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Development and evaluation of a high-fidelity, multi-disciplinary simulation training course for high-consequence infectious diseases using fluorescence visualization

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Background: High-consequence infectious diseases (HCIDs) include contact-transmissible viral haemorrhagic fevers and airborne-transmissible infections such as Middle Eastern Respiratory Syndrome. Assessing suspected HCID cases requires specialized infection control measures including patient isolation, personal protective equipment (PPE), and decontamination. There is need for an accessible course for NHS staff to improve confidence and competence in using HCID PPE outside specialist HCID centres.
Aim: To produce and evaluate a training course for National Health Service (NHS) staff on recognition and assessment of patients with suspected HCID infection.
Methods: We developed a multi-disciplinary course blending online learning with in-person, high-fidelity simulation using a manikin which employs fluorescent tracers to simulate airborne, contact, and fomite transmission. This facilitates visualization of contamination pre- and post-PPE removal and supports team-based debrief of performance. Training culminated in competency-based assessment. Educational effectiveness was evaluated through curriculum-linked pre- and post-course tests, and self-rated confidence using Likert scales.
Findings: Between December 2022 and April 2024 180 nurses, specialty registrars and consultants were trained. Educational effectiveness was evaluated in 60 consecutive participants between December 2022 and April 2023. Pre- and post-course assessments revealed significant improvements in knowledge (mean score 61% vs 83%, $P<0.0001$). Pre-course, 36% of learners reported feeling confident in HCID PPE donning and doffing, rising

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to 97% post-course. Participants unanimously rated the learning experience as high- or very-high quality.
Conclusion: This course, incorporating ultraviolet markers for contamination visualization, represents a novel approach outside military settings. The results demonstrate its effectiveness as an educational intervention, improving staff confidence and competence in PPE use.

Introduction

High-consequence infectious diseases (HCIDs) are rare but dangerous diseases characterized by high case—fatality ratios and potential for human—human transmission. Examples of HCID include contact-transmissible viral haemorrhagic fevers such as Ebola virus disease (EVD) and Lassa fever, and airborne transmissible pathogens such as Middle Eastern respiratory syndrome.

In 2015, prompted by the EVD outbreak in West Africa, the National Health Service (NHS) England commissioned a new HCID programme to provide a national system of readiness, based around a network of hospitals offering specialist infection control facilities, and defined processes and protocols for managing suspected and confirmed HCID cases [1].

Patients are deemed at risk of having an HCID based on recent travel (within a defined period) to a geographical location known to be endemic for an infection or with a known outbreak [2]. Enhanced infection control precautions are required for safe patient care. While engineering and administrative procedures are preferred measures in the hierarchy of infection control, individual measures including personal protective equipment (PPE) and contamination reduction behaviours are often the only options [3]. For this reason, it is important to ensure that PPE is fully protective and used consistently at all hospitals treating HCID patients. Consequently, research was undertaken to develop a single unified HCID assessment PPE ensemble, supported by structured protocols for donning and doffing, and this was adopted across the network of HCID treatment centres and recommended for use across the wider NHS [4,5]. The PPE ensemble consists of respiratory protection (disposable filtering face piece respirators — FFP3); head protection; eye protection; fluid-resistant surgical gown; plastic apron; three layers of gloves; and wellington boots (Figure 1) [6].

Assessment and management of patients with suspected HCID infection is conducted by specialists in infectious diseases, emergency medicine and intensive care medicine. To support national roll out of the standard protocols for HCID assessment PPE and other enhanced infection control procedures, a need arose for an accessible, educationally effective training course to acquire theoretical understanding and practical competence. Due to infrequency of presentation and the complexity of infection control precautions required, regular training is necessary to maintain those skills.

Traditional paradigms for teaching skills in medicine have focused on enabling learners to understand theory through didactic teaching and demonstration followed by supervised deliberate practice [7]. However, when patient presentation is infrequent and as the potential risk associated with procedural error is high when managing HCID, simulation-based approaches grounded in deliberate practice are essential for delivering educationally effective HCID PPE training [8—10]. The use of ultraviolet (UV) fluorescent markers to visualize cross-contamination following PPE doffing allows formal validation of the effectiveness of the PPE ensemble against airborne and contact transmission routes [5]. Specific focus is placed on PPE donning and doffing, which is a complex procedural skill with technical, teamwork and communication elements [4]. This appears to result in superior adherence to infection control measures when compared with traditional training for infection prevention and control (IPC) and has previously been used for HCID training during the 2014—2016 EVD outbreak [11,12].

