Optimization of Nonambulant Mass Casualty Decontamination Protocols as Part of an Initial or Specialist Operational Response to Chemical Incidents

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Optimization of Nonambulant Mass Casualty Decontamination Protocols as Part of an Initial or Specialist Operational Response to Chemical Incidents

Robert P. Chilcott, MSc, PhD, Hannah Mitchell, BSc(Hons), MSc, Hazem Matar, MSc, PhD

Abstract

Objective: The UK's Initial Operational Response (IOR) is a new process for improving the survival of multiple casualties following a chemical, biological, radiological or nuclear incident. Whilst the introduction of IOR represents a patient-focused response for ambulant casualties, there is currently no provision for disrobe and dry decontamination of nonambulant casualties. Moreover, the current specialist operational response (SOR) protocol for nonambulant casualty decontamination (also referred to as "clinical decontamination") has not been subject to rigorous evaluation or development. Therefore, the aim of this study was to confirm the effectiveness of putatively optimized dry (IOR) and wet (SOR) protocols for nonambulant decontamination in human volunteers. **Methods**: Dry and wet decontamination protocols were objectively evaluated using human volunteers. Decontamination effectiveness was quantified by liquid chromatography–mass spectrometry analysis of the recovery of a chemical warfare agent simulant (methylsalicylate) from skin and hair of volunteers, with whole-body fluorescence imaging to quantify the skin distribution of residual simulant. **Results**: Both the dry and wet decontamination processes were rapid (3 and 4 min, respectively) and were effective in removing simulant from the hair and skin of volunteers, with no observable adverse effects related to skin surface spreading of contaminant. **Conclusions**: Further studies are required to assess the combined effectiveness of dry and wet decontamination under more realistic conditions and to develop appropriate operational procedures that ensure the safety of first responders. **Key words**: initial operational response, IOR; specialist/strategic operational response, SOR; vulnerable population; mass casualty; decontamination; dry decontamination; wet decontamination

Introduction

United Kingdom policy and guidelines for managing chemical, biological, radiological, and nuclear (CBRN) incidents have previously utilized a generic approach ("Model Response") for the management of multiple, contaminated individuals that encapsulates an "all-hazards" incident management strategy (1). Corresponding studies (2) indicated that the Model Response tends to focus on process rather than casualties and so recommendations were made for new emergency working practices, which became known as the Initial Operational Response (IOR) and Specialist (or Strategic) Operational Response (SOR) (3). Essentially, the IOR introduces the disrobe and *ad hoc* dry decontamination process at the earliest opportunity, whereas the SOR relies on the deployment of specialist, mobile shower units.

A significant objective of the IOR is to complete disrobe and decontamination procedures as soon as practically possible. The most pragmatic option is to use any readily available (nonproprietary) absorbent material to treat exposure to noncaustic liquids, such as chemical warfare agents and toxic industrial chemicals (4). Recent work has identified a number of such materials (5,6). However, while the IOR represents a substantial improvement in the initial clinical management of ambulant casualties, there is currently no comparable protocol for nonambulant patients.

The SOR is a well-defined plan that originates from the UK's Model Response and involves the deployment of specialist resources, such as mass decontamination units (MDUs). While the MDU showering protocol for ambulant casualties has been well defined and evaluated (4,7-9), the nonambulant equivalent ("clinical decontamination") has not been subjected to rigorous testing. Consequently, there is currently no evidence-based guidance for clinical decontamination.

Here we report the outcomes of 2 human volunteer studies that evaluated putatively optimized dry (IOR) and wet (SOR) disrobe and decontamination protocols. The studies were performed using a relevant chemical warfare agent simulant (methylsalicylate) containing a fluorescent dye (curcumin).

MATERIALS AND METHODS

Chemicals

Methylsalicylate (99%) and curcumin (98 + %, a mixture of dimethoxycurcumin and bis-dimethoxycurcumin) were purchased from Acros Organics, UK. The simulant dosing solution ("CMX") was prepared on the day of each experiment by gradually adding 250 mg curcumin to 25 mL methylsalicylate (giving a final curcumin concentration of 10 mg mL^{-1}) in a lightproof glass container. The mixture was then sonicated (Nickel Electro Ltd. model SW3H, Fisher Scientific, UK) for 15 min under lightproof conditions and stored at room temperature for a maximum of 1 h before use.

Isopropyl alcohol (high-performance liquid chromatography [HPLC] grade), acetonitrile (HPLC grade), methanol (HPLC grade), and glacial acetic acid (HPLC grade) were purchased from Scientific Laboratory Supplies Ltd., Nottinghamshire, UK. Ultra-pure water (>18.2 MΩ) for LC analysis was filtered from the municipal supply via a MilliQ Integral 3 (Millipore, MA, USA).

Volunteers were provided with plain black swimwear (bikinis for female volunteers, swimming briefs for males) and plain black unisex outer garments (100% cotton long-sleeved t-shirts and leisure trousers), all purchased from Primark, Hampshire, UK.

Protocol for Evaluation of Disrobe and Dry Decontamination Protocol (Study 1)

Ethical approval was granted by an Independent Research Ethics Committee (protocol ITX-IERC-0117A) and the study was performed in compliance with the International Conference on Harmonization (ICH) Tripartite Guidelines on Good Clinical Practice (GCP). The study was listed with the International Standard Randomised Controlled Trial Number Register (reference ISRCTN12832762). Following completion of

a medical questionnaire to exclude those with relevant pre-existing conditions, a total of 16 volunteers (8 females and 8 males, average age 33.8 years, range 19 to 59 years) were enrolled and provided informed consent to participate in the study. Each volunteer was instructed not to apply any topical formulations (creams, lotions, sprays, etc.) for at least 24 h prior to participating in the study. Volunteers were randomly allocated to treatment groups using an on-line (pseudo-random) treatment allocator (10). Treatment groups comprised individuals who were dosed but not decontaminated ("control") and those who were dosed and subsequently treated with Blue Roll™ ("decontaminated"). Blue Roll is an absorbent paper material used for domestic and industrial cleaning and is readily available to emergency responders.

Following informed consent, each volunteer was asked to change into the swimwear and outer garments provided prior to the acquisition of initial (baseline) images in a bespoke photographic booth. The volunteer was then escorted to a dosing room, where a research team member applied 10 µL droplets of CMX dosing solution to 12 areas of the hair or skin surfaces and 100 µL droplets of CMX to the surface of 6 clothed sites (Figure 1). The droplets were applied in both instances using a calibrated, positive displacement pipette. A second set of images was then acquired immediately prior to the volunteer entering the disrobe and decontamination area.

