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INVESTIGATIVE REPORT

Effects of Silver-based Wound Dressings on the Bacterial Flora in Chronic Leg Ulcers and Its Susceptibility *In vitro* to Silver

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Silver-based dressings have been used extensively in wound management in recent years, but data on their antimicrobial activity in the clinical setting are limited. In order to explore their effects on chronic leg ulcer flora, 14 ulcers were cultured after at least 3 weeks treatment with Aquacel Ag® or Acticoat®. Phenotypic and genetic silver resistance were investigated in a total of 56 isolates. Silver-based dressings had a limited effect on primary wound pathogens, which were present in 79% of the cultures before, and 71% after, treatment. One silver-resistant *Enterobacter cloacae* strain was identified (silver nitrate minimal inhibitory concentration (MIC)>512 mg/l, positive for *sil*E, *sil*S and *sil*P). Further studies *in vitro* showed that inducible silver-resistance was more frequent in *Enterobacteriaceae* with cephalosporin-resistance and that silver nitrate had mainly a bacteriostatic effect on *Staphylococcus aureus*. Monitoring of silver resistance should be considered in areas where silver is used extensively. *Key words: silver; silver-resistance; wound dressing; ESBL; derepressed mutant.*

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Silver is a toxic heavy metal with antimicrobial activity. In its ionized form, it has been used in wound care since at least the 19th century (1). Its use fell into oblivion at the beginning of the antibiotic era, but limited usage of silver recommenced in the 1960s in the management of severe burn wounds (2). With the emergence of multiresistant bacteria, interest in alternatives to antibiotics has increased. Since the turn of the century a wide variety of silver-based dressings has become commercially available for different wound types, and the clinical use of silver has consequently increased. In England, the prescribed quantity of one of the leading silver-based dressings increased by 500% between 2003 and 2004 and by 130% between 2004 and 2005 (3).

Every time a new antimicrobial substance has been introduced, it has been a matter of time before bacterial resistance has emerged (4). Silver has been shown to induce resistance in a range of bacterial species (1, 5, 6). Several of the silver-resistant strains have been collected from silver-treated patients at burn centres, where these strains have sometimes caused outbreaks (7, 8).

An important mechanism of bacterial resistance to silver is encoded by the *sil* gene complex, which leads to reduced permeability through efflux pumps (9). This gene complex has so far been identified only on plasmids carrying genes encoding resistance to antibiotics (10, 11). Silver may thereby exert an indirect selective pressure, but there are also concerns regarding cross-resistance to antibiotics (12–14). The clinical implication of silver-resistance is, however, not yet clear.

The antimicrobial effects of silver are unspecific and are mediated by the formation of complexes with proteins, nucleic acids and biologically important anions, which impairs their function (1). The high reactivity of silver ions and their tendency to form complexes with proteins can make it difficult to show a bactericidal silver effect *in vitro*, since it is largely dependent on the medium used (15, 16). An infected chronic leg ulcer represents an even more complex environment, which could significantly decrease the bioavailability of silver and thereby its bacterial toxicity. Silver concentrations within the wound environment can thereby be suboptimal. Although silver-based dressings are marketed as alternatives to antibiotics, few randomized controlled studies on chronic leg ulcers have investigated the direct antimicrobial effects of silver-based dressings (17). To further complicate the situation, there are no standardized methods to determine bacterial susceptibility to silver and no accepted breakpoints (18). Thus, it is a challenge to establish routines for following the prevalence of silver-resistance at a clinical microbiology laboratory or to interpret published data on the efficacy of silver as an antimicrobial substance or as a selector of resistance.

The aims of this study were to explore the effects of silver-based dressings on the quality of the bacterial flora in chronic leg ulcers, and on primary wound pathogens in particular (*Staphylococcus aureus*, beta-haemolytic streptococci and *Pseudomonas aeruginosa*). In addition, the frequency of silver resistance, the presence of three *sil* genes, and the ability to develop silver-resistance during silver exposure *in vitro* were

investigated. In the last case, Gram-negative bacteria frequently found in chronic wounds and with different degrees of susceptibility to antibiotics, beta-lactams in particular, were used.

