REVIEW ARTICLE

A review of CBRN topics related to military and civilian patient exposure and decontamination

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Abstract

Chemical and biological (CB) warfare have long been practiced, and although these types of warfare are not acceptable in modern times, this does not prevent them from occurring. This makes it important for societies to be able to appropriately respond to these events, including the best way to decontaminate victims to keep them and emergency responders safe. Decontamination methods such as chemical, physical, wet, and dry methods are discussed, as well as their downsides. Secondary contamination, which played a significant role in the Tokyo sarin attacks, has long been noted by anecdotal evidence, although it has been little studied. Biological agents cause more problems after infection has taken place, and thus preventing the spread of infection is the largest concern. There are many differences between military and civilian populations, and the response to mass casualty attacks differs accordingly. There are several emerging technologies that can make this process easier on all parties, such as bioscavengers, antitoxins, and color changing bleach for visualization. A reliable way to quantify decontamination is also needed, which would allow for better care of victims both in normal hospital situations, as well as during aeromedical transport. In addition, several gaps were identified, such as the lack of scientific basis for 90 percent reduction during decontamination, a way to quantify decontamination, and the lack of studies on toxic industrial chemicals and secondary contamination.

The views expressed in this article are the work of the authors and do not necessarily reflect the official policy or position of the US Government, the US Department of Defense, or the US Air Force.

Key words: CBRN, decontamination, biological, chemical, decontaminants

Introduction

History of CBRN

Chemical and biological (CB) threats have been recorded throughout the history of warfare using a variety of agents and methods. This has included the use of venom on arrowheads or burning sulfur or mustard plants as irritants to slow the digging of siege tunnels.[1] A complete history of the use of CB agents and toxins is beyond the intent of the current work. Modern warfare draws battle lines under such agreements as the Geneva Convention and the Convention on the Prohibition of the Development, Production, Stockpiling, and Use of Chemical Weapons and on their Destruction administered by the Organisation for the Prohibition of Chemical Weapons to eliminate the use of chemical warfare agents (CWAs) on the battlefield and against dissident civilian populations. Under the convention, the use of toxic chemicals with the specific intent to harm or kill is prohibited, as well as the munitions that aid in delivery and dispersal of these chemicals.[2]

The Department of Defense (DOD) recognizes the threats posed by toxic industrial chemicals and materials (TICs/TIMs) in addition to threats posed by chemical, biological, radiological, and nuclear (CBRN) agents. AFTTP 3-2.55 lists the civilian references applicable to TIC/TIM response.[3] The DOD is focused on CWAs because they are intended to be highly lethal at very low concentrations, even immediately after exposure. Specially designed personal protective

DOI:10.5055/ajdm.2019.0324

equipment (PPE) such as Mission Oriented Protective Posture (MOPP) gear and specific Tactics, Techniques, and Procedures (TTPs) for delineating decontamination operations are the primary means of counter CBRN activities.

After a chemical or biological warfare attack, there is a need to decontaminate victims in order to reduce the negative physiological effects from prolonged exposure to these agents. This work reviewed literature on decontaminants and attempts to understand the current state of the science as well as gaps in the knowledge. The scholarly literature was searched from September 2018 to February 2019 for works relating to CB decontamination and relevant topics. In addition, some relevant military literature and TTPs were reviewed.

Decontamination

The current US doctrine on decontamination during mass casualty events is summarized in a 2013 report from Edgewood Chemical and Biological Center (ECBC).[4] This report suggests that moving victims from the "Hot Zone," followed by the immediate removal of clothing and flushing with water at 50-60 psi should remove 80-90 percent of contamination. This document is the basis for mass casualty response and describes in detail the requirements for zoning and decontamination. Mass decontamination processes require controlled access to and exit from the contamination source and should be oriented in ways that account for weather conditions. They also rely on a flow through line system to allow for mass washing of victims. Decontamination is clearly defined in this report as making any personnel, material, or area safe by neutralizing or removing CB agents or nuclear material. Quantification of contamination or decontamination is not covered by the document.

Broadly, decontamination is the removal or neutralization of hazardous agents on people, equipment, or surfaces.[5-11] Decontamination is important to protect both victims and first responders as well as future users of contaminated equipment.[5,12-21] Decontamination processes can be classified by whether they are chemical or physical or whether they are wet or dry.

