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A Novel Comprehensive Efficacy Test for Textiles Intended for Use in the Healthcare Setting

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Abstract

Soft surfaces, including textiles are found throughout healthcare settings. Pathogens can survive for long periods of time on textiles, and can be transferred to and from the skin. Antimicrobial fabrics are used as an engineering control to prevent infection. Efficacy testing standards have limitations, including single organism challenges, multiple fabric plies tested, and lengthy contact times. We developed a novel method that better models in-use conditions through testing standardized mixtures of pathogens and normal skin microorganisms, artificial soils, and a 15-minute contact time. Reproducible growth of all organisms from frozen stocks was achieved using this method. A novel rechargeable, monitorable N-halamine cotton cellulose fabric, containing 5885 ± 98 ppm of active chlorine, was evaluated with the new method using PBS, artificial sweat, and artificial sweat plus 5% serum as soil. Pathogens tested included *Acinetobacter baumannii*, *Candida albicans*, *Escherichia coli*, vancomycin-resistant *Enterococcus faecalis*, methicillin-resistant *Staphylococcus aureus*, methicillin-susceptible *Staphylococcus aureus*, and *Pseudomonas aeruginosa*. Each was tested singly and in the presence of a representative normal skin flora mixture, including: *Acinetobacter Iwoffii*, *Corynebacterium striatum*, *Micrococcus luteus*, and *Staphylococcus epidermidis*. When tested singly, all organisms were reduced by 3.00 log₁₀ or greater, regardless of artificial soil. In mixture, 4.00 log₁₀ or greater reductions were achieved for all organisms. These results suggest that the novel testing method can be used to provide more comprehensive and realistic efficacy information for antimicrobial textiles intended for use in healthcare. Furthermore, the N-halamine fabric demonstrated efficacy against multiple pathogens, singly and in mixtures, regardless of the presence of artificial soils.

Keywords

Antimicrobial Fabric; Antimicrobial Efficacy Testing; Healthcare-Associated Infections

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1. INTRODUCTION

Soft surfaces are found abundantly in the healthcare setting ranging from healthcare worker attire and wound dressings, to bed linens, privacy curtains, and upholstered furniture. Similar to hard surfaces, soft surfaces risk becoming contaminated with pathogenic microorganisms. Due to their large surface area and porous nature, soft surfaces are prone to microbial growth and biofilm development, particularly in the presence of appropriate nutrient, temperature, and moisture levels (Adlhart et al., 2018; Ahonen et al., 2017; Dunne et al., 2017).

Numerous studies have demonstrated the persistence of pathogens on hospital textiles, some of which can survive on soft surfaces for months (Burden et al., 2011; Burden et al., 2013; Du et al., 2017; Koca et al., 2012; Kramer et al., 2006; Lopez-Gigosos et al., 2014; Mitchell et al., 2015; Sanon et al., 2012; Sattar et al., 2001; Treacle et al., 2009; Wiener-Well et al., 2011). Additionally, bacteria can be transferred from contaminated textiles to human skin, especially when the fabrics are moist (Sattar et al., 2001).

Because of the growing public health awareness of soft surface contamination, particularly in the healthcare setting, extensive research and development have been devoted to the generation of textiles hostile to microbial growth. Antimicrobial textiles are an effective strategy for reducing the bioburden on soft surfaces (Adlhart et al., 2018; Ahonen et al., 2017; Lopez-Gigosos et al., 2014; Morais et al., 2016; Santos et al., 2016; Sun et al., 2012; Treacle et al., 2009; Wiener-Well et al., 2011). Use of antimicrobial textiles as an engineering control in the healthcare setting has been proposed to mitigate the cross-contamination and spread of healthcare-associated infections (HAIs). Antimicrobial agents can either be incorporated into materials or grafted to fabric surface as a finishing agent after assembly of the basic fabric (Adlhart et al., 2018; Burden et al., 2013; Koca et al., 2012; Kramer et al., 2006; Mitchell et al., 2015; Sanon and Watkins 2012; Sattar et al., 2001). To maximize benefit, the antimicrobial finishing should be effective against a broad range of microorganisms with low toxicity to the user and the environment. Additionally, the antimicrobial finishing should be durable throughout its service life, and be able to endure laundering, drying, and day-to-day use. Lastly, antimicrobial finishes should ideally not impair the textile appearance or texture (Morais et al., 2016). Numerous antimicrobial textiles are currently available, each of which differs in the mode of action of their microbial components (Table 1).

One of the most interesting antimicrobial approaches, and the textile used in this study, is the rechargeable N-halamine based fabric. The characteristics of this fabric have been previously published in detail (Luo and Sun, 2006). In brief, N-halamines are compounds containing one or more nitrogen-halogen bonds, which demonstrate a broad spectrum of biocidal activity. The antimicrobial properties of N-halamines are based on the exchange of halogen (commonly chlorine) atoms with microorganisms in the presence of water. The N-halamine-based fabric possesses several desirable characteristics suitable for application in the healthcare setting (Adlhart et al., 2018; Ahonen et al., 2017; Luo and Sun, 2006). N-halamine textiles: 1) are highly stable for a long period of time in ambient temperatures, 2) have a low dissociation constant, which makes the N-halamine much more stable and safer for human use than free chlorine or bleach, 3) are compatible with nylon, polyester, acrylics, and cotton-cellulose, 4) can be synthesized with specific concentrations (%) of N-

halamine, 5) have the ability to be regenerated or recharged with a diluted bleach rinse after the halogen functional groups have been consumed, and 6) are monitorable for antimicrobial action (active chlorine components).

Effective testing is the key to understanding the performance of antimicrobial textiles. There are several published standards for assessing antimicrobial efficacy that include both qualitative (absorption or halo-methods) and quantitative methods (see Table 2). While the existing standards can be utilized to assess antimicrobial activity of individual textiles, they have different testing parameters and procedures. The lack of standardization and differences between each method analyzing antimicrobial activity makes meaningful comparison between the performance of different fabrics challenging (Pinho et al., 2011). The purported antimicrobial activity of one fabric determined by one method cannot readily be compared to antimicrobial activity determined by a different method. Furthermore, there exists limited data comparing the performance of distinct antimicrobial textiles in real-world scenarios.

Currently the most commonly applied standards in the U.S are the qualitative American Association of Textile Chemists and Colorists AATCC 147:2019 “Assessment of Textile Materials: Parallel Streak Method” and the quantitative AATCC 100:2011(2016e) “Antibacterial Finishes on Textile Materials: Assessment of” (AATCC, 2016, AATCC, 2019). Both standards specify testing against pure cultures of *Staphylococcus aureus* and *Klebsiella pneumoniae* as representative Gram-positive and Gram-negative pathogens. Additional organisms may be included at the discretion of the testing party, but are not mandated. Additionally, the standards do not define pass-fail criteria, ultimately allowing the manufacturer or testing party to determine its own antimicrobial success. The AATCC 147 method is easily reproducible and relatively easy to perform, and provides qualitative data on the fabric’s bacteriostatic capabilities. The AATCC 100 is a quantitative method, but it does not specify the final concentration of bacteria to be tested (the protocol states adjust to ‘appropriate dilution’). In addition, the test swatches utilized must be able to absorb 1 mL of liquid, therefore more than one fabric swatch (comparable to plies of fabric) are commonly utilized since a single swatch usually cannot absorb the full volume, even if the proposed use of the textile would be single ply.