MATERIALS AND METHODS

Bacterial isolates

A total of 56 isolates were included in the study (for distribution, see Tables I and II). They were routinely collected during the period November 2006 to September 2007 from chronic leg ulcers exhibiting signs of infection or delayed healing. The patients attended the wound treatment centre at Uppsala University Hospital, Sweden. Depending on the length of the treatment, the patients were categorized into two groups.

*Group 1 (*n = *7)*

This group was treated with Aquacel Ag® (ConvaTec, NJ, USA) for 3–5 weeks. The wound dressings were changed three times a week. Bacterial samples were collected before and after silver treatment, and other antibacterial therapies, topical or systemic, were registered. None of the patients had been treated with topical silver in the last month prior to the first culture.

*Group 2 (*n = *7)*

This group was treated with silver-based dressings for a at least 2 months, and only the local treatment was recorded. Aquacel Ag® or Acticoat® (Smith & Nephew, Mölndal, Sweden) were used, and the dressing were changed with the same intervals as in group 1. Bacterial samples were collected only at the end of the observation period.

Bacterial cultures

After washing the ulcers with tap water according to local recommendations, samples were collected from the edge of the ulcers, using swabs. The swabs were thereafter placed in transport medium with charcoal (Copan, Corona, CA, USA). The samples were cultured on blood agar (Oxoid Ltd Base, Hampshire, UK), chocolate agar (Acumedia Manufacturers, Lancing, MI, USA), cystine lactose electrolyte deficient (CLED) agar (Becton-Dickinson, Franklin Lakes, NJ, USA), and anaerobic agar (Acumedia Manufacturers, Lancing, MI, USA). The agar plates were incubated for 48 h at 37ºC in appropriate atmospheres. Bacteria were identified using standard laboratory procedures and the Vitek 2® AutoMicrobic System (bioMerieux, Hazelwood, MI, USA). Carriage of genes encoding Panton-Valentine leukocidin or other staphylococcal exotoxins were not investigated. All isolates were frozen at –70ºC until analysed.

Antibiotic susceptibility

For primary wound pathogens and any silver-resistant isolate, the susceptibility to appropriate antibiotics was tested on IsoSensitest agar (Oxoid Ltd, Basingstoke, UK). The disc diffusion method was performed as recommended by the Swedish Reference Group for Antibiotics (SRGA, www.srga.org). Minimal inhibitory concentration (MIC) determination by Etest (AB Biodisk, Solna, Sweden) was performed when indicated and according to the manufacturer's instructions. All plates were incubated for 18–24 h at 35ºC in room atmosphere. The species-related breakpoints defined by the SRGA were used for the categorization of isolates into susceptible, indeterminate, or resistant.

Screening for silver resistance

The MIC of silver nitrate was determined by suspending bacteria in IsoSensitest broth (Oxoid Ltd) containing silver nitrate at concentrations ranging from 4 to 512 mg/l. The final bacterial concentration was 10^5 colony-forming units (cfu)/ml, controlled by viable count. After 24 h incubation, MIC was recorded as the lowest concentration yielding no visible growth. A silver nitrate MIC>512 mg/l classified the bacterium as silver-resistant.

Minimum bactericidal concentration of silver

Minimum bactericidal concentration (MBC) was determined for all isolates of *S. aureus* and three randomly chosen Gram-negative rods (*Enterobacter cloacae* SM0700090 III, *Proteus mirabilis* SM0604597 II, and *P. aeruginosa* SM0700863 II) collected from patient group 2. The MBC was determined according to the SRGA guidelines and corresponded to the lowest silver concentration that killed 99.9% of a bacterial inoculum.

Exposure of bacteria to silver in vitro

Due to the results of the clinical investigation, the ability to develop silver-resistance during silver exposure *in vitro* was explored in 14 strains with different degrees of susceptibility to antibiotics. Two were culture collection strains and 12 were clinical strains isolated at the Departments of Clinical Microbiology, Uppsala or Malmö University Hospital: *Escherichia coli* S0506373 (multi-resistant, extended spectrum beta-lactamase (ESBL) positive), ATCC 25922, B0709322, and B0801711, *E. cloacae* S0707396, S4279/06, AI3210/03 (all three derepressed mutants (resistant to cefotaxime and ceftazidime), the first strain in addition colistin-resistant), B0708431, and S0801360, *Klebsiella pneumoniae* CCUG 54718 (multi-resistant, ESBL positive) and B0716185, and *P. aeruginosa* 20080 (multi-resistant, metallo-beta-lactamase positive), A36634 (carbapenem-resistant), and AI2884.

