Decontamination and Management of Contaminated Hair following a CBRN or HazMat Incident

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ABSTRACT

This in vitro study evaluated the “triple protocol” of dry decontamination, the ladder pipe system (a method for gross decontamination), and technical decontamination for the decontamination of hair following chemical contamination. First, we assessed the efficacy of the 3 protocols, alone or in combination, on excised porcine skin and human hair contaminated with either methyl salicylate (MS), phorate (PHR), sodium fluoroacetate (SFA), or potassium cyanide (KCN). A second experiment investigated the residual hair contamination following decontamination with the triple protocol at different intervals postexposure. In a third experiment, hair decontaminated after exposure to MS or PHR was evaluated for off-gassing. Though skin decontamination was highly effective, a substantial proportion (20%–40%) of the lipophilic compounds (MS and PHR) remained within the hair. The more water-soluble contaminants (SFA and KCN) tended to form much smaller reservoirs within the hair. Interestingly, substantial off-gassing of MS, a medium volatility chemical, was detectable from triple-decontaminated hair up to 5 days postexposure. Overall, the decontamination strategies investigated were effective for the decontamination of skin, but less so for hair. These findings highlight the importance of contaminated hair serving as a source of potential secondary contamination by contact or inhalation. Therefore, consideration should be given to the removal of contaminated hair following exposure to toxic chemicals.

Key words: hair decontamination; skin decontamination; mass casualty; secondary contamination; decontamination; off-gassing.

The deliberate release of hazardous materials, as exemplified by the Tokyo subway attack (Okumura et al., 1996), and accidental releases of hazardous materials, such as the Seveso and Bhopal incidents (Broughton, 2005; Eskenazi et al., 2018), are acknowledged as worldwide chemical disasters affecting several hundreds, if not thousands of people. In recent years, attacks such as the assassination of Kim Jong-nam with VX and the use of novichok in the UK, had the potential to develop into mass casualty incidents due to the brazen way these chemicals were deployed in public spaces, posing a significant threat to public health.

Mass casualty decontamination within the United States following a hazardous materials (HAZMAT) or chemical, biological, radiological, and nuclear (CBRN) event has traditionally used a gross decontamination method known as the “ladder pipe” decontamination system (LPS) (Chilcott et al., 2018; Lake et al., 2013). This ad hoc procedure involves positioning fire engines in parallel to each other to deliver a high-volume, low-pressure water mist into a corridor through which casualties pass. The intricacies of this response vary across the United States (Power et al., 2016). However, the overall response to mass casualty chemical incidents has been revised to incorporate disrobing (the removal of clothing), an improvised form of dry decontamination (DD) and specialist methods of decontamination (technical decontamination [TD]), similar to the principles being adopted in the United Kingdom (Chilcott et al., 2019a; UK Home Office, 2015).
Current research focuses mainly on skin, rather than hair decontamination. Mass casualty decontamination guidelines emphasize the use of improvised DD, wet decontamination (including the LPS), and TD (Amlöt et al., 2017; Chan et al., 2013; Kassouf et al., 2017; Matar et al., 2014; Tayse et al., 2007; Thors et al., 2017). Human volunteer trials have demonstrated the effectiveness of such procedures (Chilcott et al., 2019b). Recently, emphasis has been placed on decontamination of scalp hair (Josse et al., 2015; Rolland et al., 2013; Spiandore et al., 2014, 2017, 2018). It is well established that the removal of contaminants from hair is difficult (Duca et al., 2014) and the affinity with which chemicals bind to hair has been exploited for forensic purposes (Blank and Kidwell, 1995).

Hair decontamination studies have found that the efficacy of the decontamination protocols employed for skin decontamination may not apply in the case of hair decontamination, particularly for more lipophilic compounds such as methyl salicylate (MS) and phorate (PHR) (Matar et al., 2018). Thus, there is a need to investigate the potential dangers of hazardous chemicals that are bound or otherwise retained within the hair shaft after decontamination protocols have been completed.

The purpose of this study was to simulate and evaluate the efficacy of DD, LPS, and TD (Chilcott et al., 2019b), alone or in combination, following contamination of skin and hair. The main aim of this study was to investigate the binding affinity of contaminants to hair and whether these pose a secondary hazard over time following decontamination.