Where applicable, the disrobe and dry decontamination process was performed by 3 decontamination team members (DTMs) as follows (Figure 2):

1. Each volunteer was asked to lie on a stretcher lined with Blue Roll (Wypall, Tork) and to remain flaccid and unresponsive. Decontamination Team
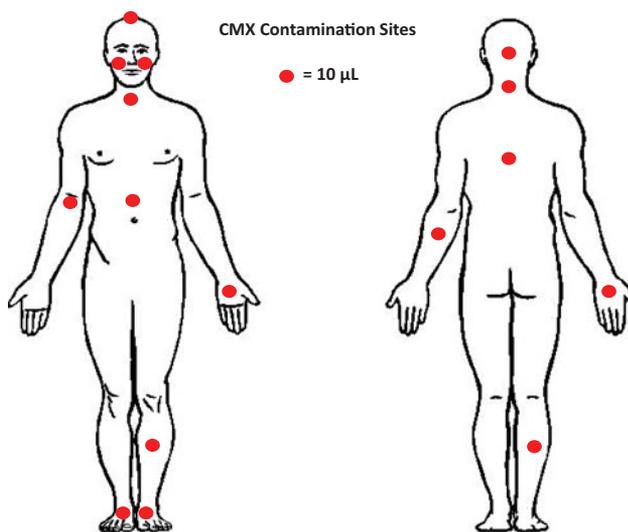

FIGURE 1. Location of chemical warfare agent simulant (CMX) droplets applied to the clothing, skin and hair of volunteers in the disrobe and dry decontamination study. The total applied dose of CMX was 0.72 mL (842 mg).

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FIGURE 2.   Representative photographs demonstrating the various stages of the nonambulant disrobe and dry decontamination process. A = disrobe; B = prioritisation of potentially exposed skin surfaces (hair, face, arms, hands); C = change of Blue Roll and decontamination of previously clothed skin surfaces; D = body roll of casualty into recovery position on second spine board; E = prioritisation of potentially exposed skin surfaces (hair, face, arms, hands); F = cleaning of original spine board and replacement of Blue Roll; G = body roll of casualty back to supine position on original (clean) spine board; H = completion of process – casualty ready for evacuation.

Member 1 (DTM1) supported the head and neck, using a strip of Blue Roll placed under the volunteer's head.

2. The front of the volunteer's clothing was cut using trauma shears (Tuff Cut, Reliance Medical, UK) and peeled away (Figure 2A). During this time, DTM1 started to blot the hair with Blue Roll.

3. The DTM to the left of the casualty (DTM2) started blotting accessible areas of the lower limbs, while DTM3 (to the right of the casualty) blotted the accessible areas of the upper body (Figure 2B). Both DTM2 and DTM3 prioritized the areas of skin that had not been clothed (i.e., feet, hands, and face), particularly if liquid contaminant was visible on the skin surface.

4. Following a change of Blue Roll, Team Members progressed from blotting to rubbing the skin surfaces (Figure 2C), after which the volunteer was carefully rolled to their left on to a clean stretcher (which was covered with fresh Blue Roll) and placed into the recovery position. At this and all other times, DTM1 was using the Blue Roll to support the head and neck to prevent direct contact with the hair (Figure 2D).

5. With the volunteer lying in the recovery position (Figure 2E), step 3 was repeated with fresh Blue Roll.

6. The original stretcher was wiped down with the existing Blue Roll (by DTM3) to remove any overt contamination. The contaminated Blue Roll was then replaced with fresh material (Figure 2F).

7. The volunteer was then rolled back on to the original stretcher, with care to support the head and neck (Figure 2G).

8. After being placed supine (Figure 2H), the volunteer was instructed that the decontamination

process was completed and was escorted to the photographic booth for a final photograph.

9. Finally, the volunteer was escorted to a sampling room for skin and hair surface swabbing.

Each of the aforementioned steps was timed according to a predefined protocol, with DTM1 instructing DTM2 and DTM3 to proceed through each step (Table 1). The whole process took exactly 3 min. Volunteers in the control group were also subjected to the disrobe procedure and rolled between the stretchers (according to the timed protocol) but did not undergo dry decontamination with the Blue Roll.

The swatches of Blue Roll used in the study (for decontamination of the casualty and lining/cleaning of the stretchers) were individually weighed, placed into glass jars and immersed in 300 mL isopropanol (IPA). All samples were subsequently stored in light-proof boxes at room temperature (21°C) for up to 3 weeks.

At the end of the study, the white Tyvek suits worn by the DTMs were imaged to identify any areas of cumulative cross-contamination from the volunteers.

Protocol for Evaluation of Wet Decontamination Protocol (Study 2)

Ethical approval was granted by an Independent Research Ethics Committee (protocol ITX-IERC-0217A) and the study was performed in compliance with the International Conference on Harmonization (ICH) Tripartite Guidelines on Good Clinical Practice (GCP). The study was listed with the International Standard Randomised Controlled Trial Number Register (reference ISRCTN61073828). Following completion of

TABLE 1. Summary of disrobe and dry decontamination protocol

	Main Tasks		
Time (min:sec)	DTM1 (head)	DTM2	DTM 3
0–1:50	Check airway. Support head and neck.	Disrobe.	
	Perform hair decontamination.	Decontaminate, with initial focus on potentially exposed areas of skin followed by all other skin surfaces.	
1:50	Verbal command to prepare for body roll.	Finish current decontamination activity and prepare casualty for recovery position.	
2:00	Verbal command to perform body roll.	Roll casualty into recovery position on second stretcher.	
	Check airway. Support head and neck. Continue hair decontamination.	Decontaminate, with initial focus on potentially exposed areas of skin followed by all other skin surfaces.	
2:40	Verbal command to prepare for body roll.	Continue decontamination.	Prepare first stretcher (clean and fresh Blue Roll).
3:00	Verbal command to perform body roll.	Roll casualty back to supine position on first stretcher.	

Tasks were performed by 3 decontamination team members (DTMs).

a medical questionnaire to exclude those with relevant pre-existing conditions, a total of 18 volunteers (9 females and 9 males, average age 34.1 years, range 19 to 59 years) were enrolled and provided informed consent to participate in the study. Each volunteer was instructed not to apply any topical formulations (creams, lotions, sprays, etc.) for at least 24 h prior to participating in the study. Volunteers were randomly allocated to treatment groups using an on-line (pseudo-random) treatment allocator (10). Treatment groups comprised a control (no decontamination) and a decontamination group.