To induce silver-resistance, 1 cfu of each strain was inoculated into IsoSensitest broth. After an overnight incubation at 37ºC, 10 µl of the bacterial suspension was inoculated into a series of tubes, each containing 1 ml IsoSensitest broth with increasing concentrations of silver nitrate (8–512 mg/l). The tubes were incubated overnight, and a new inoculum was collected from the tube with the highest silver nitrate concentration and still visible growth. The experiment was repeated until a silver nitrate MIC>512 mg/l was reached, or 10 passages had been performed. Susceptibility testing to appropriate antibiotics with the disc diffusion method was performed before and after the silver exposure. MIC-determination was performed on all strains with an inhibition zone difference of 5 mm or more.

To control how stable the resistance to silver was, all silver-resistant strains were subcultured six times on CLED-agar (Becton-Dickinson) without silver. After each passage, at least five colonies from each strain were tested to determine if they were still able to grow in IsoSensitest broth supplemented with silver nitrate (512 mg/l).

Detection of silver resistance genes

To investigate whether any of the strains carried genes encoding silver resistance (*sil*E, *sil*P and *sil*S), a polymerase chain reaction (PCR) assay was performed. Templates were prepared by heating a bacterial suspension at 95ºC for 10 min. Each PCR reaction contained 2 µl template DNA, 4 µl respective primer pair and HotStarTaq MasterMix (Qiagen, Hilden, Germany) to a total reaction volume of 25 µl. The primers had the following sequences: *sil*E forward 5'-GTACTCCCCGGACATCACTA-ATT-3' and reverse 5'-GGCCAGACTGACCGTTATT-3'; *sil*P forward 5'-CATGACATATCCTGAAGACAGAAAATGC-3'

Table I. *Bacterial findings according to laboratory records before and after 3 weeks of treatment with silver-based dressings (group 1)*

			Bacterial findings	
Patient	Topical treatment	Systemic treatment	Before treatment	After treatment
1	Aquacel Ag®	Floxacillin	*S. aureus* *Morganella morganii*	*S. aureus*
2	Aquacel Ag®	Floxacillin	*S. aureus*	*S. aureus* Faecal flora
3	Aquacel Ag®	Clindamycin	Group G streptococcus *S. aureus* *P. aeruginosa*	Group G streptococcus *P. aeruginosa* Skin flora
4	Aquacel Ag®	None	Faecal flora	Faecal flora (including a silver-resistant *E. cloacae*) Skin flora
5	Aquacel Ag® Acetic acid	None	*S. aureus* *P. aeruginosa*	*S. aureus* *P. aeruginosa*
6	Aquacel Ag® Acetic acid	None	*Acinetobacter* sp. *Pseudomonas* sp. *Enterococcus* sp.	Faecal flora Skin flora
7	Aquacel Ag®	Floxacillin	*S. aureus*	Skin flora

and reverse 5'-CGGGCAGACCAGCAATAACAGATA-3'; *sil*S forward 5'-GGAGATCCCGGATGCATAGCAA-3' and reverse 5'-GTTTGCTGCATGACAGGCTAAAGACATC-3' (19). The mixtures were processed in a GeneAmp PCR system 9700 cycler (PE Applied Biosystems, Foster City, CA, USA), the programme consisting of 95ºC for 2 min, followed by 40 cycles of 1 min at 95ºC, 1 min at 55ºC, and 3 min at 72ºC. The final extension step was performed at 72ºC for 5 min. As positive and negative controls, *K. pneumoniae* strain U-0608239 (carrier of the complete *sil* gene complex) and dH_2O were included. Each DNA sample was run twice. Ten µl of each PCR reaction was analysed on a 1.2% agarose gel (Shelton Scientific Inc., Shelton, CT, USA) with ethidium bromide. The size of the PCR products was compared with a DNA molecular weight marker (O´GeneRuler™, Fermentas). After completed electrophoresis, the gel was photographed and the bands analysed.