Standardized in-lab qualitative and quantitative tests are an essential first step in evaluating the antimicrobial activity of a fabric. However, for textiles intended for use in healthcare, there are several aspects of real-world application that are not reflected in these protocols. Antimicrobial textiles can be marketed and utilized in the healthcare setting without accompanying data validating the performance of the textile under actual use conditions. We hypothesized that a novel, more comprehensive, efficacy test for antimicrobial healthcare textiles could be used to evaluate a textile’s performance in the presence of: 1) pure cultures of important HAI-causing microbes and normal skin organisms, 2) reproducible mixtures of skin organisms with pathogens, and 3) artificial soils, including artificial sweat and 5% serum. We also hypothesized that the N-halamine fabric would effectively reduce microorganism contamination under the conditions tested. Our protocol builds on the existing methods to provide a broader and more realistic characterization of the antimicrobial efficacy of fabrics intended for use in healthcare.

2 MATERIALS AND METHODS

2.1 Bacterial Strains and Materials.

All bacterial strains were purchased from the American Type Culture Collection (ATCC, Manassas VA). Lyophilized samples were rehydrated and cultured onto appropriate media and subcultured at least 3 times before use. Pathogens included: *Acinetobacter baumannii* (ATCC 19606), *Candida albicans* (ATCC 24433), *Escherichia coli* (ATCC 29214), vancomycin-resistant *Enterococcus faecalis* (ATCC 51575), methicillin-resistant *Staphylococcus aureus* (ATCC 43300), methicillin-susceptible *Staphylococcus aureus* (ATCC 6538), and *Pseudomonas aeruginosa* (ATCC 10145). Representative normal skin flora included: *Acinetobacter lwoffii* (ATCC 15309), *Corynebacterium striatum* (ATCC BAA1293), *Micrococcus luteus* (ATCC 49732), and *Staphylococcus epidermidis* (ATCC 14900).

All bacteriological media, chemicals, and disposable laboratory supplies were purchase from ThermoFisher Scientific (Waltham MA) unless otherwise noted.

Preparation of Individual Organism Testing Inoculum for Single Organism Challenge—Two well-isolated colonies from the stock plate were aseptically transferred to a sterile 1 mL BHI broth and incubated overnight at 37°C with agitation. The overnight suspension was aseptically transferred to sterile 1.5 mL microcentrifuge tubes and centrifuged at 6,000 RPM for 10 minutes. The supernatant was removed using aseptic technique with care not to disturb the microbial pellet. The pellet was then resuspended with selected soils – PBS, artificial sweat, or 5% serum in artificial sweat. The suspension was standardized spectrophotometrically (600 nm) to approximately 7.5×10^7 CFU/mL.

2.2 Preparation of Organism Mixtures for use in Mixture Challenge.

The goal of the mixture is to grow representative countable colonies of each individual component of the mixture. In order to achieve inter-run reproducibility, mixtures were prepared and frozen in large batches. This procedure has 4 main steps: 1) freezing individual organisms at a consistent absorbance, 2) identifying the concentration of organism in frozen aliquot, 3) mixing specific quantities of each to obtain the desired concentration, and 4) preparing frozen aliquots of the final mixture.

Step 1: For each organism to be incorporated into the mixture, 5 well-isolated colonies from the stock plate were aseptically transferred to sterile 5 mL BHI broths in duplicate. BHI broths were incubated at 37°C with agitation to approximately mid-log phase, as determined by a standard growth curve procedure. Individual organisms were adjusted spectrophotometrically to 0.582 absorbance at 600 nm. The adjusted organism was then mixed in a 1:1 ratio with 40% sterile glycerol (final 20% glycerol) in a sterile 15 mL tube and vortexed for 2 minutes. One mL of the organism-glycerol preparation was then aliquoted to sterile low-temperature cryovials and frozen at –80°C. A purity plate was set up with remaining organism-glycerol preparation.

Step 2: A single cryovial of each organism was thawed at room temperature and subsequently vortexed for 1 minute to homogenously resuspend organisms. The vial was

then serially diluted in PBS to $1:10^{10}$. One hundred μL of each dilution was plated in duplicate to sterile BHI plates using the spread plate method. Plates were incubated at 37°C overnight. Each dilution was evaluated for growth, and CFU per mL for the frozen stock was calculated.

Step 3: In order to make 10 mL of mixed organisms with a concentration of 7.5×10^7 CFU/mL, the volume of each individual organism to be mixed was calculated using the formula $(C1)(V1) = (C2)(V2)$. A sample table utilized to calculate organism mixtures is shown in Table 3. The media into which each organism was mixed was a 1:1 mixture of PBS in 40% glycerol (effective 20% glycerol) at the pre-determined final mixture volume.

Step 4: Once each organism was added to the PBS - glycerol solution, the tube was vortexed for 2 minutes. One mL aliquots were prepared and frozen at -80°C .

2.3 Preparation of Artificial Soils.

The artificial soils utilized in this protocol were: sterile phosphate buffered saline (PBS, the control soil), sterile artificial sweat, and sterile 5% serum in artificial sweat. All solutions were stored at 4°C .

An artificial sweat solution was prepared according to the European Standard EN 1800:2011 using sodium chloride, sodium hydroxide, urea, and lactic acid and pH adjusted to 6.5. To generate the serum in artificial sweat solution, sterile pooled human serum was added to an artificial sweat solution to a final concentration of 5%.

2.4 N-Halamine Fabric Synthesis.

The synthesis method for the N-halamine fabric has been previously published (Luo and Sun, 2006). In brief, free radicals were generated on the cotton cellulose backbone molecules in order to graft methacrylamide (MMA) onto the cotton cellulose fabric. Once MMA monomers are polymerized onto the fabric, a diluted bleach solution (pH 7) is used to convert some of the amide groups to N-halamines. Fabric was then washed 8-10 times in distilled water and allowed to dry in ambient air. The available chlorine content (% chlorine) of the fabric was determined by iodometric titration. The N-halamine fabric prepared for this study contained 5885 ± 98 ppm of active chlorine.

2.5 Test Procedure.

Rectangular swatches of control (untreated) and test (N-halamine) fabrics were cut to approximately $(6.0 \times 3.5 \text{ cm}) \pm 0.5 \text{ cm}$. One-ply fabric swatches were wrapped around non-absorbent $6.0 \times 3.5 \text{ cm}$ stainless steel coupons (Metal Samples Co, Munford, AL) and secured using two metal bobby pins (purchased at a local retailer). Assembled carriers were placed in glass petri plates (Fig. 1). Before use, assembled control fabric swatches and carriers were autoclaved.

