RESEARCH ARTICLE

Preliminary evaluation of military, commercial and novel skin decontamination products against a chemical warfare agent simulant (methyl salicylate)

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Abstract

Rapid decontamination is vital to alleviate adverse health effects following dermal exposure to hazardous materials. There is an abundance of materials and products which can be utilised to remove hazardous materials from the skin. In this study, a total of 15 products were evaluated, 10 of which were commercial or military products and five were novel (molecular imprinted) polymers. The efficacies of these products were evaluated against a 10 μl droplet of 14C-methyl salicylate applied to the surface of porcine skin mounted on static diffusion cells. The current UK military decontaminant (Fuller’s earth) performed well, retaining 83% of the dose over 24 h and served as a benchmark to compare with the other test products. The five most effective test products were Fuller’s earth (the current UK military decontaminant), Fast-Act® and three novel polymers [based on itaconic acid, 2-trifluoromethylacrylic acid and N,N-methylenebis(acrylamide)]. Five products (medical moist-free wipes, 5% FloraFree™ solution, normal baby wipes, baby wipes for sensitive skin and Diphotérine™) enhanced the dermal absorption of 14C-methyl salicylate. Further work is required to establish the performance of the most effective products identified in this study against chemical warfare agents.

Keywords

Absorbent, chemical warfare agent, decontamination, methyl salicylate, percutaneous absorption, skin

Introduction

The deliberate release of chemical, biological, radiological and nuclear (CBRN) materials poses a significant threat to civilian populations as exemplified by the 1995 Tokyo sarin incident¹. Skin decontamination of civilians following exposure to hazardous materials is vital to mitigate local or systemic absorption and subsequent toxicity. Current UK mass casualty decontamination procedures require the casualty to disrobe and decontaminate within bespoke showering units. This procedure has many logistical issues such as time taken to erect the shower units, potential crowd management issues and triage of casualties which may delay decontamination²,³. Moreover, previous studies have shown that water may enhance the penetration of certain chemicals through the skin via the “wash-in effect”⁴–⁷. Within the current procedure, there is a window in which rapid decontamination prior to or in lieu of showering within the bespoke showering units can be performed. Therefore, the identification or development of an effective decontamination product which can be used at the scene of an incident by members of the public may represent a significant improvement for managing mass casualty incidents requiring decontamination. Clearly, such products need to be evaluated to ensure their effectiveness against a range of toxic chemicals.

Methyl salicylate (MS) is generally regarded as an appropriate simulant of toxic non-reactive lipophilic compounds that also has skin absorption properties similar to that of chemical warfare agent sulphur mustard [bis(2-chloroethyl) sulphide]⁸. It has been applied in various scenarios from evaluating medical countermeasures to assessment of protective clothing⁹–¹³. However, one of the main limitations of using MS as a simulant for sulphur mustard in the screening of effective decontaminants, is that MS is not as chemically reactive as sulphur mustard.

The purpose of this study was to identify an effective product which can be rapidly deployed at the scene of a CBRN incident prior to the availability of bespoke decontamination facilities. A range of products were selected for evaluation: commercial off the shelf (COTS) products were selected on the basis of suppliers’ claims of efficacy; some were chosen as they may be readily available (such as baby wipes). Novel polymers were selected based upon their binding affinities to MS, sulphur mustard, soman and VX which was determined by in silico modelling using the LEAPFROG algorithm. Military products were chosen on the basis that they may serve as a benchmark of “standard efficacy” and also to evaluate their efficacy against the chemical warfare agent simulant MS.

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Materials and methods

Ring-labelled (1\(^{14}\)C) MS (55 mCi mMol\(^{-1}\)) was purchased from ARC (UK) Ltd (Cardiff, UK). Non-radioactive MS was purchased from Sigma Aldrich (Poole, UK) and was reported to be >99% pure. These were mixed in an appropriate proportion to give a working solution with a nominal activity of 0.2 \(\mu\)Ci \(\mu\)l\(^{-1}\).

Soluene\(^{\circledR}\)-350 and Ultima Gold\(^{\circledR}\) liquid scintillation counting (LSC) fluid were purchased from PerkinElmer (Cambridgeshire, UK). Propan-2-ol and ethanol were obtained from Fisher Scientific (Leicestershire, UK).