We developed a course which aimed to provide healthcare workers with the knowledge and skills to recognize, assess and provide initial management for patients with suspected HCID in the UK context, while maintaining personal safety from exposure to infectious agents. This paper describes the course and presents formal evaluation data.

Methods

Rationale for employing simulation training using UV fluorescent markers

Practical training exercises using UV fluorescent markers to simulate infectious contamination on PPE are widely used in healthcare [13,14]. Scenario-based training exercises exposing healthcare workers to simulated body fluids incorporating UV fluorescent markers proved highly effective in preparing Army Medical Corps staff prior to deployment to West Africa during the EVD outbreak [12]. The same principles were therefore subsequently adopted by the HCID network to simultaneously compare PPE ensembles and validate their protectiveness and usability [4,5]. Consequently, to extend competence across the HCID network this was considered to be the best method to develop practical IPC skills in situations that require the use of HCID PPE.

Course structure

Course content and curriculum were developed by a multidisciplinary group of content experts, informed by a survey of learners' knowledge and confidence of HCID PPE use. The curriculum is summarized in Table I. The course used a blended learning approach, including online learning and formative

Figure 1. Unified high-consequence infectious diseases assessment personal protective equipment ensemble recommended for use in the National Health Service.

simulation exercises, culminating in summative assessment of knowledge and practical skill.

Online learning

Six interactive online learning modules were used to introduce key theoretical concepts underpinning the recognition and care for patients with suspected HCID infection, including enhanced infection control measures, risk assessment, diagnostic testing, and clinical care. Learning modules are available at: www.hcid-training.co.uk.

Simulation training

The simulation training comprised four formative simulation scenarios, focusing on key skills of case recognition, risk assessment, diagnosis, enhanced infection control measures, including PPE, and referral pathways. The scenarios encouraged participants to apply theoretical concepts and refine practical skills including PPE donning and doffing, teamwork, communication, and contamination reduction behaviours. Scenarios included repeated cycles of formative assessment, with each exercise followed by a period of debrief to review strengths and challenges encountered in the scenario. Self, peer, and facilitator feedback were used, followed by a period of reflective action planning to reinforce learning [15,16].

Scenarios typically consisted of a clinical case where a team of learners were required firstly to perform a relevant HCID risk assessment based on a history and epidemiolocal features, and subsequently work as a team to undertake a clinical assessment whilst wearing HCID assessment PPE. Figure 2 shows a schematic layout of the simulation suite divided into three zones: green/clean zone for donning PPE prior to entering the red zone patient room/area; red zone containing the manikin/patient and all the equipment required; amber zone for doffing potentially contaminated PPE, and a UV tent to review the participants' contamination with fluorescent body fluid simulants.

UV contamination model

Based on previous work [4], a specialized manikin was used to simulate pathogen transmission by airborne and contact routes by excreting body fluid simulants with UV fluorochromes via coughing, diarrhoea, vomit and sweat. Each scenario focused on a different transmission route (contact, fomite, airborne). Through contact with the manikin and surrounding environment, participants became contaminated with fluorescent tracer.

Vomit, diarrhoea and cough aqueous-based simulants were delivered from reservoirs by manually operated pumps connected via hoses to the manikin. Vomit simulant used a blue fluorochrome (Tinopal CBS, Fluotechnic), diarrhoea a green fluorochrome (fluorescein, Sigma Aldrich), and cough a red fluorochrome (Luminochem). Sweat simulant (glycerol-based to aid adhesion) used a yellow fluorochrome (Invisible Yellow,

Table I
High-consequence infectious disease (HCID) assessment personal protective equipment (PPE) course curriculum