**MATERIALS AND METHODS**

**Materials.** Methyl salicylate (99%) was purchased from Acros Organics, UK. Potassium cyanide (KCN; > 98%), inhibitor-free diethyl ether (99.9%), and Amberlite XAD-2 (20–60 mesh) were purchased from Sigma Aldrich (St. Louis, Missouri). Phorate (PHR; 95%) and sodium fluoracetate (SFA; 99%) were custom synthesized by American Radiolabeled Chemicals (St. Louis, Missouri). Acetonitrile (HPLC grade), ethanol (Absolute), and propan-2-ol (HPLC grade) were purchased from Fisher Scientific, Leicestershire, UK. Ultra-pure water (> 18.2 MΩ) for receptor fluid media and sampling was obtained by ultrafiltration of the municipal supply via a MilliQ Integral 3 (Millipore, Massachusetts).

Ring-labeled (14C) MS (70 mCi mMol⁻¹), PHR (50 mCi mMol⁻¹), SFA (50 mCi mMol⁻¹), and KCN (58 mCi mMol⁻¹) were purchased from American Radiolabeled Chemicals (Table 1). Their nonradioactive analogs were added in an appropriate proportion to give a working solution with a nominal activity of 0.5 μCi μl⁻¹. Solueze-350 and Ultima Gold liquid scintillation counting (LSC) fluid were purchased from PerkinElmer, Cambridge, Massachusetts.

Full-thickness skin was obtained postmortem from female pigs (Sus scrofa, large white strain, weight range of 15–25 kg) purchased from a reputable supplier following ethical approval. The skin was close clipped and removed from the dorsal aspect of each animal. The excised skin was then wrapped in aluminum foil and stored flat at –20°C. Prior to the start of each experiment, a skin sample from 1 animal was removed from cold storage and thawed for approximately 24 h. The skin was then dermatomed to a thickness of 1000 μm (Humeca Model D80; Eurosurgical, Surrey, UK). Once dermatomed, the skin samples were mounted on diffusion cells (19.64 cm² surface area). Skin diffusion cells and manifold delivery system were custom manufactured by Protosheet Ltd, Kent, UK, as previously described in Matar et al. (2014).

A variety of human hair swatches were collected from unisex hair salons within the Hertfordshire and Hampshire areas of the United Kingdom or purchased from Pivot Point Education Ltd (Milton Keynes, UK). Hair curtains (swatches) were assembled using 3 different visual hair types: thin (brown), dyed blonde, and thick (dark brown or black). The hair swatches/curtains were prepared as previously described by Matar et al. (2018).

**Table 1. Summary of Chemical Contaminants**

|               | MS   | PHR  | SFA   | KCN   |
|---------------|------|------|-------|-------|
| Molecular weight (g/mol)             | 152.149 | 260.365 | 100.024 | 65.116 |
| Log P             | 2.234 | 3.56 | No data | No data |
| Vapor pressure (mmHg) at 20°C       | 0.045 | 0.0008 | 0      | No data |

Data obtained from PubChem open chemistry database, U.S. National Library of Medicine.
The experiment was started by the addition of 20 μl of either 14C-MS, 14C-PHR, 14C-SFA, or 14C-KCN to the skin and another 20 μl to the hair (total 40 μl dose per cell). Dry decontamination was performed on the skin/hair surface 4 min postexposure by applying a sterile trauma dressing (McKesson Medical-Surgical, Llantrisant, UK). Each tube was filled with 150 mg of Tenax TA 35/60 sorbent. Filled Tenax tubes were subjected to conditioning prior to use by purging under nitrogen and a heat cycle, according to the manufacturer’s instructions.

Air from within the donor chamber was sampled using constant volume pumps (Pocket Pump model 210-1002MTX, SKC Ltd, Dorset, UK) set at a sampling volume of 75 ml min⁻¹. Glass sorbent tubes were purchased from Markes International (Llantrisant, UK). Each tube was filled with 150 ± 5 mg of Tenax TA 35/60 sorbent. Filled Tenax tubes were subjected to conditioning prior to use by purging under nitrogen and a heat cycle, according to the manufacturer’s instructions.