Proprietary products obtained for evaluation were Fuller’s earth (Sigma Aldrich, Poole, UK), KBDO (potassium butadieene monoxide) liquid (E-Z-EM Inc., Anjou, Quebec, Canada; free-flow bottle and sponge formulations), normal baby wipes (“Pampers baby fresh”, Proctor & Gamble, Cincinnati, OH), Diphotérine\(^{\circledR}\) eye wash (Prevor, Valmondois, France), FastAct\(^{\circledR}\) chemical containment and neutralisation system (NanoScale, Manhattan, KS), FloraFree\(^{\circledR}\) detergent (DEB Ltd, Belper, UK), medical moist-free wipes (MMFW) (Safety First Aid Group, London, UK) and an industrial skin decontamination cream (D-TAM SKIN\(^{\circledR}\); Colormetric Laboratories Inc., Des Plaines, IL).

Novel polymers were prepared by the University of Cranfield (Cranfield, UK) as previously described in a patent\(^{14}\). The materials were synthesised using ethylene glycol dimethacrylate (EGDMA) cross-linker and various monomers which confer different functional groups (e.g. amide, amine, carboxylate) to the resulting polymer. The cross-linker and functional monomer were mixed in a 4:1 molar ratio with a free-radical initiator (1,1’-azobis(cyclohexane-carbonitrile), 1% w/w of total mixture) which decomposes under UV light or heat. Dimethylformamide (DMF, volume equivalent to the combined mass of reactants) was used as solvent and porogen. The monomers, initiator and solvent were mixed in a glass bottle and degassed with nitrogen for 5 min. The bottle was then sealed with a screw cap and the reaction initiated by heating to 80°C for 18 h. Control polymers were prepared with EGDMA in the absence of any functional monomers. Following polymerisation, the resulting material was ground then wet-sieved with methanol to collect particles ranging from 40 to 90 \(\mu\)m diameter which were subsequently washed with hot methanol for 24 h and dried at 80°C overnight.

Full-thickness skin was obtained post-mortem from female pigs (Sus scrofa, large white strain, weight range 15–25 kg) purchased from a reputable supplier. The skin was close clipped and excised from the dorsal aspect (full thickness) from each animal. The skin was then wrapped in aluminium foil and stored flat at −20°C for up to 3 months before use. Prior to the commencement of each experiment, a skin sample from one animal was removed from cold storage and thawed in a refrigerator (5°C) for ~24 h. The skin was then dermattomed to a nominal depth of 500 \(\mu\)m using a Humeca Model D42 (Eurosurgical Ltd, Guildford, UK) and the thickness of the resulting skin section confirmed using a digital micrometer gauge (Tooled-Up, Middlesex, UK). Once dermattomed, the skin was cut into squares (3 × 3 cm) for mounting onto diffusion cells.

Static skin diffusion cells were purchased from PermeGear (Chicago, IL) based upon the design of the Franz diffusion cell\(^{15}\). Each diffusion cell comprised an upper (donor) and lower (receptor) chamber with an area available for diffusion of 1.76 cm\(^2\). Dermatomed skin sections were placed between the two chambers (epidermal surface facing the donor chamber) and the ensemble was securely clamped. The receptor chambers were filled with 50% (v/v) aqueous ethanol (~14 ± 0.8 ml), so that the meniscus in the sampling arm was level with the surface of the skin sample. Each diffusion cell was placed in a Perspex\(^{\circledR}\) holder above a magnetic stirrer which constantly mixed the receptor fluid via a (12 × 6 mm) Teflon\(^{\circledR}\)-coated iron bar placed within the receptor chamber. The receptor chambers were of the jacketed variety through which warm (36°C) water was pumped from a circulating water heater (Model GD120; Grant Instruments, Cambridge, UK) via a manifold to ensure a constant skin surface temperature of 32°C (as confirmed by infrared thermography; FLIR Model P620 camera, Cambridge, UK). Once assembled, the diffusion cells were left in situ for an equilibration period of up to 24 h.

Thirty-six diffusion cells were used in each experiment, divided into six treatment groups (each comprising \(n = 6\) diffusion cells). Each experiment was initiated by the addition of 10 ml \(^{14}\)C-radiolabelled MS (0.2 \(\mu\)Ci \(\mu\)l\(^{-1}\)) to the skin surface of each diffusion cell. Samples of receptor fluid (250 \(\mu\)l) were withdrawn from each diffusion cell at regular intervals (i.e. every 3 h) up to 24 h post-exposure and were placed into vials containing 5 ml of LSC fluid. Each receptor chamber was replaced with an equivalent volume (250 \(\mu\)l) of fresh fluid to maintain a constant volume in the receptor chamber.