Following informed consent, each volunteer changed into the provided swimwear before acquisition of a baseline image. The volunteer was then escorted to a dosing room where a research team member applied 10 µL droplets of a curcumin/methylsalicylate mixture (CMX) to 16 areas of the hair or skin surfaces (Figure 3) using a calibrated, positive displacement pipette. The volunteer was then escorted to a photographic booth for a second picture, immediately prior to entering a standard NHS clinical decontamination unit (MD16 and MD36 subsections and associated ancillary equipment) kindly provided by NARU (Winterbourne Gunner, Wiltshire, UK). Water was delivered to the decontamination unit directly from the local municipal supply via a heater (Hughes Portaheater 75) at a temperature of 32–40°C. The flow rate of water at each spray nozzle was calculated (by the time taken to fill a 1 L bottle) as 4.5 L min^{-1}.

Each volunteer lay down on a stretcher mounted on a roller-bed (Hughes Safety Showers Ltd.) within the decontamination unit and was instructed to remain flaccid and unresponsive.

The decontamination team comprised 4 trained research staff. Each team member wore a standard NHS powered respirator protective suit (PRPS), kindly provided by NARU (Winterbourne Gunner, Wiltshire, UK) when performing casualty decontamination. Four clean, absorbent cellulose sponges ("Tesco Sponge Wipes") were used for the decontamination of each volunteer.

Clinical decontamination was performed according to a 4-min protocol (developed during a previous, unpublished study). Briefly, an initial (30 s) rinse of anterior skin and hair surfaces was followed by a 1.5 min wash with sponges (no soap). Following a partial (90°) roll of the volunteer on to his/her right side, the process was repeated (30 s rinse, 1.5 min wash), after which the stretcher was washed before the volunteer was returned to the supine position. After dismounting from the stretcher, the volunteer was
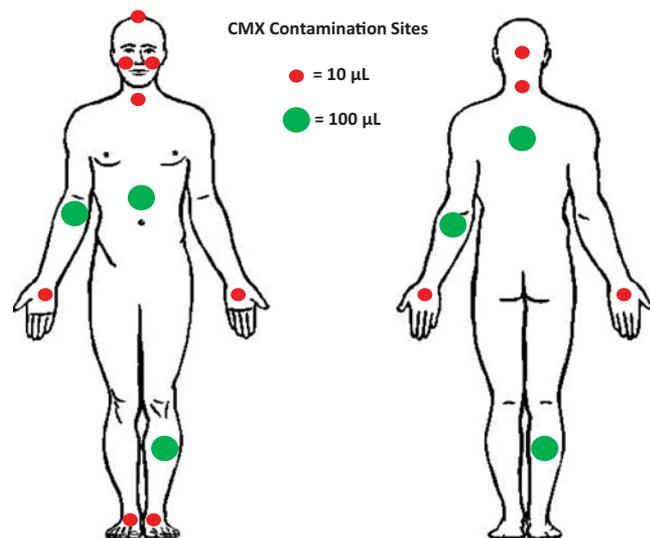

FIGURE 3. Location of chemical warfare agent simulant (CMX) droplets applied to the skin and hair of volunteers in the wet decontamination study. The total applied dose of CMX was 0.16 mL (187 mg).

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handed a disposable towel (Waffle White Body Towel, Scrummi, Kent, UK) and instructed to dry for 30 s. Each of the used towels was weighed and placed into jars containing IPA (1 L). Immediately after toweling, the volunteers were escorted to the photographic booth for a final set of images. The volunteer was then taken to a sampling room, where each of the dosed sites was swabbed as described in the following sections.

Participants in the control group underwent the same procedures (image acquisition, dosing, placement/movement on stretcher in decontamination unit, and swabbing) but were not subject to the decontamination and toweling stages.

At the end of the study, each DTM was imaged in the photographic booth whilst wearing their PRPS in order to identify any areas of cumulative cross contamination from the volunteers.

Hair and Skin Surface Swabbing

Swabs were taken from the surface of exposed skin and hair surfaces (Figures 1 and 3) of all volunteers to quantify the recovery of the simulant. To reduce sampling error, swabbing was consistently performed by the same 2 members of the research team. The swabbing process was performed at each site by the serial application of 3 Q-tips™ (Unilever, USA) within a circular (2.5 cm diameter) orifice of a single-use, plastic template placed over the sampling area. The first Q-tip was applied dry, the second was pre-wetted with IPA and the third was used dry. Each Q-tip was applied to the hair or skin surface using light pressure with a circular swabbing motion. After use, the 3 Q-tips were placed into pre-weighed 20 mL vials, which were re-weighed prior to the addition of IPA (5 mL). Samples were subsequently stored at room temperature (21°C) within lightproof boxes for up to 4 weeks.

Sample Preparation

Skin and hair swab samples were vortexed and sonicated for 30 s prior to withdrawal of a 1 mL aliquot, which was filtered through a 0.2 μm filter (13 mm OTFE filter, Chromacol Ltd, Hertfordshire, UK) and transferred into a 2 mL glass chromatography vial (KRSS, UK).

Towels and Blue Roll samples were removed from their storage jars and wrung using a 3.5 L stainless steel fruit press (AlcoFermBrew, Poland) to extract any absorbed IPA. The press was thoroughly cleaned between samples to prevent cross-contamination. The resulting effluent was transferred back to the original sample jar, after which an aliquot (1 mL) was filtered through a 0.2-μm filter and placed into a 2-mL chromatography vial.

Fresh sets of calibration and matrix standards (curcumin: 0.001–10 μg mL^{-1}; methylsalicylate: 0.2–1180 μg mL^{-1}) were prepared for each batch of Q-tip, Blue Roll and towel samples.

Sample Analysis

All samples were analyzed by liquid chromatography–diode array detector–mass spectrometry (LC–DAD–MS). Chromatography was performed using an Agilent 1100 LC system, which consisted of a quaternary pump, an autosampler, a column oven, and a diode array detector. The column (Modus C18, 5 μm, 150 × 2.1 mm; Chromatography Direct, Cheshire, UK) was maintained at a temperature of 30°C. The mobile phase was a mixture of ultra-pure water adjusted to pH 3 with acetic acid (60%) and acetonitrile (40%). Methanol water (50:50) was used as a washing solution and the needle was washed pre- and postsampling. The injection volume was 2 μL, with a run time of 10 min at a flow rate of 0.4 mL min^{-1}. The diode array detector was set to monitor 303 nm (methylsalicylate) and 420 nm (curcumin) wavelengths. Fresh samples for quality control were prepared prior to each run by diluting freshly prepared stock solutions to 1.18, 177 and 826 μg mL^{-1}. All chromatograms were analyzed and quantified using proprietary software (Chromeleon v7.2).