A single test procedure includes a total of 4 test swatches: positive control (non-antimicrobial fabric with bacteria), negative control (antimicrobial fabric with no bacteria), and 2 tests (antimicrobial fabric with bacteria). The positive control and 2 test swatches were inoculated with 10 μL of the standardized bacterial suspension in selected soil (PBS,

artificial sweat, or 5% serum in artificial sweat) to the center of the fabric within the glass petri plate and incubated at room temperature for 15 minutes (15-minute contact time). The negative control was not inoculated with the microbial suspension.

The antimicrobial action of the fabric was stopped after 15 minutes by utilizing DE Neutralizing broth. All swatches were transferred using sterile forceps to individual 50 mL conical tubes containing 15 mL of neutralizing broth. The tubes were incubated at room temperature for 10 minutes with constant agitation on a wrist action shaker.

The neutralizing broth for each fabric swatch was serially diluted in sterile 1x PBS, and 100 μ L of each dilution was plated in duplicate to BHI agar. Following overnight incubation at 37°C, plates were evaluated visually for growth and colonies counted. All runs were performed in duplicate. Average percent and log₁₀ reductions in comparison to the positive control were calculated. T-tests were performed in JMP® (SAS® Software) to determine statistical significance between non-antimicrobial cotton cellulose and N-halamine fabric performance. Antimicrobial textiles that achieved 3.00 log₁₀ reduction (99.9%) in all soils were considered appropriate for use in the healthcare setting (EPA, 2012).

3 RESULTS

3.1 Organism Growth and Reproducibility in the Test Procedure.

The testing protocol was successful in producing both adequate colony growth of all single and mixtures of organisms and the soils had no impact on the growth of the microorganisms. For single organism runs, the procedure consistently generated growth of every organism attempted. Each run was performed in duplicate and quantity of growth was consistent between associated pairs of plates. For runs that involved mixtures of organisms, the procedure consistently generated growth of each representative colony type in approximately equivalent concentrations. The maximum number of organisms attempted with this procedure was five. Each mixture run was also performed in duplicate, and representative colonies from each organism in the mixture were comparable in quantity between associated pairs of plates. Fig. 2 shows plate replicates with A) normal flora and MRSA and B) normal flora and *E. coli*. Colony morphologies were easily distinguishable and can be confirmed utilizing a Gram stain.

Frozen aliquot preparation generated the desired volume of broth containing approximately equivalent CFU/mL of each representative organism. Freezing aliquots of mixtures, i.e. “frozen stocks,” of organisms as outlined in the procedure successfully allowed for thawing and utilization of the organism mixtures in future experiments. Organism growth between subsequent freeze-thaw cycles was consistent between runs, and reliably generated plates with countable colonies of representative organisms. Fig. 3 displays plate images for all mixtures.

3.2 Single Organism Reductions.

Overall, there was a statistically significant reduction in all organisms on the N-halamine fabric after 15 minutes of contact in the presence of all soils ($P<0.05$) (Table 4). All organisms were reduced by 3.00 log₁₀ or greater, and the combined average reduction for

all organisms was 4.91 log₁₀ (99.9581%). When separated by soil type, the overall average log₁₀ reductions were 5.10 for PBS, 4.86 for artificial sweat, and 4.78 for 5% serum (Table 5). No statistical significance was found between soil types ($P>0.05$).

3.3 Mixed Organism Reductions.

Mixtures containing the 4 representative normal flora organisms, with and without an additional pathogen, were tested against the N-halamine fabric with a 15-minute contact time. Overall, there was a statistically significant reduction in all organisms in the mixtures on the N-halamine fabric in the presence of all soils ($P<0.05$) (Table 6). All organisms were reduced by 4.00 log₁₀ or greater, and the overall average log₁₀ reduction for all mixtures was 4.86. When separated by soil type, the overall average log₁₀ reductions were 4.86 for PBS, 5.03 for artificial sweat, and 4.86 for 5% serum (Table 7). No statistical significance was found between soil types ($P>0.05$). Fig. 4 shows scanning electron micrograph images of untreated control and N-halamine fabric with the normal flora mix plus *C. albicans*.

4 DISCUSSION

Despite improved hygiene practices and dynamic infection prevention programs, the transmission of microorganisms in the healthcare setting remains of great concern. It is well documented that soft surfaces in the healthcare setting, particularly fabric, are contaminated with pathogens, and therefore play a role in the chain of infection, including the transfer of microbes from fabric to human skin (Boutin et al., 2014; Koca et al., 2012; Lopez-Gigosos et al., 2014; Nordstrom et al., 2012; Scott et al., 2015). Incorporating antimicrobial soft surfaces in the healthcare setting can serve as an engineering control to reduce the spread of HAIs. While there are several published standards for antimicrobial efficacy testing, none account for the dynamic environment in the healthcare setting. In this study we present a more comprehensive testing method to evaluate textile performance against a number of important HAI causing microbes, including bacteria and fungi, as well as interfering soils, including sweat and serum. We also present the performance of a novel rechargeable, monitorable N-halamine fabric using this protocol (Luo and Sun, 2006).

While there are several published standards that evaluate the efficacy of antimicrobial textiles, those standards do not reflect exposures to microorganisms in a realistic setting, evaluating the activity against single organisms only in near perfect conditions, and supplying the test organisms with nutrients in a high-level of moisture for up to 24 hours of contact with the antimicrobial agent. Ideally, antimicrobial textiles should exert effects rapidly, over brief periods of time, and should be tested in conditions that mimic in-use conditions as much as possible. While testing the fabric against individual organisms is valuable, it is important to also challenge the fabric against a combination of microbes as textiles are in close contact with skin, which hosts a myriad of microbes. Furthermore, the addition of common soils that may decrease the activity or deactivate the antimicrobial property all together should be incorporated into testing algorithms.

A unique characteristic of this method is that it specifically evaluates healthcare-specific antimicrobial textiles in simulated in-use conditions. Many antimicrobial fabrics are intended for use in clothing such as scrubs and lab coats, as well as other soft surfaces

such as bed linens, privacy curtains, and upholstered furniture. These fabrics may have direct contact with human skin, pathogens, as well as exposure with organic soils such as blood and other body fluids. The current methods used to test the efficacy of antimicrobial materials do not fully address the potential impact of organic soils, nor do they take into account the human skin environment, including sweat and normal skin microorganisms. The fabrics currently worn by healthcare workers are in close contact with their own skin as well as that of their patients. It is unknown how a diverse microbial environment impacts the performance of antimicrobial soft surfaces. No studies exist that evaluate the performance of antimicrobial fabrics in the presence of these factors. This more extensive testing provides a more rigorous performance evaluation, enabling a better understanding of antimicrobial efficacy by including commonly encountered pathogens in the presence of normal flora and soils with potential to alter the performance of the fabric.

We also report a reproducible method for mixing organisms at relatively equal concentrations. By freezing mixtures in large batches, testing parties will minimize inter-run variability. While the method as presented focuses on the skin and healthcare environment, it is designed to be flexible. Depending on where the antimicrobial textile will be implemented, the organism types and concentration can easily be altered, as well as adjusting soils and contact time.