Learning objective	Teaching method	Assessment method
Curriculum aim: to produce appropriately skilled healthcare professionals who can safely and reliably recognize, assess and provide evidence-based care for patients with suspected high-consequence infectious disease (HCID)		
A. Definition and categorization of HCID in the UK		
A1: Define an HCID in the UK and recall the important HCIDs A2: Describe the specific modes of transmission of important contact and airborne HCIDs	Online module 1: HCID Introduction & simulation day	Post-course MCQ
B. Enhanced infection prevention and control measures for HCID		
B1. Apply the hierarchy of controls of infectious disease to the assessment of patients with suspected HCID infection (patient placement, protocols, PPE) B2. Describe the principles of waste management and room/surface decontamination for HCID B3. Describe the principles of environmental decontamination following transfer of an individual with a confirmed HCID B4. Apply methods of reducing personal risk when assessing a patient with suspected HCID, including contamination reduction behaviour, to clinical scenarios	Online module 2 & Simulation Day	Post-course MCQ
C. HCID assessment PPE		
C1. Describe the elements of the recommended HCID assessment PPE ensemble in relation to transmission reduction C2. Demonstrate safe HCID assessment PPE donning and doffing technique C3. Demonstrate competence as a doffing buddy C4. Apply the important aspects of staff welfare and communication methods when wearing HCID assessment PPE (personal management, communication with patient and colleagues)	Online module 2 & simulation day	Practical assessment
D. Clinical features of HCIDs		
D1. Demonstrate and apply knowledge of the epidemiology, transmission, clinical features, and diagnosis of the following HCIDs; MERS, Ebola, Lassa, CCHF, avian influenza, Mpox, to clinical cases to recognize where HCID infection should be considered D2. Be aware of less common designated HCIDs; know where to obtain information on their epidemiology, transmission, clinical features, and diagnosis	Online module 3: & simulation day	Post-course MCQ
E. HCID risk assessment and sampling of the important HCIDs		
E1. Demonstrate and apply knowledge of HCID risk assessment algorithms to clinical cases where HCID is in the differential	Online module 3 & simulation day	Post-course MCQ
E2. Describe where to find information on the sampling and transport requirements for laboratory diagnostics, and apply this to a clinical case	Online module 4 & simulation day	
F. Referral pathways for individuals where HCID is suspected or diagnosed		
F1. Apply understanding of the role of local and national bodies involved in HCID assessment including local services, imported fever service, UKHSA and NHS EPRR to clinical cases	Online module 1 & simulation day	Post-course MCQ

CCHF, Crimean-Congo haemorrhagic fever; MCQ, multiple-choice questionnaire; MERS, Middle Eastern respiratory syndrome; NHS EPRR, National Health Service emergency preparedness, resilience and response; UKHSA, United Kingdom Health Security Agency.

Chemox Pound) and was applied manually to the skin of the manikin and nearby touch surfaces (bed rail, furniture, telephone receiver).

At the end of each exercise the participants exited the red zone to a blackout tent equipped with UV lights (Titan LED, UV Light Technology, Birmingham, UK) and a mirror so that the participant could observe, and be debriefed, on the level of contamination on their PPE. The UV light source comprised two LED lights emitting UVA at 365 nm. Safety protocols based on the use of this lighting set-up included acceptance criteria for exposure time. These were calculated to be 4 h maximum within an 8-h period per day for unprotected skin and 40 min for unprotected eyes. Risk assessments undertaken during the development of the training course determined that each participant would spend less than 5 min in total under the light source, the majority of this while wearing PPE.

As each body fluid simulant was tagged with a different colour fluorescent tracer, when visualized under UV light the participant could see what body fluid type had contaminated their PPE, and how contamination may have arisen through

