Antimicrobial Textiles for Long Duration Space Flight

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Antimicrobial Textiles for Long Duration Space Flight

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Objective

The review that follows was performed with the objective of contributing to the development, methodology and evaluation analysis of developing antimicrobial textiles for long duration space flight (LDSF) of which there has been little study. This is of much importance as the study of microbiomes in space travel is still limited and there are no mechanisms available for efficiently washing clothes during space travel. The current launch costs for space travel are high (approx. $10,000 per pound) so the weight of clothes needs to be carefully allocated for at least three years of travel to mars. This study is a comprehensive literature review and each chapter discusses antimicrobial textiles that has application in many fields like medical, military, sports and a some in space. The risks pertaining to the use of antimicrobial textiles and their effect on humans are also identified in this review. This study will help in finding a way to use antimicrobial textiles in space to minimize the need for washing garments. Garments in space are worn for longer and only fewer garments are taken on a mission due to the lack of laundry capabilities. Antimicrobial textiles in medical, military, sports and space-travel use are compared and summarized for uses and functions in this study.

Introduction to Antimicrobials

The presence of antimicrobial textile goods in the market is now greater due to growing consumer demand for hygienic clothing that does not compromise safety, comfort and sustainability. These textiles also address the challenges of spreading infections. The global antimicrobial coatings market in 2012 was $1.5 billion and is estimated to reach $2.9 billion by 2018, growing at a compound annual rate of 11.8% from 2013 to 2018 under normal conditions (Thilagavathi & Viju, 2016)
Textiles serve as a good medium for the proliferation and survival of microbes due to their moisture retaining properties. Microbes grow slower in synthetic fibers when compared to natural fibers since the synthetics are hydrophilic, but human perspiration held in the interstices encourages microbes to grow. This results in health issues, bad odors, and fabric damage like discoloration and loss of tensile properties. (Wasif & Laga, 2009) Requirements of antimicrobial agents are low toxicity to the human body, cost effectiveness, eco-friendliness, and good durability in laundering that does not affect the quality of the product. They should also not affect the skin microflora that fight against pathogens. (Nayak & Padhye, 2015)

Antimicrobial agents can be either biostatic that inhibit the growth of microorganisms or biocides that kill the microorganisms. The mechanism of these agents is a leaching mechanism (controlled release) which involves the gradual release of the agent from the reservoir into the textiles. The regenerated or bonded antimicrobials are molecularly bound by covalent bonding to the textile material. This unlimited reservoir agent is released to become biocidal during actions like laundry. There are also coatings that perform barrier antimicrobial mechanism that act as physical barrier between fabric and microbes. (Nayak & Padhye, 2015) There are also different methods of coating antimicrobial agents to the textiles. They are pad-dry-cure process, sol-gel coating, microencapsulation, enzyme immobilization, crosslinking process, layer by layer deposition and polymerization grafting. (Nayak & Padhye, 2015)

**Antimicrobial actions of different agents**

The different actions of antimicrobial agents involve inhibition of cell wall synthesis, inhibition of protein synthesis, inhibition of cell membrane, disruption of DNA metabolism, or alternation of cell membrane permeability. (Parthiban et al., nd) The antimicrobial finishes are organic, mineral, organometallic and mineral compounds. Metallic ions like silver, zinc and
copper serve as good antimicrobial agents with the diffusion of metallic ions into the fibers that provide biocidal activity. Silver nanoparticles and metal oxide nanoparticles like titanium dioxide, zinc oxide and copper oxide with their small size and larger surface area contribute to the antimicrobial activity by denaturation and oxidative stress to the microorganisms. (Nayak & Padhye, 2015)

Polybiguanides have polycationic amines with a hydrophobic backbone that cause the antimicrobial action against the cell membrane of the microbes. N halamines in the presence of water, these compounds undergo electrophilic substitution of chlorine (Cl) with hydrogen (H). The free Cl cations bind with cell enzyme acceptor regions of the microorganism causing its destruction. (Morais, Guedes & Lopes, 2016) Quaternary ammonium compounds are agents that have cationic ammonium groups that destroy the anionic cell membrane of microbes. Triclosan agent stops the lipid biosynthesis and inhibits microbial growth. Chitosan from the shells of crustaceans is a natural antimicrobial agent with a polycationic nature that causes the antimicrobial action. Some herbal antimicrobial products are neem, aloe vera, tea tree oil, eucalyptus oil and azuki beans. Tannins in natural dyes extracted from plants also have antimicrobial properties. (Nayak & Padhye, 2015)

Microbes and Human Skin Microbiome in space

NASA researchers have found microbes to exist at a height in space and a depth in sea of 32 km and 11 km respectively (Wasif & Laga, 2009). When humans travel to space, microbes that survive decontamination protocols hitchhike along with them. In a recent article, Robert L. Hotz (2017) discusses investigations of how microbes become more of a danger to human farther from earth and possible ways of keeping astronauts safe during long space travel whose immune system is compromised. Microbes in space craft grow faster, mutate more readily, are more
resistant to antibiotics, and are more infectious when compared to those on earth. Microbiology research is also finding how the skin microbiome that influences the human body immune system is also changing. (Hotz, 2017) In microgravity, microorganisms also quickly sense and adapt to the lower levels of fluid shear in parts of the human body (stomach fluid in intestinal tract and mucous fluid in respirator area) which are also common infection sites. (Love, 2016) Microgravity affects virulence, growth kinetics and the formation of thicker and faster biofilms of pathogens. Figure 1 shows the variables causing risk of infectious disease and their transmission during space travel. (Mermel, 2012)

Figure 1 (Mermel, 2012)

The change or alteration in virulence of microbes in space is influenced by the environmental stimulus which is the nutrient growth medium required for microbial culture. The mechanisms that initiate bacterial response in space is unclear and needs to be better understood. (Wilson et al., 2008)
In 1967 US scientists discovered that the *E. coli* and *Salmonella* grew twice as fast in space than on Earth. Russian researchers in 1982 discovered that microbes like *Staphylococcus* increased resistance against oxacillin, chloramphenicol and erythromycin antibiotics and *E. coli* increased resistance against colistin and kanamycin antibiotics. (Love, 2016). In 2006 Dr. Nickerson, a microbiologist from Arizona State University, did an experiment where *Salmonella* was grown and cultured in space. The same experiment was simultaneously done on Earth mimicking the temperature, humidity, and other conditions in a space flight but in Earth’s gravity. When the bacterium cultured in space was returned after the mission it was found that compared to the Earth experiment there were changes in 167 gene expressions and in the production of 73 proteins. It was administered to mice and was more lethal than an equivalent strain grown on aEarth. Nickerson said the changes might be due to mechanical stress of microgravity on the bacterial cells. (Bourzac, 2012)

Scientist are also worried that pathogens that are harmless can become harmful in space. DNA analytical techniques also prove that the microbes living in human gut and skin are also affected by the microgravity. In 2016 aerospace engineer Luis Zea with his team compared *E. coli* bacteria in space and Earth and proved that the cells of the microbes grew thirteen times faster and active in space than in Earth. (Hotz, 2017)

NASA in an ISS mission from 2007 to 2008 studied and proved the microbial drug resistance and virulence of *Salmonella enterica* and *Serovar Typhimurium* (*S. Typhimurium*) in space. These studies have prompted many follow-up studies regarding the characteristics of microbes in space (“NASA-Microbial Drug Resistance, 2018). NASA, with Hernan Lorenzi as the primary investigator, has been investigating the effects on crews’ microbiomes and the immune systems for long term space travel on ISS missions from 2013-2016, by collecting
swabs samples of the nine crews’ urine, blood, fecal matter and sweat before, during and after a six months mission in ISS. They are suspecting the loss of healthy microbes in the microflora thereby leading to opportunistic infections. The results have not been published yet but the fact that this is been investigated shows that the human microbiome in long duration space flight is of serious concern as it has an influence on human adaptation and their safety (“NASA-Study of the Impact of Long-Term Space Travel, 2018).

The behavior of microbes in space needs to be well understood and taken into consideration when choosing the type of antimicrobial textiles and designing experiments to determine the antimicrobial efficacy for long term space travel.

Chapter 1

Application of antimicrobial textiles in medical and healthcare settings

According to a report by Grand View Research, Inc. the antimicrobial medical textiles market could reach USD 799.7 million by 2024. Some of the key findings of the report included the rapid pace of application of polymeric materials to medical textiles. In 2015 various nano metallic salts dominated with 55% of revenue market share and the demand for nano silver is increasing with the development of advanced materials. The demand for healthcare and hygiene products like bedding, gowns and wound dressing to prevent infections also accounted for 40% of the largest market share in 2015 with Europe dominating the market. The major players of this industry are Trevira GmbH, Microban International, Biocote Ltd., Anovotek LLC, Herculite, PurThread Technologies, and Surgicotfab Textile Pvt. Ltd. (‘Antimicrobial Medical Textiles Market’, 2016) Hospital specialty markets including masks, scrubs, towels and linens would increase the cost savings in more than 6000 hospitals and 35 million patients discharged annually. Another market potential for antimicrobial socks in the medical field is for diabetic
patients who suffer from foot ulcers. These socks can help prevent the infections on diabetic patients causing slow healing wounds and even amputation. Other markets are for military supplies and sportswear. (“Hospital, Hospitality”, 2010) With consumers becoming very conscious about their healthy lifestyle antimicrobial textiles are now perceived as a necessity.