Decontamination was conducted 5 min post-exposure by the addition of a test product comprising powder (200 mg), liquid (200 \(\mu\)l) or swab/wipe (5 × 5 cm) to each contaminated skin surface. Each product remained in situ for 24 h at which point they were removed and placed into 20 ml glass vials. Twenty-four hours post-exposure, test products were recovered from each skin surface. The powder or liquid formulations (KBDO-sponge, KBDO-liquid, Fuller’s earth, FloraFree\(^{\circledR}\), D-TAM\(^{\circledR}\), Diphotérine\(^{\circledR}\), Fast-Act\(^{\circledR}\) and all polymers) were placed into glass vials containing 20 ml LSC fluid whereas the wipe, swab or sponge formulations (MMFW, baby wipes normal and sensitive formulations) were placed in 20 ml of isopropanol. The contents of each receptor chamber were removed and placed into 20 ml glass vials. Each skin surface was then swabbed with a dry gauze pad which was subsequently placed in 20 ml isopropanol. Finally, the skin from each diffusion cell was removed and placed into pre-weighed vials. The difference in the weight of each vial before and after the addition of each skin sample allowed a calculation of the skin weight. Each skin sample was then dissolved in 10 ml of Soluene-350.

All vials were stored at room temperature (with occasional shaking) for up to 5 days after which aliquots (250 \(\mu\)l) were removed and placed into vials containing 5 ml LSC fluid. Standard solutions were prepared on the day of each experiment by the addition of 2 \(\mu\)l \(^{14}\)C-radiolabelled MS to (i) known weights of fresh test products in 20 ml LSC fluid or 20 ml isopropanol, (ii) unused gauze pads in 20 ml...
isopropanol and (iii) unexposed skin tissue dissolved in 10 ml Soluene-350. Each of the standard solutions was prepared in triplicate and was then subject to an identical sampling regime (250 μl aliquots into vials containing 5 ml LSC fluid). A standard receptor chamber solution was also prepared in triplicate by the addition of 10 μl of 14C-MS, 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 of the samples (i.e. skin, receptor fluid, swabs and decontaminants) were placed into vials containing 5 ml of liquid scintillation fluid and were subject to LSC.

The radioactivity in each sample was quantified using a Perkin Elmer Tri-Carb (Waltham, MA) liquid scintillation counter (Model 2810 TR), employing an analysis runtime of 2 min per sample and a pre-set quench curve specific to the brand of liquid scintillation fluid (Ultima Gold™). The amounts of radioactivity in each sample were converted to amount of 14C-radio labelled chemical warfare simulant by comparison to the corresponding standards (measured simultaneously). Quantification of the amounts of MS recovered in each receptor chamber enabled a calculation of the cumulative dermal absorption over 24 h. These were averaged at each time point for each treatment group and plotted as total amount penetrated (μg cm⁻²) against time for each experiment.

In order to permit an inter-experimental comparison of the performance of each treatment, the data were normalised relative to controls within each experiment (Equation 1).

\[
\% CD_{24} = \left( \frac{QT_{24}}{QC_{24}} \right) \times 100
\]  

(1)

Where %CD₂₄ is the percentage of the control dose penetrating the skin, QT₂₄ is the quantity of contaminant penetrating the skin at 24 h following treatment (decontamination) and QC₂₄ is the quantity of penetrant penetrating control (untreated) skin at 24 h. A surrogate measure of flux (percentage of control dose penetrating the skin at 3 h; %CD₃) was calculated in a similar fashion (by substituting the amount penetrated at 3 h for that penetrated at 24 h).

A test for normality (Kolmogorov–Smirnov) was conducted on all data acquired from the in vitro studies: the data were found to be not normally distributed (non-Gaussian) and so analysed using non-parametric statistical tests. Treatments effects were analysed using the non-parametric equivalent of a one way ANOVA (analysis of variance; Kruskal–Wallis) followed by Dunn’s post-test which allow comparisons of each group against a control group.

**Results**

There was substantial variation in the performance of the 15 test decontamination products: 10 reduced the dermal absorption of 14C-MS, one had no demonstrable effect and four enhanced absorption (Figure 1). When assessed using the Kruskal–Wallis ANOVA with Dunn’s post-test, treatment with Fuller’s earth (FE), D-TAM™, Fast-Act® (FA), itaconic acid (IA), 2-trifluoromethylacrylic acid (TFMAA) and N,N-methylenebis(acrylamide) (MBA) caused a statistically significant (p < 0.05) reduction in the total amount of 14C-MS penetrating the skin at 24 h (expressed as percentage of control dose; %CD₂₄) in comparison with their respective controls.