Image Acquisition and Analysis

Whole-body fluorescent images were acquired with a Canon EOS 700D digital camera (exposure time 2 s, aperture f/4.5, focal length 10 mm) in a light-proof booth of dimensions 3 m (h) × 2 m (w) × 2 m (d). An array of 6 × 1200 mm length LED lighting tubes (Arcadia T8, LED Marine Blue, Arcadia Ltd., Surrey, UK) was positioned horizontally in front of the camera. Volunteers were asked to stand 1.5 m from the camera with the aid of a floor-mounted jig to ensure consistent positioning when facing towards or away from the camera.

The area and intensity of residual simulant (CMX) on skin and hair surfaces was quantified by image analysis of the baseline, post-dose and post-decontamination photographs of each volunteer. The resulting images were analyzed by one research team member using National Institute of Health open-source software (11). Briefly, each baseline image was subtracted from the corresponding post-decontamination image to reduce or eliminate background noise. This produced a single "clean" image that was subsequently saved as a separate JPEG file. Each clean image was then subjected to spatial calibration by reference to a grid of known dimensions within the photographic booth. Image thresholds were adjusted manually to enable detection of residual CMX. Areas of the body were delineated into discreet zones to account for contaminant spreading (Figure 4).
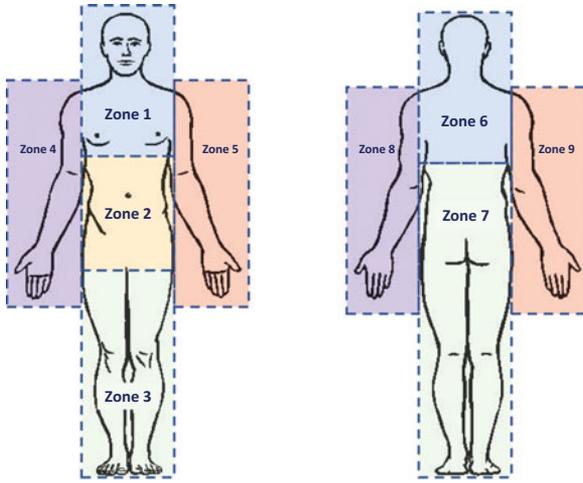
FIGURE 4.   Schematic representation of the image analysis zones.

Data and Statistical Analysis

The efficacy of decontamination was calculated from Equation 1:

$$\%E = 100 - \left(\frac{Q_d}{Q_c} \times 100 \right) \tag{1}$$

where Q is the quantity of methylsalicylate recovered from control (c) or decontaminated (d) areas. Statistical analysis was performed using proprietary software (GraphPad InStat, version 7.0b).

RESULTS

Statistical analysis (D'Agostino & Pearson) indicated that the quantities of methylsalicylate recovered from skin, hair, Blue Roll and towel matrices were nonparametric. A Kruskal–Wallis test of the skin and hair recoveries between different anatomical sites of (untreated) controls (when grouped by unclothed or clothed sites) indicated that the variation between different anatomical sites was significantly greater than could be attributed to chance alone ($p < 0.0007$). Thus, a standard nonparametric analysis of variance (ANOVA) with multiple comparisons post-test, to identify treatment-related effects between different anatomical sites with (Bonferroni) correction for multiple comparisons, was not deemed appropriate. Consequently, treatment-related effects within each anatomical site were investigated using a nonpaired, single-tail Mann–Whitney U-test. The single-tail test was deemed appropriate as there could only be a decrease in the
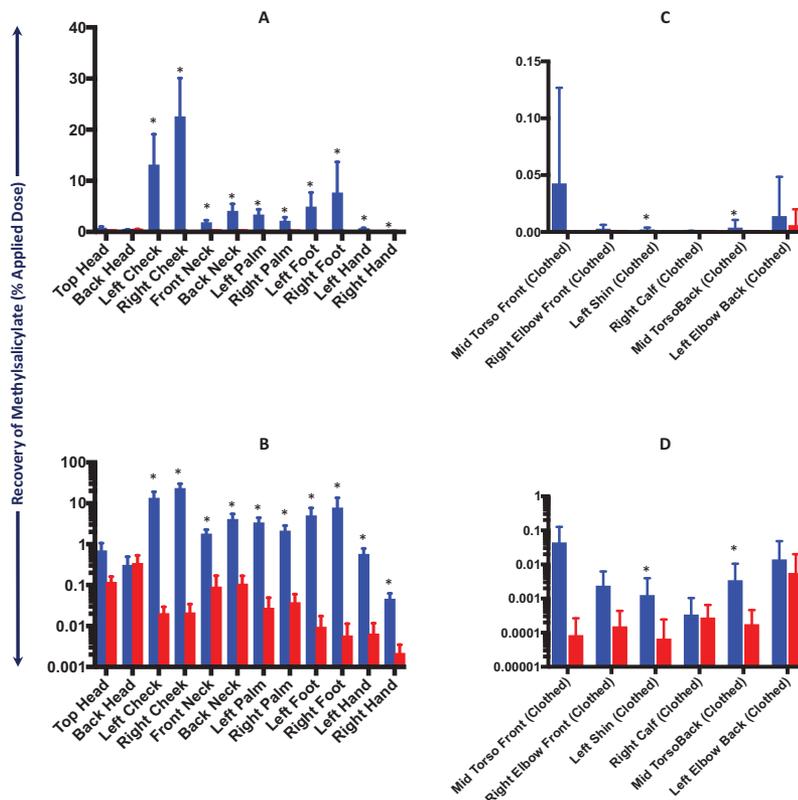
FIGURE 5.   Recovery of methylsalicylate from different anatomical locations of volunteers in control (■) or disrobe and dry decontamination treatment groups (■). A & B = unclothed skin (10 μL droplets); C & D = clothed skin (100 μL droplets). Values expressed as mean ± standard error of the mean (SEM) (n = 8 per treatment group). The asterisk indicates that recovery of methylsalicylate at that anatomical site differs significantly ($p < 0.05$) between control and decontaminated treatment groups. Actual p-values are presented in Table 2.