The radioactivity within the samples (swabs, Tenax, tubing, receptor chamber fluid, skin, etc.) was quantified using a PerkinElmer Tri-Carb liquid scintillation counter (Model 2810 TR) employing an analysis runtime of 2 min per sample and a preset quench curve specific to the brand of LSC fluid (Ultima Gold, PerkinElmer, UK). The amounts of radioactivity in each sample were converted to quantities of 14C-MS, 14C-PHR, 14C-SFA, or 14C-KCN by comparison with standards (measured simultaneously). The standards were prepared on the day of each experiment by the addition of a known amount of each contaminant to (1) cotton wool swabs in 10 ml propan-2-ol or dH₂O; (2) tin foil, Tenax, tubing, flannel, and towel swatches in 10–40 ml in propan-2-ol or dH₂O; (3) 375 ml of shower fluid and 120 ml of TD fluid; (4) trauma dressing in 25 ml propan-2-ol or dH₂O; and (5) skin tissue dissolved in 50 ml soluene-350. The extraction solvent used for each of the samples was chemical-dependent. Propan-2-ol was employed for 14C-MS and 14C-PHR, whereas deionized water was used for 14C-SFA and 14C-KCN. A standard receptor fluid solution was also prepared by the addition of 10 μl of 14C-MS, 14C-PHR, 14C-SFA, or 14C-KCN to 990 μl of fresh receptor fluid (50% aqueous ethanol), from which a range of triplicate samples (25, 50, 75, and 100 μl) were placed into vials containing 5 ml of LSC fluid to produce a standard (calibration) curve. Aliquots (250 μl) of each sample obtained from the experiment were taken and placed into vials containing 5 ml of liquid scintillation fluid for LSC. For clarity, the sum of the amounts of contaminant detected in the receptor fluid, in the skin and on the skin surface is referred to as the bioavailable fraction.

Hair extraction studies. Human hair swatches were cut to 3 × 1.5 cm and secured to a polystyrene petri dish with duct tape (skin was not used for these studies). For each of the 4 chemicals (14C-MS, PHR, SFA, and KCN), the effects of delayed decontamination (described above) were quantified by comparing each treatment group to Control No decontamination. Technical decontamination was conducted 12 min postexposure at a flow rate of 74 ml min⁻¹ cm⁻² at 35°C using a washcloth with gentle rubbing for 90 s. The experimental decontamination was conducted 8 min postexposure for Combined Skin and Hair Decontamination Studies (Table 2).

### Table 2. Summary of Treatment Groups Used for Combined Skin and Hair Decontamination Studies

| Study Group                | Treatment Group | Parameters                                                                 |
|----------------------------|-----------------|-----------------------------------------------------------------------------|
| Single techniques          | Control         | No decontamination                                                          |
|                            | DD              | Decontamination performed 4 min postexposure using wound dressing           |
|                            | LPS             | Showering performed 8 min postexposure using water with a flow rate of 10 ml min⁻¹ cm⁻² at 10°C for 15 s |
|                            | TD              | Showering performed 12 min postexposure at a flow rate of 74 ml min⁻¹ cm⁻² at 35°C using a washcloth with gentle rubbing for 90 s |
| Combined techniques        | Control         | No decontamination                                                          |
|                            | DD + LPS        | DD performed 4 min postexposure followed by LPS at 8 min                    |
|                            | DD + TD         | DD performed 4 min postexposure followed by TD at 12 min                    |
|                            | LPS + TD        | LPS performed at 8 min postexposure followed by TD at 12 min                |
|                            | DD + LPS + TD   | DD performed at 4 min, LPS at 8 min and TD 12 min postexposure              |
| Hair extraction and hair off-gassing | Triple Protocol | DD, LPS, and TD performed immediately after each other at either 0, 5, 10, 20, 30, 60, 120, or 240 min postexposure |

Air from within the donor chamber was sampled using constant volume pumps (Pocket Pump model 210-1002MTX, SKC Ltd, Dorset, UK) set at a sampling volume of 75 ml min⁻¹. Glass sorbent tubes were purchased from Markes International (Llantrisant, UK). Each tube was filled with 150 ± 5 mg of Tenax TA 35/60 sorbent. Filled Tenax tubes were subjected to conditioning prior to use by purging under nitrogen and a heat cycle, according to the manufacturer’s instructions.

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Once the triple decontamination procedures had been completed, the hair swatches were placed into pre-weighed 20 ml vials, which were weighed before and after the addition of 20 ml of acetonitrile, ethanol, ether, water, or JBS in water (0.085% v/v). Samples were then stored at 4°C.