Chemical decontamination uses a chemical agent which can degrade or neutralize the contaminant into a less toxic form. This can be done by hydrolysis (washing with water and soap), oxidation (oxidative chlorination is common), or by acid or base hydrolysis (although this can be very caustic to the skin, as is the case with sodium hydroxide or concentrated bleach).[6,9,22]

Physical decontamination is the physical removal of a contaminant from the skin by washing with water, mechanical brushing, or adsorption onto a decontaminant. It is very important for biological decontamination to prevent later infection.[11] One advantage of physical decontaminants is that the agent does not have to be known for physical decontamination to be effective.[22] However, there are disadvantages to both chemical and physical decontamination methods. Chemical methods can be slow as they rely on chemical reactions.[6,22] On the other hand, while physical methods are much quicker, they merely relocate the hazardous agent from the victim to the decontaminant. This creates a great deal of contaminated waste that must be managed appropriately.[7]

Decontamination methods may also be distinguished by whether they are a wet or dry method. Dry decontaminants are absorbent materials used to soak up contaminants, making them most useful for liquids, oils, fatty, or greasy contaminants.[5,19] Dry decontaminants can be commercial off-the-shelf (COTS) products such as Fuller's Earth or M291 resin, or they may be improvised decontaminants such as paper towels, cloths, baking powder, or talc.[19,22]

Wet decontamination consists of washing the affected area with plain or soapy water to remove the chemical agent. Showering is the most recommended decontamination method.[15,19,23-26] However, it should not be used for water reactive agents, or during cold weather to protect against hypothermia.[5,18,19,27]

There are several principles of conventional wisdom pertaining to decontamination. Disrobing is considered the first crucial step, followed by showering. Ventilation to promote off-gassing is also occasionally suggested, although not as widely as disrobing or showering. Finally, it is recommended to start decontamination as soon as possible after being exposed to a hazardous agent.

It is often stated that disrobing will remove between 70 and 90 percent of contamination.[5,18,21,23,28] This is widely accepted to be true and informs many official CBRN decontamination and response guidelines. However, during the course of this review, no definitive scientific basis was found.

Showering to remove contaminants is highly recommended during decontamination.[7,18,19,22,23,25] However, it has been shown that the efficacy of showering may depend on water pressure, temperature, flow rate, the use of detergents, and presence of clothing.[6,21-24,29] In addition, there is some evidence that showering may increase absorption due to the "wash-in" effect.[19,24,30,31] The "wash-in" effect is the enhancement of dermal penetration of a chemical due to washing, although it has not been well characterized. One review proposes that the effect may stem from degradation of the barrier qualities of the stratum corneum due to hydration, surfactants, acidic, or basic qualities of washing aids or liquid decontaminants, or friction from physical washing.[31] They also note that the majority of studies have been done in vitro, so the effect may be an artifact of the methodology.[31]

Ventilation of the body or clothing may be helpful if the exposure was to a gaseous agent, although few sources considered this.[25] In addition, if there were high levels of exposure with the potential for off-gassing, ventilation could be recommended to avoid trapping contaminants between clothes and creating continuing exposure. However, ventilation of areas is often recommended as a protective measure for both victims and first responders. Ventilating decontamination, triage, or care areas when chemically contaminated patients are involved is important in order to minimize risk of gas build-up and creating a secondary exposure source for parties in the area.[13,16,18-20] In addition, patients suspected to be exposed to highly infectious biowarfare agents (or those obviously showing symptoms) should be isolated from workers and other patients by having separate ventilation.[32]

Decontamination is recommended to start as soon as possible, although the importance of this timing has not been well characterized.[8,10,30,33] One research group demonstrates that starting decontamination sooner increases the decontamination efficiency by showing that the penetration rate of VX decreases more quickly the sooner decontamination is started.[8]

Decontamination method efficacy differs depending on contaminating agent, countermeasures employed, and duration of exposure before commencing decontamination procedures. Efficacy of decontamination of soman was studied comparing treatments with 0.5 percent bleach, 1 percent soapy water, Reactive Skin Decontamination Lotion (RSDL), and M291 skin decontamination kit (M291 SDK) on the skin of exposed guinea pigs. Each decontamination was performed 2 minutes following soman challenge and efficacy was measured by calculating a protection ratio (PR) from the adjusted LD_{50} after decontamination. RSDL, with a PR of 14, provided the best PR under the experimental design, however, subsequent delayed decontamination trials showed greatly reduced efficacy.[34] The other decontaminants tested showed significantly smaller protections factors with 1 percent soapy water having a PR of 2.18, 0.5 percent bleach having a PR of 2.63, and M291 SDK having a PR of 2.73.[34]

Discussion

Secondary contamination

Secondary contamination is the spread of contamination to people who were not present during the initial attack, such as emergency responders, by contact with victims who were.[5,12,16,24] This is often cited as a potential threat to first responders and emergency department healthcare workers due to contact or inhalation of vapors from contaminated patients. It is widely recognized as a risk from anecdotal evidence but has been little studied or quantified.

