DISASTER MEDICINE/ORIGINAL RESEARCH

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

Robert P. Chilcott, PhD*; Joanne Larner, PhD; Adam Durrant, BSc (Hons); Philip Hughes, BSc (Hons);
Devanya Mahalingam, MSc; Samantha Rivers, MSci; Elliot Thomas; Nevine Amer, MRes; Mark Barrett, BSc (Hons);
Hazem Matar, PhD; Andreia Pinhal, MSc; Toni Jackson, BSc (Hons); Kate McCarthy-Barnett, EdD; Joseph Reppucci, MS

*Corresponding Author. E-mail: tox.publications@herts.ac.uk.

Study objective: The aim of this study was to evaluate the clinical and operational effectiveness of US federal government guidance (Primary Response Incident Scene Management [PRISM]) for the initial response phase to chemical incidents.

Methods: The study was performed as a large-scale exercise (Operation DOWNPOUR). Volunteers were dosed with a chemical warfare agent simulant to quantify the efficacy of different iterations of dry, ladder pipe system, or technical decontamination.

Results: The most effective process was a triple combination of dry, ladder pipe system, and technical decontamination, which attained an average decontamination efficiency of approximately 100% on exposed hair and skin sites. Both wet decontamination processes (ladder pipe system and technical decontamination, alone or in combination with dry decontamination) were also effective (decontamination efficiency >96%). In compliant individuals, dry decontamination was effective (decontamination efficiency approximately 99%), but noncompliance (tentatively attributed to suboptimal communication) resulted in significantly reduced efficacy (decontamination efficiency approximately 70%). At-risk volunteers (because of chronic illness, disability, or language barrier) were 3 to 8 times slower than ambulatory casualties in undergoing dry and ladder pipe system decontamination, a consequence of which may be a reduction in the overall rate at which casualties can be processed.

Conclusion: The PRISM incident response protocols are fit for purpose for ambulatory casualties. However, a more effective communication strategy is required for first responders (particularly when guiding dry decontamination). There is a clear need to develop more appropriate decontamination procedures for at-risk casualties. [Ann Emerg Med. 2018;■:1-14.]

Please see page XX for the Editor's Capsule Summary of this article.

INTRODUCTION

Background

Contaminated casualties present unique challenges to the first-responder community. In particular, toxic chemicals may rapidly elicit adverse health effects, and thus quick and effective mitigation strategies are required.[1] A variety of documentation has been developed to cover the response to hazardous material or chemical, biological, radiologic, nuclear, and explosive incidents,[2-11] with more recent US federal guidance (Primary Response Incident Scene Management [PRISM]) incorporating evidence-based protocols.[12] The PRISM model is focused on the initial "disrobe and decontaminate" response to chemical incidents. Thus, emphasis is placed on the rapidity of the initial response to prioritize casualty survival.

Importance

The established emergency response to major chemical incidents in the United States is the implementation of "gross decontamination" of casualties. Essentially, this entails showering individuals with a high-volume, low-pressure mist of water delivered into a corridor formed by 2 fire engines parked in parallel, with an aerial spray delivered from a hose strapped to an overhead ladder—hence, the alternative term "ladder pipe system."[13] Previously, this emergency form of decontamination was performed on fully clothed casualties[14]; this practice is now known to transfer contamination from clothing to the underlying skin.[12] Deployment of the ladder pipe system decontamination is relatively rapid and so provides an opportunity for early intervention while advanced facilities are being established,

Editor's Capsule Summary

What is already known on this topic

Contaminated victims of hazardous materials or terrorist attacks need to be decontaminated.

What question this study addressed

Several methods of decontamination have been proposed and deployed. Their effectiveness and efficiency had not been rigorously tested previously.

What this study adds to our knowledge

In healthy ambulatory victims, dry decontamination and ladder pipe decontamination are comparable to full technical decontamination. In nonambulatory victims and those with barriers to following instructions, dry and ladder pipe decontamination take much longer, so more resources must be committed to achieve rapid decontamination.

How this is relevant to clinical practice

People tasked with emergency planning and response for communities, hospitals, and emergency departments can now choose among decontamination methods that work well.

such as technical decontamination: specialist units that provide warm water, a degree of privacy, and containment of effluent.[15] Current planning entails supplementing this conventional approach with the introduction of a "disrobe and dry decontamination" stage as part of a revised initial operational response strategy (Figure 1).

The primary rationale for performing disrobe and dry decontamination is time; a delay of 10 to 20 minutes to establish ladder pipe system decontamination is not unrealistic, and during this time, the window of opportunity to effectively remove toxic chemicals from hair and skin may

be missed.[12] The introduction of a dry decontamination stage therefore makes full and effective use of this inherent delay and should not affect the concept of operations for delivery of the conventional incident response. Any form of absorbent material will suffice for dry decontamination[16]; for example, tissue paper, toilet paper, paper towels, diapers, or absorbent materials carried routinely on ambulances (eg, wound dressings, incontinence pads). Therefore, dry decontamination can be rapidly implemented because it does not rely on specialist resources.

Goals of This Investigation

The aim of this present study was to evaluate the clinical and operational benefits of the revised (PRISM) response process during a multiagency, large-scale exercise (Operation DOWNPOUR), performed in Rhode Island. The study was designed to investigate the effects of single or combined decontamination strategies, with particular reference to the hair and underlying scalp. A proportion of volunteers represented "at-risk casualties," the PRISM definition of which is "individuals who are unable, for any reason, to comply with verbal instructions." The use of at-risk volunteers was deemed essential to account for and address meaningful access to decontamination planning and procedures for the approximately 20% of the current US population who have a disability,[17] thus satisfying the legal requirements for equal access before, during, and after a disaster in compliance with extant legislation (Americans with Disabilities Act, Pub. L. No. 101-336, tit. II, § 202, 104 Stat. 337 [1990]; Rehabilitation Act of 1973, Pub. L. No. 93-112, § 504, 87 Stat. 394 [29 U.S.C. § 794]). At-risk volunteers were recruited for the exercise and comprised individuals with a disability or individuals whose main language was not English. The primary measure of clinical effectiveness was quantification of a chemical warfare agent simulant recovered from the hair and skin of volunteers at the end of the exercise. This was supplemented with
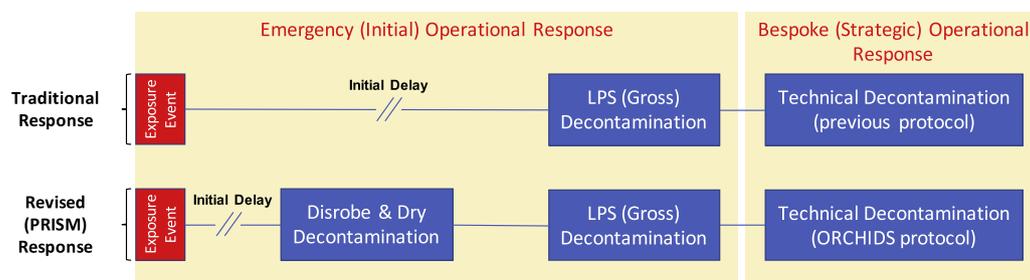