The following day, a minimum extraction period of 18 h, hair samples were removed from cold storage. From each vial, a 250 µl aliquot was removed from each sample and placed into a vial containing 5 ml of Ultima Gold liquid scintillation fluid for counting. Samples were replenished with 250 µl of the appropriate solvent and reweighed to maintain a constant volume of 20 ml in all hair samples. Subsampling and replenishment of hair samples were repeated over a total of 5 days. On the fifth day, once all subsampling had been completed, the hair swatches were removed from the solvent, blotted dry with absorbent paper towels (WypAll, Kimberly-Clark) and transferred into fresh pre-weighed jars before the addition of 20 ml of Ultima Gold. The following day, an aliquot of 250 µl was removed from each jar and placed in liquid scintillation vials with 5 ml of Ultima Gold. Sample analysis was performed as described above; standards were prepared on the day of each experiment by the addition of each contaminant to each hair type in their respective solvents.

Hair off-gassing studies. Human hair was obtained as described above and the swatches of hair were prepared and secured to polystyrene petri dishes in the same way. Each of the hair swatches was contaminated with a 20 µl droplet of either 14C-Ms or PHR and left for 0, 5, 10, 20, 30, 60, 120, or 240 min before the triple protocol decontamination procedure was performed. Immediately following decontamination, each hair swatch was placed in a small box lined with tin foil (ABS enclosure, 40 × 40 × 20 mm; RS Components, UK), Amberlite XAD-2 (approximately 1 g), a passive absorbent was then placed in each box under a perforated metal support to prevent direct contact with the hair. The box was then closed, its lid was screwed tight, and the box was placed on a bespoke silicone heat mat (Holroyd Components Ltd, UK) with a thin metal aluminum sheet to facilitate heat dispersion. The aluminum sheet was set to 31°C to achieve a box temperature of 30°C.

Every 6 h, up to a total period of 120 h, the hair was transferred into a new box with fresh Amberlite and tinfoil, allowing a 4-min delay between each sample. The Amberlite and tinfoil were then removed and placed into their respective pre-weighed scintillation vials, where each sample was weighed and 20 ml of propan-2-ol was added and left to extract. At 120 h of sample acquisition, the hair was removed from the box and placed into a screwcap vial containing 20 ml of Ultima Gold. All samples were left for a minimum of 24 h to allow for the contaminant to be extracted and each sample was vortexed prior to aliquoting. Each 250 µl aliquot was placed into a 6.5 ml plastic scintillation vial filled with 5 ml of Ultima Gold. Radioactive sample analysis was performed as described above.

Statistics. Statistical analysis was performed using GraphPad Prism 7. Normality tests (Shapiro-Wilk) were performed on all data. Normally distributed data were analyzed using 1-way ANOVA or a 2-tailed t-test. For nonparametric data sets, treatment effects were analyzed using the nonparametric Kruskal-Wallis test. The Mann-Whitney test was performed to verify some of the results, specifically when no significance was shown. The Spearman test was used to find any correlations between groups when data were not normally distributed and the Pearson test for data that were normally distributed.

RESULTS

Skin and Hair Absorption Studies

For the non-decontaminated group (control) the majority of the applied dose was recovered from either the bioavailable fraction (the total amount of receptor fluid, remaining within the skin and on the skin surface) or hair for cells contaminated with 14C-MS, 14C-PHR, 14C-SFA, or 14C-KCN (Figure 1). The bioavailable fraction was found to be significantly smaller (p < .05) for all treatment groups when compared with their respective controls. Generally, there were no statistically significant (p > .05) differences between the decontamination protocols except between DD and DD+LPS+TD for all the contaminants. Further significant differences were found between DD versus DD+TD and DD versus LPS+TD following contamination with 14C-SFA and 14C-KCN. The amount of contaminant recovered from the hair was greater for hair contaminated with 14C-MS or 14C-PHR than for 14C-SFA and 14C-KCN. Interestingly, all decontamination protocols significantly (p < .05) reduced the amount of contaminant in the hair when compared with their respective controls, with the exception of DD for hair contaminated with 14C-MS, PHR, SFA, or KCN, which demonstrated effectiveness, but was not statistically significant. No statistically significant differences were found between the different decontamination methods for hair contaminated with 14C-MS or 14C-PHR. However, a statistical difference was observed between DD versus DD+LPS+TD and DD versus DD+LPS for 14C-SFA and 14C-KCN, respectively. The proportions of unbound (mobile; hair surface) contaminant from hair were generally lower following decontamination when compared with non-decontaminated (control) hair. Furthermore, there were no statistical differences in the amounts of unbound contaminant between all of the decontamination protocols evaluated. Full dose distributions are provided within the Supplementary Data.

