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'VIOLET': a fluorescence-based simulation exercise for training healthcare workers in the use of personal protective equipment

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SUMMARY

Background: Healthcare workers caring for patients with high-consequence infectious diseases (HCIDs) require protection from pathogen exposure, for example by wearing personal protective equipment (PPE). Protection is acquired through the inherent safety of the PPE components, but also their safe and correct use, supported by adequate training and user familiarity. However, the evidence base for HCID PPE ensembles and any associated training is lacking, with subsequent variation between healthcare providers.
Aim: To develop an evidence-based assessment and training tool for evaluating PPE ensembles and doffing protocols, in the assessment of patients with suspected HCIDs.
Methods: VIOLET (Visualising Infection with Optimised Light for Education and Training) comprises a healthcare mannequin adapted to deliver simulated bodily fluids containing UV-fluorescent tracers. On demand and remotely operated, the mannequin projectile vomits (blue), coughs (red), has diarrhoea (yellow) and is covered in sweat (orange). Wearing PPE, healthcare staff participate in an HCID risk assessment and examination of the 'patient', thereby becoming exposed to these bodily fluids. Contamination of PPE is visualized and body-mapped under UV light before and after removal. Observational findings and participant feedback, around its use as a training exercise, is also recorded.
Findings: Significant contamination from different exposure events was seen, enabling evaluation of PPE and doffing procedures used. Observational data and participant feedback demonstrated its strengths and success as a training technique.
Conclusion: Simulation exercises using VIOLET provide evidence-based assessment of PPE ensembles, and are a valuable resource for training of healthcare staff in wearing and safe doffing of PPE.

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Introduction

Selection and training in the use of personal protective equipment (PPE) plays a vital role in outbreak and pandemic planning. In recent years outbreaks of high-consequence infectious diseases (HCIDs) have repeatedly highlighted the need for PPE training and adherence to doffing protocols, rather than just a reliance on safety of the PPE components; failures have resulted in high rates of infected healthcare workers and have forced health providers to review their preparedness [1—3].

During the West Africa Ebola virus disease (EVD) outbreak, UK healthcare providers adopted PPE to suit the equipment and facilities available, resulting in country-wide variations [4]. Training and competency assessment were the responsibility of the healthcare provider to deliver and maintain, although without national guidance on methodology. Moving forward, the ideal would be to have a unified PPE ensemble and doffing protocol for use by all acute healthcare providers in the UK, accompanied by a training package. This would simplify staff training, allowing standards and competency in PPE use to be set and nationalized, and is in line with the objectives of NHS England's HCID programme [5].

Removal of PPE is a complex procedure, with studies showing that there are high rates of doffing errors even with basic PPE, and that self-perceived proficiency correlates poorly with correct use [6—10]. However, contamination is more likely to occur when incorrect technique is noted [11,12]. Ensuring safe practices for high-risk, high-potential exposure scenarios, to minimize risks of contamination therefore requires the user to be well trained and with proven competence, as well as using safe PPE components.

Immersive simulation, where the user engages in an exercise recreated from the real world, can be used to address the human, system and technical elements of PPE [13]. Integral to healthcare education, simulation training ensures familiarity prior to patient care, providing a safe environment for 'deliberate practice' of procedural skills, communication and teamwork, and management of medical emergencies [14]. An example of simulation that has expanded greatly in recent years is the use of ultraviolet (UV) fluorescence markers, well established as a means of assessing compliance with hand hygiene, but also for assessing contamination of the environment and equipment [15—22]. Their value in assessing PPE and user competence, especially for HCID pathogens, is increasingly recognized, with visualization of cross-contamination providing strong and instant feedback to users. However, these studies have low numbers of participants. The lack of clear evidence for PPE components and training methods required for their correct use and doffing was concluded in a Cochrane review, which called for higher-powered studies to address both issues [23].

The success of simulation-based training for PPE use was demonstrated by the UK Army Medical Services Training Centre's pre-deployment programme for staff working in the West Africa EVD outbreak. A large number of personnel underwent assessment of 'field PPE' competency, providing them reassurance and allowing high-risk sections of the doffing process to be identified [24]. However, as the model focused on EVD it did not include airborne transmission.

