Infection Control & Hospital Epidemiology (2024), **45**, 1050–1056
doi:10.1017/ice.2024.84

SHEA

Original Article

A bacteriophage-based validation of a personal protective equipment doffing procedure to be used with high-consequence pathogens

Brandon A. Berryhill BS[1,2], Kylie B. Burke BS[1,3], Andrew P. Smith BA[1], Jill S. Morgan BSN[4], Jessica Tarabay MPH[4], Josia Mamora BSN[4], Jay B. Varkey MD[3,4], Joel M. Mumma PhD[3] and Colleen S. Kraft MD[3,4,5]

[1]Department of Biology, Emory University, Atlanta, GA, USA, [2]Program in Microbiology and Molecular Genetics (MMG), Graduate Division of Biological and Biomedical Sciences (GDBBS), Laney Graduate School, Emory University, Atlanta, GA, USA, [3]Division of Infectious Diseases, Department of Medicine, Emory University School of Medicine, Atlanta, GA, USA, [4]Emory Healthcare, Atlanta, GA, USA and [5]Department of Pathology and Laboratory Medicine, Emory University School of Medicine, Atlanta, GA, USA

Abstract

Objective: To determine if the high-level personal protective equipment used in the treatment of high-consequence infectious diseases is effective at stopping the spread of pathogens to healthcare personnel (HCP) while doffing.

Background: Personal protective equipment (PPE) is fundamental to the safety of HCPs. HCPs treating patients with high-consequence infectious diseases use several layers of PPE, forming complex protective ensembles. With high-containment PPE, step-by-step procedures are often used for donning and doffing to minimize contamination risk to the HCP, but these procedures are rarely empirically validated and instead rely on following infection prevention best practices.

Methods: A doffing protocol video for a high-containment PPE ensemble was evaluated to determine potential contamination pathways. These potential pathways were tested using fluorescence and genetically marked bacteriophages.

Results: The experiments revealed existing protocols permit contamination pathways allowing for transmission of bacteriophages to HCPs. Updates to the doffing protocols were generated based on the discovered contamination pathways. This updated doffing protocol eliminated the movement of viable bacteriophages from the outside of the PPE to the skin of the HCP.

Conclusions: Our results illustrate the need for quantitative, scientific investigations of infection prevention practices, such as doffing PPE.

(Received 28 November 2023; accepted 30 March 2024; electronically published 6 May 2024)

Introduction

To protect healthcare personnel (HCPs) caring for patients with communicable diseases, protocols have been established to mitigate the risk of transmission.[1] Central to these protocols is personal protective equipment (PPE). The PPE used to minimize exposure to high-consequence infectious diseases (HCIDs), such as Ebola virus disease, utilizes layers of barrier precautions including fluid-resistant coveralls, impervious aprons or gowns, fluid-resistant footwear, powered air-purifying respirators (PAPRs), and gloves. Protocols that outline proper donning and doffing of the PPE are fundamental to mitigating self-contamination for HCPs and preventing the transmission of contaminants outside patient rooms.[2] However, PPE protocols are often based on manufacturer recommendations of individual products and infection prevention best practices. Accordingly, ensembles of PPE and their corresponding protocols usually have not been empirically validated.

Previous studies have demonstrated that adherence to PPE doffing protocols is challenging and variable among HCPs[2]; previous studies have quantitatively examined and discovered high rates of deviations from established protocols.[3] Doffing protocols would optimally be safe even considering this high underlying variability. Moreover, rigorous risk assessments of PPE ensembles should consider this factor in evaluating PPE safety.

This study explores contamination risks of an established doffing protocol. To validate this protocol's efficacy, we applied a quantitative analysis of the PPE ensemble to test for self-contamination. This investigation consisted of two phases: (1) examination of the original PPE ensemble and its doffing

Corresponding author: Brandon A. Berryhill; Email: Brandon.Berryhill@emory.edu
Brandon A. Berryhill and Kylie B. Burke contributed equally to this work.

Cite this article: Berryhill BA, Burke KB, Smith AP, *et al.* A bacteriophage-based validation of a personal protective equipment doffing procedure to be used with high-consequence pathogens. *Infect Control Hosp Epidemiol* 2024. 45: 1050–1056, doi: 10.1017/ice.2024.84

protocol with fluorescence and bacteriophages; and (2) determination if an amended protocol decreased self-contamination.

This study highlights the need for infection prevention protocols, such as high-containment PPE doffing, to be evaluated in a quantitative, experimental fashion. We present results from both phases of our investigation below.