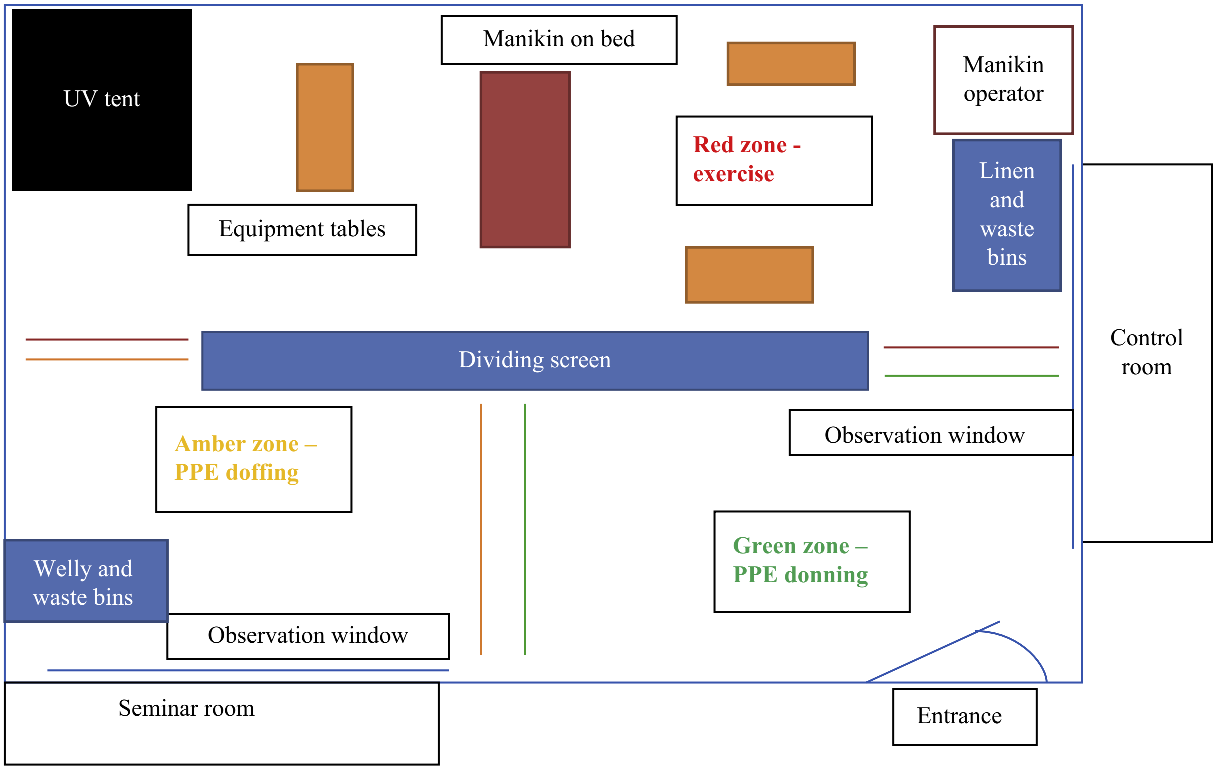

Figure 2. Schematic layout of simulation suite. UV, ultraviolet.

mode of transmission. For example, leaning against a contaminated bed rail could contaminate the lower part of the gown with sweat, while projectile vomiting could contaminate the upper apron area and gloves (both contact transmission), and cough could contaminate the visor and hood (airborne transmission). The debrief after visualizing contamination provided participants with the opportunity to learn contamination reduction behaviours.

The participant then entered the amber zone to be assisted to doff, supervised by a 'hands-off' buddy following the doffing protocol. The participant placed waste PPE into one bin before finally stepping out of their wellies into the green zone then reaching back to place the wellies in another bin. After doffing, participants returned to the UV tent to determine whether doffing was successful by assessing for residual fluorescent tracer on skin, hair or scrubs.

Summative assessment

Training culminated in curriculum-linked summative assessments to verify competence and provide additional learning opportunity [17]. Knowledge was assessed using a curriculum-linked single best-answer multiple-choice questionnaire. Pass marks were derived by content experts using Angoff Referencing [18]. Practical skill of HCID assessment PPE donning and doffing was assessed by a trained member of the faculty using a structured mark scheme. Participants were assessed against standardized national HCID assessment PPE donning and doffing protocols. This requires participants to complete all donning and doffing steps in the correct order with good technique to pass the practical assessment [6]. Participants were additionally required to demonstrate competence as a doffing buddy by displaying appropriate levels of situational awareness and communication.

Course evaluation

The impact of course attendance to date on practical skill was evaluated in two ways. Firstly, participants were asked to self-rate their confidence in HCID assessment PPE donning and doffing in anonymized pre- and post-course surveys using a Likert score (Figure 3). Participants were asked to complete pre-course surveys prior to accessing learning materials, whilst post-course surveys were sent electronically 24 h following course completion. Results were aggregated and change in

How confident are you in your ability to safely don and doff HCID assessment PPE?

☐ Very confident ☐ Confident ☐ Neutral ☐ Unconfident ☐ Very unconfident

Figure 3. Users rated their confidence in high-consequence infectious disease (HCID) personal protective equipment (PPE) donning and doffing before and after the course.

confidence described. Secondly, results of summative practical tests were described. Participants were additionally asked to rate the overall quality of their learning experience on the post-course questionnaire, summarized in Figure 3.

The impact of course attendance on knowledge of key curriculum items was evaluated by administering a curriculum-linked multiple-choice questionnaire before the course and a comparable curriculum-linked multiple-choice questionnaire after the course. The pre-course questionnaire is available in the Supplementary data S1. Data were collected as part of routine course evaluation and ethical approval was not sought.

Results

Figure 4 shows a typical training scenario. Clinical assessments and procedures were simulated, such as venepuncture and vital signs monitoring of the manikin, during which participants may have been exposed to body fluid simulants.