Figure 1. Traditional and revised (PRISM) chemical incident response models. After a contamination event, there was a delay between exposure and functional deployment of LPS decontamination during the initial operational response phase. The revised version reduces the delay by the introduction of a disrobe and DD step. *DD*, Dry decontamination; *LPS*, ladder pipe system of decontamination.

whole-body fluorescent imaging to visualize the distribution of simulant on the volunteers. Global Positioning System (GPS) trackers were used to provide information on casualty flow and so provided an objective measure of operational effectiveness. Postexercise questionnaires were used to collate information from the perspective of the volunteers and incident response personnel.

MATERIALS AND METHODS

First-responder teams ("players") were kindly provided by North Kingstown Fire Department, South Kingstown Fire Department, Kingston Fire Department, North Providence Fire Department, Hopkins Hill Fire Department, the University of Rhode Island Emergency Medical Services, Rhode Island Department of Health, and the Federal Emergency Management Agency. Clinical support (volunteer examination and emergency medical cover) was provided by the Rhode Island Disaster Medical Assistance Team.

The exercise was performed on August 3, 2017, at the University of Rhode Island's Ryan Center. The prevailing weather conditions were 24°C to 27°C (75°F to 80°F), 85% relative humidity, with a southerly wind of 16 to 32 km/hour (7.5 to 20 miles/hour). The response teams and corresponding equipment were predeployed to the parking lot immediately to the north of the Ryan Center (Figure E1, available online at http://www.annemergmed.com). When appropriate, fire department personnel wore full protective gear with breathing apparatus, in accordance with local incident response protocols for chemical incidents.

Methyl salicylate (99% purity) and curcumin (98%) were sourced from Acros Organics (Geel, Belgium). Propan-2-ol, acetonitrile, methanol, and acetic acid (all high-performance liquid chromatography grade) were sourced from FisherScientific (Loughborough, UK), UK. Deionized water was produced in house by filtration of tap water through an Integral-3 water purifier (Millipore, Watford, UK). Multitrauma sterile wound dressings (30.5×76.2 cm) were purchased from Grainger Inc (Warwick, RI), disposable cotton towels (80×140 cm; "Scrummi") from Fabricsmart Ltd (Kent, UK), cotton washcloths (30×30 cm; AmazonBasics) from Amazon UK Services Ltd (London, UK), and Johnson & Johnson's Baby Shampoo and baby oil in the UK. GPS trackers (TK102 Nano GPS) were purchased from Rewire Security (Bristol, UK) and were used in conjunction with proprietary analytical software (GPSLive; REM Trading Ltd, Bristol, UK). Syringe filters (PTFE 0.2 μm) were purchased from ThermoScientific; syringes (1 mL) and glass autosampler vials (2 mL), from FisherScientific.

Selection of Participants

The study was conducted in accordance with the principles of the Declaration of Helsinki and was independently approved by the University of Hertfordshire's Research Ethics Committee and the Rhode Island Department of Health Institutional Review Board. Initial recruitment of 103 volunteers was coordinated by The Olsen Group Ltd (VA), using an online registration system. After a medical screen by Rhode Island Disaster Medical Assistance Team health professionals, 16 volunteers were excluded from participation. A total of 87 volunteers (aged 19 to 74 years; 51 men and 36 women) were subsequently enrolled, of whom one voluntarily withdrew during the exercise. Twenty-one of the volunteers (8 men and 13 women) self-declared as being at risk according to the PRISM definition.[12] Of these individuals, 6 had a visual disability, 4 had a chronic illness, 3 had a cognitive or developmental disability, 5 had a physical disability requiring mobility assistance, and 3 had a first language that was not English; the latter were asked to communicate only in their first language and to act as if they were unable to understand English. After a briefing, the volunteers were invited to give written, informed consent to participate.

Participants were allocated to 1 of 9 treatment groups: dry decontamination, ladder pipe system decontamination, technical decontamination, dry decontamination+ladder pipe system decontamination (dry followed by ladder pipe system decontamination, also performed on at-risk individuals), dry decontamination+technical decontamination (dry followed by technical decontamination), dry decontamination+ladder pipe system decontamination+technical decontamination (dry, then ladder pipe, and then technical decontamination), and 2 control groups ambulant control and at-risk controls) (Table 1). Allocation of treatments was pseudorandom: on registration (at 1 of 10 desks operating in parallel) on the day of the exercise, each ambulant volunteer received a packet taken from the top of a single stack that had been arranged in recurring treatment group order (ie, serial repetition of control, dry decontamination, ladder pipe system decontamination, technical decontamination, dry decontamination+ladder pipe system decontamination, dry decontamination+technical decontamination, and dry decontamination+ladder pipe system decontamination+technical decontamination). The same process was performed for at-risk volunteers. Therefore, the process was pseudorandom in that the resulting treatment allocations could not have been predicted and ensured that the number of volunteers in each group was the same (before the medical assessment).

Table 1. Summary of treatment groups, corresponding activities, and demographics of volunteers.

Treatment Group Designator	Exercise Activities	Participant Demographics, No.; Age, Years
DD (n=10)	Disrobe in area A, DD, transfer to area E	8 ♂; 24–60 2♀; 20–37
LPS (n=7)	Transfer from area B to area C for disrobe, LPS decontamination, transfer to area E	5 ♂; 24–58 2 ♀; 20–36
TD (n=10)	Transfer from area B to area D for disrobe, TD, transfer to area E	5 ♂; 25–41 5 ♀; 23–54
DD+LPS (n=10) DD+LPS (AR) (n=10)	Disrobe in area A, DD, transfer to area C, LPS decontamination, transfer to area E	4 ♂; 28–74 6 ♀; 19–61 7 ♂; 28–38 3 ♀; 26–51
DD+TD (n=10)	Disrobe in area A, DD, transfer to area D, TD, transfer to area E	7 ♂; 26–38 3 ♀; 23–51
DD+LPS+TD (n=10)	Disrobe in area A, DD, transfer to area C, LPS decontamination, transfer to area D, TD, transfer to area E	7 ♂; 23–60 3 ♀; 19–27
CON (n=12) CON (AR) (n=11)	Transfer from area B to area E (synchronous with participants in LPS and TD treatment groups), disrobe at area E.	7 ♂; 19–66 5 ♀; 33–67 4 ♂; 40–61 7 ♀; 24–60

♂, Men; ♀, women; TD, technical decontamination; AR, at-risk casualty group. CON, controls.