One study simulated decontamination of a patient and measured the breathing zone concentrations of vapor and particulate contaminants.[17] The authors simulated a "worst-case" scenario where decontamination was undertaken in a room with blocked ventilation. The clothing of a mannequin was saturated with an organic solvent or metal oxide particles and the air in the room was sampled, as well as the breathing zone of both physicians performing

the decontamination and that of the mannequin.[17] The physicians had breathing zone values which were about a third of the American Conference of Governmental Industrial Hygienists (ACGIH) short-term exposure limit (STEL) for the organic solvents and significantly less than the available Occupational Safety and Health Administration permissible exposure limits for the particulates.[17] Although the ACGIH STELs have been revised since the original study, the exposures would be below the 2018 STELs. However, when the researchers extrapolated to more hazardous chemicals, the predicted exposures were much higher than the relevant STELs.[17] In addition, the authors point out the uncertainty about the linearity of the relationship between relative evaporation rates and vapor pressure and recommend further testing be done on different chemicals to determine this.

A subsequent article cited this study and extrapolated the results to sarin. This extrapolation predicted a sarin concentration maximum of no more than 50 ppm.[16] The authors note that the saturation volumes used in the original study would likely be a significant overestimation of a true exposure during a mass casualty situation and thus this maximum concentration would likely not be reached.[16] However, according to the US Environmental Protection Agency's Acute Exposure Guideline Levels, the nondisabling 10-minute exposure to sarin should be less than 0.0012 ppm.[35] The authors also point out that if healthcare workers wear respirators with organic vapor cartridges, there should be little risk, based on the findings of an ECBC study which tested organic vapor cartridge respirators against sarin for up to 6 hours and exhibited no breakthrough of the cartridges.[36]

Another study was reviewed, in which the author exposed different types of clothing to a high concentration of methyl salicylate (MeS), a sulfur mustard simulant. The air near the clothing was periodically measured for MeS until the concentration was 0.[37] This author found that lightweight clothing, such as cotton t-shirts or jeans reached a zero concentration very quickly, with an average of 7 minutes, while down-filled outerwear took much longer, a mean of 42 minutes to reach 0.[37] Mass decontamination showers take significant amounts of time to set up, up to 30 minutes by some estimations.[15,27] From this, the author concluded that decontamination showers may be unnecessary for victims only exposed to vapor as all contamination likely would have dissipated before showers were set up.[37] However, decontamination showers are still recommended for patients exposed to liquid or solid contaminants. While decontamination may not be necessary for victims waiting outdoors, if patients enter enclosed spaces, such as an ambulance, within 35 minutes of exposure, there could be significant risk of vapor accumulation from clothing off-gassing, thus contaminating the space or emergency responders.[37] Due to unique chemical properties between even chemicals in the same family, there is a need for further studies examining the off-gas potential for different chemical agents, as well as for testing different clothing types.

Decontaminants

There are a variety of COTS decontaminants available. The two most widely used are RSDL and Fuller's Earth. In addition, some US Air Force instructions recommend the use of M291 skin decontamination kits. These decontaminants have mainly been tested against CWAs and may not have the same efficacy against TIC/TIMs or biological agents.

RSDL is a unique decontaminant because it utilizes both chemical and physical methods of decontamination. It contains a reactive oxime (diacetyl monoxime, DAM) along with the potassium salt of DAM which is used to neutralize chemical agents as well as polyethylene glycol monomethyl ether (mPEG) which is used to absorb them.[5,7,8,38] RSDL has a low water content, which may increase solubilization of lipophilic compounds such as the organophosphate (OP) VX.[7]

The shelf-life of a product is important to consider when it is purchased for emergency situations and may not be replenished frequently, as is the case with decontaminants. The shelf-life of RSDL was evaluated in a 2018 study.[38] Due to its use in military campaigns, RSDL may not always be stored under ideal conditions. To understand the shelf-life under nonideal conditions, they evaluated the stability and degradation

of DAM, as well as the formation of dimethylglyoxime (DMG), a degradation product of DAM. They stress-tested the product through short-term storage at very high temperatures in order to determine the kinetics. DAM degradation followed first-order kinetics, while DMG formation followed zero-order kinetics.[38] These constants were used to predict the shelf-life of stored military samples. These samples were taken from a military storage depot where the product was kept at 20°C, within the manufacturer's specifications, and from a training mission in Mali, where it was kept at ambient temperature.[38] The mean kinetic temperature during this training mission was 31°C, above the manufacturer's specifications.[38] The stress testing showed that even short-term periods of storage above the manufacturer's specifications can significantly degrade DAM, although the infrequent fluctuations in temperature above the manufacturer's specifications during the training mission did not significantly affect the active ingredient.[38] This study shows the importance of evaluating storage and mission conditions to understand the impact of temperature on decontaminants vital to personnel survival in emergency situations.