**Textiles in Hospital Settings**

Hospital materials such as theater drape, sheets, masks, pillowcases, and surgical gowns are major sources of postoperative disease transmission and cross infections. These materials need therefore to be treated with antimicrobial finishes. (Elshafei & El-Zanfaly, 2011)

Antimicrobial textiles with bioactive properties need to meet the demands of both in external medical applications (bandages, masks, gowns, nappies) and internal applications (surgical threads, vascular grafts and implants). These agents need to be non-toxic to humans and degrade easily causing less impact on the environment. Natural bioactive compounds such as amino polysaccharide including chitosan, especially for wound care management are good examples of safe and eco-friendly textile finishing. However bioactive compounds have less durability since most of them cannot form bonds with textiles. Cellulose fibers in medical textiles are very common for various functional properties like good moisture retention, antistatic, low impurity and good mechanical properties. However, they are the most prone to microorganism attacks because of their hydrophilic nature. The surface modifications of these fibers have excellent antimicrobial capabilities. Quaternary ammonium salts have less durability to washing. Triclosan is harmful to humans and animals. Polyhexamethylene Biguanide- PHMB agent is commonly used for wound dressings. N-halamines cause yellowing and fabric strength loss. Metal nano particles of silver with large surface area of contact with microorganisms are used in medical applications like surgical masks but concerns about bacterial resistance and concentration
toxicity arise. There are many tests to evaluate the efficacy of the antimicrobial textiles, however they have disadvantages since these tests are performed in conditions that are rarely found during the normal use of the textile product (Ristic et al., 2011).

The test methods (Gao & Cranston, 2008) used to evaluate the efficacy of the antimicrobial textiles fall under two main categories which is the agar diffusion test and suspension test. Gram-positive and Gram-negative bacterial cells are the recommended bacterial cells for inoculation. The agar test is qualitative and used for large sample size. The zone of inhibition of bacterial cells inoculated in nutrient agar plates contacting the laid textiles at incubated period of time (37 degree Celsius and 18-24 hours) is evaluated. The potency of the antimicrobial textiles or the release rate of the antimicrobial agents depends on the size of the zone of inhibition caused due to the diffusion of the agents into the agar.

The suspension test provides quantitative results and is time-consuming. Bacterial inoculum of small quantity is fully absorbed into the textile sample ensuring intimate contact and is incubated (37 degree Celsius and 18-24 hours). The bacteria is then eluted and the total number is calculated by serial dilution and plating on nutrient agar plates. The percentage of reduction determining the antimicrobial activity is then found by comparing the size of the population initially and after incubation. Samples without antimicrobial finishing are also tested and compared with the finished samples so that it is known that reduction in bacteria is purely caused due to the antimicrobial agents and not any other factors. However, lab and test conditions like nutrients in the inoculum and the saturating moisture in the test fabric in which these tests use affects the action of antimicrobial activity and it is not the case in normal wearable conditions of these textiles. (Gao & Cranston, 2008)

**Nosocomial Infections**
Burn wound nosocomial (in hospital) infections caused on burn- patients after injury cause serious complications with high cost of treatment, uncertainty in the treatment success, prolonged hospital stays and disability. Antimicrobial textiles in the form of bed sheets, blankets, patient apparel, towels, uniforms and gowns help in the effective control of hospital infections and cross pathogens contamination between patients as well as doctors. Argirova et al. (2017) examined and compared the efficiency, comfort and safety of an antimicrobial zinc oxide agent (ZnO) coated by a sonochemical process against non-antimicrobial linen in a clinical trial with 37 patients in a burn department. It was shown that the effect of ZnO coated textiles (linens) on 21 patients when compared to the conventional linens (65% cotton and 35% polyester) on 16 patients, lowers the contamination level of nosocomial pathogen, MDR- *Acinetobacter baumannii* that is difficult to eradicate. (Argirova et al.,2017)

Another study (Romanò et al.,2012) on antimicrobially treated and untreated hospital white coats and surgical gowns and drapes was evaluated by comparing the number of isolated bacteria according to the European guideline EN ISO 20645. Results from the in vitro, clinical and surgical settings showed that the treated textiles compared to the untreated textiles showed markedly low contamination of bacteria except for *Pseudomonas aeruginosa* for white coats after 1 week of use and surgical gowns after the surgery. (Romanò et al.,2012) Hospital-acquired infections (HAIs) are the most common problem faced in hospitals causing economic issues with increased cost in its treatment.

**Silver and Nano-Metals**

For thousands of years, silver with its good safety record is known to have natural healing properties and it is to date used in various purification processes. The Nanohorizons company globally offers diverse lines of cost-effective SmarSilver™ nanoparticles registered by EPA and
Oeko-Tex that can be used as antimicrobial additives in the health care field. These additives are used during dyeing as well as coating and do not change the mechanical property of the textiles. Greenology USA LLC’s Do No Harm brand used these additives in their eco-friendly medical scrubs. (Henry, 2010)

Researchers under the SONO project used adhesive enzymes to embed antibacterial magnesium oxide, copper oxide and zinc oxide nano particles within hospital textiles in bedding and bandages using the sonochemical process, the application of antimicrobial agents under ultrasonic radiation. This decreased the hospital nosocomical infections, saving many patients. A pilot plant for this line using the sonochemical ultrasonic reactor process application was used. The effectiveness of these textiles was tested in a hospital in Sofia, Bulgaria, on twenty-five patients who dressed in and slept on these textiles versus nineteen patients who slept on regular textiles. Results proved the quality of the antibacterial textiles with less contamination on the twenty-five patients. They also proved effective to inhibit the growth of microbes and were effective even after seventy laundry cycles This proved to be cost effective with an easier application process than silver nanoparticles. (Toor, 2012) (“Reducing hospital infections through innovative textiles”, 2015)

**Bacteria on Clothing**

The sleeves of doctor’s white coats are often contaminated with various types of bacteria even though the doctors wash their hands regularly. O’Meara (2016) performed an investigation of different germs under organic load like blood and saliva with short resistance times and infectious properties of antimicrobial textiles compared to uncoated textiles in germ transfer models. This study shows findings of great importance to realistic practical conditions than standardized antimicrobial testing methods. Antimicrobial textiles can be used in bed linens of
health care settings which is not widely used in practice currently. In this study silver and polybiguaniode-based antimicrobial products proved to be effective antimicrobial agents with good reaction against bacteria and high washing durability.

However, a study by researchers from Duke university hospital (Macdonald, 2017) contradicts this, showing that bacteria still lurk in antimicrobially treated hospital gowns. Three antimicrobial scrubs made of traditionally cotton –polyester, silver-alloy embedded fiber clothing and a combination of antibacterial material surgical scrubs were examined to see if they were effective in preventing bacteria contamination on 40 nurses who wore these scrubs over 3 consecutive 12-hour shifts. Researchers took cultures from patients, environment (bed rails, bed, supply cart) and nurses scrubs (sleeves, abdomen and pocket) after each shift. There were no differences in contamination based on the different type of scrubs because of the low disinfectant capabilities of these textiles with repeated continuous exposure in a short time frame.

(Macdonald, 2017)

Chapter 2
Antimicrobial textiles in the Military

Antimicrobial agents applied to textiles to resist microbes are used in military operations, health care and medical environments and sportswear. Antimicrobial agents degrade or suppress the organic compounds in human sweat that are released by the growth of microorganisms on the skin. These compounds cause bad odor and personal hygiene issues like skin allergies. Examples of usage would be the needle punched antimicrobial fabrics used in the shoe lining, shoes and socks for soldiers and shoe material for athletes. Towels treated with antimicrobial agents remain relatively clean and can be used in homes, offices, trains, and aircraft. Antibacterial finishes are
also used in the linings of shelves, storage boxes and refuse bins to avoid foul smells and mold-growth. (Pekhtasheva, 2012)

Military personnel during deployment have varied access to laundering and bathing depending on the combat zones, the harshness of the environment that they are exposed to, and the duration of combat; soldiers may wear the same clothes for days. (Swofford et al., 2007) The degradation of soldiers’ textiles and essentials from microorganisms have long been of big concern. A study by Steven Arcidiacono and a team at the US Army Natick soldier center (Arcidiacono et.al, 2018) gives an historical perspective on military antimicrobial treatments. In the 19th century, vulcanized rubber was added to soldiers’ blankets making them waterproof and reducing the growth of mold and fungus. The degradation rate of the material was also slow that it had only 30.9% weight loss after 5 years in a controlled environment.