The packets provided to each volunteer contained relevant items (T-shirt and shorts to be worn over the participant's own swimwear, sandals, a color-coded (treatment-specific) wristband, volunteer identification number plate, GPS tracker, clinical record forms, and participant information). After changing into their exercise attire, attending a safety briefing, and eating a light lunch, the participants were organized into treatment groups and transferred to the relevant exit within the building's north lobby (Figures E1 and E2) to await dosing with simulant.

The simulant was prepared on the day of the exercise by dissolving curcumin in methyl salicylate to produce a 10-mg/mL solution that was then mixed in a 9:1 ratio (weight/weight) with baby oil. The composition of the simulant was chosen because methyl salicylate has been extensively used as a surrogate for lipophilic, medium-volatility, chemical warfare agents (eg, sulfur mustard, soman) and the fluorophore (curcumin) provided a noninvasive means of visually identifying or quantifying the area of exposure. The lipophilicity of the simulant provided a more robust test of the decontamination protocols. The resulting solution was transferred to high-density polyethylene spray bottles (50-mL capacity; Ampulla Ltd., UK) with a 20-mm-diameter atomizing orifice. Each spray actuation delivered 240 mg ±12 mg (SD) of simulant. Each spray bottle was fitted with a spacer (manufactured in house from polylactic acid on an Ultimaker2 Extended+ 3D printer; Ultimaker BV, Netherlands) to ensure a consistent distance between the spray nozzle and the hair or skin sites on each volunteer. When placed against skin, each spray actuation resulted in a reproducible, circular (8-cm-diameter) area of contamination. Each volunteer was dosed at 3 sites: back of the head (480 mg), upper chest (240 mg), and palm of the right hand (240 mg). The back of the head was contaminated to allow an evaluation of hair decontamination. The palm of the right hand was dosed to identify any potential transfer of contaminant to other areas. The upper chest was selected because it was clothed and so would provide confirmation of the effectiveness of disrobing. The higher dose on the head was required to ensure detectable quantities on the underlying skin because we have previously demonstrated that hair provides a high degree of protection against skin contamination.[18]

At the start of the exercise, volunteers from each treatment group were dosed simultaneously as they exited the building into area A or B (Figure E1, available online at http://www.annemergmed.com), where they subsequently mixed with individuals from other treatment groups. The dosing process was completed within 1 minute and provided a realistic, en masse presentation of casualties. Volunteers were subsequently guided to relevant treatment areas by marshals positioned at strategic points throughout the exercise area (Figure E2, available online at http://www.annemergmed.com). To limit interference with the exercise, marshals were instructed not to transfer participants unless given a clear signal by the exercise players. Egress of a volunteer from area A (under the control of emergency medical services [EMS] personnel) was used as a signal for marshals in area B to send one volunteer (not undergoing dry decontamination) from each treatment group to the next appropriate position in the exercise. The purpose of this was to synchronize the participation of volunteers not undergoing initial disrobe and dry decontamination so that (1) all control (untreated) volunteers were dispatched to the rendezvous point along timescales similar to those for individuals undergoing decontamination treatments, and (2) there was an objective prompt for marshals to introduce volunteers into the exercise for treatment groups not requiring dry decontamination (and thus not initially under the direct control of the exercise players). The routes taken through

the exercise by individuals in each treatment group are illustrated in Figure E2, available online at http://www.annemergmed.com.

Dry decontamination was performed in accordance with PRISM guidelines.[12] Volunteers in area A were instructed by EMS personnel to disrobe (down to their swimwear). Decontamination material (packets of wound dressing) were thrown into the area by EMS staff (Figure E3, available online at http://www.annemergmed.com), who constantly provided verbal instruction in alignment with the PRISM guidance. When deemed appropriate, EMS personnel instructed volunteers to proceed to the next phase of the exercise.

Ladder pipe system decontamination was deployed according to a standard, local protocol. Briefly, 2 fire engines (Renegade 2,000 gallon/minute pump trucks; Pierce Manufacturing, Appleton, WI) were parked in parallel to produce a central corridor approximately 3.7 m (12 ft) wide, into which a high-volume, low-pressure water mist was introduced through side nozzles (1.75-in Task Force Tip). A ladder truck (E-One HP100 series; Emergency One Inc, Ocala, FL) was used to position a spray nozzle (Elkhart Brass Manufacturing Company Inc, IN) directly above the corridor to provide an overhead source of water (Figure E4, available online at http://www.annemergmed.com). The time taken to predeploy the ladder pipe system decontamination was approximately 12 minutes. On arrival at area C, volunteers were instructed to disrobe (if still wearing outer garments) and subsequently enter the ladder pipe system decontamination corridor under the command and supervision of fire department officers. The ladder pipe system decontamination protocol involved a 15-second immersion in the middle of the decontamination corridor. During this time, volunteers were instructed to rub themselves with their hands from head to toe. On exiting the corridor, the volunteers were given a towel and instructed to dry themselves for 30 seconds before being transferred to the next appropriate area.

Technical decontamination was performed with specialist decontamination units (FSI North America, Sheffield, OH) (Figure E5, available online at http://www.annemergmed.com) in accordance with the Optimisation through Research of Chemical Incident Decontamination Systems showering protocol.[15,19,20] Each unit contained 6 overhead hoses with manually activated spray nozzles, which supplied warm (35°C [95°F]) water at a maximum rate of 56 L/minute from a water heater (Model 200A; FSI International) connected to a fire hydrant. Volunteers arriving at area D were instructed by fire department officers to disrobe (if not already done) and enter the decontamination unit, where they were asked to shower while wiping themselves down with a washcloth (pretreated with 10 mL baby shampoo). After washing for approximately 90 seconds, the volunteers were asked to discard the washcloth and exit the unit, where they were given a clean towel to dry themselves before being directed to area E.