Hair Extraction Studies

The triple protocol for hair decontamination was effective for the hydrophilic chemical SFA, as no detectable hair residue could be extracted by the aqueous solvent systems (water or Johnson’s shampoo solution) for exposure periods up to 240 min (Figure 2). Furthermore, no residue of KCN could be extracted from hair decontaminated immediately post-exposure, with 5%–25% of the applied dose being recovered after 5 min.

The triple protocol, when performed immediately post-exposure (t = 0), reduced the residual amount of MS and PHR extractable from within the hair to approximately 30% of the applied dose (Figure 2). The performance of hair decontamination rapidly declined with time postexposure (after a delay of 5 min or more) as the contaminant residue increased to approximately 65% of the applied dose.

Differences in the extent to which the different solvent systems extracted the residual hair contamination reflected the known solubility of the contaminants. Water and Johnson’s shampoo solution were less effective for extracting the lipophilic contaminants (MS and PHR), whereas the organic solvents were less effective for extracting the hydrophilic contaminants (SFA and KCN; Figure 2).

Hair Off-gassing Studies

Human hair contaminated with 14C-MS was found to off-gass with time (Figure 3). In contrast, minimal but variable amounts of 14C-PHR off-gassed over the 120-h period (Figure 4). With regard to 14C-MS, the amounts off-gassed were generally lower for
decontaminated than for non-decontaminated (control) groups. Furthermore, the amounts of MS recovered from off-gassing decreased over time for all the exposure times evaluated ($r = -0.87, p < .0001$; Figure 3).

The average maximum rate ($v_{\text{max}}$; the maximum rate of vapor loss per treatment group against time) of vapor loss was generally higher within the first 20 min postexposure for non-decontaminated controls (Figure 5). In contrast, the rate of vapor loss was relatively consistent for decontaminated hair. Interestingly, the greater vapor loss within the first 20 min post-exposure appeared to be attributable to the higher amounts of contaminant remaining on the hair surface, and not within the hair, as compared with decontaminated hair.

**DISCUSSION**

This study utilized a previously characterized skin and hair diffusion cell (Matar et al., 2014, 2018) that models the LPS to investigate and highlight the generic effectiveness of hair and skin decontamination. Further experiments evaluated the consequences of this residual hair contamination.

Overall, the decontamination strategies investigated were effective for the decontamination of skin (Chilcott et al., 2019b). However, relatively large proportions of the contaminant remained in the hair even following several decontamination methods. It was apparent that the majority of the applied dose was removed by whichever decontamination protocol was performed first. However, DD was generally not as effective as wet...
Figure 2. Extraction (expressed as percentage of applied dose) of methyl salicylate, phorate, sodium fluoroacetate, and potassium cyanide from hair curtains originally exposed to a liquid droplet of contaminant for durations of 0–240 min prior to either triple decontamination (dry, LPS, and technical) or no treatment (control). Extractions were performed in ethanol, ether, acetonitrile, water, or a 0.5% aqueous solution of Johnson’s Baby Shampoo. Each data point is average ± standard deviation (n = 5).
decontamination in decontaminating hair. This is probably attributable to the fact that the area of exposure of the wound dressing pad was limited to the uppermost hair strands, limiting the amount of contaminant available for decontamination. This contrasts with other studies, in which the military decontaminants fuller's earth and RSDL were found to be effective products for decontaminating VX from hair (Rolland et al., 2013).

It should be noted that both these substances have the ability to coat or surround contaminated hair strands. It is widely accepted that hair is a difficult matrix to decontaminate, even after several washes (Duca et al., 2014). This innate ability of hair to retain chemicals has been exploited mainly in the field of forensics and drug analysis (Blank and Kidwell, 1995). It should be noted that certain solvent mixtures
could be employed to remove chemicals from hair (Duca et al., 2014). However, there is a paucity of data relating to the persistence of chemical contaminants following standard decontamination techniques. For the purposes of managing casualties contaminated as the result of a HAZMAT or CBRN incident, it is important to assess the binding affinity of contaminants to hair. If chemicals are found to leach with time, this may result in secondary vapor exposures affecting the casualty, first responders, and/or medical personnel, as reported with contaminated clothing (Feldman, 2010).