Arbitrarily primed PCR

Ten isolates from three patients from group 1 were analysed with arbitrarily-primed polymerase chain reaction (AP-PCR) in order to compare the DNA-patterns of isolates of the same species before and after treatment. Included isolates were *S. aureus* from patient 2, *Enterococcus* sp. and *Proteus* sp. from patient 4 and *S. aureus* and *P. aeruginosa* from patient 5. DNA was extracted by an M48 robot (GenoVision, West Chester, PA, USA) with the MagAttract DNA Mini M48 Kit (Qiagen, Solna, Sweden). The primers used had the following sequences: ERIC1R 5'-TGTAAGCTCCTGGGGATTCAC-3', ERIC2 5'-AGTAAGTGACTGGGGTGAGCG-3', A70-10 5'-CAGACACGCC-3', 208 5'-ACGGCCGACC-3', and 272 5'-AGCGGGCCAA-3' (20). The same PCR kit as above was used, and the reaction mixture contained 10×PCR buffer, 1.5 mM MgCl2, 200 µM of each dNTP, 0.5 µM primer (Eurogentec S.A., Seraing, Belgium), 0.625 U HotStarTaq DNA polymerase, and 5 µl template DNA. The total reaction volume was 25 µl. The PCR programme consisted of 95ºC for 4 min, followed by 45 cycles of 1 min at 95ºC, 1 min at 36ºC, and 2 min at 72ºC. The final extension step was performed at 72ºC for 5 min. The PCR products were analysed as described above.

RESULTS

Bacterial findings after silver treatment in vivo

Five out of 7 patients in group 1 were colonized with primary wound pathogens before initiating the treatment. The species most frequently isolated was *S. aureus*, followed by *P. aeruginosa*. For details, see Table I. Three out of 5 patients were still culture-positive for *S. aureus* and two out of two for *P. aeruginosa* after 3 weeks with topical silver treatment. Continued growth of the same species in leg ulcers after treatment was in all five investigated cases due to a lack of bacterial eradication, as shown by the indistinguishable DNA patterns generated by AP-PCR (Fig. 1). The two patients in whom primary wound pathogens were successfully eradicated had received additional treatment with antibiotic drugs. No increased antibiotic resistance was observed after the silver treatment.

In group 2 patients, primary wound pathogens could be found in all chronic wounds except for one after

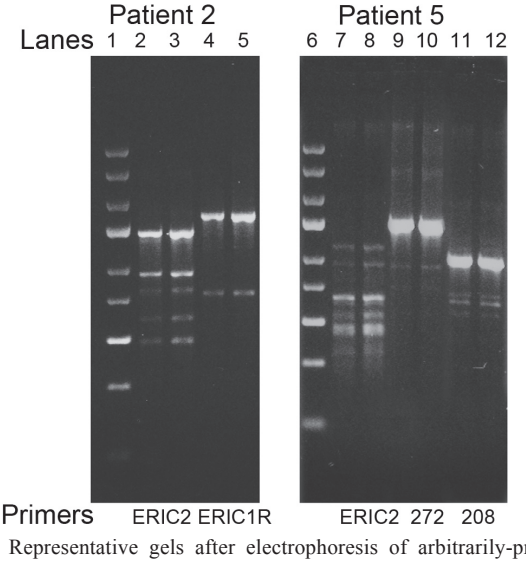

Fig. 1. Representative gels after electrophoresis of arbitrarily-primed polymerase chain reaction products from isolates obtained before and after treatment for 3 weeks with silver-based dressings. Lanes 1 and 6: DNA size markers; lanes 2, 4 before and lanes 3, 5 after treatment of *S. aureus* isolates from patient 2; lanes 7, 9, 11 before and lanes 8, 10, 12 after treatment of *P. aeruginosa* isolates from patient 5. The primers used are indicated at the bottom.