The exercise finished when the last volunteer reached area E (rendezvous point). Any volunteers who remained clothed (ie, control treatment groups) were instructed to disrobe. All volunteers were immediately transferred back to the Ryan Center for whole-body fluorescence imaging and skin and hair swabs to visualize and quantify the recovery of any residual simulant.

Swab samples were taken from 8 sites on each volunteer: right palm, upper chest, hair at the back of the head, underlying scalp skin, abdomen, left palm, left cheek, and lower back. Prepared sets of glass vials containing 3 cotton swabs or jars containing 3 cotton pads were weighed before use. A (single-use) plastic template (with a 3-cm-diameter circular aperture) was applied to each skin site, from which serial, triplicate swabs of the site were taken with cotton swabs. The first and last swabs were performed with dry cotton swabs, whereas the second swab was immersed in solvent (propan-2-ol) before use. To facilitate access for scalp skin samples, a comb was used to part the hair at the swabbing site before application of the plastic template. The cotton swabs were returned to their original glass vial. The procedure for acquiring hair swabs was similar, except that an 8-cm-diameter plastic template was used in conjunction with 3 cotton pads. All hair and skin swab samples were subsequently immersed in propan-2-ol (10 mL per cotton swab vial and 200 mL per cotton pad jar), reweighed, and stored in lightproof boxes at ambient temperature before analysis.

Before leaving the exercise, volunteers received a brief medical assessment and completed a postexercise questionnaire to elicit opinions on how clean the individuals felt after their treatment and how they perceived their interactions with the emergency service personnel. The response to each question was graded numerically (1 to 5). First responders attended a "hot debrief" immediately after the exercise to provide verbal feedback.

Data Collection and Processing

Whole-body fluorescent imaging was performed within a lightproof unit. Volunteers entered the unit in pairs and were illuminated by an array of 12 light-emitting diode tubes (Arcadia T8, LED Marine Blue; Arcadia Ltd., Surrey, UK), between which 2 digital single-lens reflex cameras (EOS 80D; Canon UK Ltd, Surrey, UK) were positioned. Video footage (30 ft/second) of the front and back of each pair of volunteers was acquired in less than 10 seconds. Spatial calibration (pixels/millimeter) was performed with a

test card positioned at the same distance from the camera as each volunteer. Individual frames of the front and back of each volunteer were extracted from the video footage with Final Cut Pro software (version 10.3.1; Apple Inc, Cupertino, CA). The analysis work flow consisted of the delineation and removal of extraneous areas of fluorescence (eg, from swimwear) from each image, using a graphics tablet (Wacom Intuos Pro, Düsseldorf, Germany) in combination with Adobe Photoshop CC (version 2017.1.1; Adobe Systems, San Jose, CA). Open-source software (Fiji, version 1.021)[21] was subsequently used to convert each image to 8-bit format and to extract red-channel data. A blanket segmentation threshold limit of 75 was selected and applied for subsequent particle analysis and calculation of the area of residual contamination (skin fluorescence).

Quantification of the recovery of methyl salicylate in the swab samples was performed with a ThermoScientific UltiMate U3000 high-performance liquid chromatography system (quaternary pump, autosampler, and column oven) and a ThermoScientific Vanquish Diode Array Detector. Separation was achieved with a ThermoScientific HyPurity C18 column (150×2.1 mm, 5-µm internal diameter). Instrumentation was controlled by proprietary software (Chromeleon, version 7.2; ThermoScientific). All swab samples were briefly vortex mixed before being syringe filtered into vials (2 mL) for direct autosampler injection (2 µL). The mobile phase comprised 60% aqueous acetic acid (pH 3) and 40% acetonitrile at a flow rate of 0.4 mL/minute. The column temperature was 30°C (86°F) and ultraviolet detection was set at a maximum wavelength of 303 nm. A nonmatrix calibration standard series (0.0289 to 1,184 µg/mL) was analyzed with each batch, with quality control samples (0.0474, 3.55, and 829 µg/mL) bracketing up to 20 samples to confirm the acceptable accuracy (85% to 115%) and precision (±15 [SD]) of the chromatographic system. Samples were quantified against a matrix calibration series (0.025 to 1,100 µg/mL) diluted from a matrix (cotton pad or cotton swab) spiked with the dosing simulant on the day of the study and extracted in propan-2-ol as per the exercise samples. Unspiked (blank) solutions were prepared simultaneously for each sample matrix.

The time spent by each volunteer in areas A to E was estimated from the GPS tracking data. Briefly, rectangular coordinates corresponding to areas A to E were identified with mapping software (Apple Maps version 2.0; Apple Inc). The data from each GPS tracker were downloaded onto a Microsoft Excel spreadsheet (version 15.33; Microsoft, Redmond, WA) and the cumulative time spent in each area was calculated. Individuals' GPS data were checked visually by plotting the tracker coordinates on a graph with an overlay of each area (Figure E6, available online at http://www.annemergmed.com).

Primary Data Analysis

Each data set was evaluated with the D'Agostino-Pearson omnibus normality test for Gaussian distributions. The data were found not to be normally distributed, so nonparametric tests were performed. The 2 control groups were not significantly different from each other ($P>.99$) and so these data were pooled to improve statistical power. Differences between treatment groups were evaluated with an unpaired (Kruskal-Wallis) ANOVA, with multiple comparisons posttest (with Bonferroni correction). Statistical analysis was performed with GraphPad Prism (version 7.a; GraphPad Software, La Jolla, CA). The relative effectiveness of each decontamination protocol was expressed as the reduction in contamination as a percentage of control,

$$\%E \ = \ 100 - \left(\frac{Q_D}{Q_C} \times 100 \right) \qquad \text{Equation 1}$$

where decontamination efficiency is the percentage effectiveness of decontamination and Q is the average quantity of simulant recovered from the skin surface of decontaminated (D) or control (C) volunteers.

Empirical modeling of the GPS tracker data was performed by plotting the time of entry into dry decontamination (area A), ladder pipe system decontamination (area C), and technical decontamination (area D) as a function of the duration in each area, followed by nonlinear regression using a least squares (ordinary) fit with asymmetrical 95% confidence levels. The resulting equations were used to predict the times and duration of ladder pipe system decontamination and technical decontamination. These predictions were compared against those acquired during the exercise by expressing the outputs in terms of number of casualties per decontamination area with time.