Methods

Investigational procedures

Movie analysis

Doffing protocols were captured on video. Each movie was analyzed by authors BAB, KBB, APS, and JSM who viewed and stopped the movie and recorded comments when potential hazards were observed.

For each doffing trial, footage was taken from four camera angles using camcorders (Canon, Japan, Model #HF R80) supplied by the Healthcare and Human Factors Lab at Emory. Comments were made for possible contamination during the Phase 1 phage trial and deviations from the protocol in the Phase 2 phage trial (Supplementary Table 1).

Fluorescent testing

To verify the contact we observed in the movie described above, we used a 0.5% fluorescein solution (Millipore Sigma, USA, Catalogue #F6377) and Glo Germ powder (Glo Germ, USA, #GGP10) to visualize contamination and identify the steps where spread of contaminant may occur. To conduct this test, a trained HCP donned a complete high-containment PPE ensemble and was then sprayed with the fluorescein solution. The solution was sprayed to coat surfaces of the PPE that may be exposed to contact with patients (patient-facing surfaces). The HCP then doffed according to the protocol. Pictures were taken from multiple angles to record how fluorescein transfer; ultraviolet flood lights (Onforu, China, #UFLAU004102) were used to emphasize fluorescence. A separate test was performed for aerosolization risk where the heavy-loading filter on top of the PAPR hood was laden with Glo Germ powder. After the filter was removed, pictures were taken with ultraviolet to capture results of the experiment.

Phage testing

Using a previously validated procedure,[4] we sprayed with small spray bottles (Bürkle, Germany, #10216-888) with high densities (approximately 10^8 phages per mL) of three genetically distinct λ phages on HCP volunteers to reflect densities of pathogens found in patient samples (Supplementary Table 2). 2 mL of λ phages were sprayed onto three locations, and each site was sprayed with a different variant of λ: one marked with a kanamycin resistance gene was sprayed on the wrists; one marked with a chloramphenicol resistance gene was sprayed on the back of the hood; and one lacking an antibiotic marker at the critical triangle, described below. HCPs then doffed, after which their hands, forearms, and PAPR were swabbed and scrubs were collected and tested for bacteriophage presence and identification.

Materials and technical methods

Strains

Escherichia coli strain C was acquired from Marie-Agnès Petit from INRAe, France. Bacteriophages λ (λ^{Temp}), λ^{Chl}, and λ^{Kan} was obtained from Maroš Pleška at The Rockefeller University.

Bacteriophage lysate preparation and distribution

Each type of λ phage lysate was inoculated, shaken, centrifuged, and filtered per the methods in Burke et al.[4] to create high-titer lysates (PFU/mL between 1×10^8 and 1×10^9). These lysates were stored in spray bottles, transported, and primed per the methods in Burke et al.[4] Immediately after priming, each lysate was sprayed with one pump from a distance of 10 cm onto the target sites for initial contamination. The spray dried clear and was unidentifiable to the naked eye. Contamination occurred no earlier than five minutes before the start of the doffing.

Bacteriophage recovery

Immediately after the doffing procedure, skin was sampled by applying a saline wipe (Hygea, USA, #C22370) around the hands and a wipe around the forearms; these wipes were stored in conical tubes (Corning, USA, #352070). Disposable scrubs were then stored in a Whirl-Pak (Nasco, USA, #B01542). Four sites of interest were swabbed with self-contained saline swabs (Hardy Diagnostic, USA, #SRK35) using a progressive back-and-forth motion until the entire surface appeared damp. To liberate phage from the saline wipe, the wipe was squeezed to remove excess liquid and the extracted solution was tested. To recover phage from the scrubs, 300 mL of deionized water was added to the bags that contained the scrubs and shaken vigorously to ensure scrubs were fully saturated. Excess liquid was poured into a conical tube for testing. To recover phage from the swabs, the saline containers were vortexed vigorously.

After bacteriophage recovery, all surfaces with possible phages were sprayed with 70% ethanol (Decon Labs, USA, #2716) and wiped with Sani-Cloth Disposable Wipes (Professional Disposables International, Inc., USA, #Q55172).

Bacteriophage identification and quantification

Phage identification was performed by polymerase chain reaction (PCR), using the methods and materials used by Burke et al.[4] Band sizes of 800bp were called λ^{Temp}, 1500bp called λ^{Chl}, and 1900bp called λ^{Kan}. The PCR was performed with an O'Gene Ruler DNA Ladder (Thermo Fisher Scientific, USA, #SM1563).