A cut off of $3.0 \log_{10}$ (99.9%) was used as the pass-fail criteria for the soft surfaces utilized in this study. In the absence of guidelines for soft surface \log_{10} and percent reductions, the cut off of $3.0 \log_{10}$ (99.9%) was chosen based on the existing EPA product performances guidelines for evaluating disinfection of hard surfaces embedded with antimicrobials (EPA 2012).

To date, the N-halamine cotton cellulose fabric is the first antimicrobial fabric fully tested with the proposed more comprehensive antimicrobial efficacy test method. Since it has been reported that “clean” service textiles can be contaminated within hours we chose 15 minutes as the contact time to challenge the fabric (Burden et al., 2011; Mitchell et al., 2015; Ohl et al., 2012). Overall, the N-halamine fabric was highly effective at reducing the number of microorganisms within 15 minutes, with an average \log_{10} reduction of 4.93 (99.9757% reduction) of microbial load for all runs, including individual organisms and organism mixtures, in all 3 soils. The antimicrobial fabric did not show variability between soils, indicating that sweat and proteinaceous serum do not impede the action of the N-halamine at the concentrations tested.

The organisms tested comprised a broad spectrum of organisms, including Gram-positive bacteria, Gram-negative bacteria, and yeast. Furthermore, the fabric was able to kill multiple organism populations simultaneously, which is most representative of real-world application. When testing the fabric against individual organisms, the N-halamine was able to reduce or completely eliminate major HAI-causing microorganisms, including antibiotic resistant and encapsulated strains. When testing against single organisms, the fabric performed best against Gram-negative organisms, *A. lwoffii*, *A. baumannii*, *E. coli*, and *P. aeruginosa*. The average \log_{10} reduction for Gram-negative organisms was 4.96 (>99.99% reduction). Among all organisms tested, Gram-positives, namely *Staphylococcus* spp., were the most

challenging to eliminate. This is consistent with previously published data regarding the differences between Gram-positive and –negative bacteria in their susceptibility to antimicrobial agents and disinfectants (Santos et al., 2016). Generally, the Gram-positive bacteria have a thicker cell wall, which has been suggested to provide an enhanced level of protection against the penetration of agents.

When tested against mixed organism, a 100% reduction was achieved with all mixes. The improved performance may be due to organism concentrations: all runs, mixed and single, were performed with approximately 5.00 log₁₀ of bacteria applied to the fabric. However, in the mixtures, each bacterial species was at a lower concentration, therefore improving the ability of the fabric to kill each individual species. In healthcare applications, mixed bacterial populations are highly likely.

It is important to note that the N-halamine fabric significantly reduced organisms classified as normal skin flora, both individual strains and in mixtures. Therefore, there are limitations surrounding implementation of this fabric into everyday-use soft surfaces that will be in close contact with the skin, as this may negatively impact the dynamic and critical skin microbiome. Previously published data regarding long-term topical antimicrobial treatment showed shifts in residential flora, and ultimately reduced healthy skin flora critical for preventing the colonization of opportunistic or pathogenic microbes (SanMiguel et al., 2017). There are also occasions when normal skin flora, *S. epidermidis* in particular, can cause serious nosocomial infections, particularly in individuals with indwelling devices (Gomes et al., 2014; SanMiguel et al., 2017). Such circumstances include: immunocompromised, chronic indwelling catheters or chest tubes, other percutaneous catheters, mechanical ventilation, chronic wounds, and burns. Therefore, in these circumstances it might be advantageous to reduce the number of normal flora organisms to prevent serious infections. A possible means of doing so would be incorporating N-halamine based textiles into bandages, tapes and other coverings that occlude the sites of percutaneous infection or utilizing N-halamine fabric for bed linens and wound bandages. Further study is required in order to determine how the N-halamine fabric would alter skin microbiome in otherwise healthy individuals.

These data suggest that this technology has the potential to greatly reduce the bioburden of microbial populations on textiles quickly, and therefore is a strong candidate for implementation in the healthcare setting. It could also be valuable to incorporate N-halamine antimicrobial soft surfaces into high touch areas within high-risk patient accommodations, such as operating rooms and precaution rooms. N-halamine based textiles can be incorporated into privacy curtains, bed linens, as well as precaution gowns.

There are several unique advantages to utilizing N-halamine based textiles over others currently commercially available. N-halamine based antimicrobial fabrics possess many appealing characteristics, especially for healthcare soft surfaces. N-halamine fabrics can be grafted to several types of textiles, including cotton cellulose and polyester. The concentration of chlorine can be controlled based on the MAA graft, remaining activity can be monitored, and it can be recharged once the chlorine is consumed, as previously

reported (Luo and Sun, 2006). Most importantly for healthcare textiles, N-halamine is a quick acting antimicrobial with a broad spectrum of bactericidal activity.

There are limitations to this study. The lack of a recognized minimum standard for antimicrobial fabric performance is problematic for all efficacy protocols. In addition, the ideal bacterial and soil concentrations are unknown. Future studies should address the level of contamination and organism concentrations found in healthcare settings, as well as performance of other types of antimicrobial textiles. Additional microbes that should be tested may include more resistant bacteria such as vancomycin-intermediate and vancomycin-resistant *S. aureus* (VISA and VRSA), carbapenem-resistant Enterobacteriaceae (CRE), and *Candida auris*, an emerging multi-drug resistant yeast. We also suggest the inclusion of spore-forming microorganisms and their corresponding spores, such as *Clostridioides difficile*. Additional interfering soils may help better characterize antimicrobial fabrics, particularly those intended for use in the healthcare setting. Suggested soils include whole blood, sebum, urine, and feces. The N-halamine fabric should be tested at different chlorine concentrations to determine the most effective level, and samples should be tested following multiple laundering and recharge cycles to determine the lifespan of the fabric.

This novel, quantitative method provides a more realistic challenge for textiles intended for use in the healthcare setting by utilizing HAI-causing microbes as challenge organisms, as well as mixtures of microorganisms. Additionally, this method includes potentially inhibiting factors, such as sweat and serum, to aid in qualifying the real-world effectiveness of antimicrobial textiles. Based on the overall performance of the fabric with the novel efficacy method, the rechargeable, monitorable N-halamine based fabric is a strong candidate for implementation into healthcare soft surfaces.