TABLE 2. Summary of statistical differences in the recovery of methylsalicylate between controls (untreated) and dry (IOR) or wet (SOR) decontamination treatment groups, derived from nonpaired, single-tail Mann–Whitney U-test

Anatomical Location	DRY (IOR)	WET (SOR)
Left cheek	p = 0.0024	p < 0.0001
Right cheek	p < 0.0001	p < 0.0001
Front neck	p = 0.0005	p < 0.0001
Back neck	p = 0.0249	p = 0.0001
Left palm	p = 0.0003	p < 0.0001
Right palm	p = 0.0003	NM
Left foot	p = 0.0010	p < 0.0001
Right foot	p = 0.0007	p < 0.0001
Left hand	p = 0.0016	NM
Right hand	p = 0.0088	p < 0.0001
Mid-torso, front[*]	p = 0.0758	p < 0.0001
Mid-torso, back[*]	p = 0.0350	p < 0.0001
Right elbow (front)[*]	p = 0.0464	p < 0.0001
Left elbow (back)[*]	p = 0.1524	p = 0.0006
Left shin[*]	p = 0.1615	p < 0.0001
Right calf[*]	p = 0.4282	p < 0.0001
Top head[†]	p = 0.1613	p = 0.0070
Back head[†]	p = 0.3598	p = 0.0050

NM, not measured.
[*]These skin sites were initially clothed.
[†]See discussion; study design.

recovery of methylsalicylate following decontamination.

Skin and Hair Recoveries of Methylsalicylate

Dry Decontamination

The average amounts of methylsalicylate recovered from control (untreated) skin sites were consistently greater than those from decontaminated sites for both unclothed and clothed skin (Figure 5). There was considerable variation in the performance of dry decontamination, with the reduction in contamination ranging from 0% (head) to 99.9% (right cheek) of the control dose recovered. However, a minimum 95% reduction in skin contamination was observed for the majority of anatomical locations investigated (12 out of 15).

Whilst dry decontamination had a significant effect on the majority of unclothed skin sites (Figure 5A and B; p < 0.05), the recoveries of methylsalicylate from areas of skin that had been subject to combined disrobe and dry decontamination were not significantly different to those from controls (disrobe only) at 4 of the 6 anatomical sites (Figure 5C and D). The recovery of methylsalicylate from all initially clothed skin sites (i.e., disrobe only or combined disrobe and decontamination) was one to 3 orders of magnitude lower than that from unclothed control sites,

despite the clothed sites having received 10 times the initial dose of methylsalicylate compared to unclothed skin.

The outcome of the statistical analysis for dry decontamination is presented in Table 2.

Wet Decontamination

Wet decontamination resulted in consistent and significant (p < 0.05) reductions in the amounts of methylsalicylate recovered from all anatomical locations (Figure 6). Overall, wet decontamination reduced skin surface contamination by ~95–100% in comparison with controls. A 99% or greater reduction in the recovered dose was observed at more than 2 thirds of the exposed sites (11 out of 16).
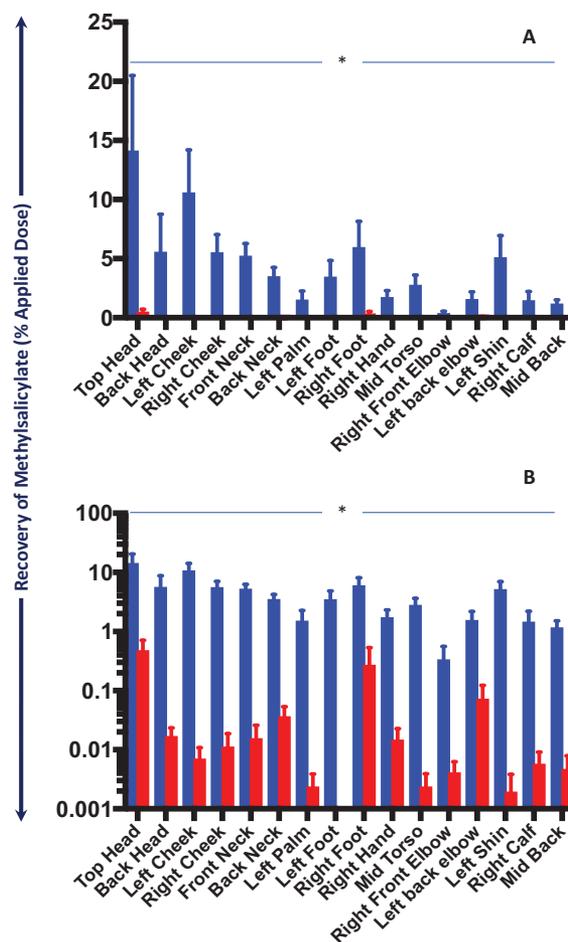

FIGURE 6. Recovery of methylsalicylate (applied as 10 µL droplets) from different anatomical locations of volunteers in control (■) or wet (■) decontamination treatment groups. Values expressed as mean ± standard error of the mean (SEM) (n = 9 per treatment group), using linear (A) or logarithmic (B) axes. The asterisk indicates that recovery of methylsalicylate differed significantly (p < 0.05) between control and decontaminated treatment groups at all anatomical sites. Actual p-values are presented in Table 2.
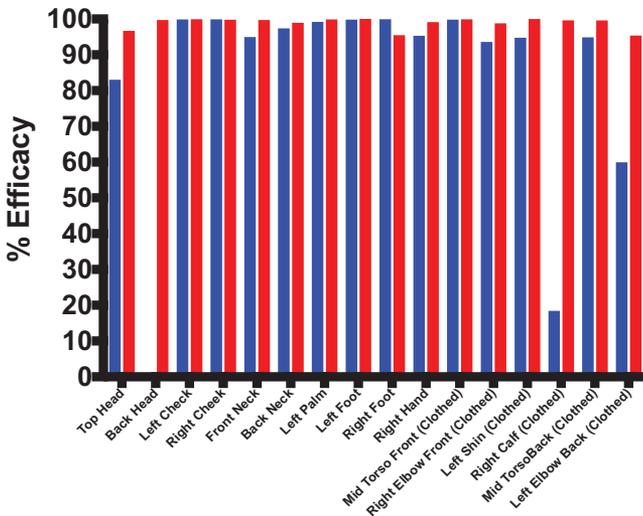
FIGURE 7. Percentage efficacy of dry (■) or wet (■) decontamination (combined from all anatomical locations) of volunteers, expressed as mean of n = 9.

Comparison of Wet and Dry Decontamination Efficacy

Overall, both methods of decontamination were consistently effective in removing the simulant from a range of anatomical locations (Figure 7). The notable outliers were dry decontamination of the top of the head (scalp hair) back of head, right calf, and left elbow.