Differences in extraction efficacy were observed between the different contaminants and solvents used. Generally, 14C-MS and PHR were readily (fully) extracted using ethanol, ether, or acetonitrile within the first 24 h of extraction, whereas for water and shampoo solution the extraction was gradual overtime. This is probably attributable to the solubility of the

Figure 4. Percentage of applied dose of 14C-phorate expressed as cumulative vapor loss from human hair over 120 h (6 hourly intervals). Each swatch of human hair was exposed to a 20 µl droplet of 14C-PHR and subjected to either no decontamination (control) or decontamination using combined dry, ladder pipe system, and technical decontamination (triple protocol) at 0, 5, 10, 20, 30, 60, 120, and 240 min postexposure.
contaminants in these solutions. Conversely, $^{14}$C-SFA and KCN were not as readily extracted in ethanol, ether, or acetonitrile when compared with H$_2$O and shampoo solution. However, both $^{14}$C-SFA and KCN were effectively removed following decontamination, unlike $^{14}$C-MS and PHR. It is worth noting that this part of the study was designed to evaluate the affinity with which the contaminants are bound to hair and not the suitability of these solvents as hair decontaminants (given the long, 5-day submersion).

The underlying mechanism behind the affinity of these chemicals for human hair is unclear (Duca et al., 2014), but it is likely to be influenced by the lipophilicity of the contaminant. The structure of human hair, from the inner layer to the outer layer, consists of the medulla, the cortex, and the cuticle. The outermost layer of the cuticle (epicuticle) is a lipoprotein membrane that is estimated to be 10–14 nm thick (Swift and Smith, 2001) and may be coated with sebum (Eberhardt, 1976). Therefore, a strong physicochemical attraction between the lipophilic chemicals and the lipid-rich hair could explain why decontamination of these chemicals from the hair proved to be more problematic. The implications of this association depend on the affinity with which a given contaminant bonds with the hair: if the bond is irreversible, there will be no toxicological hazard (as the contaminant will not transfer, or become mobile for inhalation or dermal exposure); if it is not, then the contaminant may be transferred to either hand or scalp, or absorbed via the follicular pathway, and will thus still pose a threat (Knorr et al., 2009).

An important aspect of this study was the investigation of chemical off-gassing from contaminated human hair. Our findings highlight the significance of contaminant off-gassing, even from hair that has undergone decontamination procedures. An interesting result was that large proportions of the applied dose were not off-gassed within the first 24 h. This means that contaminated casualties may continue to pose a risk to themselves, emergency responders, and/or hospital staff following decontamination. Conversely, nonvolatile organic chemicals, such as PHR, were found not to off-gas with time. Consequently, large proportions of the contaminant remained within the hair. Upon further analysis, the rate of off-gassing (Figure 5) can provide some evidence that the residual contaminants were absorbed into the hair rather than adhering to the hair surface. The difference between control and decontaminated hair is that most surface contamination would be removed by decontamination. Thus, the higher initial rate of vapor loss from controls implies that hair surface contamination is the predominant factor for early vapor loss. A previous study (Matar et al., 2018) demonstrated that PHR and MS partition rapidly into the hair; thus, there would be less surface contamination to contribute to the initial vapor loss phase. The similarity in rate of vapor loss between control and decontaminated hair over the second, longer phase of vapor loss probably reflects evaporation from within the hair. Raman microscopy was used to assess molecular interactions of the contaminants with hair with no significant differences observed in the spectra (data not shown).

**Limitations**

The experiments that made up this study had a number of limitations. First, the hair and skin model used did not take into account the potential for chemical absorption via the hair and scalp, which might reduce the amount on or within hair but would increase the bioavailable fraction. In addition, the use of $^{14}$C-radiolabeled chemicals is unable to distinguish (without further analysis) whether the contaminant is intact, rather than a breakdown product or metabolite bound to hair. However, because this model was designed to represent a conservative approach to hair exposure and decontamination, the measurements assumed the worst-case scenario of no chemical degradation.