During the advent of the second world war, synthetic rubber, waxes, and resins were used but military tents were still susceptible to fungal growth. Ammoniacal copper salt, copper naphthenate, and other copper compounds were investigated for this purpose but caused fabric color changes. There was also a high demand for copper during the war for weaponry and vehicles reducing the metal’s availability. Other organic molecules like phenols and quaternary ammonium salts when subjected to soil burial tests had good antifungal properties but were incompatible with wax finish and leaching due to the instability in light. In 1944, a 1% application of organomercury compound formula was approved for usage. Cadmium metal was found to be not as effective as zinc and zinc was less effective than copper. Silver was very effective but costly. Each of these fungicides based on their properties were applicable to tents, ropes, webbing, combat boots with paranitrophenol (PNP) shoe polish, surgical floor cloth shelters. (Arcidiacono et.al, 2018)
After WWII, there was a rise in the study of synthetic polymers and resin coatings that were more resistant to microorganisms than cotton. Chemical modification by copper naphthenate of cotton by acetylation or cyanoethylation resulted in appreciable antimicrobial sandbags. Acrylic sandbags performed better than polypropylene sand bags. Later, from 1964 to 1990 with strict EPA (Environmental Protection Agency) regulations, military labs started seeking environmentally friendly compounds and they found that Diodomethyl-p-tolylsulfone (DIMPTS) and isothiazol-3-one and PNP were promising unlike aqueous CU-8. Next-to-skin military textiles were evolved in 2000s for the maintenance of soldier health. Triclosan (2,4,4'-Trichloro-2'-hydroxydiphenyl ether), silver, polyhexamethylene biguanide, and silane quaternary ammonium compounds were used in combat uniforms, t-shirts, boot socks, and fuel handler’s coveralls and boots. (Arcidiacono et.al, 2018)

In two studies, the health issues and their medical cost analyses were explained to clarify the monetary impact of complications caused by microorganisms which depicts the necessity to use antimicrobial textiles. The reportable issue data source for the incidence rates and demographics was from taken from the Defense Medical Epidemiological Database and the Total Army Health and Injury Outcome Database. Among the reportable issues cost analysis using the Medical Cost Avoidance Model (US Army Public Health Command) it was found that the medical cost per year for bacterial soft skin tissue infections was $91.9 M, followed by female health issues at $81.0M, and then fungal issues totalling $46.6 M. Non-reportable issues like malodor and skin irritations were tested qualitatively and showed that most of the soldiers use antimicrobial textiles to control body and foot odor to improve their quality of life and performance. This study showed the gaps found in using antimicrobial textiles in military settings. The gaps found are the magnitude of the non-reportable issues among the soldiers, the efficacy of the antimicrobial textiles in a
military environment is not examined and the effect of these textiles during prolonged wear on the skin is not known. (Spitiz & Arcidiacono, 2016) (Spitiz et al., 2016)

Antimicrobial treated fabrics protect soldiers from skin irritation, bad odor and rashes. In doing so they reduce stress and have a strong effect on soldier’s overall comfort. This treatment increases the fabric’s overall performance, and reduces laundering, thereby reduces water usage which is beneficial in combat environments. In a project done by the Microban company for the US Army Natick Soldier Research, Development and Engineering Center, the antimicrobial fabrics were tested in the laboratory and field test evaluations were done to test the efficacy and durability of the material. (Swofford et al., 2007).

The first part of this study was to run a pilot scale of antimicrobially treated fabrics (advanced combat uniforms, polyester t shirts, boot socks) and to test their efficacy and durability in the laboratory. The second part of this study involved a field wear evaluation by soldiers. The first pilot scale that tested the efficacy and durability of Triclosan, silane quaternary ammonium compounds and PHMB (polyhexamethylenimine). The laboratory testing Test Method 100 and AATCC test Method 147 for antimicrobial efficacy and wash wheel method 5556 for laundering durability. Silane quat was ineffective against the four tested bacteria and had poor wash durability. Triclosan was effective against Staphylococcus aureus but had poor wash durability. PHMB was the best among the two other agents fighting against two, Streptococcus pyogenes and Corynebacterium out of four microorganisms. It also was durable to 50 launderings. For the second pilot scale, they decided to combine triclosan and PHMB. Table 1 shows the results obtained. (Swofford et al., 2007).
Table 1 Second pilot scale results obtained. (Swofford et al., 2007).

<table>
<thead>
<tr>
<th>Active</th>
<th>Durability</th>
<th>Triclosan conc. (ppm)</th>
<th>Staph.</th>
<th>Strep</th>
<th>Coryn</th>
<th>Pseud.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triclosan</td>
<td>Unwashed</td>
<td>1333</td>
<td>NR</td>
<td>NR</td>
<td>31.0%</td>
<td>NR</td>
</tr>
<tr>
<td>(Original)</td>
<td>25</td>
<td>690</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>810</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Triclosan</td>
<td>Unwashed</td>
<td>2133</td>
<td>99.8%</td>
<td>99.4%</td>
<td>99.8%</td>
<td>NR</td>
</tr>
<tr>
<td>(2nd trial)</td>
<td>25</td>
<td>973</td>
<td>31.4%</td>
<td>84.7%</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1200</td>
<td>24.0%</td>
<td>NR</td>
<td>12.0%</td>
<td>NR</td>
</tr>
<tr>
<td>Triclosan</td>
<td>Unwashed</td>
<td>2267</td>
<td>99.9%</td>
<td>99.9%</td>
<td>99.7%</td>
<td>NR</td>
</tr>
<tr>
<td>+ PHMB</td>
<td>25</td>
<td>1200</td>
<td>98.3%</td>
<td>64.1%</td>
<td>33.2%</td>
<td>NR</td>
</tr>
<tr>
<td>(2nd trial)</td>
<td>50</td>
<td>1567</td>
<td>99.9%</td>
<td>99.5%</td>
<td>99.2%</td>
<td>NR</td>
</tr>
</tbody>
</table>

For field wear evaluation, the second pilot scale products with a combination of Triclosan and PHMB was used. This study was done with an effort to find the best agents for military antimicrobial textiles. The future scope of this study was to find the effect of long-term wear of these textiles, specifically on the wearers’ skin. The data was inconclusive and so a second field wear evaluation was done. The difference between the evaluation was that soldiers were given either all treated or all untreated garments as opposed to the first wear evaluation which involved evaluation of each type of garment separately. This was done to clearly delineate between treated and untreated garments. Soldiers felt a difference with treated garments as they controlled body odor with less discomfort. They also felt that it could be worn longer before changing. The reduction in the use-level of hygiene products like deodorant was also seen. Less data was collected on socks as it was considered secondary to data on uniforms and T-shirts in the questionnaire. (Swofford et al., 2007).

The Medetech development corporation, in their Phase 1 investigated and achieved durable and rechargeable N-Halamine antimicrobial textile finishing technology on cotton and polyester that is water soluble, self-curable with good antimicrobial performance as well as eco-friendly.
These textiles are used for underwear and uniforms of soldiers, as well as military shelters, to control body odor, and to reduce risk of infections by pathogens. The chemistry behind this technology is the high-density covalent bonding cross linkage of N-Halamine finishing on fabrics. (Cao, 2013)

As seen in figure 2, in the treated cotton fabrics the increase in polymeric N-halamine concentration from 0.1 to 5 wt% led to the increase in grafting yield from 0.04 to 3.12 wt% and also the increase in chlorine content from 46 ppm to 1242 ppm at 100 % wet pickup, 180°C curing temperature and 2 min curing. As seen in figure 3, in the treated polyester fabrics, the increase in polymeric N-halamine concentration from 0.1 to 5 wt% led to the increase in grafting yield from 0.02 to 1.35% and also the increase in chlorine content from 23 ppm to 482 ppm at 100 % wet pickup, 180°C curing temperature and 2 min curing. Higher wet pickups, curing temperatures and longer curing time improved grafting yield and chlorine contents. (Cao, 2013)

This finishing did not alter water vapor permeability, or mechanical properties like abrasion resistance, bursting strength, tear resistance, and fabric hand. Treated fabrics with higher chlorine content than 404 also showed 99.9 % reduction of the microorganisms in 30 minutes duration. They also passed the leaching the tests with no observable leaching N-Halamine after 24 hours agitation. 50 cycles of home laundering also left these fabrics unchanged, assuring quality and cost effectiveness as well. When the weather resistance was evaluated with the UV light exposure part of the chlorine in cotton fabrics was lost but 90% was regenerated during chlorination. They also did a preliminary cost analysis and found that the antimicrobial treatment of 1 kg dry textile costed $0.346. For commercialization, the Phase 2 study was proposed in this article to further develop optimal conditions for the application of the technology on a range of synthetic fabrics including
nylon and polyaramid textiles. The safety of the dermal toxicity and skin irritation also had to be evaluated with other tests done in Phase 1 (Cao, 2013).

