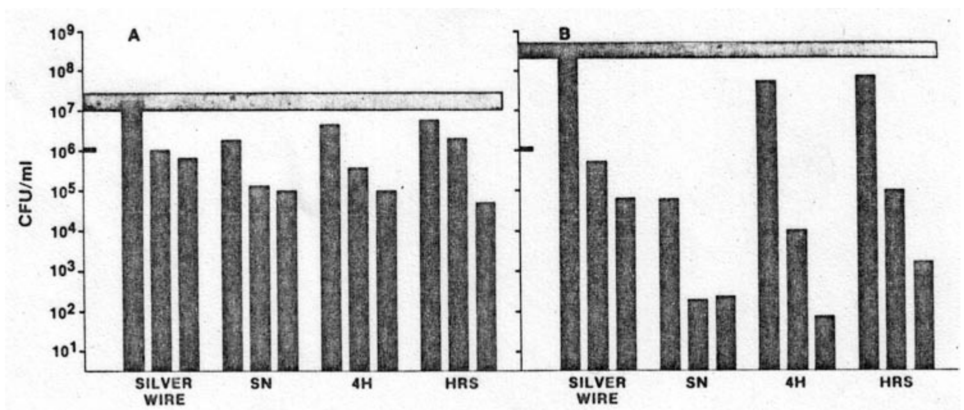

Figure 3. S. aureus concentrations associated with silver wire and silver-nylon fabrics. Cross-hatched region indicates average and SD from control beakers. Index mark at left indicates initial concentration. In each data group the indicated concentrations were associated with (from left to right) 0, 1, 2 V respectively. A, 7 hr; B, 23 hr.

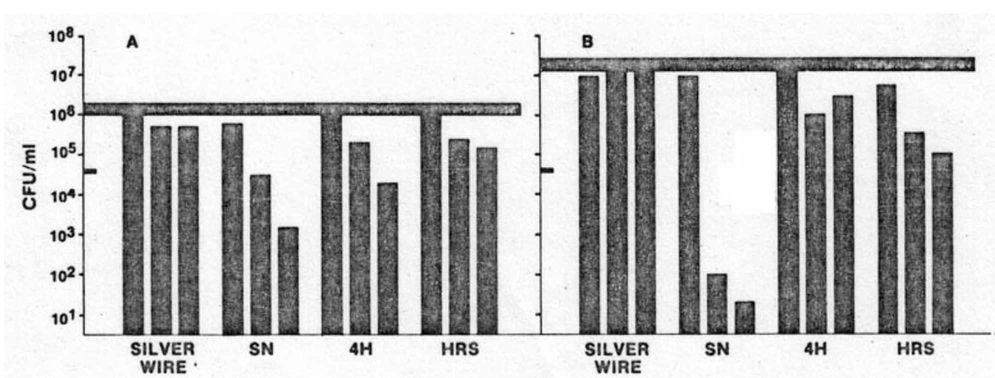

Figure 4. C. albicans concentrations associated with silver wire and silver-nylon fabrics. Cross-hatched region indicates average and SD from control beakers. Index mark at left indicates initial concentration. In each data group the indicated concentrations were associated with (from left to right) 0, 1, 2 V respectively. A, 7- hr, B, 23 hr.

TABLE 1

Physical properties of silver-nylon fabrics. Silver-content values are the average of triplicate determinations.

	Fabric style		
	HRS	SN	4H
Pattern	Weave	Knit	Knit
Cell shape	Square	Square	Hexagonal
Cell size (mm)	Closed	Closed	2.5
Weight (g/m^2)	84.6	111.7	13.54
Silver content ($\mu g/cm^2$)	2545	4364	500