Recoveries of Methylsalicylate from Auxiliary Materials

The majority of the applied dose of methylsalicylate recovered from samples of Blue Roll was
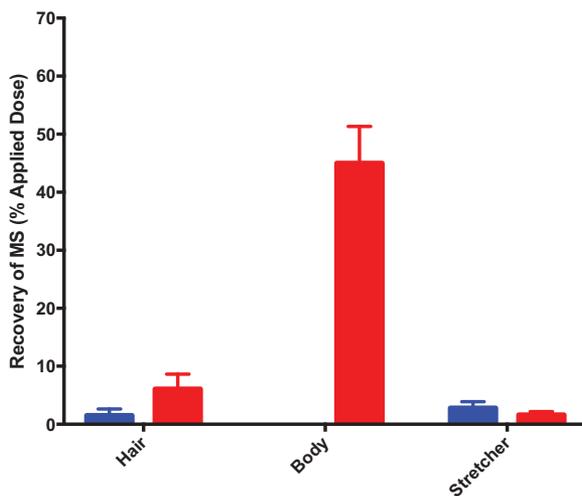

FIGURE 8. Percentage of applied dose of methylsalicylate (MS) recovered from blue roll of control (■) or decontaminated (■) treatment groups. Each data point represents the mean ± standard error of the mean (SEM) of n = 8 replicates.

extracted from swatches used for body decontamination (Figure 8). Less than 10% of the applied dose was recovered from Blue Roll used on the hair, which was not significantly different to the corresponding control. Transfer of methylsalicylate to the stretcher did not differ significantly between the control and decontaminated groups. Negligible amounts of methylsalicylate (<0.05% applied dose) were recovered from the towel following clinical decontamination.

The total recoveries of methylsalicylate from all experimental compartments indicated an unaccounted fraction of 30–45% of the applied dose (Figure 9), with
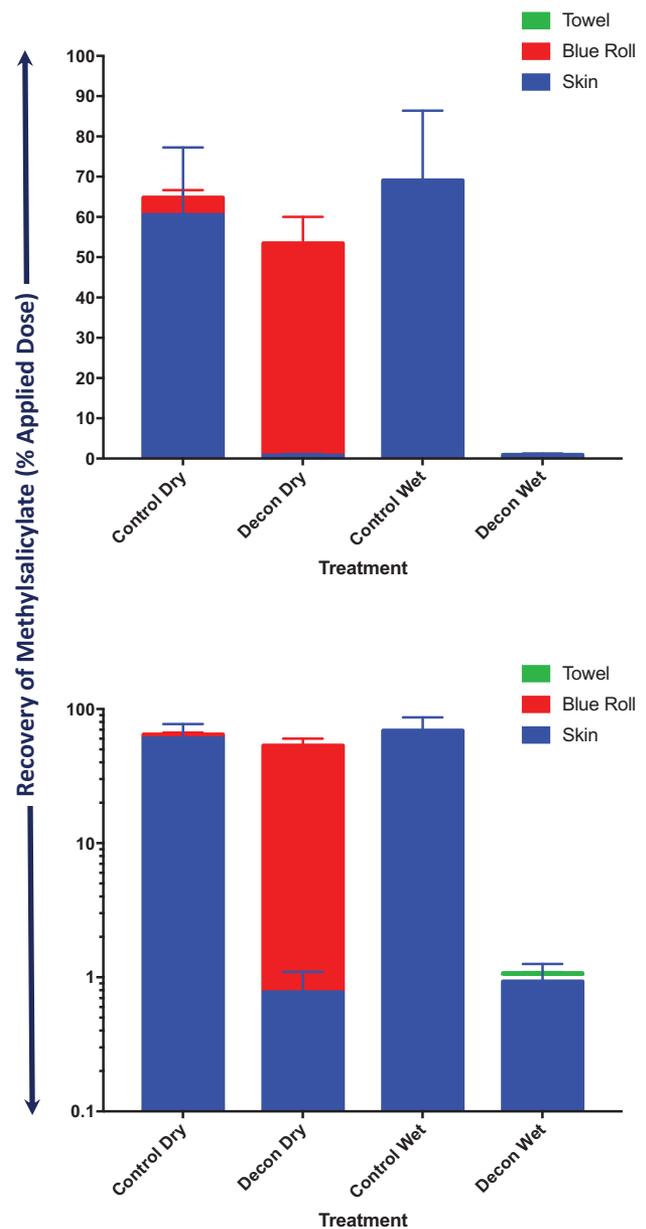

FIGURE 9. Total recoveries of methylsalicylate from all experimental compartments. Values are mean ± standard error of the mean (SEM) of n = 8 (dry decontamination study) or n = 9 (wet decontamination study).

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less than 1% of the applied dose being recovered from the skin following wet or dry decontamination.

Image Analysis

In general, the area of contamination was not adversely affected by dry decontamination, with no significant differences in skin surface spreading within each anatomical zone (Figures 10A & B). The intensities of the contaminated skin areas were consistently (but not significantly) lower for decontaminated sites (Figures 10C and D). Similarly, the area of contamination following wet decontamination resulted in no discernible differences between decontaminated and control groups (Figure 10E and F). The intensity of contamination was found to be significantly lower following wet decontamination for zone 1 (face, neck, and chest).