Figure 2 (Cao, 2013)

![Graph showing grafting yield and chlorine content](image)

Figure 3 (Cao, 2013)

![Graph showing grafting yield and chlorine content](image)

There is a lot of relevance of nanotechnology to military practices due to its consistency and scalability of its research. Nichols, Davis & Ramsburg (2016) performed an extensive literature review of the surface applications of Nanotechnology at the Homeland Defense and Security Information Analysis Center (HDAIC). Table 2 shows the use of nanotechnology in textiles. Nanomaterials due to the strong binding on a nanoscale to the fibers is more feasible than traditional antimicrobial agents for effective antimicrobial functions. Silver nanoparticles proved
to be the most effective in resisting bacteria. The most common fabric for Ag nanoparticle application is cotton with good performance and durability. Other metal-like titanium dioxide and zinc oxide nanoparticles show promising results. Sol gel process and electrospinning are techniques used to effectively application of nanomaterial on the fabrics. The sol gel method uses chemical sol that acts as a precursor for the gel. Sol then converts to gel that can be coated as thin film on polymeric substrates. In electrospinning technique, high voltage is applied to polymer solution that is sprayed through a nozzle and this forms the nanofibers that is deposited on a board to achieve web-like fibers. (Nichols, Davis & Ramsburg, 2016)

Table 2 Use of nanotechnology in textiles (Nichols, Davis & Ramsburg, 2016)

<table>
<thead>
<tr>
<th>Application in Textile</th>
<th>Nanomaterial Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro conductive and antistatic</td>
<td>Carbon black, Carbon nanotubes (CNT), Cu, Polypyrrole, Polyamiline</td>
</tr>
<tr>
<td>Increase durability</td>
<td>Al₂O₃, SiO₂, CNT, ZnO, Polybutylacrylate</td>
</tr>
<tr>
<td>Antibacterial</td>
<td>Ag, Chitosan, SiO₂ (as matrix), TiO₂, ZnO</td>
</tr>
<tr>
<td>Self-cleaning/ dirt and water repellent</td>
<td>CNT, Fluoroacrylate, SiO₂ (as matrix), TiO₂</td>
</tr>
<tr>
<td>Moisture absorbing</td>
<td>TiO₂</td>
</tr>
<tr>
<td>Improved staining / reduce fade</td>
<td>Carbon black, Nanoporous hydrocarbon on Nitrogen coating, SiO₂ (as matrix)</td>
</tr>
<tr>
<td>UV protection</td>
<td>TiO₂, ZnO</td>
</tr>
<tr>
<td>Fire proof</td>
<td>CNT, Borosiloxane, Montmorillonite (nano clay), Sb₂O₅</td>
</tr>
<tr>
<td>Controlled release of active agents, medicinal products or fragrances</td>
<td>Montmorillonite (nano clay), SiO₂ (as matrix)</td>
</tr>
</tbody>
</table>

There are many factors affecting variations in the skin microbiome of soldiers: Environmental exposure, stress, medications, hygiene, behavioral practices, and genetic variation. (Grice & Serge, 2011). However, there is still little to no information on the long-term effects of prolonged wear. It was found that the silver antimicrobial textiles (50% fibers coated with metallic silver and polyamide fiber with silver staining) temporarily reduced the bacterial flora of the skin during a nine-hour exposure by determining the colony forming units on 1cm². After the removal of the swatch the reduced skin flora level was maintained for an additional nine hours and the full recovery of the flora after thirty-six hours. (Kramer et al., 2006)
Questions around the toxicity issues of the antimicrobial textiles, their prolonged exposure, and the emergence of resistant microbes were addressed by Arcidiacono (2015). Antimicrobial compounds are considered safe as they are approved by US environmental Protection Agency (EPA) and the US Food and Drug Administration (FDA). They however may cause skin irritation and rashes on individuals with sensitive skin. Quaternary Ammonium Compounds (QAC) and triclosan have been associated with skin sensitivity. Factors such as the modes of application and chemical form can influence the compounds. (Arcidiacono, 2015)

Antimicrobial textiles alter the skin microflora composition in the same way that antibiotics alter the gut microbial population. Many mechanisms like efflux pumps, modification of cellular targets, inactivation, and plasma mediated resistance in microbes used for resistance against antimicrobial textiles are the same as the mechanism of microbes in the gut that resist antibiotics. But it is also stated that the emergence of microbial resistance depends on the modes of action and level of use. Under laboratory conditions, triclosan, silver, QAC, copper and PHMB antimicrobial agents may result in resistant microorganisms but this is not applicable to real environmental situations. Silver, being the best studied antimicrobial compound and used for long time in history has no evidence of emergence to resistance by microorganisms. Increased resistance to QAC has been reported in the food and medicine industry but not associate to textiles. So, more studies need to be done for the prolonged wear effects of QAC (Arcidiacono, 2015).

Chapter 3

Sports Application of Antimicrobial Textiles

Body Odor

The use of antimicrobial textiles in sportswear is mainly for odor control in response to people’s awareness and societal perception of body odor. Sweat glands produce sweat that creates
a breeding environment for microbes which causes odor, even after washing the smell of sweat in some textiles. Body odor varies from textiles made of different materials. Sweat inducing indoor exercises where individuals are in close proximity to one another are now commonplace. Due to this proximity, the ability of clothing to maintain a boundary between the individual and society, allows the body to be accepted in different social situations. Marketers of odor controlling products especially used in sportswear application have taken advantage of this boundary in addressing that odor is socially problematic rather than mainly addressing the functionality and properties of their product. These textiles are being marketed in advertisements as the reason for reducing malodor, solving the problem of stink, to overcome social stigma of smelling sweaty, and also as being ecologically beneficial due to the of reduction in laundry needs. (Klepp, Buck & Kjeldsberg, 2016)

Klepp, Buck, and Kjeldsberg performed a sensory test with a panel of twelve untrained consumers using thirteen different sportswear fabric samples made of wool, cotton, odor control polyester, and polyester that went through cycles of sweat accumulation, airing and washing. Pre-washed samples were stitched to gym mat covers that thirty circuit training participants used it for a ninety-minute session. The panel then assessed the odor intensity levels. The thirteen fabrics were grouped to three main evaluation groups that were sweaty, aired and washed. The odor-controlled fabrics were found to smell less intensely than untreated polyester fabrics but wool and cotton smelled less intense than the odor-controlled fabrics and polyester that were sweaty and aired. After washing, the odor-controlled fabric’s odor intensity was between that of cotton and wool. This can be seen in Figure 4. Also, the odor-control treatment did not make a difference in laundering frequency as it was the second highest fabric judged to go into wash after polyester. This can be seen in Figure 5. This study shows that there are fabric materials (in this study cotton
and wool) that smell less intense and that can be washed less frequently when compared to textiles that claim odor control.

Figure 4 Odor intensity of textiles (Klepp, Buck & Kjeldsberg, 2016).

![Figure 4 Odor intensity of textiles](image)

Figure 5 Laundering frequency (Klepp, Buck & Kjeldsberg, 2016).

![Figure 5 Laundering frequency](image)

Researchers at the Ghent University Laboratory of Microbial Ecology and Technology (Callewaert et al., 2014) investigated the growth and odor development of microbes in T-shirts made of cotton and synthetic fabrics. It also showed that different fabrics made of different fiber composition promote the growth of different microbes responsible for malodor. Sweat samples were collected from twenty-six individuals with healthy skin after bicycle spinning sessions of one hour and it was incubated for twenty-eight hours before analysis. Seven selected human assessors then assessed these samples for their seven odor characteristics which were hedonic value,
intensity, mustiness, sweetness, ammonia, strength, and sourness. It was found that polyester had a more intense and unpleasant odor when compared to cotton tee-shirts. This was due to the poor odor absorbency (hydrophobic nature) of synthetic polyester thereby emitting odor. A micrococcus bacterium was detected in all synthetic fabrics by a denaturing DNA gradient gel electrophoresis fingerprinting method. An in vitro growth inhibition experiment also isolated this species in polyester and confirmed this. *Staphylococcus* microorganism was found abundantly on cotton when compared to polyester. No bacterial growth was seen on viscose indicating that further research should be done on viscose as an odor control textile. Wool was the textile with the highest bacterial growth although it had the lowest odor intensity ratings. This study provides a rationale for antibacterial clothing for functionalized sports clothing that reduces malodor. (Callewaert et al., 2014)

**Nanotechnology Applications and Products of Brands**

Euromonitor International, a market research company, talks about nanotechnology that has been mostly tailored towards sportswear and footwear for its odor resistant/neutralizing technology either through coating technology or fiber and fabric integration. (Potts, 2018) Nanotechnology in textile materials in the form of nanofibers, nanocomposite fibers and mano-finished textiles has opened many windows for functional sportswear and antimicrobial application. Although organic metals, quaternary ammonium compounds and organic silicones are used for antibacterial finishing, nanoparticles are commonly used for sports textile applications. Antibacterial properties of nanoparticles can be used for various sports applications such as sport socks, mountaineering tents, sports shoes insoles, swim suits, outdoor sports apparel, and more. *Staphylococcus aureus* commonly found in athletic teams causes and spreads infections and antibacterial clothing can protect the athletic teams and reduce odor thereby increasing the athlete’s
efficiency. (Harifi & Montazer, 2016) The in-situ synthesis without a final fixation step of nanoparticles such as silver, TiO$_2$, ZnO, TiO$_2$/Ag and ZnO/Ag nanocomposites finishing technology imparts antibacterial properties to the textiles. In-Situ sonosynthesis of nano TiO$_2$ on cotton fabric using ultrasonic bath at low temperature also showed good antibacterial properties. (Harifi & Montazer, 2016)