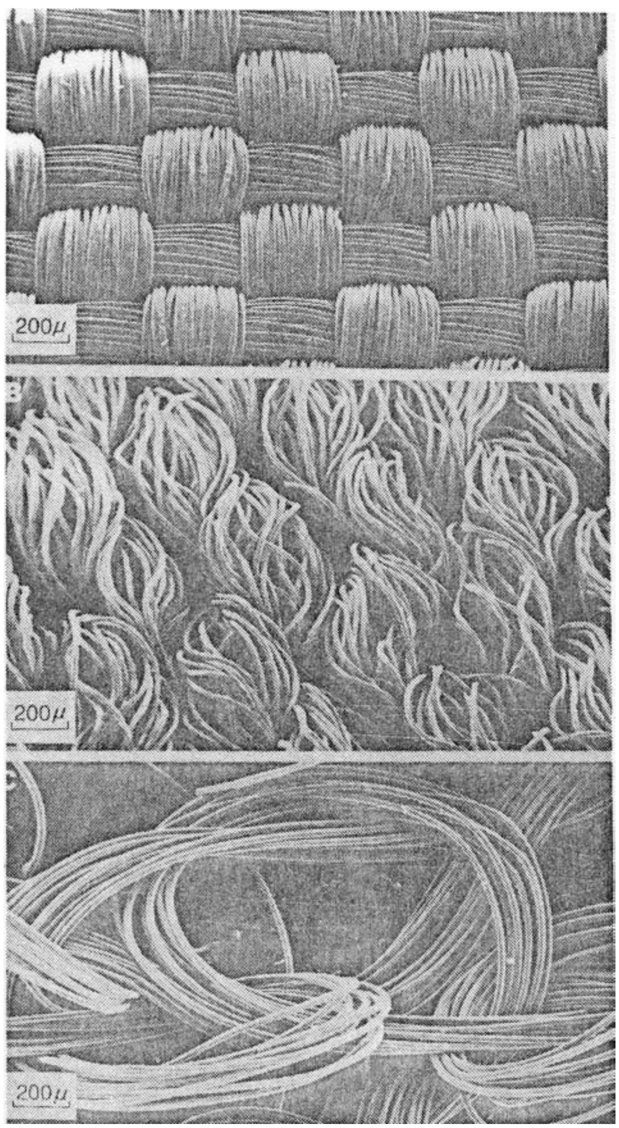

Figure 1. Scanning electron micrographs of silver-nylon fabrics. A, HRS; B, SN; C. 4H.

magnitude below the 7-hour control. At 23 hr the SN levels were still 5 orders of magnitude below the control. HRS was less effective than the other fabrics, but more effective than silver wire at both 7 and 23 hr.

At 2 V, the fabrics produced a further decrease in growth at both 7 and 23 hr except in the cases of SN and 4H, where the 1-V bacterial levels were already vanishingly small.

S. aureus: All the fabrics exhibited an oligodynamic effect on growth at 7 and 23 hr, especially SN (Fig. 3). This pattern was also observed at 1 V, but at 2 V the materials were all more nearly equal in their effectiveness in preventing the growth of the bacteria. At 23 hr, both SN and 4H reduced the concentrations about 7 orders of magnitude below the control level.

C. albicans: None of the fabrics tested has a significant oligodynamic impact on growth (Fig. 4). At 1 and 2 V, SN markedly reduced the measured concentrations at both 7 and 23 hr when the microbial levels were determined (Table 2). The silver concentrations were not affected by the presence of organisms in the broth.

DISCUSSION

SN was the most effective material in reducing microbial growth via the passage of current. It reduced the concentration of P. aeruginosa to near the detection limit at 7 hr; thereafter, the concentration increased but remained 6 and 8 orders of magnitude (1 and 2 V respectively) below the control at 23 hr. A different pattern was seen with S. aureus and C. albicans. where the microbial concentrations were lower at 23 hr compared to 7 hr.

4H was effective in reducing growth at 7 hr, particularly with the bacteria. This effectiveness was not reflected at 23 hr, however, because of an electrical change that occurred in the fabric that resulted in a current drop-off (Marino et al., 1984). Briefly, silver-nylon fabrics can support an ionic current for a limited period, after which electrochemical changes occurring in the fabric cause the total current to drop precipitously to

TABLE II
Silver levels produced in broth at 37°C. Average of triplicate measurements at (from top to bottom in each data group) 0 V (material present in the anodic beaker, but no applied voltage), 1 V, and 2 V.

Materials	Silver concentration (g/ml)				
	1 hr	2 hr	4 hr	7 hr	23 hr
Silver wire	-0-	-0-	-0-	-0-	-0-
	1.1	2.1	4.4	7.0	21.3
	1.6	3.2	6.5	9.4	26.6
HRS	0.8	1.0	1.4	1.8	2.6
	1.4	2.2	3.9	7.3	14.0
	3.1	5.3	10.2	13.2	20.9
SN	2.3	3.0	4.4	5.8	11.5
	3.2	4.7	8.3	12.1	21.3
	3.4	6.4	11.2	15.2	25.0
4H	0.7	0.9	1.4	1.9	3.0
	2.5	4.3	7.9	11.8	---
	4.6	8.6	17.6	---	---

current to drop precipitously to near zero. The time to occurrence of the current drop-off depends on many factors, including the particular fabric. applied voltage. and fabric surface area actually in contact with the solution. After the occurrence of the current drop-off, the rate of silver production drops to the oligodynamic baseline level. Since 4H exhibited the drop-off between 7 and 23 hr at 1 V. and between 4 and 7 hr at 2 V, it is not surprising that its microbicidal effect was less after 23 hr of incubation than after 7 hr.