The serum resistance lipoprotein (*bor*) gene (Gene ID: 2703532, NCBI) of the λ phages was amplified by PCR using the following primers designed in PrimerBLAST (NCBI): Forward (borRG1Fw) 5'-GCTCTGCGTGATGATGTTGC-3' and Reverse (borRG1Rv) 5'-GCAGAGAAGTTCCCCGTCAG-3'. Using the double-layer soft agar method.[5] LB soft agar overlays containing 0.1 mL of a turbid *E. coli* C overnight were prepared and allowed to harden. 0.01 mL of serially diluted saline recovery solution was spotted on the overlay at four densities. These plates were grown overnight at 37°C, and plaques were enumerated the next day.

If samples were determined to be PCR positive but negative via spot testing, 100 µL of sample were cultured with 1×10^7 CFU/mL log-phase *E. coli* C in 10 mL of LB broth. These cultures were grown with shaking for 6 hours, centrifuged, and filtered through a 0.22 µm filter to generate boosted lysates. 300 µL of these lysates were plated on *E. coli* C lawns to determine viable bacteriophage presence.

Process documentation (videography and still photography)

For the fluorescein and Glo Germ experiments, pictures were taken with an iPhone under ultraviolet illumination in a dark room; footage was recorded with one camcorder. During doffing

https://doi.org/10.1017/ice.2024.84 Published online by Cambridge University Press

Table 1. Events of concern noted during annotation of the personal protective equipment doffing movie

Event description	Step number
When removing the outer gloves, the sleeves of the coverall may come into contact with the front surface of the PAPR hood	17
Removing the heavy-loading PAPR filter creates a high risk of aerosolization	19
The tie at the neck of the PAPR is not fully covered by the apron and could potentially contaminate the gloves when it is broken	21
Incidental contact to the inside of the PAPR hood may occur when reaching in to unzip the coverall	27
When the coverall is being pulled down the PAPR hood is free to move about and may contact skin of participant	28
When marching in place to remove coverall, incidental contact with the PAPR hood occurs	30
When marching in place, the PAPR hood is free to move around, potentially generating aerosols	30
When the coverall is removed from the legs, one is instructed to "keep your hands together." Forearms came in contact with the front of the PAPR hood that is not covered by the apron (henceforth referred to as the PAPR hood Critical Triangle)	31
When disposing of the coverall, there is a risk of incidentally interacting with patient-facing surfaces should care not be taken when picking the coverall off the ground	32*
When removing the PAPR hood, the back of the hood is pulled forward from the back of the head to cover the face shield. The corner of the PAPR hood can fold out so that the PAPR hood Critical Triangle is exposed and the HCP removing the PAPR has no way of seeing this	37
When the PAPR hood is flipped forward, the back of the PAPR can contact the front of one's scrubs	38
While reaching back and grabbing the hood, there is a large amount of contact between bare forearms, scrubs, and the PAPR hood Critical Triangle	37
When locating the edges of the visor, incidental contact with the face may occur	38
General procedural notes	
The alcohol sanitation is only being performed on gloves and not the forearms or wrists	

*This step in the movie deviated from the written protocol.