RSDL has been reported by the manufacturer to be effective against most CWAs and one biological warfare agent.[6] One lab group evaluated the decontamination efficacy of RSDL against neat VX, VX diluted in water to 20, 75, or 90 percent, and a hydrophilic organophosphorus compound.[7,8] In one study, they tested three formulations of RSDL: RSDL as a concentrated lotion, RSDL as a diluted lotion, or RSDL delivered by a sponge against neat VX or 20 percent VX.[7] Three other decontaminants (alldecontMED, Fuller's Earth, and PS104) were tested in addition to the different formulations of RSDL. These were tested for varying contact times, decontamination start times, and removal protocols. Overall, concentrated RSDL lotion was the most effective at reducing the penetration rate of VX into human skin. However, the concentrated and dilute RSDL lotions were left on the skin for 30 minutes, while the sponge was used to swab the skin for a 2-minute contact time, which could bias the results toward the lotion. A different study from the same group evaluated the decontamination efficiency of concentrated RSDL lotion against neat or dilute VX or triethyl phosphonoacetate (TEPA).[8] TEPA is a hydrophilic organophosphorus compound, while VX is a lipophilic compound.[8] RSDL significantly reduced the penetration of VX while there was not a significant decrease for TEPA. This signals that solubility in RSDL may increase the efficacy of decontamination for lipophilic compounds.[8]

Another common decontaminant is Fuller's Earth. Unlike RSDL, Fuller's Earth is purely a physical decontaminant. It is also considered a dry decontaminant as it is a highly absorbent, nonplastic type of clay which contains aluminum-magnesium silicate and can easily adsorb fats, greases, and oils but has no degradation properties.[5-7] A downside of this decontaminant is that prolonged contact may cause skin irritation and inhalation is a potential hazard.[6]

One study compared the efficacy of Fuller's Earth to hemostatic (clotting) agents on damaged and undamaged skin.[39] This study evaluated Fuller's Earth, QuikClot Advanced Clotting Sponge Plus, ProQR, and WoundStat against the CWAs VX, HD, and GD.[39] The authors found that both Fuller's Earth and WoundStat reduced penetration significantly and at similar rates.[39] One limitation of this study, however, was that total recovery of the dose of chemical agent was low, less than 40 percent.[39] In addition, the study used porcine skin rather than human, so the results must be extrapolated which introduces error. Finally, the amount of chemical agent present in various fractions was measured by analyzing radioactivity by Liquid Scintillation Counting which cannot distinguish between the original CWA and metabolites. However, this would assume a worst-case scenario so it should not be considered a significant shortfall.

In a previously discussed study, Fuller's Earth was compared to RSDL, PS104, and alldecontMED for reduction of penetration efficiency against VX.[7] In this study, decontamination was started either 5 or 30 minutes after exposure to the agent and Fuller's Earth was left on the exposure site for 30 minutes.[7] In this scenario, Fuller's Earth was least effective at reducing the penetration of VX when applied 5 minutes after exposure, but was the most effective product tested when applied 30 minutes after VX exposure.[7]

A study evaluated two COTS decontaminants (Fuller's Earth and Fast-Act) along with three novel polymers (itaconic acid, *N,N*-methylenebisacrylamide, and 2-trifluoromethylacrylic acid) for decontamination efficiency against sulfur mustard, soman, or VX.[9] The decontaminants were all applied 5 minutes after exposure to the CWA and left on for 24 hours while penetration rate was measured. The authors found that Fuller's Earth, itaconic acid, and 2-trifluoromethylacrylic acid all significantly reduced the total penetration of all three CWAs tested.[9] One limitation of the study is that the amount of sulfur mustard recovered was very low, around 2 percent, while around 70 percent of VX was recovered.[9] This could limit the significance of the conclusions drawn for sulfur mustard.

Recently, it has been recognized that the scalp could provide a significant exposure pathway for CWAs. In addition, contaminants could be trapped in the hair, prolonging exposure to the agent or creating a reservoir for secondary contamination. One study exposed locks of hair to one of two sulfur mustard simulants, MeS or 2-chloroethyl ethyl sulfide (CEES).[26] The hair was exposed to the vapor for 2 hours, then Fuller's Earth or RSDL was used to decontaminate the hair prior to washing with soap and water. This study revealed that using a decontaminant resulted in significantly less MeS or CEES remaining in the hair compared to just soap and water.[26] However, there was still a significant mass of both CEES and MeS present after decontamination, showering, and drying, which could lead to secondary exposure by off-gassing. Overall, decontamination efficiency was higher for CEES than MeS.[26] This is promising because although MeS is a favored sulfur mustard simulant, the physical structure of CEES is much closer to that of sulfur mustard, differing only by the presence of one chlorine atom.[26] One limitation of this study was that the decontaminants were applied and then removed without mechanical washing. This was important to the authors to reduce tester variability, although this variability would be present in real-world scenarios so it should be incorporated into testing.