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REFERENCES

- Adlhart C, Verran J, Azevedo NF, Olmez H, Keinänen-Toivola MM, Gouveia I, Melo LF, Crijns F., 2018. Surface Modifications For Antimicrobial Effects in the Healthcare Setting: A Critical Overview. *J Hosp Infect* 99:239–249. 10.1016/j.jhin.2018.01.018. [PubMed: 29410096]
- Ahonen M, Kahru A, Ivask A, Kasemets K, Kõljalg S, Mantecca P, Vinkovic Vreck I, Keinänen Toivola MM, Crijns F., 2017. Proactive Approach for Safe Use of Antimicrobial Coatings in Healthcare Settings: Opinion of the COST Action Network AMICI. *Int J Environ Res Public Health* 14:E366. 10.3390/ijerph14040366. [PubMed: 28362344]
- AATCC 100:2011(2016e), 2016. Test Method for Antibacterial Activity of Textile Materials: Parallel Steak. American Association of Textile Chemists and Colorists.
- AATCC 147:2019, 2019. Test Method for Antibacterial Finishes on Textile Materials: Assessment of. American Association of Textile Chemists and Colorists
- Boutin MA, Thom KA, Zhan M, Johnson JK., 2014. A randomized crossover trial to decrease bacterial contamination on hospital scrubs. *Infect Control Hosp Epidemiol* 35:1411–1413. 10.1086/678426. [PubMed: 25333437]

- Burden M, Cervantes L, Weed D, Keniston A, Price CS, Albert RK., 2011. Newly cleaned physician uniforms and infrequently washed white coats have similar rates of bacterial contamination after an 8-hour workday: a randomized controlled trial. *J Hosp Med* 6:177–182. 10.1002/jhm.864 [PubMed: 21312328]
- Burden M, Keniston A, Frank MG, Brown CA, Zoucha J, Cervantes L, Weed D, Boyle K, Price C, Albert RK., 2013. Bacterial contamination of healthcare workers' uniforms: a randomized controlled trial of antimicrobial scrubs. *J Hosp Med* 8:380–385. 10.1002/jhm.2051. [PubMed: 23757125]
- Du ZY, Zhang MX, Shi MH, Zhou HQ, Yu Y., 2017. Bacterial contamination of medical uniforms: a cross-sectional study from Suzhou city, China. *J Pak Med Assoc* 67:1740–1742. [PubMed: 29171571]
- Dunne CP, Keinänen-Toivola MM, Kahru A, Teunissen B, Olmaz H, Gouveia I, Melo L, Murzyn K, Modic M, Ahonen M, Askew P, Papadopoulos T, Adlhart C, Crijns FRL., 2017. Anti-microbial coating innovations to prevent infectious diseases (AMiCI): Cost action ca15114. *Bioengineered* 8:679–685. 10.1080/21655979.2017.1323593. [PubMed: 28453429]
- EPA, 2012. Product Performance Test Guidelines: OPPTS, in Sanitizers for Use on Hard Surfaces - Efficacy Data Recommendations. United States Environmental Protection Agency: National Service Center for Environmental Publications (NSCEP).
- Gomes F, Teixeira P, Oliveira R., 2014. Mini-review: *Staphylococcus epidermidis* as the most frequent cause of nosocomial infections: old and new fighting strategies. *Biofouling* 30:131–141. 10.1080/08927014.2013.848858. [PubMed: 24283376]
- Koca O, Altöparlak U, Ayyıldız A, Kaynar H., 2012. Persistence of nosocomial pathogens on various fabrics. *Eurasian J Med* 44:28–31. 10.5152/eajm.2012.06. [PubMed: 25610201]
- Kramer A, Schwebke I, Kampf G., 2006. How long do nosocomial pathogens persist on inanimate surfaces? A systematic review. *BMC Infect Dis* 6:130. 10.1186/1471-2334-6-130. [PubMed: 16914034]
- Lopez-Gigosos R, Mariscal A, Gutierrez-Bedmar M, Mariscal-Lopez E, Fernandez-Crehuet J., 2014. Persistence of nosocomial bacteria on 2 biocidal fabrics based on silver under conditions of high relative humidity. *Am J Infect Control* 42:879–884. 10.1016/j.ajic.2014.04.019. [PubMed: 24930955]
- Luo J, Sun Y., 2006. Acyclic N-halamine-Based Fibrous Materials: Preparation, Characterization, and Biocidal Functions. *Journal of Polymer Science, Part A, Polymer Chemistry* 44:3358 – 3600. 10.1002/pola.21465.
- Mitchell A, Spencer M, Edmiston C Jr., 2015. Role of healthcare apparel and other healthcare textiles in the transmission of pathogens: a review of the literature. *J Hosp Infect* 90:285–292. 10.1016/j.jhin.2015.02.017. [PubMed: 25935701]
- Morais DS, Guedes RM, Lopes MA., 2016. Antimicrobial Approaches for Textiles: From Research to Market. *Materials (Basel)* 9:E498. 10.3390/ma9060498. [PubMed: 28773619]
- Nordstrom JM, Reynolds KA, Gerba CP., 2012. Comparison of bacteria on new, disposable, laundered, and unlaundered hospital scrubs. *Am J Infect Control* 40:539–43. 10.1016/j.ajic.2011.07.015. [PubMed: 22177668]
- Ohl M, Schweizer M, Graham M, Heilmann K, Boyken L, Diekema D., 2012. Hospital privacy curtains are frequently and rapidly contaminated with potentially pathogenic bacteria. *Am J Infect Control* 40:904–906. 10.1086/678426. [PubMed: 22464039]
- Pinho E, Magalhaes L, Henriques M, Oliveira R., 2011. Antimicrobial activity assessment of textiles: standard methods comparison. *Annals of Microbiology* 61:493–498. 10.1007/s13213-010-0163-8.
- SanMiguel AJ, Meisel JS, Horwinski J, Zheng Q, Grice EA., 2017. Topical antimicrobial treatments can elicit shifts to resident skin bacterial communities and reduce colonization by *Staphylococcus aureus* competitors. *Antimicrob Agents Chemother* 61: e00774–17. 10.1128/AAC.00774-17. [PubMed: 28630195]
- Sanon MA, Watkins S., 2012. Nurses' uniforms: How many bacteria do they carry after one shift? *J Public Health Epidemiol* 4:311–315. 10.5897/JPHE12.074. [PubMed: 25285235]
- Santos MRE, Fonseca AC, Mendonca PV, Banco R, Serra AC, Morais PV, Coelho JFJ., 2016. Recent Developments in Antimicrobial Polymers: A Review. *Materials (Basel)* 9:E599. 10.3390/ma9070599. [PubMed: 28773721]

- Sattar SA, Springthorpe S, Mani S, Gallant M, Nair RC, Scott E, Kain J., 2001. Transfer of bacteria from fabrics to hands and other fabrics: development and application of a quantitative method using *Staphylococcus aureus* as a model. *Journal of Applied Microbiology* 90:962–970. 10.1046/j.1365-2672.2001.01347.x [PubMed: 11412326]
- Scott E, Goodyear N, Nicoloro JM, Marika DJ, Killion E, Duty SM., 2015. Laundering habits of student nurses and correlation with the presence of *Staphylococcus aureus* on nursing scrub tops pre- and postlaundering. *Am J Infect Control* 43:1006–1008. 10.1016/j.ajic.2015.05.007. [PubMed: 26143576]
- Sun X, Cao Z, Porteous N, Sun Y., 2012. An N-halamine-based rechargeable antimicrobial and biofilm controlling polyurethane. *Acta Biomater* 8:1498–1506. 10.1016/j.actbio.2011.12.027 [PubMed: 22244984]
- Treake AM, Thom KA, Furuno JP, Strauss SM, Harris AD, Perencevich EN., 2009. Bacterial contamination of health care workers' white coats. *Am J Infect Control* 37:101–105. 10.1016/j.ajic.2008.03.00 [PubMed: 18834751]
- Wiener-Well Y, Galuty M, Rudensky B, Schlesinger Y, Attias D, Yinnon AM., 2011. Nursing and physician attire as possible source of nosocomial infections. *Am J Infect Control* 39:555–559. 10.1016/j.ajic.2010. [PubMed: 21864762]