The Health and Safety Executive (HSE) research laboratory collaborated with Sheffield Teaching Hospitals NHS Foundation Trust (STH) with the aim of providing an evidence-based PPE assessment and training tool for UK healthcare workers. The design, similar to that used by the Army, was to be standardized, reproducible, transferable and applicable to units assessing patients with any suspected HCID. The objectives were:

- to develop a practical simulation tool where volunteer staff would perform a first assessment exercise of such patients;
- to simulate exposure to bodily fluids and assess the level of contamination on to PPE, to determine whether cross-contamination occurred during established doffing procedures.

The ultimate aim was to unify staff training across the UK by delivering a training package and providing a standard of good practice for all those trained in PPE.

Methods

'VIOLET' (Visualising Infection with Optimised Light for Education and Training)

VIOLET was built around a female healthcare training mannequin (multifunctional nursing skills mannequin; Quirumed, Valencia, Spain), adapted to show symptoms consistent with HCIDs. The bodily fluids selected were vomit and diarrhoea, being well-described symptoms of viral haemorrhagic fever (VHF), and sweat, suggested as a non-visible and possibly under-considered source of VHF exposure [25]. Cough was also added to mimic respiratory infection, thereby building a comprehensive training tool to assess pathogens via multiple transmission routes. The simulated bodily fluids and their delivery methods were developed as below and incorporated into the mannequin.

Bodily fluid simulants

A qualitative fluorochrome-based design was selected to represent the pathogens (fluorescence present or absent, but not quantified), with multiple colours used to identify the source of contamination events. A range of commercially available UV markers was evaluated; those selected were ideally transparent or colourless under normal lighting conditions, but clearly visible under UV light with a range of distinguishable colours. The strength of fluorescence, effect of combining with other fluids, and compatibility with PPE material and colours were taken into consideration. The intention was to create a reasonable representation of the bodily fluids in terms of method of transfer and quantity of contamination for the purposes of the scenario, with the simulant fluids and delivery mechanisms designed as follows:

- Vomit: This was created using the mechanism from 'Vomiting Larry', a pneumatic system designed to simulate projectile vomiting in norovirus infection (Figure 1a) [17]. A blue UV tracer (Tinopal CBS-X) was incorporated into water, in this case with a volume of 800 mL to reflect estimated maximal human vomit [26]. The liquid chamber and piston-driven delivery mechanism from 'Larry' was connected into the mannequin via a pipe through the back of the head to her mouth (Figure 2a); this allowed her to vomit when the piston was triggered remotely.

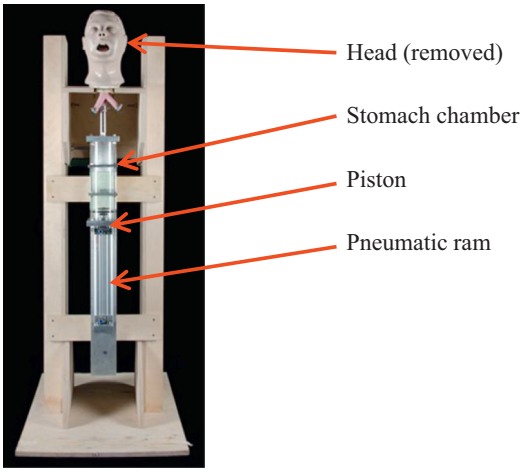


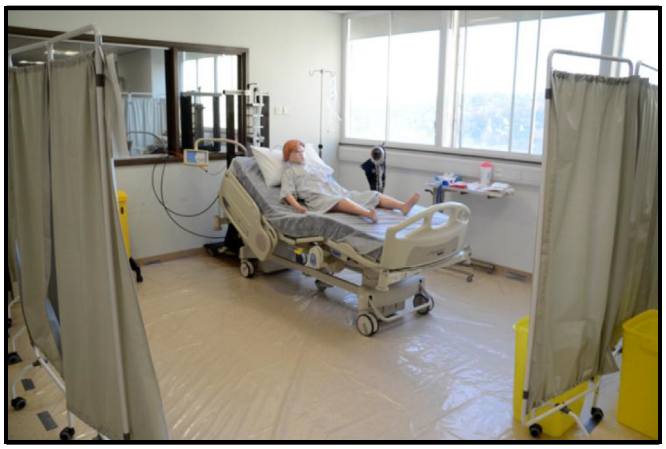
Figure 1. 'Vomiting Larry' mechanism adapted for use in VIOLET (visualizing infection with optimized light for education and training).