A second study aimed to understand the permeability of human scalp skin to VX compared to human abdominal skin and porcine ear and scalp skin. The scalp is likely to be more exposed than other parts of the body, and may be easier to penetrate due to the number of hair follicles which can aid chemical penetration of the stratum corneum, as well as act as reservoirs.[40] This study showed that porcine ear skin could be used as a model for human scalp permeability studies due to the statistically similar penetration rates of VX, the similar stratum corneum thickness, and the similar follicle diameter.[40] The follicle density was higher in the human scalp than porcine ear, but the reservoir capacity was similar, indicating that the number of follicles is less important than the diameter.[40] This was also shown to be true for penetration ability. The authors noted that many studies ignore hair follicles due to the assumption that the number of follicles is negligible compared to the skin surface area, however, in the case of the scalp and face, this is false.[40] This is important because the head and face are often left uncovered in most populations.

Selected case studies

Japan, Sarin. In 1994 and 1995, separate CWA attacks occurred on civilian populations using sarin gas. The 1994 incident took place in Matsumoto, Japan, dispersing an impure form of sarin from a truck, which affected approximately 600 people, seven of whom died and 58 of whom were admitted to the hospital.[41] The 1995 incident, in which sarin gas was released on the Tokyo subway, resulted in 12 deaths and around 5,500 people exposed. During this incident, it is estimated that roughly 20 percent of emergency department workers and 10 percent of emergency first responders suffered symptoms resulting from secondary exposure.[41] Eight of 53 personnel deemed rescuers, along with one doctor, reported mild symptoms resulting from patient interaction. After exposure, it was determined that 124 patients had miosis that adversely affected vision with some cases lasting 30 days post exposure.[42]

The sarin gas attacks in Tokyo in 1995 resulted in significant civilian and healthcare worker casualties.[16] The majority of patients who entered emergency departments in the aftermath of the attacks had self-presented, meaning that they had no decontamination

prior to care at the hospital.[16] In addition, healthcare workers who treated these patients did so in poorly ventilated rooms without wearing any respiratory protective equipment.[16] This resulted in ~20 percent of healthcare workers (over 100 workers) who treated patients after this attack becoming contaminated and showing symptoms of sarin exposure.[16,37]

Gulf War, Sarin. The DOD reported exposure of service members to sarin and cyclosarin during the 1991 Gulf War during munitions dump detonation at Khamisiyah, Iraq. Reported exposures were modeled with high dose ranging from 0.072 to 0.144 mg min/m^3 to no exposure depending on the proximity of the unit during the depot destruction. Neurobehavioral evaluation was performed on soldiers with known exposures prior to public acknowledgement of the event for comparison with follow up testing to evaluate long-term effects of exposure to survivable doses of sarin and cyclosarin.[43] The results indicate reduced visuospatial and manual dexterity in a dose dependent manner but lack pre-deployment baseline evaluations. This case study indicated the importance of thorough medical screening prior to deployment of US forces due to unforeseen exposures that could be encountered in future theatres of operation.

Biologicals

Responding to biological warfare agents often focuses on treating clinical symptoms to prevent the spread of infection, rather than on decontamination.[5] In addition, decontamination after a biological attack is not as time critical because most biological agents are not able to penetrate the skin the way chemical agents can.[22,28] Thus, recommendations for biological attacks are to wash the hands with soap and water or a 0.5 percent hypochlorite solution to remove microorganisms and prevent the risk of ingestion or inhalation later.[22] While outside the scope of this article, it is worth noting that although there is little literature on how to decontaminate a patient after a biological attack, there is a wealth of information within the medical community on how to decontaminate surfaces and materials after highly infectious patients have used them.

Patients who have been infected with biological warfare agents should be handled similarly to treatment of highly infectious patients (such as severe acute respiratory syndrome or Ebolavirus). Depending on treatment availability and patient condition, highly infectious patients may need to be transported between medical facilities. This is called medical evacuation if patients are transported by ground vehicle or aeromedical evacuation (AE) if they are transported by aircraft.[44] The US Air Force routinely flies AE missions. Critical Care Air Transport Teams (CCATT), which include critical care nurses, physicians, and respiratory therapists, accompany patients to provide medical care.[45] These healthcare providers receive special training to understand the physiological stresses imparted by air transport.[45]

During flight, highly infectious patients should be isolated to prevent the spread of disease to the CCATT team, the aircrew, or any other patients.[44,46] Care members or patients may also need to wear appropriate PPE such as air purifying respirators to protect themselves and those around them.[32,44]

Civilian versus military populations

Several factors separate military from civilian populations. The scale of an attack, the amount of training, the location of equipment used for decontamination, and the make-up of the populations are all different. Military personnel undergo training for emergency situations such as CBRN attacks and decontamination, whereas this is not present in the general population.[14,28]