RESULTS

In control individuals, the largest recoveries of methyl salicylate (expressed as mean; 95% confidence interval [CI]) (Figure 2) were from the hair (1,317 µg; 95% CI 296 to 2,337 µg), scalp skin (69 µg; 95% CI 5 to 133 µg), chest (35 µg; 95% CI –34 to 104 µg), and lower back (29 µg; 95% CI –29 to 88 µg), with relatively small recoveries from the abdomen (0.6 µg; 95% CI –0.5 to 1.8), right palm (0.7 µg; 95% CI 0.2 to 1.2 µg), left cheek (0.3 µg; 95% CI –0.2 to 0.7 µg), and left palm (0.05; 95% CI –0.02 to 0.12 µg). The ratio of methyl salicylate contamination between the hair and underlying scalp skin
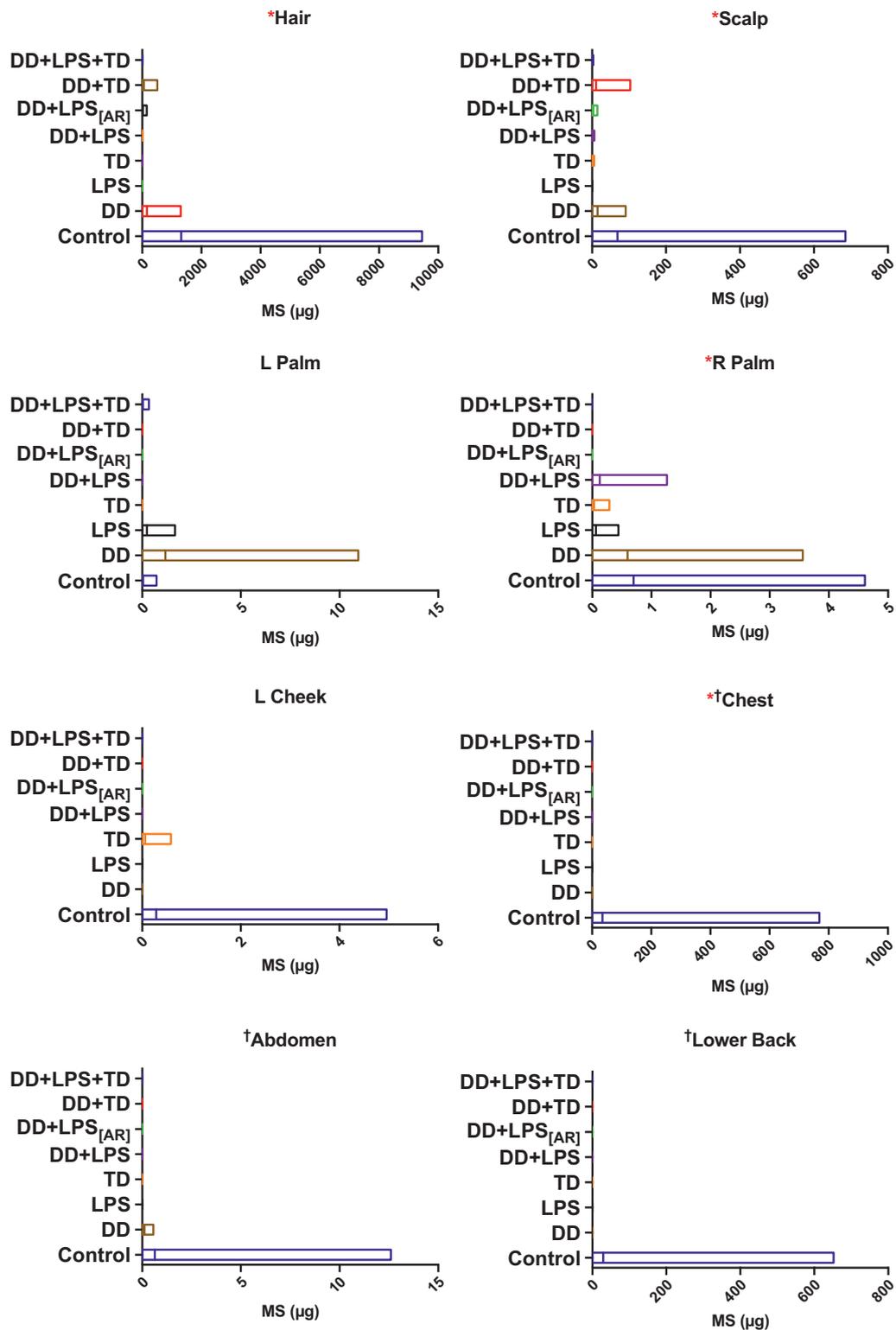
Figure 2. Recoveries of simulant (MS) from the 8 swabbed hair and skin locations. For statistical analysis, refer to Table 2. *Site was dosed with simulant or †originally clothed. *MS*, Methyl salicylate.

was approximately 20, indicating that the majority of the dose applied to the head remained in the hair. The relatively low recoveries of methyl salicylate from the majority of sites that were not directly contaminated (left palm, left cheek, and abdomen) implied minimal cross contamination from exposed skin sites.

Table 2. Percentage effectiveness of decontamination (see the in-text equation) for each treatment group.

Treatment Group	Hair*	Scalp*	Left Palm	Right Palm*	Chest*†	Abdomen†	Back†	Mean %E‡
DD								
n=10	88.2	78.5	–2,253	14.8	99.4§	82.7	100§	70±38
n=8	[99.1]§	[97.6]	[100]§	[100]§	[99.4]§	[82.7]§	[100]§	99±1
LPS (n=7)	99.9§	99.6§	–378	91.0	100.0§	100.0	99.8	98±4
TD (n=10)	99.8§	97.4	100.0	81.9	99.8§	100.0	100.0	95±9
DD+LPS (n=10)	99.6§	98.0§	100.0	81.9	99.8§	100.0	100.0§	95±9
DD+LPS (AR) (n=10)	97.9	95.3§	100.0	100.0§	100.0§	100.0	100.0§	98±2
DD+TD (n=10)	95.8§	83.9	100.0	100.0§	100.0§	100.0	100.0§	95±8
DD+LPS+TD (n=10)	99.8§	98.8§	32.7	100.0§	100.0§	100.0	100.0§	100±1

%E, Percentage effectiveness of decontamination ± SD.
*Site was dosed with simulant.
†Site was originally clothed (before disrobe). Numbers in square brackets indicate %E value after removal of 2 (DD) outliers (n=8). The %E value at all left cheek sites was 100%.
‡The mean value of %E across all hair and skin sites dosed with simulant. For description of treatment groups, see Table 1.
§Treatment was statistically significantly different from controls (*P*<.05).