- Diarrhoea: A flour-, water- and salt-based mixture was used to mimic type 7 on the 'Bristol stool scale', to which a yellow UV tracer (UV Gear Ltd, Reigate, UK) was added [27]. A representative volume was placed in the mannequin's underwear and incontinence pad before each simulation exercise started.
- Sweat: Glycerol was considered a suitable simulant for sweat, mixed with an orange UV tracer (UV Gear Ltd) and manually applied to the skin of the mannequin immediately before starting each exercise. Although the viscosity differs from that of human sweat, it was acceptable for the purpose of this exercise, staying in place after application without 'pooling' or dripping off, yet transferring well on contact as determined by prior testing.
- Cough: Both aerosol and droplet spread of particles are potential routes of respiratory infection transmission such as Middle East respiratory syndrome and severe acute respiratory syndrome (SARS) coronavirus, and so the aim was to replicate both [3]. Advice was sought from an aerosol physicist about cough velocity, droplet/aerosol mix and spread, concluding that a commercially available artist's airbrush delivered an acceptable simulation, and could be adapted to fit into the mannequin's lower jaw (Figure 2b). A similar approach has previously been used to mimic a cough/sneeze in respiratory protection challenge studies using a breathing mannequin [28]. The airbrush reservoir was filled with an aqueous solution of a red UV tracer (UV Gear Limited) and activated remotely to spray into the zone the healthcare worker would enter during the patient care scenario.

Experimental set-up

The scenario was set up in the simulation suite of the STH Medical Education Centre. This comprises a large training room and offset 'scrub room' with washing facilities. An adjacent control room with one-way vision window allowed observation of the main room, with an intercom system facilitating two-way communication; this permitted dialogue between participants and the 'patient', voiced by the project team. A

(a)



(b)

Figure 2. (a) Sheffield Teaching Hospitals simulation suite set up for scenario. Mannequin connected to vomiting and cough mechanisms and scenario overseen from control room (other side of mirrored window). (b) Mannequin showing two delivery nozzles for simulated vomit and cough delivery in centre of mouth, and face coated in simulated sweat (also on rest of body).

single-bed isolation ward environment was set up, supplied with necessary medical equipment, supplies such as replacement gloves, and waste disposal. The mannequin was placed on a standard UK hospital bed with the vomiting system connected behind (Figure 2a, b). A demarcated 'doffing area' was situated away from the 'isolation ward' zone to ensure that PPE removal could be done in a non-contaminated environment. Cameras were positioned at multiple angles to record activities, with screens in the control room to view in real-time.

UV lighting system

The Fluorescence Interactive Video Exposure System (FIVES) developed by HSE was used [29]. This comprises a dodecahedral frame with 18 W UV-A strip lights covered by 3 mm UVA-pass filters to reduce UV-B and blue light transmission. The frame can accommodate a standing person for qualitative analysis of fluorescence on their outer clothing or skin. FIVES was set up in the simulation suite inside a tent lined with black plastic sheeting, providing the required 'black out' environment to visualize fluorescence (Figure 3). A camera