HRS was the least effective fabric despite its relatively large silver content (Table 1). The textile properties of the fabrics differed widely (Fig. 1). and it seems clear that they affect various properties of the metallic coating itself which, in turn. are important with regard to the dynamics of current-induced silver-ion liberation into solution.

We believe that SN was the most effective material because of the nature of its response to electric current. Figure 5 depicts the rate of silver production at both I and 2 V up to 7 hr. SN produced relatively high silver concentrations quickly and maintained its silver production throughout the test period (Table 2). 4H yielded equally large initial silver levels. but did not sustain the silver production because of the current drop-off. HRS did maintain its current, but both its initial rate of production and its 23-hr silver levels were below those of SN. The 23-hr levels produced by silver wire were the highest measured. but its low rate of silver-ion production at 0-7 hr resulted in its having only a small effect on growth. Thus, SN's relative efficacy may be attributed to the facts that 4H failed. HRS produced too little silver, and silver wire did not produce it quickly enough.

Was the antimicrobial activity related primarily to the silver level, or did the

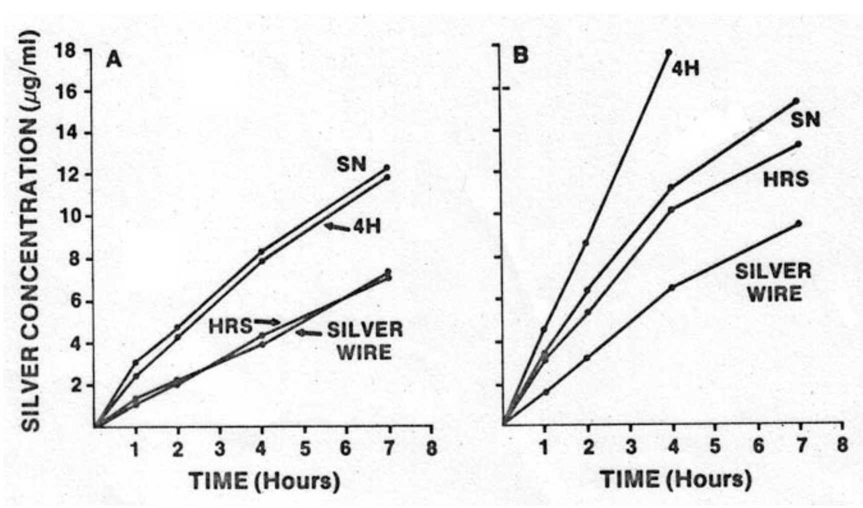

Figure 5. Silver production from the different materials during the first 7 hr of electrical conduction. A, 1 V (total current 22 A amperes); B, 2 V (total current 54 A).

different electrochemical reactions occurring with the different materials and voltages also affect growth? Figure 6 is a scattergram of the normalized microbial concentration (NMC) versus silver levels at 7 hr. It displays the effect on growth associated with various silver levels irrespective of material, voltage, or whether the level were produced oligodynamically or electrolytically. It can be seen that there is a good correlation between a decrease in NMC and an increase in silver level, thereby suggesting that the antimicrobial effects are associated primarily with the silver-ion concentrations. At 23 hr the correlations are generally not as good (Fig. 7), but this may be attributed to the rate and duration of silver-ion production by 4H, HRS, and silver wire as described, above. Most of the points in Fiq. 7 showing a significant effect on NMC were obtained with SN.

In summary, the fabrics exhibited antimicrobial activity in vitro that increased significantly when a current was passed through them. The effect correlated well with the measured silver level, indicating that the silver-ion level -- rather than that of other electrochemical species -- was responsible for the effect.

Both the rate of silver-ion production and its duration were important factors in providing the antimicrobial effects. Of the materials studied, SN showed the highest rate of silver production, both oligodynamically and electrolytically, within the first 7 hr, and it was able to maintain a current over the entire 23-hr test period. Consequently, it exhibited the greatest antimicrobial effect. Thus, antimicrobial effectiveness was related to silver-ion concentration which, in turn, was related to the fabric style itself, and to its geometry. Different nylon substrates yielded fabrics with different electrical properties when subjected to the same metallizing process. This opens up the possibility of tailoring fabrics to particular clinical applications.