Figure 5 gives examples of participants observed under UV lighting following exposure to body fluid simulants during scenario training exercises. This clearly shows the difference in modes of transmission of contaminants between contact, mainly affecting the lower apron and gown but also sleeves and gloves, while airborne transmission showed contamination on the upper body and sleeves but also the visor and hood.

Between 1st December 2023 and 11th April 2024, 180 healthcare workers completed the course. During the evaluation period, 60 healthcare workers completed the course. This included 27 specialist registrars/consultants, 32 nurses and one physician associate. All participants in this early cohort worked in regional infectious disease units. Of those 60 participants, 53 provided data for the pre-course questionnaire and 35/60 provided data for the post-course questionnaire.

Prior to course attendance, 36% (20/53) of respondents reported being confident or very confident in safe HCID assessment PPE donning and doffing. This rose to 97% (34/35) in a post-course survey, with only one rating themselves as neutral, and none as unconfident or very unconfident. These data are summarized in Table II and detailed in Supplementary data S1.

There were significant improvements between pre- and post-course knowledge assessments, with a mean score of 63% pre-course compared with 81% post-course ($P<0.0001$), but also showing improvements across all grades. These data are summarized in Table III and detailed in Supplementary data S2.

All participants passed the post-course competency-based practical assessments, and 58/60 passed the knowledge assessment. Of the 180 who have now completed the course, visible evidence of cross-contamination was detected on only two occasions. One of these was attributable to a donning error and one to a known problem with removing an item of PPE. Participants unanimously rated the learning experience as high- or very-high quality in the post-course survey.

Figure 4. Clinical scenario exercise in progress with manikin.

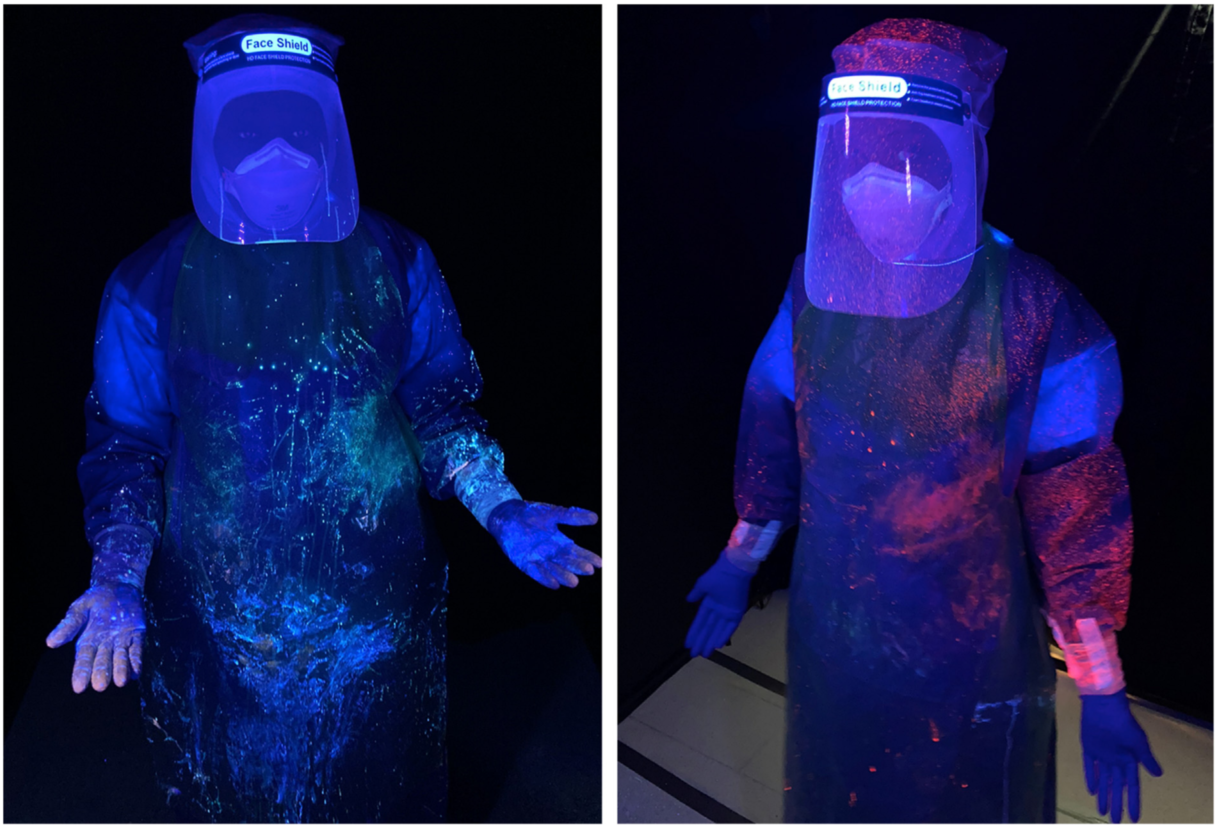

Figure 5. Body fluid simulant contamination on personal protective equipment post-exercise. Left: typical contact transmission (sweat, diarrhoea, vomit). Right: typical airborne transmission (cough).