Odor control in sportswear fabrics is achieved by covering odor with fragrance through slow release microencapsulation technology over time, with the antimicrobial finishing thereby eliminating odor molecules. Another approach is the use of cyclodextrines, compounds that are hydrophilic on the surface but with a hydrophobic cavity. Odor being hydrophobic is trapped in cyclodextrine cavities and then released during washing. Some of the products available are bamboo athletic socks and nanosilver socks. (Mantovani et al., 2010) Major players in this sector in the United States are Nike, Adidas, Under Armour, Lululemon, New Balance, and Gore associates. In Europe, one would mention Mectec and Schoeller. The high-end active wear men’s brand Rhone incorporates silver thread and silver molecules into the fibers of garments that fight odor, sweat stains and microbes, with high breathability and fast drying nature. In December of 2016 Rhone infused 24k gold nanoparticles with the above functions and found 99% effectiveness even after 100 washes. (Taylor, 2016)

The Puckskin antimicrobial clothing line, products of Macker International Apparel Inc., were long sleeve tee-shirts, support mid short, socks and wrist bands designed for hockey players. The fabric is double layered made up of natural microfiber charcoal bamboo and embedded with nano silver ceramic ions which produces anions to filter the odor causing microbes. These clothes also have high moisture wickability with high performance features. (Leavline et al., 2015) In August 2015 one of the innovations in sports textiles of yoga T-shirts and underwear was a German
based milk-sourced silky fiber called Qmilch made of casein protein in sour cow’s milk that don’t meet food standards and cannot be consumed. This fiber is lightweight at 1.17g per cubic centimeter and it is naturally antibacterial, it also protects from UV radiation, has strong water absorption, and retains heat well. (So, 2015) The Silvadur antimicrobial technology of XStep a Chinese brand for athletic footwear came into market place in 2014. This technology treated in the lining and the soles of the running shoes has silver ions that is released to the surface of the shoes and activates only in the presence of odor causing bacteria. This technology provides long term comfort to the wearer and is very durable that it can withstand 50 rigorous launderings. (“Rise to the challenge”, 2014)

Some of the trends on the odor neutralizing developments of sportswear in 2017 are Tanatex LAVA Slurry finish made of zeolites that absorbs, traps the odor vapor and regenerates itself during the wash/dry cycle. X-Static silver yarn of Nobel Biomaterials is a visible yarn to the fabric for added detail and it also performs well under harsh conditions. An invisible silver solution would be the company’s XT2 and here the silver is incorporated in to the polyester sheath during the co-extrusion process. Other brands to take up this XT2 technology is Rhode and Anta Sports. Polygiene Permanent odor control treatment was used by North Face for their spring/summer 2017 collection. (Smith, 2017)

**Effectiveness of Antimicrobial Textiles and Questionable Risks**

Unlike objectively finding the antimicrobial activity of textiles, anti-odor testing is not done by laboratory testing but only by a panel of sensory assessors. Hence this type of testing is highly subjective, and its perception varies from person to person. Rachel Mcqueen, a human ecology scientist, found that antimicrobial textiles effective in lab tests did not translate to real life human wear tests. She conducted two experiments to prove this. The first analyzed three different
textiles coated with triclosan, zinc pyrithione derivate and a silver chloride titanium dioxide compound samples that was put under people’s arms for 24 hours. The second test was done with polyester textiles with bioactive concentrations of silver chloride compound. Neither tests produced results comparable to the vitro tested in the lab. This is because the antimicrobial properties are disrupted due to the difference in the sweat levels, skin moisture to activate the treatment or protein levels in the human body. (Betkowski, 2014)

The Swedish Chemicals Agency conducted research to check the effectiveness of antimicrobial textiles. The antibacterial effects of thirty sports/leisure textiles (training garments and socks) were examined before and after washing to find the leaching properties and the functionality of antimicrobial substances made of triclosan, triclocarbon and silver. It was found that on average, 60% of these sample’s antimicrobial substance had washed out after 10 washes. For the second study, 25 of the same samples used in the previous study were tested for their antibacterial effects for inhibition of growth of E. coli and S.aureus and it was found that 68% of the tested samples did not show any antibacterial activity after 10 washing cycles and 28% did not show any effect before washing. This study also shows that treatments are not as effective as claimed by manufacturers. (KEMI Swedish Agency 2012)

Questions of health risk appear when antimicrobial textiles are used for different applications especially in sports and leisure activities affect the skin microflora. One study (Hoefer & Hammer, 2011) shows that the antimicrobial textiles do not have any adverse effects on the ecological balance of the skin. For this study sixty volunteers with healthy skin where given form fitting t-shirts constructed with two halves. One side had silver finishes or silver loaded fibers and the non-antibacterial side was made of Polyester knitted fabric or Polyamide Tactel fabric. These were worn over a long-term wear trial period of 6 weeks. The antibacterial activity was in efficacy
levels typical for sportswear as the silver release on the skin was less than 2.5 ppm whereas for wound dressing applications it would be 40 ppm. The microflora of the scapular skin was tested and analyzed to see if there was a change due to the antibacterial clothing. The box plot graph showed no occurrence of any pathogenic germs, no deviations of the cell count, and the spectrum of microorganisms was unchanged. It was found that the skin microflora was undisturbed except when silver containing deodorant was used during short term wear trial that showed short term disturbance of microflora for eight hours and recovery by twenty-four hours. The secondary functions of the skin like the pH, moisture, transepidermal water loss did not show any significant changes of more than 0.5. (Hoefer & Hammer, 2011)

The impact of anti-odor clothing on the environment is also an issue that needs to be further investigated. Paul K Weseterloff and colleagues studied the antimicrobial effects to washing and the leaching of silver into the environment. They tested commercially available athletic shirts which had silver nanoparticles incorporated in one of four different ways. Due to the washing of these shirts, the resulting toxicity was negligible to model anima zebrafish embryos used in toxicity studies. After washing, these shirts retained their antimicrobial effect even with the remaining low concentration of the silver metal. However, the remaining silver metal will leach out of the shirt over time and thus lower concentration is necessary to reduce the environmental impact while still maintaining their antimicrobial effect (“The impact of anti-odor” 2016). The understanding of antimicrobial textiles, especially the application of nanotechnology remains blurred due to the human and environmental risk controversies, their effectiveness, irrelevant claims by manufacturers and limited knowledge of testing.

Chapter 4

Space Applications
LDSF issues and working in Space Environment

Research on laundry in space and the quest for odor free clothes, along with the research question of clothing for long term missions that last for a couple of years has been going on for years. It is unfeasible to have traditional washing machines and dryers in space ships and space stations as it is expensive to transport them, they are bulky and traditional systems would not work in microgravity. Some other ways of managing these problems are the use of antimicrobial textiles or the invention of a space-based washing machine. (Greene, 2013) There is not much research on antimicrobial textiles applications available for long-duration-space-flight (LDSF) and this is a big research area that needs to be explored. This chapter has information mostly collected from newspaper articles as little to no evidence of research articles exist.

Mass volume and maintenance of clothing must be carefully engineered. Studies have been conducted at the Johnson space center to address the length of time to be worn, as well as the perception and performance properties of these clothing. Space crew clothing can be divided into space suit systems for outside activities (extravehicular activities, or EVA) and the cabin clothes for work, exercise and sleep (intravehicular activities, or IVA). Everyday clothes for LDSF must last for three years with little to no laundering capabilities. (Orndoff, 2016) NASA’s estimation for a Mars-mission is between two and a half years to three years that includes each leg of trip to be six months and 18-20 months stay on Mars. (Lewis, 2017) On average, on the International Space Station (ISS) crew members get a pair of shorts and tee shirts for every three days of exercising. Work clothes are available to change once in ten days, underwear every other day and Polartec sock for cold feet need to be worn for about a month. Their pants are provided with Velcro fasteners and pockets so that they can keep their tools close in zero gravity. (“NASA-HSF”, 2003)
IVA clothing takes up eighteen percent of the mass in space flight for a long mission. For a Mars mission, nine tons of textile garments would be needed for six crew members. Clothing supplied to crew members make up twelve percent of the total waste mass during its disposal after wear. Twelve percent total mass of waste from these garments are generated. NASA is therefore trying make an impact on the reduction of mass and waste in space ships. (Binsted, 2013) In a news update in 2014 it was mentioned that NASA spends a delivery bill of forty-thousand dollars per pound of load of logistics and clothing accounts for nine-hundred pounds for clothing for six crew per year. (Klotz, 2014) The logistic burden beyond low earth orbit is twice as big as lower orbit missions. (Mlenger, 2015)

In space where there is low or no gravity, sweat can be hazardous byproduct. Body heat is not convective and sweat does not drip down. It collects in one place of the body forming water aura which increases body overheating, microbial growth and impedes functionality. This also demands for the development of antimicrobial textiles for sweat management that can be used in space says the principal investigator of one of the Hohenstein Institute’s Spacetex projects. (Aghajanian, 2014) (“Spacetex”, 2014)

Crew members in the international space station need to exercise for at least an hour every day to reduce the effects of zero gravity on the body like muscle atrophy and calcium deficiency in the bones. Robert Trevino, who is responsible for astronauts’ day-to-day-wear in outer space, mentioned that current exercise clothes don’t last more than two weeks. So more breathable, odor absorbing and sweat resistant textiles need to be looked into as laundring in space station is not an option. Once the clothes start smelling bad and can’t be worn anymore they trash them in a bag that is loaded into the Progressive cargo capsule/ vehicle that burns on reentry into the Earth’s atmosphere. Replacing clothing is a better solution than replenishing water, as water is a limited
resource in space. But for long term space travel the luxury of cargo ship is impractical, so if Mars water resources are limited, other options like antimicrobial textile, microwaving process, exposure to ultraviolet radiation, or exposing the textiles to vacuum of space are also possibilities. (Dilawar, 2017)