Table II. *Bacterial findings according to laboratory records after long-term treatment with silver-based dressings (group 2)*

Patient	Topical treatment	Duration of treatment (months)	Bacterial findings after treatment
1	Aquacel Ag®	3	*S. aureus* Faecal flora
2	Acticoat Acetic acid	5	*S. aureus* Faecal flora
3	Aquacel Ag®	3	*S. aureus* Faecal flora
4	Aquacel Ag®	14	*S. aureus* *Proteus* sp.
5	Aquacel Ag®	2	Group G streptococcus *S. aureus*
6	Aquacel Ag® Acetic acid	2	Group B streptococcus *S. aureus* *P. aeruginosa*
7	Aquacel Ag® Acetic acid	3	Skin flora

treatment with silver-based dressings for at least 2 months (Table II). The most common finding was *S. aureus*, followed by faecal flora. One of the *S. aureus* isolates was resistant to fusidic acid. No other resistance to antibiotics was registered.

With the two groups taken together, primary wound pathogens were present in 79% of the cultures before, and in 71% after, the topical silver treatment. Three patients, two from group 2 and one from group 1, had positive cultures for beta-haemolytic streptococci despite the silver treatment (Tables I and II).

All isolates but one had a silver nitrate MIC of ≤32 mg/l. The silver-resistant strain was an *E. cloacae* strain (MIC > 512 mg/l, SM0700965 II), which was isolated from patient 4 in Table I after 3 weeks treatment with Aquacel Ag®. In addition to its silver-resistance, the strain was resistant to cefadroxil, cefuroxime, nalidixic acid, and chloramphenicol (MIC 16 mg/l), and the strain was also indeterminate to cefotaxime (MIC 2 mg/l). The other MICs were as follows: ceftazidime 0.5 mg/l, cefepime 0.125 mg/l, imipenem 0.25 mg/l, meropenem 0.032 mg/l, ciprofloxacin 0.016 mg/l, gentamicin 0.5 mg/l, tobramycin 1 mg/l, amikacin 2 mg/l, trimethoprim-sulphamethoxazole 0.125 mg/l, and tetracycline 2 mg/l. There was no *E. cloacae* strain present in the chronic leg ulcer prior to the topical silver treatment, which is why comparisons of susceptibility patterns were not possible.

Minimal inhibitory concentrations and Minimum bactericidal concentrations for silver nitrate

The MIC values for silver nitrate were determined to 16–32 mg/l for the *S. aureus* strains and to 8–16 mg/l for the three randomly selected Gram-negative rods isolated from patient group 2. The MBCs for the Gram-negatives were close to their MICs and were in the range 16–32 mg/l. All *S. aureus* strains had a silver nitrate MBC > 512 mg/l. The MBCs for the Gram-positive bacteria were thereby more than 32 times higher than the MBCs for the Gram-negative bacteria.

Induction of silver-resistance after repeated exposure in vitro

Five out of the 14 silver-exposed strains (36%) developed resistance to silver. Of these five strains, four were resistant to third-generation cephalosporins before the silver exposure. To induce silver-resistance, 2–8 passages were necessary (Table III).

Two out of five *E. cloacae* strains (S4279/06 and S0707396) developed resistance to silver nitrate after 2–3 passages. Both were resistant to cefotaxime and ceftazidime. In addition, resistance to silver was induced in the two included ESBL-producing strains. For *K. pneumoniae* strain CCUG 54718 two passages were required, whereas *E. coli* strain S0506373 needed as many as eight passages.

The only strain without antibiotic resistance prior to the exposure and in which silver-resistance could be induced was *E. coli* strain B0709322. For this strain, five passages were necessary, but its silver resistance was relatively unstable. When the five silver-resistant strains were subcultured on a medium without silver, only *E. coli* strain B0709322 lost its silver-resistance; this occurred after two passages.

Sil *genes*

The three *sil* genes were detected in four strains: two *E. cloacae* strains and two *K. pneumoniae* strains (Table III). Of these strains, three exhibited a silver nitrate

Table III. *Characteristic of strains with phenotypic and/or genetic resistance to silver in the study*

Strain	Silver-resistance genes			No. of passages[a]	Other properties
	*Sil*E	*Sil*P	*Sil*S		
E. cloacae SM0700965 II	+	+	+	NA Stable	Cefotaxime I
E. cloacae S4279/06	+	+	+	2 Stable	D mutant Carbapenems R[b]
E. cloacae S0707396	+	–	+	3 Stable	D mutant Colistin R
E. coli B0709322	–	–	–	5 Unstable	
E. coli S0506373	–	–	–	8 Stable	ESBL positive
K. pneumoniae B0716185	+	+	+	NI	
K. pneumoniae CCUG 54718	+	+	+	2 Stable	ESBL positive, outbreak strain
P. aeruginosa AI2884	+	–	+	NI	

[a]For induction of silver-resistance and its stability.
[b]After silver exposure.
NA: not applicable; NI: no induction; D: derepressed, ESBL: extended spectrum beta-lactamase; I: indeterminate; R: resistant.