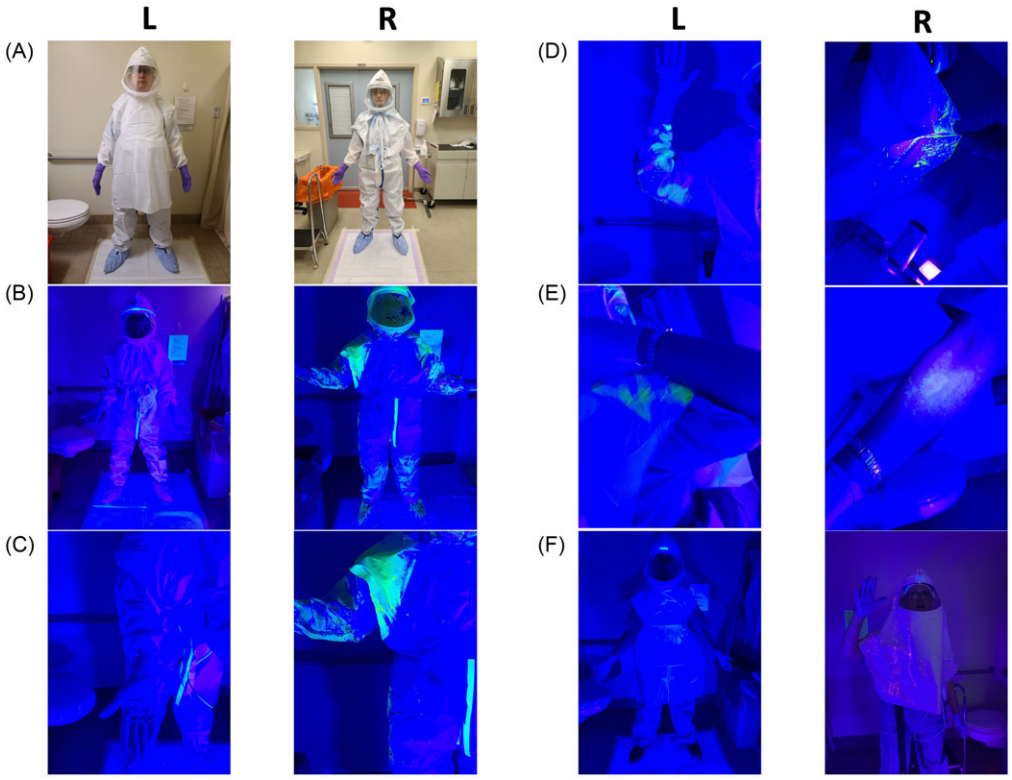

Figure 1. Fluorescent visualization of areas and actions of concern during doffing. Experimental results of doffing with fluorescent markers present for specific actions of concern or highlighting areas of concern, as found during review of the doffing protocol movie. Left (L): Before; shows areas that may be of concern. Right (R): After; shows potential concerns by transfer of fluorescence. (A) The original personal protective equipment (PPE) ensemble was in natural light, both with the apron and with the apron removed. (B) Patient-facing surfaces of the PPE not covered by the apron could become contaminated. (C) Critical Triangle area of the powered air-purifying respirator (PAPR). (D) Interaction of the coverall sleeves with the inside of the PAPR hood. (E) Transfer of contamination from the PAPR hood to the forearm that can occur during doffing. (F) Aerosolization of fine powder trapped on the heavy-loading filter.

https://doi.org/10.1017/ice.2024.84 Published online by Cambridge University Press

trials, pictures and footage were recorded under standard room lighting.

Results

Initial protocol analysis

Analysis of initial doffing movie

The investigation of the initial protocol (detailed in Supplementary Tables 3, 4, and 5) began with a movie analysis. Table 1 notes observations of potential sources of contamination to the HCP during the doffing protocol displayed in Movie 1. Steps can be correlated to the steps of the original protocol in Supplementary Table 3.

Evaluating contamination via fluorescence testing

In Figure 1 we present several pictures of testing with fluorescence that illustrate the concerns raised by the movie. We note that the protocol as performed in our trials, including this one, follows the written protocol and differs slightly from Movie 1; Movie 2 accurately portrays the written doffing protocol. There are six pairs of pictures: The left (L) panes show areas of concern, and the right (R) panes show the spread of fluorescence from those events.

The fluorescein reveals the materials in the complete PPE ensemble that are patient-facing. 1AL shows a complete ensemble, and 1AR shows the ensemble without the apron. 1BL shows the ensemble under blacklight, and 1BR shows contamination not covered by the apron. 1CL and 1CR highlight the "Critical Triangle," which includes parts of the shoulder, the side of the abdomen, and the arm.

The movement of the fluorescein demonstrated in Figure 1 reveals how contamination can move from the outside of the PPE ensemble to an intermediate location, then ultimately to the HCP. These contamination pathways are demonstrated in 1D, 1E, and 1F. 1DL shows how contamination may reach the arm or Critical Triangle of the coveralls. From here, contamination could transfer to the underside of the shroud (shown in 1DR) which could then move to scrubs. 1E shows a second pathway, where contamination on a patient-facing shoulder (1EL) transfers to arms when reaching up to roll up the PAPR hood, with that contamination demonstrated in 1ER. 1F demonstrates how aerosolized pathogens land on skin, scrubs, and footwear.

Using these results, three initial locations on the PPE were determined to pose a high contamination risk. These locations are (i) the PAPR hood Critical Triangle, located to the left and right of the apron and near shoulders, (ii) the wrist/lower forearm area of the protective coverall, and (iii) the back of the PAPR hood near the filter and shoulders.