**Intra Vehicular Activity Clothing Study**

The Intravehicular Activity Clothing Study developed under Advanced Exploration Systems Program Logistics Reduction and Repurposing Project was done by the primary investigator Evelyne Orndoff. This Project aims to reduce the logistic cost, mass and volume for missions and clothing is one of the important factors to be considered. This was a study done in search of a wardrobe of space textiles for LDSF like Mars mission. They were investigating to dress crewmembers in lightweight antimicrobial textiles. Cotton clothes for six crew members comprise more than 900 pounds of freight to ISS. (“NASA Intravehicular Clothing Study”, 2017)

Cotton is commonly used for space textiles for its properties like comfort, flame resistance and odor resistance. Cotton would char away and not melt in case of a high temperature exposures or flash fires. (Mlenger, 2015) All crew clothing material undergo a review by NASA Materials and Processes and the current minimum requirement is 95 percent cotton material. (NASA Johnson Space Center, 2003) Other than cotton garments in this study (Mlenger, 2015), wool fiber, modacrylic and polyester was revisited although polyester is worn only for a short duration in space during exercises and then stored in flame retardant bags. For missions beyond lower orbit, materials that melt in a fire need to be avoided. Wool and modacrylic garments are used for better cleanliness, odor resistance and flame resistance. These garments should fulfill the needs of NASA’s Orion Multipurpose Crew Vehicle designed for deep space exploration, where the requirements for a non-ventilated area is forty percent oxygen by volume at 10.2 psi pressure and
for ventilated area the requirement is thirty percent oxygen by volume at 10.2 psi which is stricter than current cabin requirements. (Mlenger, 2015)

Revisiting non-cotton materials, polyester, wool and modacrylic garments could reduce the weight of launches as they are lighter in weight than cotton apparel, can be worn for a longer time, being more odor resistant, and do not produce lint causing clogging of air filters in the shuttle like cotton apparel. The length of wear of odor resistant and comfortable lightweight clothes were tested. Two studies one inflight and one in ground study was done. Cotton produces a lot of lint that clogs the air filter on the ISS therefore the yield of new fabrics must be looked into. Crew members wore the exercise shirt for fifteen-day study period during their cardiovascular sessions. The shorts were made of polyester and t-shirts made of merino wool or polyester. A study was also done for routine wear made of modacrylic or merino wool. Once the clothing was used it was hung up and dried and used again until it was no longer acceptable to wear. Survey with questionnaire were filled out by crew members to understand the garment perception. The length of wear, reasons for retiring from a garment and comfort, odor parameters on an ordinal preference scale of nine sensory elements was studied from the questionnaire. (“NASA Intravehicular Clothing Study”, 2017)

Some exercises clothes and all shorts were treated with 3 (Trimethoxsilyl)propyldimethyloctadecyl ammonium chloride, manufactured by PureShield, Inc., under the brand name Bio-Protect 500. Other exercise clothes treated with copper ion thread from Cupron. The crew members were surveyed for the comfort, length of time worn and odor of these fabrics. Current guidelines are to wear underwear for two days and bottoms for a month. (Klotz, 2014)
Another problem that Orndorff mentions related to the search of space textiles for Mars mission is the process of certification and documentations of commercial retail clothes along with custom materials supplied from clothing vendors to NASA that needs to be approved from time to time to make sure they are suitable for space exploration use, for safety purposes and life support of astronauts. This is time consuming and costly process. Sometimes recertification and all the paperwork needs to be done over again as there is a problem of the product changing slightly over time. Companies who are willing to partner with NASA also need to be patient and perseverant with product development and accept the way NASA and government do business. (Tornquist, 2018)

Other Space Researches and application

The Xt2 SILVER produced by Noblebiomaterials is incorporated in synthetics during co-extrusion process provides durability to washes and antimicrobial resistance. It is used by NASA astronauts as well as European space agency astronauts. (“Introducing XT2®”, 2013)

The J-Wear clothing line was developed by researchers in Japan Women’s University and five other clothing companies for Japanese Aerospace Exploration Agency (JAXA Astronauts) (Ryall, 2009). J-WEAR consisting of a full clothing line of long-short sleeved undershirts, underwear, shorts as well as socks. It is antistatic, water absorbing, flame resistant and odor-eliminating and made from seamless cotton and polyester fabrics. The underwear was a cross between briefs and boxers and it was silver-nano coated into the material. (Dunn, n.d) In 2008, a Japanese astronaut Koichi Wakata also wore the four J-Wear underwear, each for a month, to odor test it during his four and a half months long stay at the ISS. None of his crew members complained about any odor. (Malik, 2009) JAXA was planning to make this available to NASA and other
space station partners once the development was complete. (Klotz, 2009) There is no evidence available of laboratory testing for this underwear before or after it was used.

In 2011, NASA funded a project by UMPQUA, an Oregon-based research company, for a prototype of low power, low energy, low water consumption washing device that is compatible in microgravity for long term space missions. (Greene, 2013) The contract commissioned asks not only for use on the ISS but also for LDSF where the logistics resupply of fresh crew clothing becomes very expensive and nearly impossible. (Dillow, 2011) William Michalek, the project leader explained the concept to use this machine which involves the dirty clothes to be placed in a plastic bag and then treated with jets of water entering through connected tubes that would bend the fabric creating the soap-washing tumble action without air that would have been sucked out of the bag. After this cycle, these bags of clothes would be placed in a large microwave generator for drying. (Pultarova, 2011) They also proposed to vaporize the air to make it more water efficient. (Hsu, 2011) No article exists after 2011 about the development of this project.

Figure 6 Prototype image of the UMPQUA washing device
In 2014, Yajaira Sierra Sastre a nanotechnology-based material scientist collaborated with NASA researchers and Cupron (a VA based antimicrobial technology company) to provide clothes samples for a four-month isolation in a Mars-simulator called HI-SEAS (Hawaii Space Exploration Analog and Simulation). The crew received eight exercise shirts and four pajama tops all with unknown antimicrobial properties. The fabric performance, smell, and appearance were to be surveyed by wear tests. They found that they could wear these garments for a longer duration without any odor. But the pajama tops felt heavier as the cumulative weight of several weeks’ worth of dead cell accumulation became evident. Cupron also supplied bedsheets, pillowcases, glove liners, towels, underwear, undersweats, and socks for the crew. They were made of threads with non-toxic copper oxide particles that are environmentally friendly and cost effective. The study observed how well these garments functioned in a low hygiene limited water supply environment. The survey gave information of odor, feel, and appearance change. The towels, gloves and sheets turned to be of no issues and were long lasting before they needed to be changed. But the underwear and tank top were uncomfortable and so it was not worn after the first day. Odor free textiles should also perceive other qualitative factors like fit, style, comfort, and cleanliness for the people to want to wear antimicrobial textiles. (Greene, 2013) Test results for microbial life in the Cupron products does not seem to be available.

In a NASA report from 2003, an ISS expedition (expedition #6) science officer Donald Pettit wrote in space chronicles that he wore his underwear for 3 to 4 days as the environment inside the space station is controlled with constant temperature at a comfortable level. Exerting physical force is also lesser when compared to earth due the weightlessness. Other garments like shorts are even worn for a longer duration. A method was to use underwear as a base in which to
germinate seed. Russian scientists used dirty underwear that was made into a sphere core that serve as nutrients for growth of plants. This sphere was covered with toilet paper that’s purpose was a sprouter. With this planter, the seeds germinated in two days, and it was too cold for the seeds to germinate otherwise. An offbeat idea that was not put into practice was to feed the dirty clothes like underwear to bacteria. The bacteria would digest it biochemically producing methane gas that could be used to power spacecrafts (NASA, 2003). However, this option is not at the moment viable as researchers mentioned it would take many years to find the correct bacteria combination for this process. (NASA, 2003)

A current ongoing study by Christina Morrison, a graduate student at the University of Arizona, seeks solutions for clothes to be clean in space under a NASA space grant. Ms. Morrison has found the synergistic effects of low concentrations of hydrogen peroxide on antimicrobial socks embroidered with silver ion threads when exposed to the bacteria Staphylococcus aureus. Hydrogen peroxide and silver are both resistant to germs. In one hour of application there was a 5-log reduction of about 99.999% bacteria reduction on treated silver socks when compared to 0.25 log reduction of about 43.76 percent on untreated silver socks. This way, clothes are meant to stay more germ free with these socks washed with hydrogen peroxide. Washed twice, they can stay odor free in the same time astronauts would discard three shirts, thereby reducing the mass and waste in a mission launch. The next phase of this research would be to engage human subjects for wear tests and olfactory examinations to evaluate freshness of treated and untreated antimicrobial socks swatches (Goetz, 2018). There is no article yet published as this is ongoing research at the time of this writing.