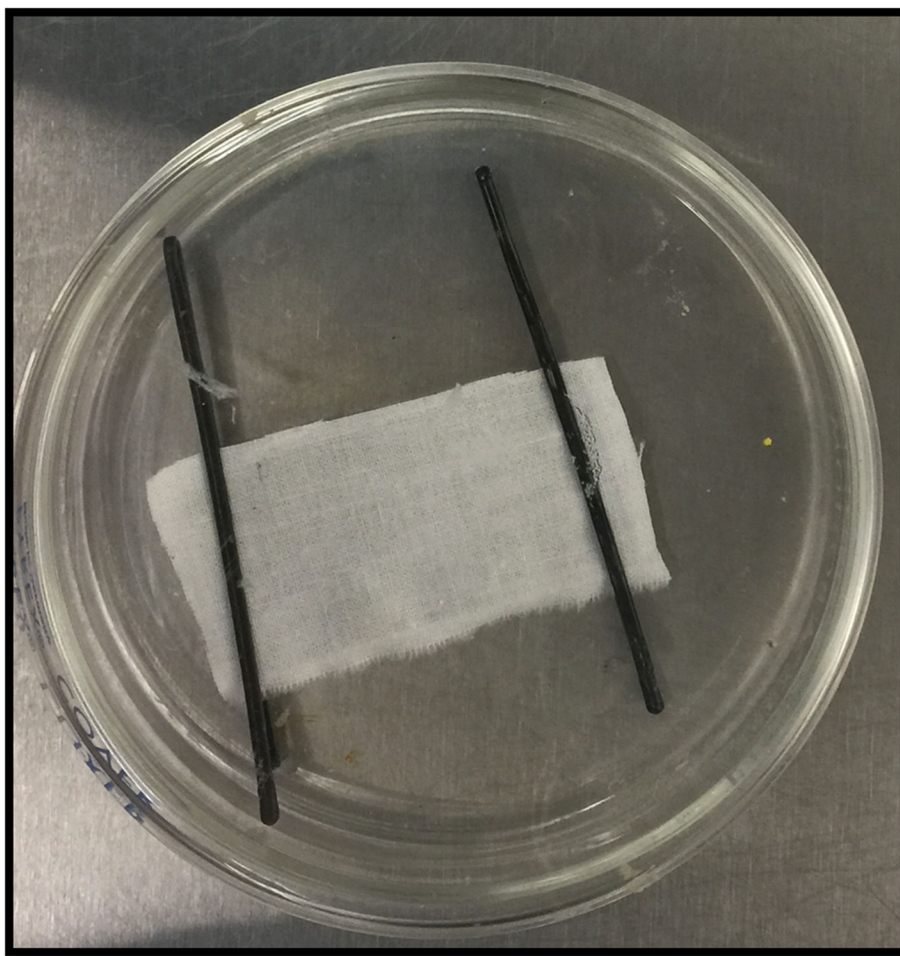


Fig. 1.
Fabric assembly for testing. Fabric swatch is wrapped around a 6.0 x 3.5 cm stainless steel coupon and fastened with bobby pins. The entire assembly is within a sterile glass petri dish.

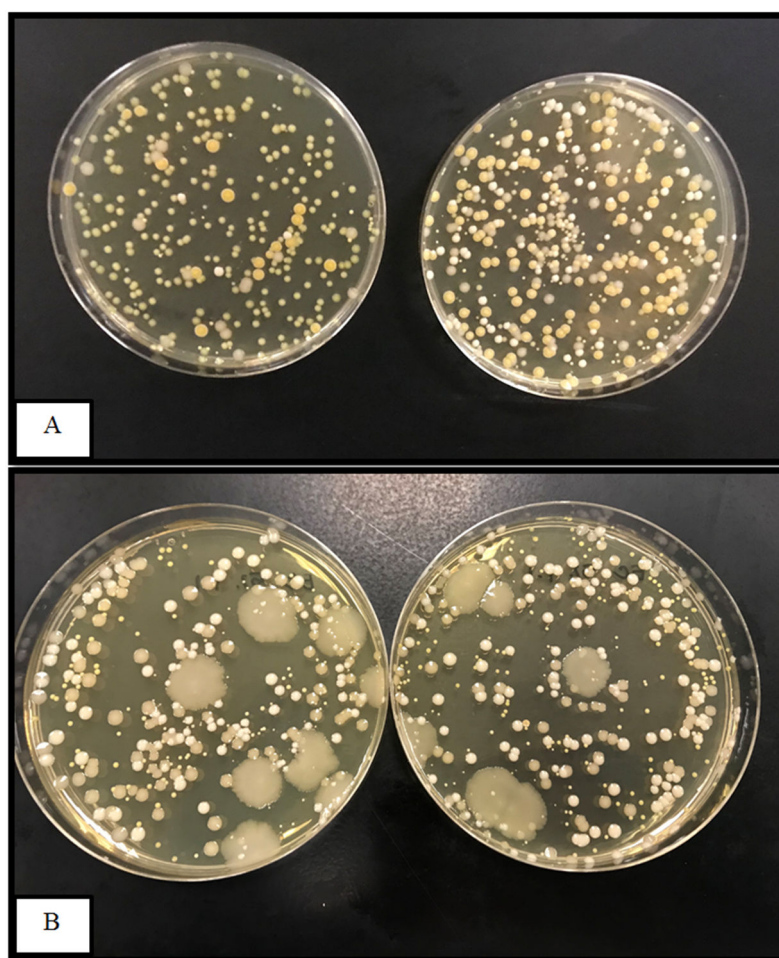


Fig. 2. Mixture plate replicates after one freeze-thaw cycle: A) Normal flora and MRSA, B) Normal flora and *E. coli*.

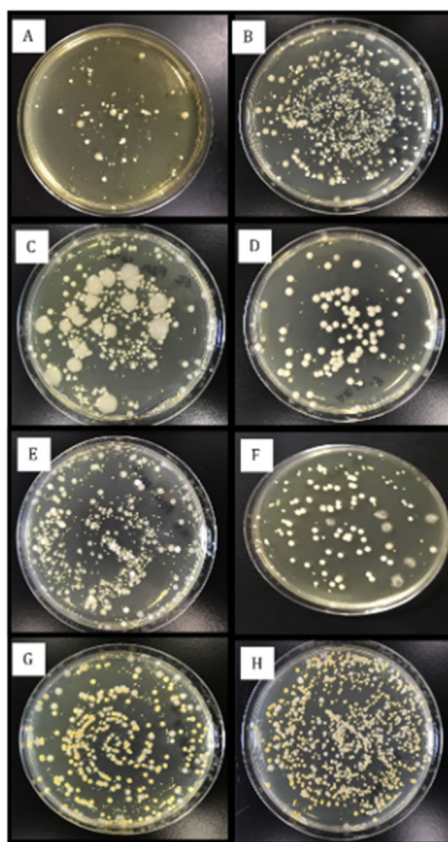


Fig. 3. Plate images of single pathogens with normal flora mixtures (A. *Iwoffii*, *C. striatum*, *M. luteus*, *S. epidermidis*). Pathogens: A: No pathogen, B: *C. albicans*, C: *E. coli*, D: *A. baumannii*, E: VRE, F: *P. aeruginosa*, G: MSSA, H: MRSA.