There are many considerations when preparing for mass casualty or mass decontamination events. Due to the nature of military operations, they must be prepared for events both in the field as well as at home bases. The home base preparations are similar to those made by civilian hospitals. Fixed decontamination facilities located at hospitals should be located near, but not within the emergency department in order to allow contaminated patients to pass through the decontamination facility prior to entering the emergency department.[15] These facilities should have exterior ventilation in order to prevent build-up of hazardous gases and vapors and subsequent secondary contamination from these vapors.[15,18]

Mobile decontamination shelters should be stored where they are easily accessible during an emergency situation.[15] Other considerations for mobile shelters include clean water sources and hook-ups, capture and storage of contaminated water, water heaters, and light sources both inside and outside the shelters.[15,18,19] In addition, personnel are needed to set up and man these mobile decontamination systems.[15]

Another difference between civilian and military groups responding to a CBRN situation is the culture and chain of command present within military units.[14] Discipline is a key facet of the military culture and it is expected that military members comply with decontamination procedures. On the other hand, civilian populations lack the command and control possessed by military organizations, thus making them less likely to comply with procedures, particularly if they are contrary to cultural norms. Public compliance with instructions during a mass decontamination situation depends on the perception of risk and amount of trust in the authorities who are asking for their cooperation.[47] Of particular concern is the issue of privacy. Doffing clothing is generally the first step in an effective decontamination response. However, this creates privacy concerns in the general population. If this issue is not adequately addressed, public compliance during a situation will be reluctant at best.[14,15,19]

The military population is much more homogenous than the general public. Civilian populations include children, the elderly, and people with illnesses and physical or mental disabilities, while the military excludes these more vulnerable groups.[14] This heterogeneity of civilian populations can also impede compliance to decontamination procedures. If young, elderly, disabled, or people who do not speak the language well are affected by a CBRN attack, they may need help to respond to decontamination instructions properly.[14,19]

Military decontamination standard operating procedures include protective outer garment decontamination as specified by AFTTP 3-2.60 and the detailed specification stated in MIL-DTL-32102, that delineates all specification and construction standards required for MOPP gear.[48,49] The most notable specifications are the duration of impermeability, 45 days of wear during a liquid challenge to HD, GD, and VX and the dispersal concentration of 10 g/m^2. The garment must also be able to withstand six launderings after exposure to a variety of contaminants found in an operational environment.

Selected emergent technologies

Bioscavengers. Bioscavengers are enzymes which prevent OP chemicals from disrupting natural cholinesterase activity leading to the accumulation of neurotransmitters which cause cholinergic crisis and, if severe enough, death. Bioscavengers are characterized as stoichiometric, pseudocatalytic, or catalytic depending on their quantity or enzymatic activity to prevent systemic nerve agent poisoning.[50] Stoichiometric bioscavengers can be artificially produced or isolated from organisms, such as butyrylcholinesterase which is collected from plasma fractionation and harvested for prophylactic treatments. Stoichiometric bioscavengers react irreversibly with OPs and are inhibited in the process of phosphorylation of OPs. Pseudocatalytic bioscavengers are oxime reactivated stoichiometric bioscavengers that are regenerated to cycle through the process of OP bonding and degradation. Catalytic bioscavengers function to break down OPs without a separate reactivation enzyme.[51]

Ricin antitoxin. Ricin toxin has long been a concern due to its relative ease to acquire and high toxicity. Antitoxin has been derived from equine serum inoculated with monomerized toxin that elicits greater antibody production with less toxicity. The antitoxin was able to afford a greater than 60 percent survival rate in mice from a challenge to lethal dose of ricin toxin when administered 24 hours post challenge and 35 percent survival rate when administered 48 hours post challenge.[52] Previous antitoxin derived from rabbits had shown a survival rate of 34 percent at 24 hours with greater cytokine levels in bronchoalveolar lavage fluid.[53]

Nanotube-lined PPE. Research has shown that single-wall carbon nanotubes with an embedded

catalytic copper functional group can breakdown OP simulants as proof-of-concept that future PPE could self-decontaminate. Structurally and chemically active nanomaterials expressed kinetic activity that was evidence of breakdown of the CWA simulant 4-nitrophenol phosphate sodium in water. Spectral absorbance was used to measure *p*-nitrophenol, the hydrolyzed product of 4-nitrophenol phosphate sodium, and the material continued to be kinetically active following 18 days of continuous exposure to CWA simulants.[54]