MIC > 512 mg/l after exposure. The *sil*E and *sil*S genes, but not the *sil*P gene, were found in two strains (*E. cloacae* S0707396 and *P. aeruginosa* AI2884), of which the *E. cloacae* strain grew in a silver nitrate concentration of 512 mg/l. The silver resistance demonstrated in *E. coli* strains B0709322 and S056373 could not be explained by the presence of *sil* genes. Both strains were PCR-negative for all three genes. None of the Gram-positive isolates were PCR-positive.

Resistance to antibiotics after silver exposure in vitro

In one of the silver-resistant strains, there was more than a 5 mm change in the size of the inhibition zone after silver exposure. *E. cloacae* strain S4279/06 showed a 32-fold increase of the MIC-value for imipenem (before: 0.25 mg/l; after: 8.0 mg/l), and a 16-fold increase for meropenem (before: 0.125 mg/l; after: 2.0 mg/l).

DISCUSSION

In the present study, 14 patients with chronic leg ulcers were treated with silver-based dressings for 3 weeks up to several months, and the bacterial flora was thereafter explored. Although it has been suggested that silver is ideal for topical management of wound infections and at-risk wounds and that the need for systemic antibiotics can thereby be reduced (6), it could not eradicate or prevent primary wound pathogens from colonizing the wounds. Furthermore, silver appeared to have had a limited impact on the faecal flora, and it took only 3 weeks of Aquacel Ag® treatment to find a silver-resistant *E. cloacae* strain carrying *sil* genes. This is, to our knowledge, the first documented clinical isolate exhibiting silver resistance after local silver treatment in Sweden. This is also the first time the exposure time and conditions have been given for selection of silver-resistance with silver-based wound dressings *in vivo*.

Several studies have reported silver resistance among Gram-negative bacteria in clinical settings. Members of the *Enterobacteriaceae* family and *P. aeruginosa* predominate the reports (7, 8, 21–25) and *E. cloacae* seems to be one of the more prone species to carry *sil* genes and develop phenotypic silver resistance according to recent studies (19, 26).

In contrast, Gram-positive bacteria are seldom implicated in phenotypic or genetic silver resistance (27). In this study, they had slightly higher silver MICs than the Gram-negative bacteria without being multi-resistant, which is in accordance with other studies (26). Most remarkable were the high silver nitrate MBCs for the *S. aureus* isolates, indicating a possible tolerance to or only a bacteriostatic activity of silver nitrate. This could be part of the explanation to why the performance of silver nitrate has been poorer than nanocrystalline silver both *in vitro* and *in vivo* on *S. aureus* (28–30). If this lack of bactericidal activity includes other silver salts and beta-haemolytic streptococci needs to be further explored, but commonly used inhibition tests or tests that cannot discover a killing rate less than 99.9% should not be applied.

For the Gram-negative bacteria the silver nitrate MICs were almost identical to the silver nitrate MBCs, and these bacteria appeared to have chosen another way to handle the silver toxicity. The most frequent resistance mechanism in this study was inducible efflux, and the pumps were encoded by *sil* genes. Since these genes are often harboured by plasmids carrying antibiotic resistance genes (10, 11), use of silver can indirectly take part in the selection of multi-resistant members of the *Enterobacteriaceae* family. Two ESBL-producing strains were included in the study, and both developed silver resistance after exposure. The clinical relevance of this finding is supported by the fact that the only silver-resistant bacterium found in the study of Ip et al. (26) was an ESBL producer. A silent horizontal transfer between non-primary wound pathogens may not be a clinical problem for the silver-using dermatologist but for the infection control team at the hospital.