Correspondingly, decontamination with FE, IA, TFMAA and MBA resulted in a significant decrease in maximum penetration rate (Jₘₐₓ): Figure 2. In addition, urocanic acid (UA) and methacrylic acid (MA) also significantly reduced Jₘₐₓ (p < 0.05), but in the absence of a statistically significant effect on %CD₂₄.

In contrast, sensitive and normal baby wips (baby wipe-S and baby wipe-N, respectively) and Diphotérine™ significantly (p < 0.05) enhanced both dermal absorption (%CD₂₄; Figure 1) and Jₘₐₓ (Figure 2), whereas MMFW and FloraFree™ solution significantly (p < 0.05) enhanced Jₘₐₓ only (no significant effect on %CD₂₄).

No significant effects on Tₘₐₓ (time at which maximum rate of penetration (Jₘₐₓ) was achieved) were observed for any of the products (Figure 2).

In terms of recovery of 14C-MS, a wide range (10–80%) of applied dose was sequestered by the decontamination products. The majority of products were not significantly different to FE in terms of dose recovery. However, FloraFree™, D-TAM™ and Diphotérine™ were significantly (p < 0.05) less effective (Table 1).

All of the polymers (UA, MA and IA) and both baby wipe formulations (BW-S, BW-N) significantly reduced the amount of 14C-MS on the skin surface in comparison with respective controls (Table 1; p < 0.05). All the other test products had no significant effect on skin surface recovery. Five products (FE, FA, IA, TFMAA and MBA) significantly reduced the amount of 14C-MS retained within the skin at 24 h (Table 1; p < 0.05).

All experiments resulted in a significant correlation between maximum rate of penetration (Jₘₐₓ) and percentage of control dose at 3 h (%CD₃), r = 0.9750, 0.9658 and 0.9887 for experiments 1, 2 and 3, respectively (Figure 3; p < 0.05).

When expressed as %CD at 3 versus 24 h, the baby-wipe formulations (normal & sensitive), Diphotérine™ and 5% FloraFree™ enhanced both the rate and amount penetrated (Figure 4; Quadrant D). Interestingly, MMFW led to an increased rate, but did not result in higher amounts of 14C-MS penetrating over 24 h (Figure 4; Quadrant C). No products enhanced the extent of penetration and decreased the rate of 14C-MS absorption (Figure 4; Quadrant B). Of the products which decreased both the rate and extent of 14C-MS absorption, IA, MBA, FE, TFMAA and FA reduced both %CD₃ and %CD₂₄ by 95 and 88%, respectively. In contrast, D-TAM™, KBDO-L, KBDO-S, MA and UA did not perform as well, with the reduction in %CD₃ and %CD₂₄ being ~70% for either parameter. Products delineated by the ring (IA, TFMAA, MA, FE and FA; Figure 4) were the top five efficacious products.

**Discussion**

This study has successfully identified a number of effective decontamination products that may have potential for use at the scene of a chemical incident. The effectiveness of decontaminants was measured in vitro using a static diffusion
cell system with (previously frozen) skin exposed to radiolabelled contaminants. Whilst this model is considered to be appropriate and validated for the assessment of skin absorption, the corresponding data need to be interpreted with some caution due to several experimental drawbacks of the model. The skin used in these studies was obtained from the dorsal aspect of pigs whereas human skin is the skin of choice for assessing dermal absorption. Due to cost and availability, it was necessary to use a viable alternative. Several animal models have been evaluated as to their suitability as a surrogate for human skin. Pig skin has been shown to have similar histological and morphological properties to human skin and is generally more akin to human in terms of permeability to xenobiotics. Skin was excised from the dorsal aspect in comparison to porcine ear, the latter being generally more comparable with human skin.