Nanomaterial Decon Wipes. A multipurpose dry decontamination wipe has been proposed and tested against various CB agents using a multilayer design incorporating zinc ($ZnTiO_3$) and silver ($AgNO_3$) nanoparticles and a layer of activated carbon. The wipe was tested against diethyl chlorophosphate (DCP) and CEES to decontaminate rats and separately to test inhibition of *E. coli* and *S. aureus* bacteria and Penicillium species with reported greater than 95 percent efficacy. Dermal exposures to DCP and CEES were evaluated using Ache inhibition assay (90 percent less inhibition than exposed group), and histopathological examination, respectively.[55]

Mid wave infrared detection of chemical agents. Demonstrating instrument parameters regarding field of view, detection threshold, and data processing are critical to future development of instruments that can meet the requirements for low limit, highly accurate agent identification in a field setting. Mid wave infrared (IR) laser sources target the 2.5-3.7 µm range, which covers the absorption bands of oxygen-hydrogen and carbon-hydrogen bonds. These can be used to identify CWAs or other chemical. A device using active hyperspectral mid wave IR in combination with an intra-cavity optical parametric oscillator IR laser source was used to cover the 2.5-3.7 µm range in 10-nm steps. Benchmark tests and calibration of M Squared Lasers Ltd Negative Contract Imager consisted of three modules: laser source, scanner/detector, and electronics. The laser source is a Q-switched laser with repetition rate of 150 kHz and nominal power output of 90 mW. The system weighed 15 kg and was battery operated. After determining reference spectra for CWA simulants, the system was used to identify VX and O-Mustard on various substrates in varying volumes. The limit of detection for VX on metal and glass was 1008 and 962 mg/m^2 for O-Mustard on sand.[56]

Color change bleach. Highlight® is a chemical additive to chlorine disinfecting solutions that imparts color which fades to transparent. The proprietary formula is designed to retain its color for desired dwell time based on the concentration of the solution. Recently, funding from a USAID grant allowed the use in Guinea in response to the Ebola outbreak of 2014-2015 to examine healthcare workers adherence to decontamination during PPE doff procedures.

Pickering emulsions. Pickering emulsions are emulsions stabilized by solid particles rather than the usual method of stabilization by surfactants.[10] Solid particles adsorb to the surface of oil particles to stabilize the oil-water interface. This may decrease the risk of the wash-in effect by not having a surfactant present. In addition, they may have increased sorbency due to having both an oil and water phase for adsorption of both hydrophilic and lipophilic compounds.[10] One research group dispersed silica and Fuller's Earth into water, then used those particles to stabilize an oil-in-water emulsion which was used to decontaminate VX.[10] Fuller's Earth in Pickering emulsion was the most effective, as the larger oil droplets were able to disperse more VX.[10] However, silica dispersed in water, as well as in the Pickering emulsion were both highly effective. The authors believed this was due to the pH of the solution being acidic, thus allowing VX to be in a majority positively charged state. In addition, silica can form both acidic and basic polar interactions.[10]

Further discussion

There is no standard methodology for testing so it may be difficult to determine the best decontaminant in scholarly literature. The ECBC published the 2007 Source Document to implement improved and rigorous test methodology in order to standardize DOD evaluation efforts.

It is difficult to draw conclusions from the numerous papers which have studied the efficacy of various commercial decontaminants. There is no standard methodology between research groups for the different factors which may affect decontamination efficacy, such as the time when decontamination starts after exposure, the contact time for decontaminants, or the amount of decontaminant applied. Some decontaminants, like RSDL, work best when applied within seconds or minutes after exposure, while others, like Fuller's Earth may have a higher efficacy when applied longer after exposure. Many studies also use a much longer contact time for decontamination than would be likely in a real-world scenario. In an emergency situation, it is likely that decontaminants would only be allowed to work on the skin for a few minutes, while many studies leave the decontaminant on the skin for hours. These differences between the chaos of a real-world situation and the studies conducted make it difficult to determine which decontaminant may be the best.

In addition, there is no standard for quantification of decontamination. In most studies, high pressure liquid chromatography, gas chromatography (with mass spectrometry or flame ionization detector) or liquid scintillation counting are used to analyze the amount of chemical remaining after decontamination, however, these methods are not practical for field use. There is a need for a reliable and precise way to measure whether decontamination of personnel or equipment in the field has been done to a protective extent. Laser or IR detectors may be useful field tools if they can be developed to meet the required limits of detection.

Another limitation of the many studies that have been conducted is that they have focused on CWAs or similar compounds, such as OP pesticides or chemical agent simulants. With the exception of pesticides, these agents are banned from use or manufacture except by specially authorized groups. This makes them unlikely, though not impossible, to be used as a weapon. However, there are numerous industrially produced chemicals which may pose a significant hazard to civilian or military populations. Called toxic industrial chemicals (or materials, TIC or TIM), these chemicals may be more easily weaponized. A chemical can be classified as a TIC if it has a lethal concentration in air to 50 percent of the test population multiplied by exposure time (LCt_{50}) of less than 10^5 mg min/m^3 or is produced in quantities greater than 30 tons/year in a single facility.[6] These chemicals are recognized by OSHA and other regulatory agencies to pose a significant threat to public welfare if they are released, yet they have not been well studied for their response to standard decontamination procedures.