Statistically, the triple-combination process (dry decontamination+ladder pipe system decontamination+technical decontamination) provided the most consistently effective performance, achieving a significant reduction in methyl salicylate recovery at all 4 sites of initial contamination (Table 2). The 3 double combinations (dry decontamination+ladder pipe system decontamination, dry decontamination+ladder pipe system decontamination [at risk] and dry decontamination+technical decontamination) and the ladder pipe system decontamination–only treatments were significantly effective at 3 of the 4 exposure sites (Table 2). Of the single-decontamination processes, technical decontamination was significantly effective at 2 of the 4 initial dosing sites (hair and chest), whereas dry decontamination was significantly effective at one (chest) (Table 2). The significant difference between all decontamination treatments and controls at the chest area implies a synergistic effect with disrobing (which was performed by the control volunteers at the end of the exercise).

The frequent lack of statistical significance in decontamination efficacy was a consequence of the inherent variability in methyl salicylate recovery measurements: the coefficient of variance ranged from 138% (dry decontamination+ladder pipe system decontamination+technical decontamination) to 293% (dry decontamination+technical decontamination), with the (pooled) control coefficient of variance being 180%. The statistical analysis detracts from the fact that the decontamination effectiveness was consistently high (average decontamination efficiency=97.3%) in all treatment groups apart from dry decontamination (Table 2).

The effectiveness of dry decontamination was apparently lower than that of all other treatments, particularly on the hair (88.2%), scalp (78.5%), right palm (14.8%), and right hand (–2,253%) (Table 2). To investigate this further, we performed a statistical analysis to identify any outliers (GraphPad Prism ROUT test, with an aggressive coefficient [Q] of 0.1%). Two outlier data points were identified at each anatomic location except the lower back and left cheek. These 2 data points were consistently from the same 2 volunteers, who were subsequently identified in video recordings of the dry decontamination area. Both individuals were observed to remove the wound pad (dry decontaminant) from the sachet and hold it in their hands. There was no video evidence to suggest that they subsequently engaged in the decontamination process. The reasons for this inactivity cannot be inferred from the video, although an obstructed view of the EMS personnel may conceivably have been a contributing factor. Removal of these outliers from the dry decontamination data set had a profound effect: after dry decontamination, recoveries of methyl salicylate from hair (*P*=.04), right palm (*P*=.02), and chest (*P*=.04) were significantly lower than those for controls, with an overall effectiveness (decontamination efficiency, averaged across all initially contaminated sites) of 99%.

There were no significant differences (*P*>.05) between control and decontamination treatment groups in the skin surface spreading of the simulant, indicating that the various decontamination methods did not cause visually detectable transfer of contaminant from the point of application to other body areas.
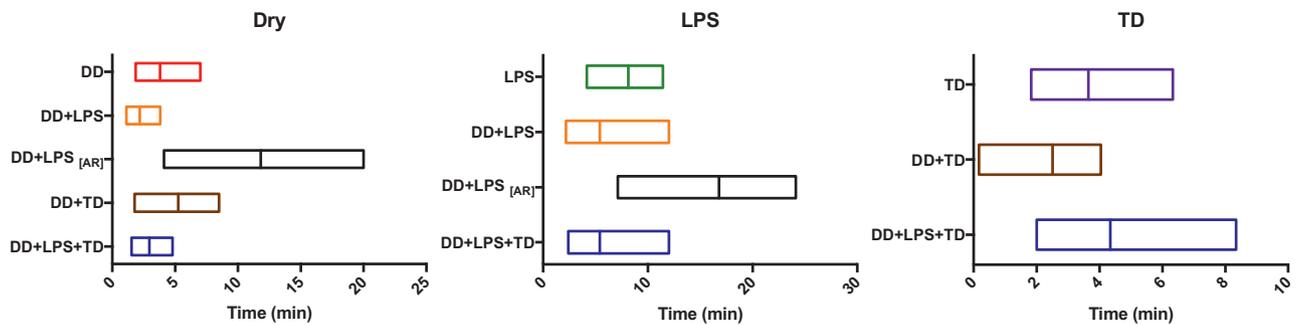
Figure 3. Summary of duration spent in each decontamination area (dry; area A, LPS; area C and TD; area D). For n values, please refer to Table 1. The duration during dry decontamination was significantly greater ($P<.05$) for at-risk casualties.

The average durations of ambulatory volunteers within areas A (dry decontamination), C (ladder pipe system decontamination), and D (technical decontamination) were 3.6±0.7 minutes (SD), 1.6±0.8 minutes (SD), and 3.5±0.5 minutes (SD), respectively. The times spent by at-risk volunteers in the dry decontamination (11.8±2.6 minutes [SD]) and ladder pipe system decontamination (16.8±3.6 minutes [SD]) areas were significantly longer than those for the corresponding ambulatory treatment group (Figure 3). The total exercise duration (calculated from the time each volunteer entered the initial holding area to leaving the rendezvous point) was 39.1 minutes.

Analysis of the GPS data indicated a trend for the duration spent in the ladder pipe system decontamination area to increase with time (Figure 4), with a modest increase or decrease in duration for dry decontamination and technical decontamination, respectively. Application of the resulting curve-fit equations to a simple linear model (Figure E7, available online at http://www.annemergmed.com) yielded a predicted maximum throughput of 1.2 casualties per minute (Figure 5).

Participants reported that they received clear instructions from the first responders during treatment(s) involving ladder pipe system decontamination or technical decontamination (Figure E8, available online at http://www.annemergmed.com). However, the response was borderline when the treatment(s) included dry decontamination: several volunteers stated that they could not adequately hear instructions because of a combined effect of distance and background noise. This was noted by one of the volunteers who stated that "There were 4 rows of 40 people out the front.… I couldn't really hear…so you needed a couple of people there with a megaphone or something to broadcast that information or repeat telling everybody what to do."

There was agreement that, in a real emergency, the volunteers would be prepared to remain at the scene of an incident to undergo decontamination treatments, although

this was less emphatic for participants who had undergone dry decontamination (Figure E8, available online at http://www.annemergmed.com). Volunteers who underwent dry decontamination were also more inclined to report a poor perceived outcome, whereas participants in the ladder pipe system decontamination or technical decontamination groups reported that they felt clean (Figure E8, available online at http://www.annemergmed.com).

There was consensus across all treatment groups that further medical assessment would be required after decontamination (Figure E8, available online at http://www.annemergmed.com).