Overall, the whole body area of skin contamination was significantly lower when clinical (wet) decontamination was performed ($p < 0.01$): no comparable change was observed following dry
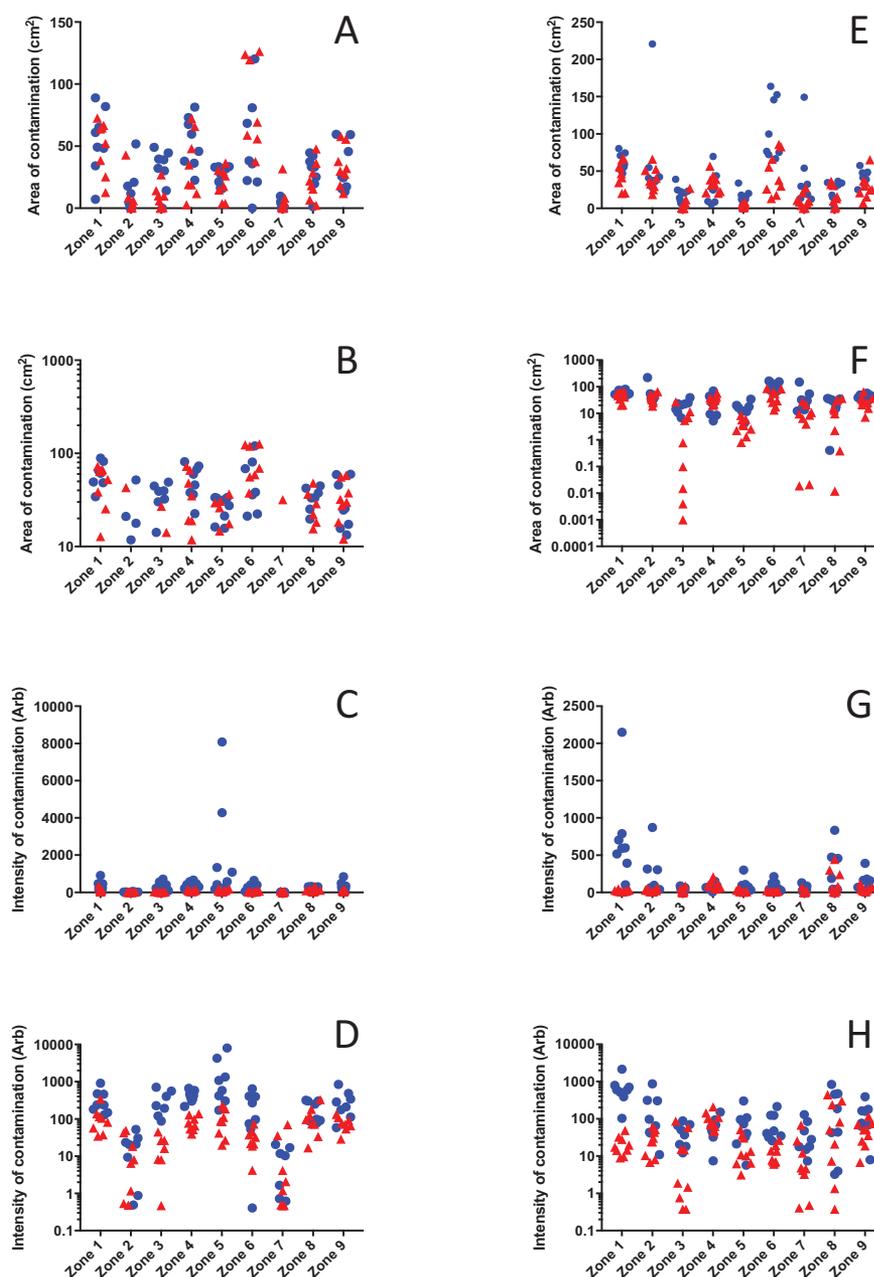
FIGURE 10. Calibrated image analysis of each zone of skin/hair for dry (A–D) and wet (E–F) decontamination studies following exposure to 10 μL or 100 μL droplets of 10 mg mL^{-1} curcumin in methylsalicylate, expressed as area of spreading (A, B, E, F) and intensity of fluorescence (C, D, G, H). Each point represents the average measurement from one individual for control (•) or decontaminated (▲) skin. For location of zones, see Figure 4. Arb, arbitrary units.

FIGURE 11.   Whole-body contaminated surface area (A) or intensity (B) measurements from wet and dry decontamination studies. Each bar represents the mean ± standard error of the mean of n = 8 (dry) or n = 9 (wet) volunteers. ** Significant difference (p < 0.01). Arb, arbitrary units.
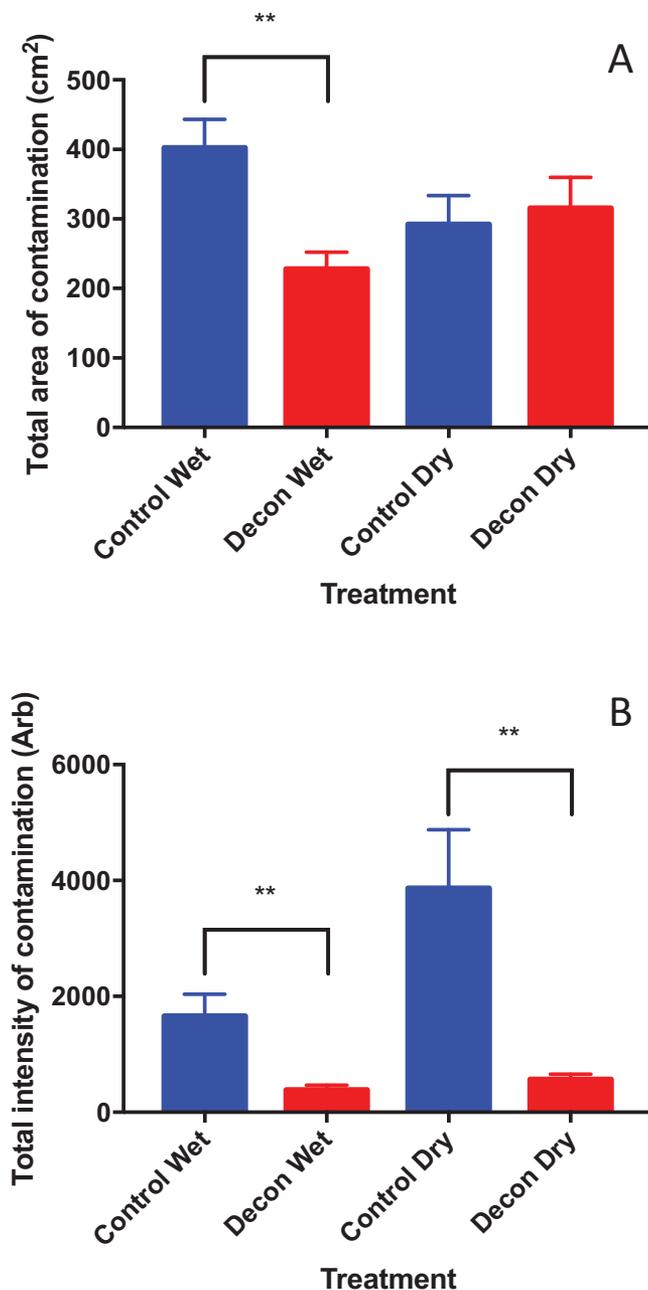
decontamination (Figure 11A). Whole-body fluorescent intensity was significantly reduced by both wet and dry decontamination protocols (p < 0.01; Figure 11B).

Additional Measurements

At the conclusion of the wet decontamination study, whole-body fluorescent images of each DTM were acquired while they were wearing PRPS: consistent areas of cross-contamination were observed in the palm and groin areas (Figure 12). An accumulation of contaminant was also observed over the head area (helmet) of one DTM.