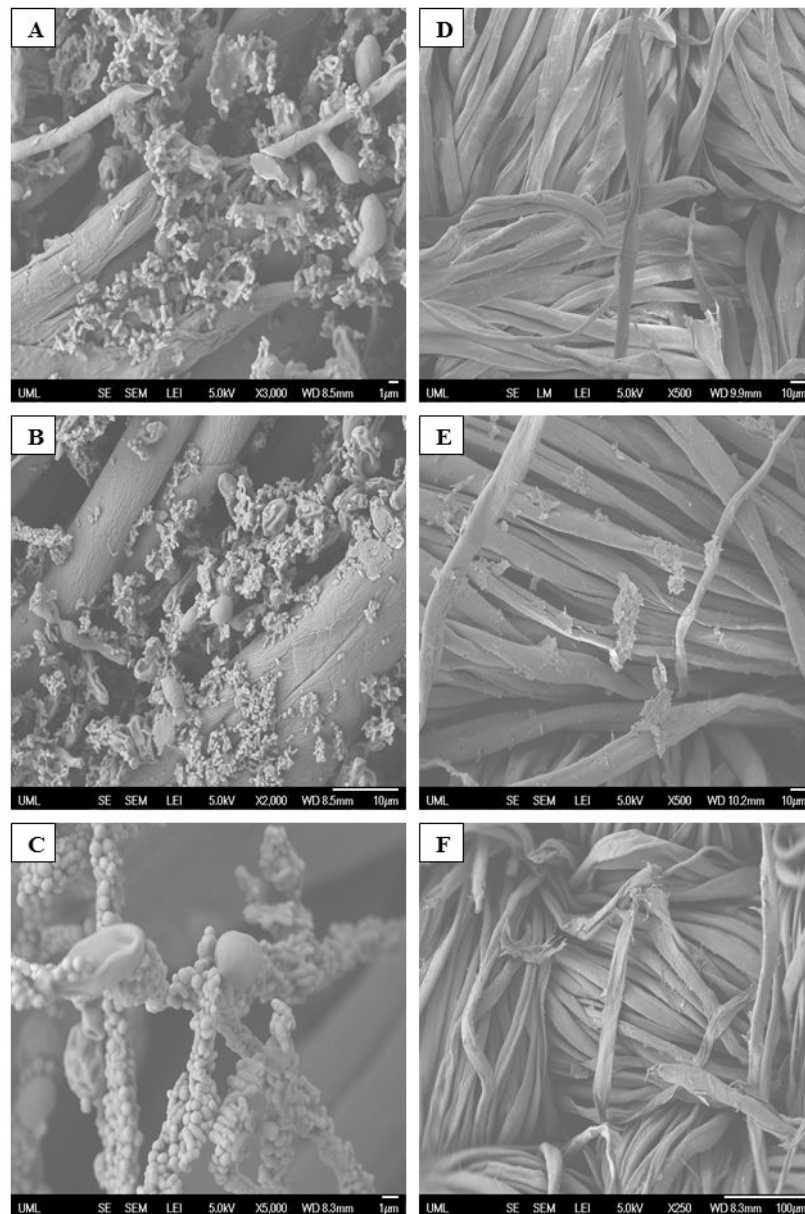


Fig. 4.
SEM Images of untreated cotton cellulose fabric (A, B, C) vs. N-halamine treated fabric after exposure to normal flora mixture + *C. albicans* (D, E, F).

Table 1

Summary of major antimicrobial agents utilized in antimicrobial textiles.

Antimicrobial Agent	Mode of Action	Fibers
Chitosan	Low molecular weight: inhibits mRNA synthesis, impacting protein synthesis High molecular weight: blocks transport of essential solutes into the cell	Cotton, Polyester, Wool
Metals and Metallic Salts	Generates reactive oxygen species Damages cellular proteins, lipids, and DNA	Cotton, Polyester, Nylon, Wool
N-halamine	Interferes with critical cellular enzymes and metabolic processes	Cotton, Polyester, Nylon, Wool
Polyhexamethylene Biguanide (PHMB)	Disrupts integrity of cell membrane	Cotton, Polyester, Nylon
Quaternary Ammonium Compounds	Damages cell membranes, denatures proteins, and inhibits DNA synthesis	Cotton, Polyester, Nylon, Wool
Triclosan	Blocks lipid synthesis and disrupts cell membrane	Polyester, Nylon, Polypropylene, Cellulose Acetate, Acrylic

Table 2

Summary of existing antimicrobial textile testing standards.

Reference	Principle	Summary
AATCC 147	Qualitative	Agar plates are inoculated with 5 parallel streaks of <i>K. pneumoniae</i> or <i>S. aureus</i> . Textile test swatch placed in direct contact with surface of agar and incubated for 24 hours. Activity assessed by zone of inhibition over 5 streaks or absence of growth directly behind fabric swatch.
AATCC 100	Quantitative	Multiple textile test and control swatches are inoculated with 1 mL overnight growth of <i>K. pneumoniae</i> or <i>S. aureus</i> in nutrient broth and incubated at 37°C for 24 hours. Comparing the viable cell count from control to test swatch assesses activity.
JIS L 1902 Halo-Method	Qualitative	Molten nutrient agar is inoculated with a suspension of <i>K. pneumoniae</i> or <i>S. aureus</i> , added to sterile petri plates, and allowed to solidify. Fabric is placed in direct contact with surface of agar and incubated overnight at 37°C for 24-48 hours. Activity is assessed by zone of inhibition around fabric swatches.
JIS L 1902	Quantitative	Control and test swatches are incubated with <i>K. pneumoniae</i> or <i>S. aureus</i> suspended in heavily diluted nutrient medium. Samples are incubated at 37°C for specific contact time. Antimicrobial activity is assessed by comparing the viable cell count from control to the test swatch. No neutralizer is applied. Pass – fail criteria provided.
ISO 20645	Qualitative	Molten nutrient agar is inoculated with a suspension of <i>E. coli</i> , <i>K. pneumoniae</i> , or <i>S. aureus</i> , added to a sterile petri plates, and allowed to solidify. Four test fabric swatches are placed in direct contact with a separate sterile nutrient agar plate. Fabric samples are then overlaid with inoculated petri plate. Plates are incubated for 18-24 hours. Activity is assessed with zone of inhibition in overlaying petri plate.
ISO 20743	Quantitative	Three test and control swatches are inoculated with pure <i>K. pneumoniae</i> or <i>S. aureus</i> suspended heavily diluted nutrient medium. Swatches are incubated at 37°C for 18-24 hours. Antimicrobial activity is assessed by comparing the viable cell count from control to the test swatch. No neutralizer is applied. Pass – fail criteria provided.
ASTM E2149	Quantitative	<i>K. pneumoniae</i> in nutrient broth is diluted in sterile buffer to standardize starting inoculum, and added to sterile jars. Control and test swatches are added to jars and agitated for 1 hour. Antimicrobial activity is assessed by comparing the viable cell count before and after contact time.