Use of CB warfare agents is a low incidence-high consequence event for military operations or against a civilian population that can have long-term implications for those affected. The abundance of emergency management and military-specific operation manuals highlights the seriousness of such an event occurring. The differences between military and civilian responses to mass casualty CB events have been discussed. It is logical that a military population would be more capable to respond to such an event. However, although military units must undergo training, the quality of the training may affect the response to an event. Military TTPs are written assuming that the people performing them are complying perfectly in order to reduce the risk for all affected personnel. However, human nature makes it likely that not all people in the decontamination line are perfectly effective at decontaminating themselves and others. It is easy to imagine that in the panic created by a situation that spots would be missed, leading to imperfect decontamination and the potential for secondary contamination of unaffected spaces or personnel. This makes human behavior an important element to plan for during emergency situations.

The use of protection factors when measuring decontamination efficacy indicates that the current state of defining "decontamination" is directly related to surviving the incident. Future technology in the form of universal detectors with the ability to accurately identify and quantify extremely low concentrations at a distance should be the focus to change the current state of decontamination as a survived exposure event. The DOD maintains several technology surveys of COTS detectors for CBRN and rates them based on manufacturer specifications to determine their suitability for diagnostics and use in a field environment.

The 2017 survey, which covered the period between January and March 2014, had 138 biological, 72 chemical, 49 radiological, and 44 combinational detectors and 12 that claimed to detect biological, chemical, and radiological agents, though failed to rate any single detector as top tier across all the categories covered in the survey. Because there is no single detector that can successfully detect all CBRN agents, the DOD must maintain multiple devices and the technical documentation to field an array of technology and research and development goals.

The DOD maintains a huge repository of information on all CBRN topics from open source to classified information. With this information being compartmentalized within the DOD, it does not always flow freely into the academic realm which creates an information gap of peer reviewed literature open to the public. The ability to methodically and reproducibly quantify decontamination is critical to scientific research of the subject matter. The quantification of decontamination needs to be standardized across methods and materials. The Defense Technical Information Center query for "decontamination" resulted in 58,079 entries and the earliest document from 1965, all results were from unclassified sources. The same search terms in EBSCO Academic Search Complete returned 10,535 from 1943 to present; while ScienceDirect had 52,328 articles returned.

While AEs are generally used to transport patients who have been stabilized, it is possible that patients may need to be transported soon after having been injured. If the injury occurred from a CBRN mass casualty attack, this could cause a significant problem for the aircrews. Although the assumption is that a patient will have been decontaminated prior to air evacuation, there is no way to quantify whether or how well decontamination has been done. If air crews assume that a patient is perfectly clean (as far as chemical contamination goes), they may not properly protect themselves from potential hazards. Off-gassing has been identified as a potential source of secondary contamination which is a risk for medical professionals. However, there has been little work done on whether a patient who has been decontaminated can still present an off-gas hazard. In addition, if decontamination is not done soon after an exposure, the chemical agent may have already entered the skin, which acts as a dermal reservoir. No evidence has been found for effects of changing altitude and pressure on this dermal reservoir which could significantly impact flight crews.

Secondary contamination of healthcare workers from care of chemically contaminated patients has been well documented but little studied. This could be an inhalational hazard in the form of trapped gas or vapor from patients clothing or hair, as well as a dermal hazard from liquid soaked clothing. Future research should further characterize this exposure and focus on understanding the risks to healthcare providers and how to mitigate this risk.

Another gap identified during this literature review was the assumption that decontamination always results in a 90 percent reduction in contamination level. Disrobing prior to decontamination is deemed important because of the fact it is assumed to remove roughly 90 percent of the contamination. It was also assumed that moving through a mass decontamination shower would result in a 90 percent reduction in contamination levels. This 90 percent rule is the basis for most military and civilian disaster response protocols, yet there seems to be little evidence to back it.

Conclusion

Although CB warfare has been practiced for centuries, the risk of these types of terrorist attacks is increasing. This makes it extremely important to understand the implications of these types of attacks, as well as the proper decontamination response procedures. Response to a mass casualty attack will depend on what type of agent is used and what decontamination procedures are available. It will also depend on the population which has been targeted, with significant differences between the responses for military and civilian populations. Several gaps were identified during the course of this review, such as the assumption of 90 percent decontamination, an adequate way to quickly quantify decontamination, and the need for further study on different toxic industrial chemicals, as well as secondary contamination risks.

Funding: *The authors declare no conflict of interest. This study was funded by a grant from the US Air Force School of Aerospace Medicine, # 2018-178R.*

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