Chapter 5

Antimicrobial Textiles Effect on Skin Flora and Human risks.
There is an open discussion about whether antimicrobial products are harmful to human skin. As conducting field trials for an antimicrobial agent’s effect on the skin flora is not feasible, the Hohenstein Institute developed a new test system that lets manufacturers of the antimicrobial products evaluate their products impact on skin flora during the R&D stage itself. An 18-hour wear simulation of these textiles is performed against artificial skin material infused with several germ types similar to a healthy human skin is done. If there is an insignificant difference between the number of germs on the artificial skin and on a control then the textile is considered safe and the products can be advertised with the Hohenstein quality label and skin flora neutral. (“Testing antimicrobial textile effects on skin”, 2013)

Table 3 shows the safety characteristics of antimicrobial textiles. (Arcidiacono, 2015)

<table>
<thead>
<tr>
<th>Antimicrobial compound</th>
<th>Dermal resorption</th>
<th>Toxicity</th>
<th>Allergenicity</th>
<th>Mutagenicity</th>
<th>Carcinogenicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>no</td>
<td>little to none</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>QAC</td>
<td>yes</td>
<td>moderate to high</td>
<td>moderate</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Polyhexamethylene biguanide (PHMB)</td>
<td>no</td>
<td>little to none</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Triclosan</td>
<td>yes</td>
<td>little to none</td>
<td>low</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Copper</td>
<td>no</td>
<td>dose dependent</td>
<td>none</td>
<td>possible</td>
<td>none</td>
</tr>
</tbody>
</table>

**Silver Risks**

Nanosilver, due to its small size, can penetrate inside the cells with more chemical reactions due to their large surface area. Some of the factors leading to the toxicity of nanosilver are its size, shape, and the kind of chemical coating used to clump the individual particles together. There are cell studies showing that nanosilver damages human cells. However, these studies exposed cells to between 100 and 10,000 times more nanosilver than people normally encounter. Cells in a lab’s petri dish are also different from cells in living things. The differences in vitro studies results are also influenced by the type of coating cell exposure, cell used, cellular uptake, intracellular dissolution. (Oosthoek, 2017)
In a risk analysis, airborne exposure through lungs, dermal exposure through skin, and ingestion exposure through the gut all need to be taken into consideration. The scientific committee on emerging and newly identified health risk has concluded that even though nanomaterials are not dangerous, there is a certainty of its safety and risk assessment that needs to be done with case by case studies. (Almeida & Ramos, 2017)

Goetz (Goetz et al., 2013) developed a test method to identify the release of nanoparticles such as nanosilver from textiles to the skin. A treated textile to be tested for release of particles was immersed in an artificial sweat solution (both alkaline and acidic sweat solutions were used) and acrylic plastic balls were used to create mechanical stress for 30 minutes. This test of using mechanical stress is similar to EN ISO 105-C06 color fastness to laundering unlike the EN ISO 105-E04 which is color fastness to perspiration but with no mechanical stress. The test result showed a 14% significant release of nanosilver in 183mg Ag/kg of textile. This test analyses the release from skin contact involving abrasion and sweat. (Almeida & Ramos, 2017)

A Nanoparticle scientist, Jim Hutchinson from the University of Oregon in Eugene has written about silver causing a condition called Argyria that turns the skin into a permanently bluish grey tinted color. Argyria only occurs during higher concentrations of chronic exposure to the metal. Argyria, however, is not harmful to health although its cosmetic effect is impactful. Reliene, a cancer researcher at the State University of NY Albany, also shared his findings in 2015 of how nanosilver seems to be toxic to tissues like immature blood cells in the bone marrow (damaging DNA), posing a risk of cancer (Oosthoek, 2017). Spleen, liver, kidney and testes are the main target organs for the silver nanoparticle deposition. Exposure to ionic silver and silver nanoparticle produces stress response and also affects gene expression. (Hartemann et al., 2015)
Nanosilver also poses a threat that resistance will develop and spread through microorganisms in the human body and the environment. In 2013, it was found that Bacillus sp. genus adapted with high tolerance to toxicity threshold against nanosilver, as a result of prolonged prior exposure to nanosilver. The mechanisms of microbial resistance are still not clearly understood. However, it may involve defense against oxidative damage invoked by bioavailable silver. Bioavailable silver is any form of silver (silver particulates and soluble silver) that is leached (by aggregation, agglomeration, dissolution) into a new environment such as when silver wound dressings makes contact with the body fluids. Cytotoxic action of silver against microorganisms depends on the bioavailability of silver. Due to prolonged exposure to bioactive silver in the body there is a need to monitor the prevalence of antimicrobial resistance. In 2015, it was found that E. coli of clinical origin showed resistance against nanosilver of 50 to 125 μg/L during prolonged exposure between 23-29 days of treatment. (Gunawan et al.,2017)

An investigation by Dr. Bevin Engelward from MIT and Dr. Philip Demokritou from the Harvard School of Public Health (HSPH) suggests how certain nanoparticles like zinc oxide and silver in consumer products produces substantial damage to DNA. Nanoparticles, since they are immensely small with different physical, biologically and chemical properties penetrate easily into cells. Nanoparticles can also produce free radicals called reactive oxygen that alters DNA. The particles, when they enter into the body, also accumulate and damage the tissues. It is important not only to evaluate the nanoparticle toxicity focusing on the cell survival after exposure but also the genotoxicity focusing on the damaged DNA that can lead to cancerous mutations if the damaged DNA is not repaired. (Trafton, 2014)

DNA damage was analyzed using the high-speed screening technology (CometChip) to study the hazards of nanoparticles at a faster rate. CometChip is a rapid version of commet assay.
which is a test involving comet-shaped smear that damages the DNA. MIT and HSPH researchers used CometChip to test the effect of nanoparticles such as silver, zinc oxide, iron oxide, cerium oxide, and amorphous silica on human blood cells called lymphoblastoids and Chinese hamster ovary cells. It was found that Zinc oxide and Silver at a concentration of 10 micrograms per milliliter produced a lot of single stranded DNA breaks. The other nanoparticles showed low DNA damage and therefore lower genotoxicity (Trafton, 2014). According to Sweden’s national agency for chemical inspection the use of silver ions for antimicrobial textiles poses a health risk of damage to human genetic material, reproduction and embryonic development. (“Safer than silver”, 2014)

**Triclosan Risks**

Triclosan is an ingredient added to many products to prevent bacterial contamination. Consumers come in contact with triclosan through many consumer personal care products like deodorant, toothpaste, soaps, clothing etc. Antibacterial soaps containing triclosan were banned in 2016 as the manufacturers could not prove to the FDA that they were safe and an improvement on regular soaps. Triclosan is contained in nearly 2000 products and 96% of it goes down the sewage system affecting the environment as well. (McMillen, 2018)

Table 4: Triclosan toxicities. (Olaniyan, Mkwetshana & Okoh, 2016)
Triclosan affects mitochondria which is essential for reproduction. Animal studies have associated triclosan with low testosterone levels and less sperm production. It also affects the thyroid. Triclosan has been also associated with making people more sensitive to allergens and asthma. There is also a chance of bacterial resistance emerging since it is used in many products. (McMillen, 2018) A study was published in May 2018 by a food science researcher who fed mice with triclosan, with an amount that is comparable to what would be absorbed when human teeth are brushed with toothpaste. After 3 weeks, it was found that the mice had gut problems such as inflammation of the colon with larger tumors leading to colon cancer. This study is an animal study and there could be an argument for limited relevance regarding human health as in this case mice can metabolize triclosan differently than humans. However, the results do raise concerns of triclosan with respect to human health and more future studies should involve the evaluation of the risks of triclosan related to human cells. (McMillen, 2018)

<table>
<thead>
<tr>
<th>Cell type</th>
<th>TCS Concentration (µM)</th>
<th>Exposure (h)</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human breast cancer cells MCF-7</td>
<td>≥345.4</td>
<td>120</td>
<td>Proliferation (oestrogenicity)</td>
</tr>
<tr>
<td>Human (A549) lung cancer cell</td>
<td>250</td>
<td>24</td>
<td>Cell membrane damage (LDH release)</td>
</tr>
<tr>
<td>Human (H460) lung cancer cell</td>
<td>10</td>
<td>24</td>
<td>Apoptotic and proliferative effect, Cell membrane damage (LDH release)</td>
</tr>
<tr>
<td>Human PBMC</td>
<td>≥8.6</td>
<td>30</td>
<td>Loss of mitochondrial transmembrane potential; metabolic acidosis; uncoupling of oxidative phosphorylation</td>
</tr>
<tr>
<td>Human keratinocytes HaCaT</td>
<td>≥8.6</td>
<td>30</td>
<td>Loss of mitochondrial transmembrane potential; necrosis</td>
</tr>
<tr>
<td>Rat fibroblast cells (RBL)</td>
<td>≥5</td>
<td>1</td>
<td>Uncoupling of mitochondrial oxidative phosphorylation</td>
</tr>
<tr>
<td>Human mast cells (HMC-1.2)</td>
<td>≥5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Mouse JB6 Cl 41-5a cells</td>
<td>≥8</td>
<td>≥48</td>
<td>Decreased growth; cell damage (increased LDH release); necrosis</td>
</tr>
<tr>
<td>Zebrifish (Danio rerio, AB strain) embryos</td>
<td>15</td>
<td>1</td>
<td>Uncoupling of mitochondrial oxidative phosphorylation</td>
</tr>
<tr>
<td>Freshwater Protozoan (Tetrahymena thermophila) Larvae.</td>
<td>3.5 nM</td>
<td>1</td>
<td>DNA damage (20 % DNA)</td>
</tr>
<tr>
<td>Chironomus riparius Larvae.</td>
<td>35 nM</td>
<td>24</td>
<td>DNA damage</td>
</tr>
</tbody>
</table>