The dry decontamination process was deemed to be successful, although some difficulty communicating with the volunteers was noted by an EMS responder: "It would be interesting to see in a real situation how far our voices can carry and how well the victims may be able to listen." When asked whether the volunteers appeared to hear the instructions, an EMS responder stated, "Yes, most of them. When you say, 'Go take off your clothes,' within 35 to 40 seconds the clothes will be off. It's kind of hard to coordinate, as not everybody takes their clothes off at the same rate, so I found myself repeating myself a lot. Some [volunteers] were just standing there waiting for instructions they may have missed. Many were further back, which made it more difficult to yell instructions." It was noted that the wound dressing packs had been difficult to distribute and that firefighters wearing full personal protective equipment had needed to intervene by picking up dressing packs from the floor to hand to the volunteers.

A ladder pipe operator stated that "It was pretty tough keeping those people in really cold water, but usually we were able to communicate with the guys standing on the end of it demonstrating to make sure you catch as much of your body as you can. Having a facecloth would have been really useful." Although it was agreed that at-risk casualties clearly benefited from assistance, this raised concerns about
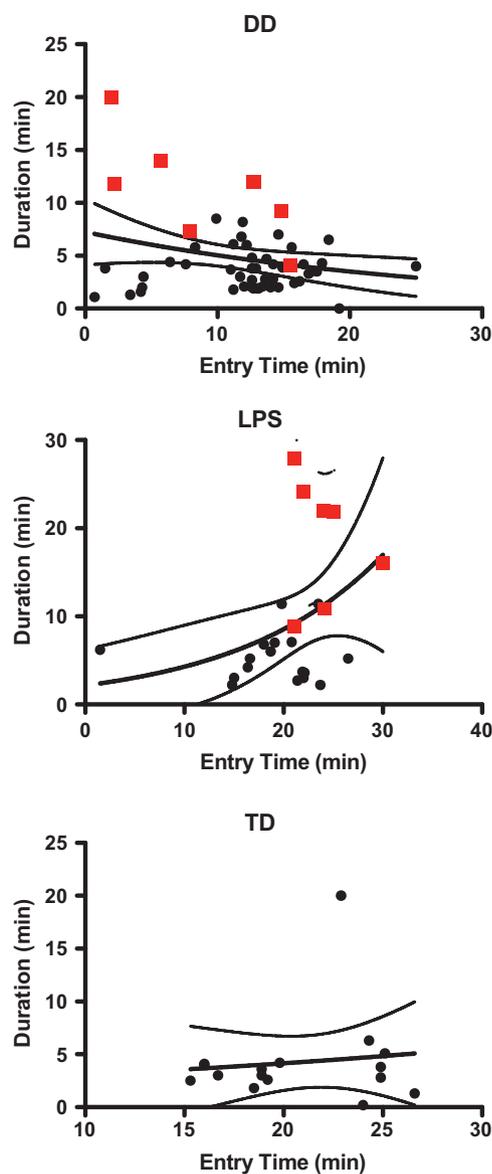
Figure 4. Curve fitting of exercise data (expressed as time each volunteer entered DD, LPS, or TD decontamination areas as a function of the subsequent duration spent in the area). At-risk individuals are represented by square data points (*red squares*). Dotted lines represent 95% CIs. No outliers were omitted from the analysis. Regression analysis was performed with an exponential growth equation (DD, LPS, and TD), with least squares (ordinary) fit.

Figure 5. Predicted duration (left *y* axis) and rate of casualty throughput (right *y* axis) for combined DD, LPS, and TD, expressed as a function of the number of casualties.

resources." It was also noted that process development was required to account for different environmental conditions: "It was a beautiful day, so the people [casualties], they're going into this cold water for 15 seconds, which to them seemed an eternity; there was some screaming going on. But if we changed this scenario to the middle of winter, then how do we do the gross decon [ladder pipe system decontamination] when they've had to disrobe…before they to go to technical decon? That's another element that will have to be staged."

Technical decontamination went "smooth and pretty quick," and it was confirmed that volunteers received instructions and guidance for the Optimisation through Research of Chemical Incident Decontamination Systems protocol (1.5 minutes, washcloth, and detergent).

LIMITATIONS

Some of the practical limitations of this exercise that were reported by the players and volunteers have been detailed above. Such exercises necessarily represent an artificial operating environment. Therefore, although measures were taken to minimize artifacts, the outcomes of this exercise should be interpreted with caution. A clear limitation of the study design was the inability to blind the volunteers to the simulant application sites; a more elaborate, volunteer-blinded method of dosing was not practically possible, given the need to introduce the large number of participants quickly into the exercise. A review of video recordings indicated that the volunteers did not focus attention on the dosing sites, and so this is unlikely to have influenced the outcomes of the study. The pseudorandom allocation of volunteers to respective treatment groups was also not ideal but a practical necessity to ensure efficient registration with an even number of volunteers in each treatment group (before the medical

staffing levels: "Tasking a few of the firefighters to specifically walk people through that needed additional assistance…starts messing up the whole process." It was thought that 2 additional fire department personnel were required (to supplement the standard team of 5) to ensure that the process flowed smoothly and that there would be resource implications: "If we are going to need 7 people, we need 7 replacements, 7 bottles, 7 packs.… We need to look at how many pieces of equipment we need, personnel or

evaluations). Finally, the use of local first-responder agencies undoubtedly introduced a selection bias. Because the clinical outcomes of the exercise were predominantly based on "self-help" procedures by the casualties, this is unlikely to represent a major confounding factor. Conversely, the exclusive use of local responder agencies would potentially decrease variation because of differences in operational response and so increase the statistical power for discriminating effects between the treatment groups.

DISCUSSION

To our knowledge, this study is the first to quantify the operational and clinical effectiveness of combined dry and wet decontamination protocols for mass casualty chemical incidents and the first to specifically address the efficacy of hair decontamination. The exercise was successful in demonstrating the practical utility and operational effectiveness of the revised (PRISM) response process and in confirming the general clinical efficacy of each protocol for hair and skin decontamination.

The most effective strategy was the triple combination of dry, ladder pipe, and technical decontamination (dry decontamination+ladder pipe system decontamination+ technical decontamination), which was significantly superior to controls at all sites that were initially exposed to the simulant (hair, scalp, right palm, and chest). Correspondingly, it would be prudent to recommend that this be adopted as the standard approach to mass casualty decontamination. The other decontamination treatments (with the exception of dry decontamination) were also effective in that there was an average removal of greater than 97.3% of chemical contaminant from hair and skin surfaces.