Table II
Participant confidence in high-consequence infectious disease (HCID) assessment personal protective equipment (PPE) donning and doffing before and after attending the course

How confident are you in your ability to safely don and doff HCID assessment PPE?		
	Pre-course *N* (%)	Post-course *N* (%)
Very confident	1 (2)	17 (49)
Confident	19 (36)	17 (49)
Neutral	25 (47)	1 (3)
Unconfident	6 (11)	–
Very unconfident	2 (4)	–
Total	53 (100)	35 (100)

Discussion

High case fatality rates are associated with many HCIDs, placing healthcare workers at significant risk. Therefore, it is imperative that those clinically assessing and caring for HCID patients are able to do so fully protected from exposure to infectious particles. Key to this is training, and healthcare workers must be provided with the opportunity to be trained in using the PPE known to protect them. Such training must use robust, educationally effective approaches. HCID training grounded in simulation has been shown to be educationally effective with demonstrable improvements in confidence post-course compared with pre-course. Factors which may have resulted in improved confidence through participation in the

Table III
Participant confidence, all participants and by grade, in high-consequence infectious disease (HCID) assessment personal protective equipment (PPE) donning and doffing before and after attending the course

Grade	Number completing pre-course assessment	Post-course score performance (mean score)	Number completing post-course assessment	Post-course score performance (mean score)
All participants	53	63	52	81
Consultant or SpR	22	73	23	90
Band 5+ nurse	26	57	26	72
Other	5	56	3	82

SpR, speciality registrar.

course were not directly established. However, we would hypothesize that the combination of simulation with deliberate practice and direct visualization of contamination using an UV contamination model was important. The subsequent verification of successful doffing through instant feedback provides candidates with confidence that the PPE ensemble offers a high level of protection against likely worst-case events, such as patients with profuse gastrointestinal illness or substantial respiratory symptoms. The debrief session after completion of each scenario enabled practical participants, doffing buddies and observers to share experiences and observations to the mutual benefit of all. Use of structured practical and theoretical assessments then allowed for verification of competence following the course and led to provision of certification to successful participants.

Potential limitations to the success of the training could include lack of familiarization with the PPE ensemble and doffing procedure, but this was remedied by including a pre-course online learning module. Another limitation could be if the participants failed to engage with the simulation, such as by not treating the manikin as they would a live patient. Although levels of engagement differed, the end result of exposure to body fluid simulants was still achieved, thus providing the same doffing challenge. A further limitation was the number of participants upon which the impact analysis was based. Although only based on a subset of the total to date that have been trained, the feedback from later participants indicated a similar degree of positivity. This suggests the results can be extrapolated, and it is expected that future participants will also benefit from the confidence instilled by the training.

Whilst standardized, evidence-based PPE ensembles have been adopted by the network of HCID centres, suspected cases of HCID do not exclusively present to these centres. For example, in 2018, nosocomial transmission of Mpox to a healthcare worker occurred in a regional hospital before the patient was transferred to a HCID unit [19]. Consequently, in future there is a need for training and standardization to be expanded nationally. Also, given the procedural complexity of HCID assessment PPE doffing and limited opportunity to practise on a regular basis, we suggest that refresher training is likely to be required, possibly at six-monthly intervals. There is a need for longitudinal evaluation of competence to establish optimum timing for this.

In conclusion, training of healthcare workers in the correct use of PPE is enhanced by high-fidelity simulation training using a manikin designed to expose trainees to simulated body fluids incorporating UV fluorochromes. Visualizing fluorochrome contamination on their PPE provides instant feedback to participants on the level of contamination and their ability to safely remove that PPE without cross-contamination by following established doffing protocols. Participation in the course led to substantial improvements in confidence in the HCID assessment PPE.

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Author contributions

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Conflict of interest statement

There are no competing interests for any of the authors.

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Appendix A. Supplementary data

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