LIMITATIONS

While the current investigation provides a robust assessment of dry and wet decontamination protocols, an obvious limitation is that the studies were performed under controlled environmental conditions with a single, mid-volatility chemical warfare agent simulant. It is strongly recommended that further evaluation of the decontamination protocols is performed under more realistic circumstances using simulants with different physicochemical properties. This would also allow the investigation of other operational factors, such as the control of waste dry decontamination materials, management of disrobed casualties, safety of dry decontamination personnel, and improved doffing procedures for emergency responders.

DISCUSSION

While there is a considerable body of evidence to support current dry (IOR) and wet (SOR) mass casualty decontamination procedures for ambulant casualties (4,5,7,12-14), optimization or assessment of procedures for nonambulant casualties have not been adequately addressed (15). This present study has established that a new procedure for nonambulant disrobe and dry decontamination is relatively effective and can be completed within 3 min. Moreover, this study has demonstrated that a revised process for nonambulant clinical wet decontamination can be performed effectively within 4 min.

The disrobe and dry decontamination protocol evaluated in this study was designed to accommodate the requirements of casualties with potentially severe injuries and so aspects of good clinical practice were observed by the inclusion of airway and spinal management techniques. This involved one DTM being responsible for supporting the head of each volunteer with the "triple airway manoeuvre" (16). A second aspect of the dry decontamination protocol design was to eliminate direct contact with the casualty and thus reduce the risk of cross-contamination. Therefore, the DTM responsible for spine and airway management used Blue Roll to form an absorbent, physical barrier around the casualty's head. This physical management of volunteers was identical between the 2 treatment groups. While representing a sound experimental design, it introduced an experimental artefact: the head of each control volunteer was in contact with the Blue Roll and was thus essentially decontaminated. Accordingly, the recoveries of simulant from the "back

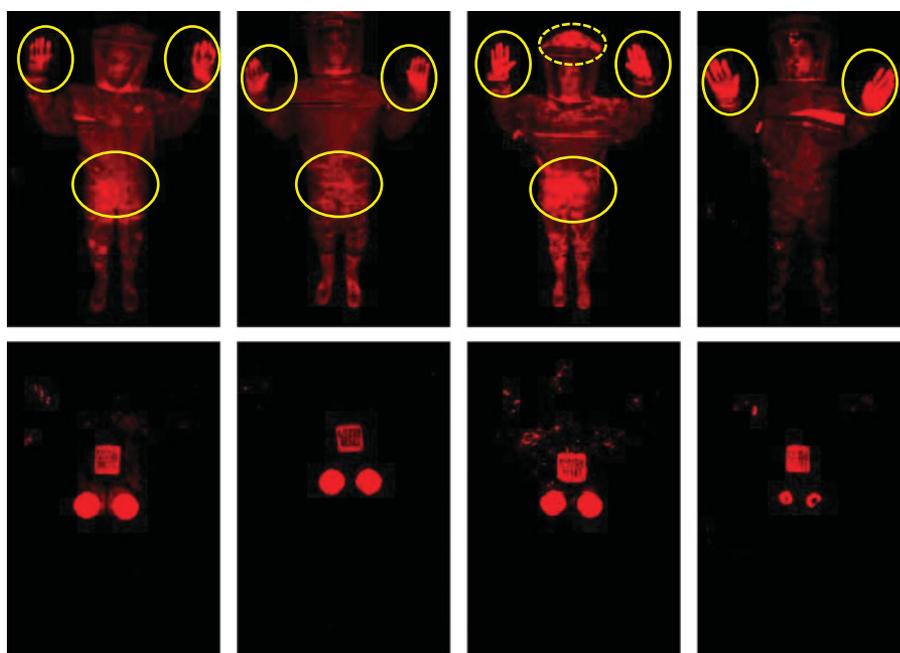R. P. Chilcott et al. Nonambulant Mass Casualty Decontamination

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FIGURE 12. Whole-body fluorescence images of Decontamination Team Members acquired at the conclusion of the wet decontamination study. Upper row = front view; lower row = rear view. Consistent areas of contamination (hands and groin) are identified within the oval areas. Helmet contamination was observed in one individual (dotted line oval).

head" area were corresponding low in both treatment groups and resulted in the apparent (complete) loss of decontamination effectiveness at that anatomical location (Table 2).

A feature of the study design was the incorporation of disrobing at a third of the exposed skin/hair sites to allow simultaneous investigation of the effects of combined disrobe and decontamination. The percentages of the applied dose of simulant recovered from disrobed (control and decontaminated) sites were 1 to 3 orders of magnitude lower than those from unclothed control sites. These data confirm the substantial benefit of disrobing identified in previous studies (14). A synergistic effect between decontamination and disrobing was not consistently observed, although this may be attributable to the effectiveness of disrobing.

Overall, both dry and wet decontamination protocols were significantly effective, although wet decontamination was more consistent and removed a greater proportion of contaminant at the majority (~70%) of exposed anatomical sites (Figure 7). It should be noted that the wet decontamination protocol is performed using bespoke, specialist assets. In contrast, dry decontamination is an *ad hoc* process that provides potentially life-saving "first aid" for chemical contamination at the earliest opportunity. Dry and wet decontamination should therefore be considered as complementary processes.

An operational consideration that needs to be addressed is the safety of individuals treating nonambulant, contaminated casualties. It is imperative to develop adequate risk assessments that address the safety of responders performing dry decontamination. Further work is required to fully define the risk arising from a range of chemical contaminants. A second consideration is that distinct patterns of PRPS contamination were observed in this and (unpublished) preceding studies, suggesting that the decontamination of PRPS (prior to doffing) should focus on cleaning areas associated with the groin and hands. It has also been observed that individuals wearing oversize PRPS frequently reposition their hood (to improve visibility). This appears to be associated with increased contamination of the head area (for example see Figure 12). Therefore, it is recommended that future studies of wet decontamination incorporate measurements of protective suit contamination.

To summarise, a protocol for disrobe and dry decontamination of nonambulant casualties has been developed and assessed: the new protocol is rapid (3-min duration), generally effective and establishes key principles for future implementation as part of the UK's IOR. However, it must be reiterated that dry decontamination is an emergency medical countermeasure that should normally be used in conjunction with subsequent wet (clinical) decontamination. This study also confirmed the reproducibility, practicality, and effectiveness of a revised wet decontamination protocol. The dry and wet decontamination protocols should be evaluated in combination under more realistic conditions to confirm their clinical effectiveness and appropriate operational

procedures must be developed that ensure the safety of first responders.

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