The apparent ineffectiveness of dry decontamination was due to the noncompliance of 2 volunteers within the treatment group. When these 2 outliers were removed from the analysis, the average amount of contaminant removed was greater than 99% and so was equivalent in performance to the other decontamination methods and in agreement with a previous study evaluating an absorbent wound dressing against the same contaminant (methyl salicylate).[16] It is possible that the noncompliance was a consequence of the communication problems reported by the volunteers and exercise players because dry decontamination is effective when performed under controlled conditions but less effective in the absence of explicit guidance and instructions.[22] Therefore, improvements in the delivery and quality of responder communication should be investigated to ensure that casualties receive more effective supervision during the dry decontamination process; the importance of good

communication has been highlighted previously.[23] During an incident response, it may be beneficial to instruct casualties to repeat the dry decontamination process until wet decontamination facilities become available. Aside from providing a distraction, propagation of the process may improve casualty compliance and so reduce potential variability in effectiveness. Inadvertent spreading of the simulant to the left palm, left cheek, abdomen, and lower back was occasionally observed (Figure 2). However, where present, the amounts of simulant recovered from nonexposed areas of decontaminated individuals were trivial (<1 μg per site, equating to <140 ng/cm^2).

Addition of the disrobe and dry decontamination stage to the conventional incident response should have little operational effect because it is a parallel process (performed simultaneously by all casualties) that can be readily performed before the availability of a functional ladder pipe system decontamination corridor. The durations of ladder pipe system decontamination and technical decontamination prescribed under the PRISM guidance are 15 and 90 seconds, respectively, which equates to a total wet decontamination duration of 105 seconds (1.75 minutes). Previous guidance recommended 30 seconds to 3 minutes for ladder pipe system decontamination[3,13] and up to 3 minutes for technical decontamination,[11] representing a combined wet decontamination duration of 3.5 to 6 minutes. Therefore, the PRISM incident response is theoretically 2 to 3.5 times faster. A previous exercise performed under similar conditions demonstrated that the PRISM ladder pipe system decontamination protocol was 2.3 times faster than the conventional ladder pipe system decontamination protocol.[12] Given that the duration of the PRISM technical decontamination protocol is half that of the conventional approach, adoption of the PRISM guidance should at least double the throughput of casualties undertaking disrobe and triple decontamination. Clearly, a major incident involving several hundred casualties would require a scaled-up response (involving multiple ladder pipe system decontamination corridors and technical decontamination units) to ensure that all casualties can be processed within an acceptable time.

The integration of a dry decontamination step into the initial operational response provides a focus for casualties and the opportunity for first responders to start communicating advice while providing reassurance and situational information. The latter may be of benefit in reducing anxiety and increasing the cooperation of casualties during an incident.[24] Good communication will also be important for providing reassurance that dry decontamination provides a tangible clinical benefit: the average response from ambulatory volunteers whose

treatment included dry decontamination consistently indicated a perception of being unclean (Figure E8, available online at http://www.annemergmed.com). This was not unexpected because the concept of dry decontamination would be considered by many to be incongruous with cleanliness, especially when compared with the established paradigm of washing with soap and water. A further benefit of the dry decontamination stage is the need to disrobe, which may potentially reduce the urge for casualties to leave the scene of a chemical incident and thus improve crowd management. From a clinical perspective, the disrobe and dry decontamination stage provides an early intervention that allows casualties compliant with instructions to remove a significant proportion (>99%) of liquid contaminants before the delayed arrival and deployment of resources for wet decontamination. Moreover, dry decontamination will eliminate the "rinse-in effect"[25-27] associated with wet decontamination methods that may enhance the dermal absorption of certain chemicals. However, the potential lack of compliance observed in this exercise and the ineffectiveness of dry decontamination against particulate contamination[16] clearly demonstrate that dry decontamination is not a substitute for wet decontamination, but should form part of an integrated response process.

The GPS trackers provided an objective means of quantifying the time spent by volunteers at discrete stages of the exercise. The calculated durations represent the time spent within a general area and so will overestimate the duration of the actual decontamination processes. Taking this limitation into account, combined disrobe, ladder pipe, and technical decontamination required approximately 13.5 minutes per ambulatory person. A comparable measure for at-risk casualties could not be calculated because at-risk volunteers did not undergo technical decontamination during the exercise. However, the average duration for combined dry and ladder pipe system decontamination for at-risk volunteers (approximately 29 minutes per person) contrasted poorly with that of the corresponding ambulatory group (approximately 7.5 minutes) and further emphasizes the need to develop more effective incident response processes specifically for at-risk individuals. Such a delay may have a detrimental effect on the clinical benefit of decontamination for both at-risk and ambulatory casualties.

Modeling of the GPS tracking data indicated that the rate at which individuals could proceed through combined decontamination would peak at approximately 1.2 casualties per minute and then start to decrease. Such a saturation effect would most likely be due to the accumulation of at-risk casualties within the decontamination areas. This is supported by the fact that at-risk casualties were slower to be processed through dry and ladder pipe system decontamination. Indeed, it was observed during the exercise that groups of at-risk casualties were the last to leave the dry and ladder pipe system decontamination areas. It is conceivable that the slower throughput of at-risk casualties is related to the limited number of fire department personnel available to provide assistance, a potential issue that was raised at the postexercise debriefing. Therefore, it seems advisable that decontamination staffing levels be reviewed to accommodate the enhanced workload associated with assisting at-risk casualties.

An interesting outcome of the exercise was the apparent protective effect of hair. In control (untreated) volunteers, the recovery of simulant from the hair was approximately 20-fold greater than that from the underlying scalp skin. This is in agreement with a previous in vitro study, in which recovery of methyl salicylate from the hair was 36-fold higher than that from the underlying skin.[18] Collectively, these data imply that the face and other exposed skin areas may be prioritized over the hair and scalp during dry decontamination.

In conclusion, this exercise demonstrated that PRISM protocols for mass casualty decontamination are effective; our findings also support the introduction of an "immediate disrobe and dry decontamination" stage for casualties who are waiting for wet decontamination assets to arrive on scene. However, it is clear that further work is required to develop more effective processes to accommodate at-risk casualties; this may necessitate a reappraisal of staffing levels to provide a sufficient number of responders for ladder pipe system decontamination. Moreover, there is a need to develop better communication strategies for first responders to ensure that decontamination protocols are performed in an optimal manner.

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