Figure 1. Cumulative amount of $^{14}$C-radiolabelled MS penetrating untreated (control) or decontaminated pig skin over a 24 h period. Ten microlitres of $^{14}$C-MS (2 µCi total per cell) was applied to the skin surface. Skin surface decontamination was conducted 5 min post-exposure using FE, MMFW, KBDO sponge, KBDO liquid and 5% FloraFree detergent solution (A), D-TAM skin cleanser, baby wipe sensitive (-S), Diphoterine, baby wipe normal (-N), FA, IA, TFMAA, MBA, UA and MA (C) Asterisk (*) indicates significant ($p < 0.05$) reductions in amount penetrated at 24 h compared to control. All data are mean ± standard deviation of up to $n = 6$ diffusion cells. Porcine skin was obtained from the dorsum of one animal.
To reduce animal numbers in accordance with the 3Rs\textsuperscript{23}, the back provided the greatest surface area for dermatoming skin for up to 36 diffusion cells. Additionally, skin from one region of the animal may reduce inter-individual variability in percutaneous permeability\textsuperscript{24,25}, thus allowing statistical differences to be confidently attributed to treatment effects. The practice of using previously frozen skin for \textit{in vitro} dermal absorption studies has not been shown to significantly affect penetration\textsuperscript{26}. The use of radiolabelled chemicals in this study also has inherent limitations, as LSC cannot distinguish between the parent molecule and its metabolites or hydrolysis products. The choice of receptor media will also influence the extent of percutaneous absorption of chemical warfare agents and simulants\textsuperscript{27}. In this study, aqueous ethanol (50:50) was chosen to aid partitioning of MS, a lipophilic compound\textsuperscript{28,29}.

Figure 2. Flux profile of $^{14}$C-radiolabelled MS penetrating untreated (control) or decontaminated pig skin over a 24 h period. Ten microliters of $^{14}$C-MS (2 $\mu$Ci total per cell) was applied to the skin surface. Skin surface decontamination was conducted 5 min post-exposure using FE, MMFW, KBDO sponge, KBDO liquid and 5% FloraFree\textsuperscript{TM} detergent solution (A), D-TAM\textsuperscript{TM} skin cleanser, baby wipe sensitive (-S), Diphoterine\textsuperscript{TM}, baby wipe normal (-N), FE, IA, TFMAA, MBA, UA and MA. (C) Asterisk, ampersand and hash (*, & and #) indicate significant ($p<0.05$) reductions and enhancements in $J_{max}$ compared to control, respectively. All data are mean ± standard deviation of up to $n=6$ diffusion cells. Porcine skin was obtained from the dorsum of one animal.

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(aq) in terms of potential ability to increase skin permeability, it could be argued that an overestimate of dermal absorption (if present) would result in a conservative assessment of decontamination and thus provide a more rigorous assessment of test products. This model also lacks physiological relevance with regard to metabolic processes, systemic clearance and toxicological end-points (non-viable skin). Diffusion cell studies are also susceptible to inter and intra-laboratory variations. Despite these drawbacks, in vitro diffusion cells are a useful tool and have historically been used for the assessment of percutaneous absorption. This model has also been used for similar work assessing product efficacy for decontamination. Thus, overall, the system is well-characterised and so the following interpretations appear to be justified.

It is worth emphasising that skin decontaminants are not intended to remain on the skin surface for such long durations (24h). The rationale for this was to evaluate contaminant leaching from the products over time. This was quantified by monitoring the increasing cumulative penetration over time compared to total amount recovered in the decontaminant. It can therefore be deduced that unrecovered contaminant was lost via off-gassing (volatilisation) from the product. This off-gassing highlights the inability of the product to fully sequester the contaminant and highlights a potential inhalation exposure. Therefore, this approach provided a conservative evaluation of product efficacy.

The decontamination products were applied to the skin surface 5 min post-exposure. This may be deemed a very rapid and unrealistic response for civilian purposes. However, the purpose of this study was to identify an effective product. Application of the product 5 min post-exposure provided an increased challenge with respect to amount of contaminant available for decontaminating. Further work is required to assess delayed decontamination with the effective products.

Initial screening of decontamination products demonstrated that a number of products were effective when applied to the skin 5 min post-exposure. Notably, all of the polymeric formulations (IA, TFMAA and MBA) tested were highly effective. The benchmark decontaminant (FE; a fine powder of natural aluminium silicate clay containing an abundance of minerals) removed 83% of 14C-MS which compares favourably to the 91% achieved against sulphur mustard on pig ear skin. From the total of 15 test products, five products (MMFW, 5% FloraFree solution, baby-wipe normal, baby-wipe sensitive and DiphotérineTM) enhanced the rate and amount of penetration, thus justifying their elimination from further testing. It is conceivable that water based products (i.e. FloraFreeTM and DiphotérineTM) may have enhanced dermal absorption due to the "wash-in effect". Additionally, the baby-wipes may have enhanced penetration due to the presence of solvents and or detergents in these wipes as they may have disrupted the lipid structure of the stratum corneum and therefore resulted in enhanced penetration.