Table 3

Example of a calculation table utilized to generate mixtures of microorganisms.

Organism	C1 Stock Titer (in 1 mL)	V1 Volume Required of Each Stock (mL)	C2 Desired Final Concentration (CFU/mL)	V2 Desired Final Volume (mL)
<i>A. lwoffii</i>	2.90×10^{10}	1.29×10^{-2}	1.50×10^7	25
<i>C. striatum</i>	5.95×10^8	6.30×10^{-1}	1.50×10^7	25
<i>M. luteus</i>	1.50×10^9	2.50×10^{-1}	1.50×10^7	25
<i>S. epidermidis</i>	7.70×10^9	4.87×10^{-2}	1.50×10^7	25
<i>C. albicans</i>	4.70×10^8	7.98×10^{-1}	1.50×10^7	25

Table 4

Overall average log₁₀ and percent reductions for individual organisms after a 15 minute contact time with the N-halamine fabric. All averages include artificial soils PBS, artificial sweat, and 5% serum in artificial sweat.

Organism	Log ₁₀ Reduction	Percent Reduction
<i>Acinetobacter baumannii</i>	5.37	100.0000
<i>Acinetobacter Iwoffii</i>	4.87	100.0000
<i>Corynebacterium striatum</i>	3.64	100.0000
<i>Candida albicans</i>	4.84	99.9993
<i>Enterococcus faecalis</i> (VRE)	6.76	100.0000
<i>Escherichia coli</i>	5.17	99.9968
<i>Micrococcus luteus</i>	4.29	100.0000
<i>Pseudomonas aeruginosa</i>	4.41	100.0000
<i>Staphylococcus aureus</i> (MSSA)	3.90	99.6479
<i>Staphylococcus aureus</i> (MRSA)	6.38	100.0000
<i>Staphylococcus epidermidis</i>	4.36	99.8952

Table 5

Average log₁₀ reduction and percent reduction for individual organisms by matrix and statistical significance of soil.

Organism	Soil	Log ₁₀ Reduction	Percent Reduction	P-Value
<i>A. lwoffii</i>	PBS	4.19	100.0000	0.0005
	Art. Sweat	3.98	100.0000	0.0032
	5% Serum	6.48	100.0000	0.0001
<i>C. striatum</i>	PBS	3.64	100.0000	0.0089
	Art. Sweat	3.84	100.0000	0.0344
	5% Serum	3.46	100.0000	0.0147
<i>M. luteus</i>	PBS	4.52	100.0000	0.0006
	Art. Sweat	4.55	100.0000	0.0004
	5% Serum	3.80	100.0000	0.0086
<i>S. epidermidis</i>	PBS	4.83	99.9877	0.0020
	Art. Sweat	4.91	99.9917	0.0087
	5% Serum	3.34	99.7061	0.0378
<i>A. baumannii</i>	PBS	5.81	100.0000	0.0212
	Art. Sweat	5.19	100.0000	0.0043
	5% Serum	5.11	100.0000	0.0002
<i>C. albicans</i>	PBS	5.61	99.9980	0.0038
	Art. Sweat	4.46	100.0000	0.0003
	5% Serum	4.47	100.0000	0.0001
<i>E. faecalis</i> (VRE)	PBS	6.46	100.0000	0.0063
	Art. Sweat	7.53	100.0000	0.0001
	5% Serum	6.29	100.0000	0.0002
<i>E. coli</i>	PBS	5.18	100.0000	0.0046
	Art. Sweat	5.58	100.0000	0.0020
	5% Serum	4.76	99.9903	0.0232
<i>P. aeruginosa</i>	PBS	5.29	100.0000	0.0044
	Art. Sweat	3.91	100.0000	0.0015
	5% Serum	4.04	100.0000	0.0002
<i>S. aureus</i> (MSSA)	PBS	4.33	100.0000	0.0042
	Art. Sweat	3.05	98.9534	0.0019
	5% Serum	4.33	99.9903	0.0042
<i>S. aureus</i> (MRSA)	PBS	6.27	100.0000	0.0286
	Art. Sweat	6.43	100.0000	0.0090
	5% Serum	6.45	100.0000	0.0001

Table 6

Overall average log₁₀ and percent reductions for normal flora plus pathogen mixtures after a 15 minute contact time with the N-halamine fabric. All averages include artificial soils PBS, artificial sweat, and 5% serum in artificial sweat.

Organisms	Log ₁₀ Reduction	Percent Reduction
Normal Flora Mixture	5.11	100.0000
Normal Flora + <i>A. baumannii</i>	5.03	100.0000
Normal Flora + <i>C. albicans</i>	4.91	100.0000
Normal Flora + <i>E. coli</i>	4.89	100.0000
Normal Flora + <i>E. faecalis</i> (VRE)	4.68	100.0000
Normal Flora + <i>S. aureus</i> (MSSA)	4.92	100.0000
Normal Flora + <i>S. aureus</i> (MRSA)	5.03	100.0000
Normal Flora + <i>P. aeruginosa</i>	5.08	100.0000

Table 7

Average log₁₀ and percent reduction for normal flora plus pathogen mixtures by matrix and statistical significance of soil.

Organisms	Soil	Log ₁₀ Reduction	Percent Reduction	P-Value
Normal Flora Mixture	PBS	5.36	100.0000	0.0001
	Art. Sweat	5.51	100.0000	0.0001
	5% Serum	4.46	100.0000	0.0032
Normal Flora + <i>A. baumannii</i>	PBS	4.68	100.0000	0.0012
	Art. Sweat	5.25	100.0000	0.0003
	5% Serum	5.15	100.0000	0.0015
Normal Flora + <i>C. albicans</i>	PBS	4.67	100.0000	0.0085
	Art. Sweat	4.99	100.0000	0.0014
	5% Serum	5.07	100.0000	0.0004
Normal Flora + <i>E. coli</i>	PBS	4.91	100.0000	0.0029
	Art. Sweat	4.96	100.0000	0.0009
	5% Serum	4.80	100.0000	0.0023
Normal Flora + VRE	PBS	4.94	100.0000	0.0013
	Art. Sweat	4.38	100.0000	0.0008
	5% Serum	4.74	100.0000	0.0015
Normal Flora + <i>P. aeruginosa</i>	PBS	4.76	100.0000	0.0048
	Art. Sweat	5.19	100.0000	0.0018
	5% Serum	4.29	100.0000	0.0014
Normal Flora + MSSA	PBS	4.73	100.0000	0.0007
	Art. Sweat	5.08	100.0000	0.0013
	5% Serum	4.96	100.0000	0.0023
Normal Flora + MRSA	PBS	4.81	100.0000	0.0055
	Art. Sweat	4.88	100.0000	0.0006
	5% Serum	5.40	100.0000	0.0066