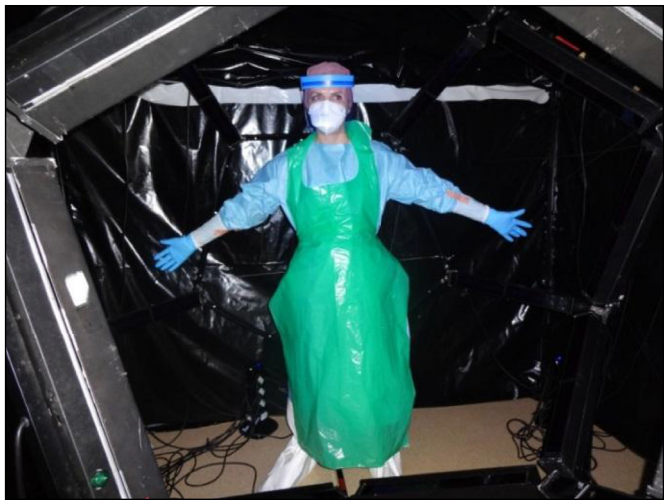


Figure 3. Portable Fluorescence Interactive Video Exposure System (FIVES) unit in blacked-out tent. Additionally used were black plastic sheeting on floor and drip trays for participants to stand on, with tent flaps closed to exclude light.

synchronized with a UV-A studio flash-lamp was set up within the tent to capture images pre- and post-simulation and post-PPE doffing. A hand-held UV torch (Nightsearcher Ltd, Portsmouth, UK) was used for closer inspection.

Participants and volunteer exercises

All substances used in the exercises were low hazard, but the project received ethics approval from HSE Ethics Sub-Committee, overseen by the University of Sheffield Medical School Research Ethics Committee. Volunteers were mostly healthcare staff from Sheffield Infectious Diseases unit but also from the HCID working group centres (London Royal Free Hospital, Newcastle, Liverpool and Glasgow, UK). Volunteers had to demonstrate competency in PPE to a staff trainer prior to the simulation. Descriptions of the PPE used can be found in separate work by Hall *et al*. [30].

After donning PPE, a doctor and nurse pair participated in a scenario based on clinical assessment of the mannequin 'patient'. The nurse took observations including tympanic temperature and blood pressure using a manual sphygmomanometer. They positioned the patient for examination by the doctor, connected a bag of fluid to the cannula, and assisted with changing the patient's underwear and incontinence pad after an episode of diarrhoea. The doctor took a brief medical history to ascertain potential pathogen risk and current symptoms, followed by a medical examination comprising neck palpation for lymphadenopathy, auscultation of the chest and palpation of the abdomen. The doctor also assisted the nurse with patient care and placed an intravenous cannula into the antecubital fossa. Volunteers were encouraged to interact with the patient for the purpose of the exercise; if necessary the 'patient' would ask questions, for example, asking the volunteers to explain what they were doing or a possible diagnosis.

At various times during the examination the volunteers were exposed to cough, operated remotely from the control room. Contact with sweat and diarrhoea occurred while examining and cleaning/changing the patient. Towards the end of the scenario, the doctor and nurse were exposed to a vomiting episode operated remotely, after which they changed the patient's gown as their last task. To ensure that all participants performed the same tasks, staff from the control room would use the intercom to remind them about outstanding activities.

Screening process

On completing the exercise staff entered the FIVES unit for fluorochrome visualization. A body map consisting of the front and back orientation of a person, divided into 35 sections, was used to record the location and type of contamination and was supported by UV photography. Volunteers exited the unit and doffed their PPE observed by a staff trainer, after which screening was repeated to detect any cross-contamination. A one-way path with staggering of volunteers was created to ensure that they could not re-expose themselves to environmental contaminants. The whole exercise was video-recorded so that any cross-contamination could be matched to a visual record.

A previously identified problem with fluorescence-based tracers is persistence of residues on inert surfaces or on exposed persons [24]. Three of the tracers could be easily removed using water, without residue. Whereas the vomit's Tinopal tracer could be removed from surfaces, it was more persistent on skin, remaining UV-visible for up to 24 h. To overcome this, participants were only used for one simulation per day, and were also screened for pre-existing fluorescence prior to each exercise. Between simulations the mannequin, bed area and reusable medical equipment were cleaned, then screened by UV torch to ensure that no residual environmental contamination was present.