The hair and skin decontamination study was performed unrealistically soon after contamination (4, 8, and 12 min for DD, LPS, and TD, respectively) and thus deviates from the longer anticipated response times. The rationale for this was to employ effective decontamination soon after exposure and thus assess whether these contaminants could be removed from hair. Furthermore, the fact that decontamination was performed so rapidly postexposure highlights the speed with which these contaminants adhere to hair. Nevertheless, it is possible that allowing a longer exposure time before the start of decontamination would reveal differences between the decontamination strategies and their combinations that were not apparent within the short time scale of this study.

In the off-gassing study, the placement of contaminated hair within sealed boxes to assess chemical off-gassing is not indicative of a realistic situation, where airflow through the hair would affect chemical evaporation and concentration. However, as this initial model was based on a conservative approach, it nevertheless effectively highlights the fact that some...
contaminants represent a significant hazard from off-gassing over surprisingly long durations.

CONCLUSIONS

The use of the triple decontamination protocol (DD + LPS + TD) has been shown to be effective for removing contaminants from skin (Chilcott et al., 2019b). In contrast, the use of DD was generally not as effective as wet protocols for decontaminating hair. Furthermore, human hair has shown a capacity to retain certain chemicals and, depending on their physicochemical properties, these may off-gas with time. Therefore, to counteract this risk, it may be prudent to close-clip and remove contaminated hair from individuals. Decontaminating hair using solvents in mass casualty scenarios may not be practical in some cases or may need to be delayed. However, when dealing with a small number of casualties it may be more feasible to decontaminate hair with appropriate solvents in a controlled manner.

SUPPLEMENTARY DATA

Supplementary data are available at Toxicological Sciences online.

DECLARATION OF CONFLICTING INTERESTS

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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REFERENCES

Amlôt, R., Carter, H., Riddle, L., Larner, J., and Chilcott, R. P. (2017). Volunteer trials of a novel improvised dry decontamination protocol for use during mass casualty incidents as part of the UK’s Initial Operational Response (IOR). PLoS One 12, e0179309.

Blank, D. L., and Kidwell, D. A. (1995). Decontamination procedures for drugs of abuse in hair: Are they sufficient? Forensic Sci. Int. 70, 13–38.

Broughton, E. (2005). The Bhopal disaster and its aftermath: a review. Environmental Health 4, 6.

Chan, H. P., Zhai, H., Hui, X., and Maibach, H. I. (2013). Skin decontamination: Principles and perspectives. Toxicol. Ind. Health 29, 955–968.

Chilcott, R. P., Larner, J., and Matar, H. (2018). Primary Response Incident Scene Management; PRISM Guidance, Vol. 1, 2nd edn. Office of the Assistant Secretary for Preparedness and Response, Biomedical Development Authority, Washington, DC.

Chilcott, R. P., Larner, J., and Matar, H. (2019a). The United Kingdom’s initial operational response and specialist operational response to CBRN and HazMat incidents: A primer on decontamination protocols for healthcare professionals. Emerg. Med. J. 36, 117–123.

Chilcott, R. P., Larner, J., Durrant, A., Hughes, P., Mahalingam, D., Rivers, S., Thomas, E., Amer, N., Barrett, M., and Matar, H. (2019b). Evaluation of US federal guidelines (primary response incident scene management [PRISM]) for mass decontamination of casualties during the initial operational response to a chemical incident. Ann. Emerg. Med. 73, 671–684.

Duca, R. C., Hardy, E., Salquébre, G., and Appenzeller, B. M. (2014). Hair decontamination procedure prior to multi-class pesticide analysis. Drug Test. Anal. 6(Suppl. 1), 55–66.

Eberhardt, H. (1976). Recoating of human hair by sebum. J. Soc. Cosmet. Chem. 27, 235–239.

Eskenazi, B., Warner, M., Brambilla, P., Signorini, S., Ames, J., and Moccarelli, P. (2018). The Seveso accident: A look at 40 years of health research and beyond. Environ. Int. 121, 71–84.

Feldman, R. J. (2010). Chemical agent simulant release from clothing following vapor exposure. Acad. Emerg. Med. 17, 221–224.