Of the remaining 10 effective products, five (UA, MA, DTAMTM and the sponge and liquid KBDO formulations) were discounted as they were generally not as effective as FE, FA, IA, TFMAA and MBA (Figure 4). Furthermore, DTAMTM was excluded on the basis of the manufacturer’s instructions which contraindicate application onto wet skin: a practical point which would clearly limit its use.

It is perhaps worth emphasising that the sponge and liquid KBDO formulations were specifically designed to decontaminate chemical warfare agents (not MS) and were not used in accordance with the manufacturer’s instructions (being left on the skin rather than immediately removed after application).

Table 1. Dose distribution on the percentage of dose applied of 14C-radiolabelled MS penetrating untreated (control) or decontaminated pig skin over a 24 h period.

| Experiment | Treatment | Skin | Skin surface | Decontaminant | Receptor fluid |
|------------|-----------|------|-------------|--------------|---------------|
| 1 Control  | FE        | 9.2 ± 1.8 0.9 ± 0.5 NA 3.1 ± 1.2 |
| MMFW      | 2.1 ± 3.9 0.1 ± 0.1 83.0 ± 10.9 0.1 ± 0.2 |
| KBDO sponges | 4.4 ± 5.3 1.7 ± 2.0 36.8 ± 43.3 0.3 ± 0.3 |
| 5% Flora-free | 4.1 ± 2.8 4.6 ± 1.1 18.9 ± 23.0 0.4 ± 0.2 |
| 2 Control  | DTAM      | 8.0 ± 3.9 3.7 ± 1.4 NA 2.5 ± 1.2 |
| FA         | Baby wipe | 19.6 ± 3.3 0.5 ± 2 19.5 ± 6 1.0 ± 5.5 |
| IA         | 12.0 ± 7.3 1.0 ± 0.4 2.2 ± 2.5 6.2 ± 3.4 |
| Baby wipe sensitive | 17.7 ± 7.3 0.7 ± 0.2 49.5 ± 15.1 0.0 ± 0.0 |
| 3 Control  | IA        | 16.3 ± 7.7 3.9 ± 2.0 NA 4.3 ± 0.4 |
| TFMAA     | 0.1 ± 0.0 0.2 ± 0.1 71.0 ± 28.3 0.1 ± 0.1 |
| MBA       | 0.5 ± 0.9 0.2 ± 0.1 98.5 ± 40.6 0.2 ± 0.3 |
| MA        | 1.0 ± 1.4 0.3 ± 0.2 77.6 ± 43.5 0.2 ± 0.4 |
|           | 1.9 ± 1.6 0.5 ± 0.3 79.4 ± 6.9 0.5 ± 0.4 |

Skin surface decontamination was conducted five minutes post-exposure using baby wipe normal, baby wipe sensitive, DiphotérineTM, FloraFreeTM detergent, MMFW, DTAMTM, KBDO liquid, KBDO sponge, MA, UA, MBA, FA, TFMAA, FE and IA. All data are mean ± standard deviation of up to n = 6 diffusion cells. Porcine skin was obtained from the dorsum of one animal.

aSignificant reductions (p < 0.05) in the amount of 14C-MS remaining within the skin at 24 h compared to controls (untreated) skin.

bSignificant (p < 0.05) reductions on amount remaining on skin surface against respective controls.

cRecovery of 14C-MS from decontaminant was significantly different (p < 0.05) to FE.
A lack of broad spectrum effectiveness is considered a disadvantage. However, the main constituent of KBDO liquid is polyethylene glycol, the primary function of which is to solubilise contaminants within the lotion. Indeed, PEG may contribute to the generic effectiveness of such decontamination products through preferential partitioning of contaminants.

A strong correlation between %CD3 and $J_{\text{max}}$ was obtained (Figure 3), indicating that %CD3 is a good surrogate for measuring skin absorption kinetics. The use of %CD3 in future studies could provide practical benefit in reducing the frequency of receptor chamber samples required to characterise the performance of a decontamination product. More importantly, %CD3 eliminates the inherent variation in skin permeability between different skin samples. Normalising the $J_{\text{max}}$ values (using %CD3) allows the performance of all products to be directly compared regardless of the experiment-specific differences in skin permeability.

Further work is required to fully evaluate the five most effective products, consisting of one military product (FE), one commercial off the shelf product (Fast Act/C213) and three novel polymers (IA, MBA and TFMAA) against chemical warfare agents: sulphur mustard (HD), soman (GD) and VX. Furthermore, evaluation of delayed administration (30–360 min post-exposure) of the products is required to assess decontamination efficacy.

**Declaration of interest**

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

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