Observational data and participant feedback

Each exercise was observed real-time by the project team. A checklist was used to ensure that all components were performed, and for recording any deviations or difficulties in donning or doffing of PPE or the simulation itself.

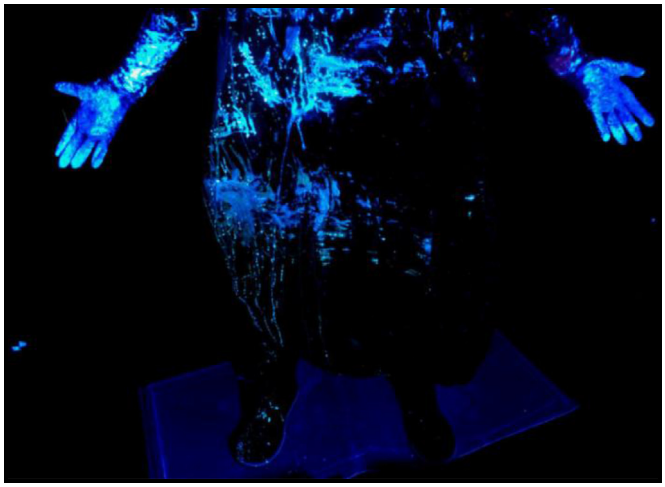
Volunteer feedback was gathered from discussions both during and immediately after the exercise. These focused on the usefulness of VIOLET as a training tool, and potential mechanisms of cross-contamination.

Results

In total, 19 VIOLET exercises were performed during the time available. After completing the scenarios, every volunteer had significant contamination on the outer surfaces of their PPE ensembles. Examples are shown in Figure 4, with 4a showing heavy vomit contamination (blue fluorescence) and 4b showing all four body fluids — vomit, sweat (orange), cough (red) and diarrhoea (yellow). The cough mechanism failed on one occasion, but, once resolved, the exercise was run repeatedly and reproducibly. Some post-doffing contamination events were observed, with mechanisms identified by retrospective review of video footage. Full results of the contamination events and PPE analysis are presented and examined further in separate work by Hall *et al*. [30].

Although not a research objective, environmental screening revealed the medical equipment, e.g. stethoscope and

(a)



(b)

Figure 4. (a) Exposed volunteer showing UV fluorescence from simulated vomit, implying heavy contamination. (b) Exposed volunteer showing UV fluorescence from simulated vomit, sweat, cough and diarrhoea.

thermometer, to be heavily contaminated after use. Of interest, yellow UV tracer (diarrhoea) was found on the back of the mannequin's head, and on the inside of a box of supposedly clean gloves in the patient's room.

Participants successfully completed the different components of the exercise, asking relevant questions and performing all required procedural tasks with only occasional prompting.

Volunteer feedback was positive, with participants stating that it was useful to practise in an unfamiliar and complex, but safe, environment. Many were surprised by the volume and distribution of contamination in the environment and on their PPE immediately after patient care, despite being aware of the occurrence of high-volume exposure episodes, such as projectile vomit, during the scenario.

Discussion

Exercises based around the use of VIOLET and UV fluorochromes in simulated body fluid exposure can provide a standardized method for testing PPE ensembles, and have also been a valuable resource for future training of healthcare staff in PPE donning, use, and safe doffing in the UK.

Previous work has demonstrated that incorrect technique, lack of training and unfamiliarity with the PPE components have contributed to some contamination events [11,12]. Encouragingly, training programmes, especially enhanced or maintained, have been shown to reduce rates of cross-contamination in several studies [11,12,20,31–33]. Furthermore, training in a safe environment can identify staff with particular issues such as claustrophobia or overheating, as well as potential systematic errors and environmental problems such as optimal placement of disposal bins and zone demarcation [34,35]. Despite the clear need for optimized training programmes, methods have been unclear to date [23].