Triclosan affects mitochondria which is essential for reproduction. Animal studies have associated triclosan with low testosterone levels and less sperm production. It also affects the thyroid. Triclosan has been also associated with making people more sensitive to allergens and asthma. There is also a chance of bacterial resistance emerging since it is used in many products. (McMillen, 2018) A study was published in May 2018 by a food science researcher who fed mice with triclosan, with an amount that is comparable to what would be absorbed when human teeth are brushed with toothpaste. After 3 weeks, it was found that the mice had gut problems such as inflammation of the colon with larger tumors leading to colon cancer. This study is an animal study and there could be an argument for limited relevance regarding human health as in this case mice can metabolize triclosan differently than humans. However, the results do raise concerns of triclosan with respect to human health and more future studies should involve the evaluation of the risks of triclosan related to human cells. (McMillen, 2018)
Summary and Conclusion of the Study

This study provides an overview of the uses of antimicrobial textiles that will provide opportunities for antimicrobial textiles research related to long duration space travel. The application of antimicrobial textiles in different fields like healthcare settings, military, sports and space applications were investigated. This study draws conclusions and understandings for long term space travel by comparing and differentiating these antimicrobial textiles used in different application.

In the medical application chapter, the huge market potential and market share of antimicrobial textiles was mentioned. The textiles are used for external applications like hospital scrubs, bed, linens, wound dressing as well as for internal applications like surgical threads and vascular grafts and implants. In a healthcare setting, antimicrobial textiles are used to prevent the transmissions of cross pathogen infections between patients as well as doctors. It is also used to assist in the wound healing process.

In military settings, these textiles are also used to protect soldiers who are exposed to harsh environments during deployment. This has been a practice since the WWII, to prevent the degradation of various textiles in tents, soldiers’ uniforms, and boots. It also reduces the medical cost of soldiers suffering from fungal infections, skin irritation and female health issues, as well as providing overall comfort, thereby not affecting their performance in the field.

In sports, antimicrobial textiles for sports application is mainly for the purpose of odor control. Many major sports brands have already incorporated antimicrobial technology for their products. Nanotechnology has been mostly tailored to sportswear and nano particles have been commonly used for sportswear antimicrobial application.
There were many research articles on the military, medical and sportswear application of antimicrobial textiles. But there were fewer articles on these textiles for space intra vehicular clothing wardrobe for long duration space flight. The luxury of washing machines and cargo ships is not yet available for these missions as the logistic shipping is very expensive. The space application of antimicrobial textiles is an ongoing research and needs to be explored. In the space application chapter the research articles also gave a little description on what antimicrobial textiles materials were used and also conclusions from their research.

Comparison table 5 of antimicrobial textiles used in medical, military, sports and space.

<table>
<thead>
<tr>
<th>Application/Concerns Purpose</th>
<th>Necessity</th>
<th>Duration of wear</th>
<th>Aesthetics</th>
<th>Research/Product Availability</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical</td>
<td>To prevent infections and speed the healing process</td>
<td>Necessary for medical application</td>
<td>Short term duration</td>
<td>Not important as it mostly serves the physiological purposes</td>
<td>Abundant research is done and many commercial products exist Not much of a concern</td>
</tr>
<tr>
<td>Military</td>
<td>To resist infections and odor control</td>
<td>Necessary for military application</td>
<td>Duration can be short or long depending on the combat period</td>
<td>Not important as they mostly use uniforms</td>
<td>Research is done and products are available for military consumption Not much of a concern</td>
</tr>
<tr>
<td>Sports</td>
<td>Odor control</td>
<td>Not a must for sports applications</td>
<td>Short term duration</td>
<td>Needs to be aesthetically appealing and not just functional</td>
<td>Abundant research is done and many commercial products exist Not much of a concern</td>
</tr>
<tr>
<td>Space</td>
<td>Odor control and to fight against microbes that dwell in space</td>
<td>More research needs to be done to confirm if it is necessary or not.</td>
<td>Long term space travel</td>
<td>Yes, for psychological well-being of crew inside spacecraft, wet to color &amp; less people</td>
<td>Little to no research is done with no products available for astronauts Is a concern due to LDSF logistics weight and launch cost.</td>
</tr>
</tbody>
</table>

Comparison table 5 of antimicrobial textiles used in medical, military, sports and space.

<table>
<thead>
<tr>
<th>Application/Concerns Fit and Comfort</th>
<th>Laundering</th>
<th>Durability to wash fastness</th>
<th>Durability of extended wear</th>
<th>Effects against microbes</th>
<th>Environmental Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical</td>
<td>Fit is not important for this application but comfort is</td>
<td>Is not a concern</td>
<td>Is a concern for hospital external products that are washed.</td>
<td>Not a concern as it is not worn for a long period of time</td>
<td>Bacterial resistance to these textiles is a concern Is a concern</td>
</tr>
<tr>
<td>Military</td>
<td>Both are important such that combat is not restricted</td>
<td>Can be a concern during long combat period</td>
<td>Not a concern during long combat period due to no laundry</td>
<td>Not a concern</td>
<td>Is a concern based on the harsh environments the soldiers are exposed to Not a concern</td>
</tr>
<tr>
<td>Sports</td>
<td>Both are important such that sport activity is not restricted</td>
<td>Is not a concern</td>
<td>Is a big concern as it is washed regularly</td>
<td>Not a concern</td>
<td>Not a concern Is a concern</td>
</tr>
<tr>
<td>Space</td>
<td>Both are important for long term space travel</td>
<td>Is a concern since washing is a big concern in space</td>
<td>Is not a concern as there is no washing utilities in space</td>
<td>Is a concern as it is worn for long term and it cannot be replenished</td>
<td>Is a concern as the microbial life in space is also an ongoing research Not a concern</td>
</tr>
</tbody>
</table>

Table 5 and table 6 provide a comparison of the antimicrobial concerns used in medical, military, sports and space. All chapters regarding the use of antimicrobial textiles discussed silver nanoparticles as the common antimicrobial material used in all application among triclosan, quaternary ammonium compounds, polyhexamethylene biguanide, N-halamine and metal oxides. Antimicrobial agents also pose a risk to the environment (water and aquatic life) due to its leaching during laundering. Only the human safety and environmental risks associated
with silver and silver nanoparticles are widely seen. Other antimicrobial agents also need to be assessed for its risks to human and environment.

It is also evident that for a short-term duration of wear, the antimicrobial textiles serve its purpose. Further research needs to be done on prolonged wear of these textiles as this information is scarce. The right antimicrobial agent with minimal human risk needs to be chosen for long term space travel. The delicate balance of human skin flora needs to be taken into account when manufactures and researchers develop antimicrobial compounds and technique. The main research question from this review is that the effect of antimicrobial textiles on the skin microflora and the efficacy of the antimicrobial agents during prolonged wear need to further explored with a research methodology and evaluation.

No research seen in this paper says laundry is not needed and if antimicrobial textiles pose a risk to humans then washing machine invention needs to be addressed. Other research gaps seen in this review is that the mechanisms of bacterial responses and the virulence of microbes in space microgravity is unclear and needs to be understood more. The study of skin flora in space needs to be addressed, as does the risk of infections when the immune system is compromised in space. These gaps lead to other questions, such as if antimicrobial textiles will be effective to fight against the microbes in space especially during long duration space missions. The development of bacterial resistance in space and in Earth against antimicrobial textiles should be analyzed well when considering common antimicrobial agents like silver.

The next possible phase after this review will be comparing the different antimicrobial agents (silver nanoparticle, PHMB and a natural antimicrobial agent) for their efficacy and assessing their effect on the skin microflora during a long-term exposure. A wear trail experiment can also be done with crew subjects participating in a mission that is carried out in a
Mars stimulator, where mimicking a Mars habitat on Earth provides an analogue. Crew members can be given treated and control t-shirts that they can wear for six months prolonged period. Six months is chosen as this duration is one leg of the trip to Mars. Bacterial skin swabs solution could be collected from one part of the body region of all the crew members in the week before the six months wear period begins, then after every consecutive week during the study and in the week following the wear period. This is see the change in microflora, whether there was a reduction in the microflora over the different weeks and the effect of different antimicrobials on the flora compared control t-shirts.

The efficacy of the antimicrobial textiles can be quantitatively tested using the AATCC TM 100 suspension test. Sensory smell test through a survey measure can also be done by the crew members once in three days during the six months. The crew members can maintain an online journal entry containing few survey questions of 0-5 Likert scale regarding the odor assessment. This is done to get a response from the subjects regarding the odor of the textiles during the six months wear period and the variation in response between the members. This is only a direction to start from which a strong methodology and data analysis can be built upon for the research to be carried out aiming to find the right antimicrobial textile and evaluate their effect on the skin microflora during long term space travel.

References


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