Another effective way to block silver is by decreased permeability. The main mechanism is loss of porins (water-filled protein channels) in the outer membrane of Gram-negative bacteria (13). This can lead to a cross-resistance to hydrophilic antibiotics, such as cephalosporins and carbapenems (13). In this context the patient isolate SM0700965 II was of interest. Its reduced susceptibility to cefotaxime could not be explained by induced production of AmpC, a chromosomally mediated beta-lactamase of *E. cloacae*. Further experiments were therefore carried out.

The results showed that the relationship between carriage of *sil* genes and phenotypic silver resistance was not straightforward. However, stable phenotypic silver resistance seemed to be associated with reduced susceptibility to third-generation cephalosporins. A cross-resistance to carbapenems was, in addition, observed in a derepressed *E. cloacae* strain after silver exposure *in vitro*. A porin deficiency could be the link between resistance to silver and to beta-lactams with broader spectrum (13, 31, 32). Users of silver-based dressings, especially in areas where ESBL-producing enterobacteria or derepressed *E. cloacae* strains are a clinical problem, should consider the potential risk that a combination of these bacteria with a certain silver pressure may have for the development of carbapenem-resistance and outbreaks. The *sil* gene carrying *K. pneumoniae* strain CCUG 54718 caused the largest Scandinavian outbreak by an ESBL producer, so far, and it originated from a patient with extensive wounds (33). Attention should therefore not only be paid to primary wound pathogens and their antibiograms when topical silver treatment is recommended.

In conclusion, silver-based wound dressings are marketed as an alternative to antibiotics. In this study they had a limited effect on the colonizing primary wound pathogens and the faecal flora of chronic leg ulcers. Apart from the fact that only 3 weeks of treatment was necessary to select for a silver-resistant bacterium, a cross-resistance to cephalosporins was identified. To be able to monitor silver resistance at clinical microbiology laboratories, it is necessary to establish an international standard with accepted breakpoints.

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The authors declare no conflicts of interest.