The value of UV visible markers has been highlighted from previous studies of both simulated and real-life doffing [9,11,36,37]. However, most used only one exposure event, or used multiple events but only one fluorochrome-limiting analysis of contamination source, or contaminants were applied directly on to PPE rather than exposure through simulated exercise [6,22,33,38,39]. When multiple transmission routes have been simulated using mannequins or even 'human volunteer' patients, they used single-fluorochrome methods and, because the focus was on EVD, omitted respiratory transmission [24]. Using a clinical scenario with a combination of identifiable transmission routes enabled better simulation of pathogen transmission dynamics during patient interaction, allowed robust assessment of contamination events, and provided a comprehensive tool for a wider range of pathogens.

Incorporating multiple UV markers powerfully demonstrated to volunteers the significant amount and wide distribution of contamination that can occur through various routes. Instant visual feedback facilitated real-time discussion about contamination routes and reinforced the need for controlled doffing, avoiding excessive movements such as kicking boots or shaking gowns. Filming each exercise allowed the footage to be reviewed retrospectively to identify mechanisms of contamination events, providing vital information to enable PPE evaluation, as discussed further in separate work by Hall *et al.* [30].

The ability of UV markers to mimic viral load, or dynamics such as effect of disinfection, has previously been challenged, with a preference for non-pathogenic viral surrogates [6,39]. However, their use is technically more complex and lacks instant visual results. For example, using UV markers facilitated timely, simple and comprehensive screening of equipment, identifying unexpected cross-contamination such as glove boxes. This would not have been possible in near-real-time with a viral surrogate. Reassuringly, work using both methods showed no difference in rates of contamination events on healthcare workers, suggesting that both are suitable for PPE assessment. Furthermore, in the absence of minimum infecting dose of HCID pathogens through cross-contamination, presence or absence of contamination is the valid basis of safety assessment [6,20,38]. Using qualitative fluorescent markers therefore provides an evidence base for real-time training.

Compared to using an actor as a 'patient' as in other studies, using the VIOLET mannequin made it possible to standardize each bodily fluid exposure [9,24]. Despite concerns that using a mannequin adds an artificial element, volunteers engaged with the scenario, and were observed to perform human interactions such as holding her hand or rubbing her back after she coughed. As some volunteers were used more than once, the travel and exposure histories were changed between days to try and overcome volunteer fatigue.

Although VIOLET was designed to simulate assessment of patients with suspected HCID, in reality, early presentation of such patients to health services would make the 'wet' phase of EVD, characterized by large volume diarrhoea and vomiting, unlikely [25]. However, participants found it useful to experience 'worst-case scenario' training, raising awareness of potential challenges around a high-risk setting, and allowing questions to be addressed ahead of real-life occurrence.

The current VIOLET is limited in portability and by delicate components, but this could be improved in future models. Despite this, its reproducibility and function as a training tool have been demonstrated, and it could be further developed. As the mannequin has veins for catheterization practice, it would be possible to add in a blood simulant incorporating a UV tracer. The feasibility of a venepuncture training package will be investigated in our next phase of work.

VIOLET could also be used for extended clinical scenarios and with other staff who might provide care for this type of patient. Other simulation studies have covered medical emergencies such as complications of EVD or cardiac arrest with SARS; they were effective in raising challenges and protocol failures in these highly stressful situations, allowing focused training ahead of potential real-life occurrence [35,40]. Whereas HCID training has often been targeted at staff in emergency departments and ID units, colleagues elsewhere, such as critical care, may also benefit from tailored exercises for their own scenarios and interventions, such as central line placement.

In conclusion, through combining multiple fluorochromes and simulated body fluids with a clinical examination exercise, VIOLET provided a novel and comprehensive training and assessment tool for PPE. The inclusion of respiratory transmission, alongside bodily fluid exposures of vomit, diarrhoea and sweat, enables adaptation for any recognized or emerging HCID pathogen. VIOLET has already provided an objective evidence-based assessment of HCID PPE in use, identifying various strengths and limitations, as discussed in Hall *et al.* [30].

User feedback demonstrated VIOLET's utility as a training opportunity, exposing participants to a high-risk scenario unfamiliar to most staff, but in a controlled and safe environment. Having now established it as a functioning training tool, it could be developed to provide further training opportunities, maximizing healthcare worker preparedness.

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Conflict of interest statement
None declared.

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