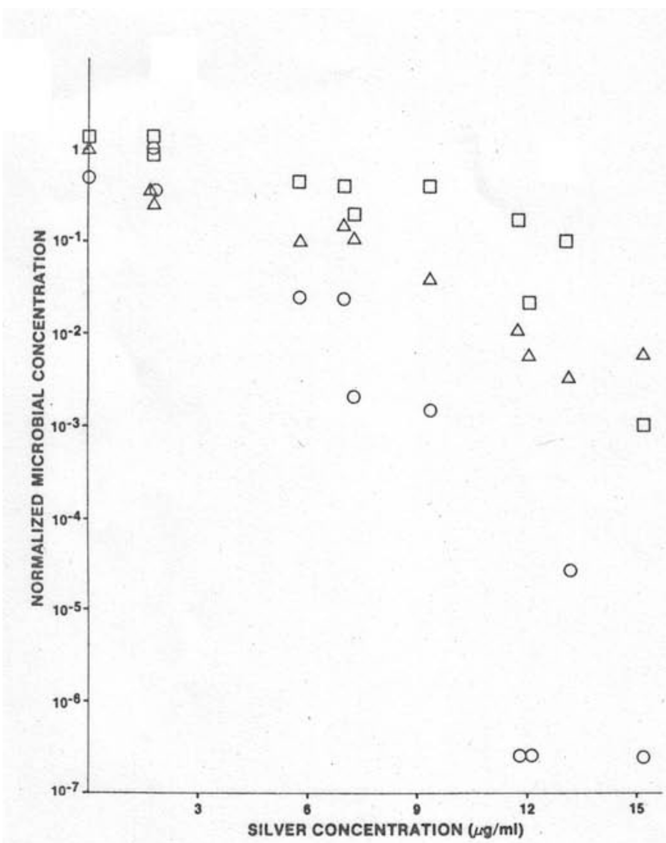

Figure 6. Normalized microbial concentrations (NMC) at 7 hr. NMC is defined as the ratio of the microbial concentrations at 0 (material only, no applied voltage), 1, or 2 V (depicted in A of Figures 2-4) to the respective control concentration. Pearson (Spearman) correlation coefficients for P. aeruginosa (○) S. aureus (Δ), and C. albicans (□) respectively; 064(0.93), 0.67(0.94), 0.85(0.97).

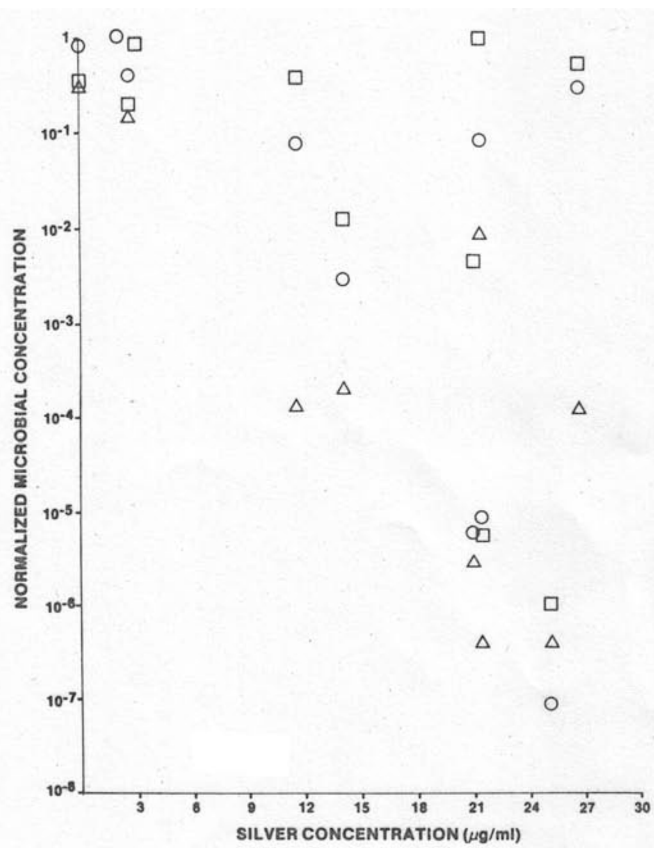

Figure 7. Normalized microbial concentrations (NMC) at 23 hr. NMC is defined as the ratio of the microbial concentrations at 0, 1, or 2 V (depicted in B of Figures 2-4) to the respective control concentration. Pearson (Spearman) correlation coefficients for P. aeruginosa (○) S. aureus (Δ), and C. albicans (□) respectively: 0.70(0.54), 0.77(0.75), 0.26(0.23).

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