REFERENCES

1. Landsdown AB, Williams A. Bacterial resistance to silver in wound care and medical devices. J Wound Care 2007; 16: 15–19.
2. Klasen HJ. A historical review of the use of silver in the treatment of burns. II. Renewed interest for silver. Burns 2000; 26: 131–138.
3. Chambers H, Dumville JC, Cullum N. Silver treatments for leg ulcers: a systematic review. Wound Repair Regen 2007; 15: 165–173.
4. Davies J, Davies D. Origins and evolution of antibiotic resistance. Microbiol Mol Biol Rev 2010; 74: 417–433.
5. Percival SL, Bowler PG, Russell D. Bacterial resistance to silver in wound care. J Hosp Infect 2005; 60: 1–7.
6. Cutting K, White R, Edmonds M. The safety and efficacy of dressings with silver – addressing clinical concerns. Int Wound J 2007; 4: 177–184.
7. Mayer KH, Hopkins JD, Gilleece ES, Chao L, O'Brien TF. Molecular evolution, species distribution, and clinical consequences of an endemic aminoglycoside resistance plasmid. Antimicrob Agents Chemother 1986; 29: 628–633.
8. Pirnay JP, De Vos D, Cochez C, Bilocq F, Pirson J, Struelens M, et al. Molecular epidemiology of Pseudomonas aeruginosa colonization in a burn unit: persistence of a multidrug-resistant clone and a silver sulfadiazine-resistant clone. J Clin Microbiol 2003; 41: 1192–1202.
9. Gupta A, Matsui K, Lo JF, Silver S. Molecular basis for resistance to silver cations in Salmonella. Nat Med 1999; 5: 183–188.
10. Gupta A, Phung LT, Taylor DE, Silver S. Diversity of silver resistance genes in IncH incompatibility group plasmids. Microbiology 2001; 147: 3393–3402.
11. Johnson TJ, Siek KE, Johnson SJ, Nolan LK. DNA sequence and comparative genomics of pAPEC-O2-R, an avian pathogenic Escherichia coli transmissible R plasmid. Antimicrob Agents Chemother 2005; 49: 4681–4688.
12. Kaur P, Vadehra DV. Mechanism of resistance to silver ions in Klebsiella pneumoniae. Antimicrob Agents Chemother 1986; 29: 165–167.
13. Li XZ, Nikaido H, Williams KE. Silver-resistant mutants of Escherichia coli display active efflux of Ag+ and are deficient in porins. J Bacteriol 1997; 179: 6127–6132.
14. SCENIHR, European Commission. Assessment of the antibiotic resistance effects of biocides. 2009. Available from: http://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_021.pdf.
15. Schierholz JM, Wachol-Drewek Z, Lucas LJ, Pulverer G. Activity of silver ions in different media. Zentralbl Bakteriol 1998; 287: 411–420.
16. Brett DW. A discussion of silver as an antimicrobial agent: alleviating the confusion. Ostomy Wound Manage 2006; 52: 34–41.
17. Sibbald RG, Contreras-Ruiz J, Coutts P, Fierheller M, Rothman A, Woo K. Bacteriology, inflammation, and healing: a study of nanocrystalline silver dressings in chronic venous leg ulcers. Adv Skin Wound Care 2007; 20: 549–558.
18. Chopra I. The increasing use of silver-based products as antimicrobial agents: a useful development or a cause for concern? J Antimicrob Chemother 2007; 59: 587–590.
19. Percival SL, Woods E, Nutekpor M, Bowler P, Radford A, Cochrane C. Prevalence of silver resistance in bacteria isolated from diabetic foot ulcers and efficacy of silver-containing wound dressings. Ostomy Wound Manage 2008; 54: 30–40.
20. Mahenthiralingam E, Campbell ME, Foster J, Lam JS, Speert DP. Random amplified polymorphic DNA typing of Pseudomonas aeruginosa isolates recovered from patients with cystic fibrosis. J Clin Microbiol 1996; 34: 1129–1135.
21. McHugh GL, Moellering RC, Hopkins CC, Swartz MN. Salmonella typhimurium resistant to silver nitrate, chloramphenicol, and ampicillin. Lancet 1975; 1: 235–240.
22. Gayle WE, Mayhall CG, Lamb VA, Apollo E, Haynes BW Jr. Resistant Enterobacter cloacae in a burn center: the ineffectiveness of silver sulfadiazine. J Trauma 1978; 18: 317–323.
23. Hendry AT, Stewart IO. Silver-resistant Enterobacteriaceae from hospital patients. Can J Microbiol 1979; 25: 915–921.
24. Starodub ME, Trevors JT. Silver resistance in Escherichia coli R1. J Med Microbiol 1989; 29: 101–110.
25. Bridges K, Kidson A, Lowbury EJ, Wilkins MD. Gentamicin- and silver-resistant pseudomonas in a burns unit. Br Med J 1979; 1: 446–449.
26. Ip M, Lui SL, Chau SS, Lung I, Burd A. The prevalence of resistance to silver in a Burns unit. J Hosp Infect 2006; 63: 342–344.
27. Loh JV, Percival SL, Woods EJ, Williams NJ, Cochrane CA. Silver resistance in MRSA isolated from wound and nasal sources in humans and animals. Int Wound J 2009; 6: 32–38.
28. Carter MJ, Tingley-Kelley K, Warriner RA 3rd. Silver treatments and silver-impregnated dressings for the healing of leg wounds and ulcers: a systematic review and meta-analysis. J Am Acad Dermatol 2010; 63: 668–679.
29. Yin HQ, Langford R, Burrell RE. Comparative evaluation of the antimicrobial activity of ACTICOAT antimicrobial barrier dressing. J Burn Care Rehabil 1999; 20: 195–200.
30. Tredget EE, Shankowsky HA, Groeneveld A, Burrell R. A matched-pair, randomized study evaluating the efficacy and safety of Acticoat silver-coated dressing for the treatment of burn wounds. J Burn Care Rehabil 1998; 19: 531–537.
31. Martinez-Martinez L. Extended-spectrum beta-lactamases and the permeability barrier. Clin Microbiol Infect 2008; 14 Suppl 1: 82–89.
32. Jacoby GA. AmpC beta-lactamases. Clin Microbiol Rev 2009; 22: 161–182.
33. Lytsy B, Sandegren L, Tano E, Torell E, Andersson DI, Melhus Å. The first major extended-spectrum beta-lactamase outbreak in Scandinavia was caused by clonal spread of a multiresistant Klebsiella pneumoniae producing CTX-M-15. APMIS 2008; 116: 302–308.