Josse, D., Wartelle, J., and Cruz, C. (2015). Showering effectiveness for human hair decontamination of the nerve agent VX. Chem. Biol. Interact. 232, 94–100.

Kassouf, N., Syed, S., Larner, J., Amlôt, R., and Chilcott, R. P. (2017). Evaluation of absorbent materials for use as ad hoc dry decontaminants during mass casualty incidents as part of the UK’s Initial Operational Response (IOR). PLoS One 12, e0170966.

Knorr, F., Lademann, J., Patzel, A., Sterry, W., Blume-Peytavi, U., and Vogt, A. (2009). follicular transport route—research progress and future perspectives. Eur. J. Pharm. Biopharm. 71, 173–180.

Lake, W., Schulze, P., and Gougelet, R. (2013). ECBC-SP-036 Guidelines for Mass Casualty Decontamination During a HAZMAT/Weapon of Mass Destruction Incident Volumes I and II. https://www.hsdrl.org/viewRoId=745138.

Matar, H., Amer, N., Kansagra, S., Pinhal, A., Thomas, E., Townend, S., Larner, J., and Chilcott, R. P. (2018). Hybrid in vitro diffusion cell for simultaneous evaluation of hair and skin decontamination: Temporal distribution of chemical contaminants. Sci. Rep. 8, 16906.

Matar, H., Larner, J., Kansagra, S., Atkinson, K. L., Skamarasquas, J. T., Amlot, R., and Chilcott, R. P. (2014). Design and characterisation of a novel in vitro skin diffusion cell system for assessing mass casualty decontamination systems. Toxicol. In Vitro 28, 492–501.

Okiura, T., Takasu, N., Ishimatsu, S., Miyanoke, S., Mitsuhashi, A., Kumada, K., Tanaka, K., and Hinohara, S. (1996). Report on 640 victims of the Tokyo subway sarin attack. Ann. Emerg. Med. 28, 129–135.

Power, S., Symons, C., Carter, H., Jones, E., Amlôt, R., Larner, J., Matar, H., and Chilcott, R. P. (2016). Mass casualty decontamination in the United States: An online survey of current practice. Health Secur. 14, 226–236.

Rolland, P., Bolzinger, M. A., Cruz, C., Josse, D., and Briançon, S. (2013). Hairy skin exposure to VX in vitro: Effectiveness of delayed decontamination. Toxicol. In Vitro 27, 358–366.

Spiandore, M., Piram, A., Lacoste, A., Josse, D., and Doumenq, P. (2014). Hair analysis as a useful procedure for detection of vapour exposure to chemical warfare agents: Simulation of sulphur mustard with methyl salicylate. Drug Test. Anal. 6(Suppl. 1), 67–73.

Spiandore, M., Piram, A., Lacoste, A., Prevost, P., Maloni, P., Torre, F., Asia, L., Josse, D., and Doumenq, P. (2017).
Efficacy of scalp hair decontamination following exposure to vapours of sulphur mustard simulants 2-chloroethyl ethyl sulphide and methyl salicylate. *Chem. Biol. Interact.* 267, 74–79.

Spiandore, M., Souilah-Edib, M., Piram, A., Lacoste, A., Josse, D., and Doumenq, P. (2018). Desorption of sulphur mustard simulants methyl salicylate and 2-chloroethyl ethyl sulphide from contaminated scalp hair after vapour exposure. *Chemosphere* 191, 721–728.

Swift, J. A., and Smith, J. R. (2001). Microscopical investigations on the epicuticle of mammalian keratin fibres. *J. Microsc.* 204, 203–211.

Taysse, L., Daulon, S., Delamanche, S., Bellier, B., and Breton, P. (2007). Skin decontamination of mustards and organophosphates: Comparative efficiency of RSDL and Fuller’s earth in domestic swine. *Hum. Exp. Toxicol.* 26, 135–141.

Thors, L., Koch, M., Wigenstam, E., Koch, B., Hagglund, L., and Bucht, A. (2017). Comparison of skin decontamination efficacy of commercial decontamination products following exposure to VX on human skin. *Chem. Biol. Interact.* 273, 82–89.

UK Home Office. (2015). Initial Operational Response to a CBRN Incident (C. Unit, Ed.). https://www.jesip.org.uk/uploads/media/pdf/CBRN%20JOPs/IOR_Guidance_V2_July_2015.pdf.