Doffing in the presence of a bacteriophage proxy

To more accurately mirror pathogenic contamination, we inoculated three genetically marked variants of λ on the three sites above to determine both the origin and final location of each virus. Presented in Figure 2 are the results of doffing performed by four HCPs with varying heights and body types and varying experience in performing the protocol.

Figure 2 demonstrates that phages moved to the four locations we had hypothesized could become contaminated. Moreover, we found these phages to be viable and present at high densities. All four HCPs demonstrated contamination.

These four HCPs were recorded from multiple angles while performing the doffing procedure. We present in Table 2 behaviors noted during our analysis of the movies that would increase the risk of contamination.

HCW1-1		Recovery Location			
		Scrubs	Hands	Forearms	Inside PAPR
Origin	Critical Triangle*	---	---	$2.5x10^3$	$5.4x10^4$
	Coverall Cuffs	---	---	---	---
	Back Hood	---	$1x10^3$	---	$5.4x10^4$

HCW2-1		Recovery Location			
		Scrubs	Hands	Forearms	Inside PAPR
Origin	Critical Triangle	---	---	---	$4x10^2$
	Coverall Cuffs	---	---	---	---
	Back Hood	---	---	$5.6x10^3$	---

HCW3-1		Recovery Location			
		Scrubs	Hands	Forearms	Inside PAPR
Origin	Critical Triangle	---	---	---	---
	Coverall Cuffs	---	---	$1.8x10^3$	---
	Back Hood	---	---	---	---

Figure 2. Phage recovery after doffing personal protective equipment. Experimental results of doffing protocols performed by four healthcare personnel with three bacteriophages initially inoculated on the powered air-purifying respirator (PAPR) Critical Triangle, coverall cuffs, and the back of the PAPR hood. Numbers inside each square represent the number of PFU/mL recovered from that location.

Updated protocol analysis

Changes to the protocol

Our analysis and experiments of the first protocol revealed insufficiencies that led to contamination of the HCP. We aimed to eliminate viable phage recovery by limiting the observed contamination pathways. Accordingly, we altered the protocol in both equipment and doffing steps (Movie 3; Supplementary Table 3; Supplementary Table 4; Supplementary Table 5). Below is a table detailing changes made to the PPE ensemble and procedure (Table 3).

Six amendments were made to the protocol. Adjustments were made based largely upon concerns raised by the phase one analysis, but amendments were also incorporated for ease of doffing. Of the six changes, three were changes in equipment; one was an additional step made for added equipment; and two were reordered steps.

Phage testing with updated protocol

We next evaluated the updated protocol with the phage testing described previously. Nine HCPs doffed using the updated

https://doi.org/10.1017/ice.2024.84 Published online by Cambridge University Press

Table 2. Concerns noted while reviewing movie of four healthcare personnel doffing

Event description	Step number
When removing the heavy-loading filter, people tend to not be conscious of where it is and have a tendency to either swing it around, aerosolizing particles, or touch it to their PAPR hood	19
During the stomping to remove the coverall, the PAPR hood moves around substantially, often coming into contact with the scrubs and in the forearms	30
One HCP misinterpreted how they should hold their hands in front of their body when removing the coverall and put their clasped hands against the front of the PAPR hood	31
Clasping the hands in front of the body when removing the coverall often results in the bare forearms interacting with the front and/or Critical Triangle* of the PAPR	31
Any manipulation above the head post coverall removal puts the HCP's forearms in contact with the PAPR hood Critical Triangle	37-39
The PAPR hood repeatedly bunches up or flips over near the shoulders	
On short HCPs, the front of the PAPR hood folds in on itself easily	
On particularly tall HCPs, the apron does not cover nearly as much of the coverall and PAPR as it does on shorter individuals	

*Critical Triangle = The side of the PAPR hood, coveralls, and arm, which may be exposed and facilitate contamination.

Table 3. Updates to the protocol

Protocol amendments			
Old protocol	New protocol	Revision	Comment
No inner shoe liner	Calf-high shoe liner over shoes and pant legs	Add inner shoe cover	Makes doffing coverall easier
Regular length inner gloves	Extended cuff inner gloves	Change length of inner gloves	Reduces risk of exposed skin at wrist
Outer gloves donned before PAPR	Outer gloves donned last	Move step for donning outer gloves	Outer gloves are worn over sleeve of gown
Apron	Gown	Replaced apron with gown	Improved coverage of PAPR hood at shoulders and Critical Triangle
Heavy- loading filter removed after apron	Heavy-loading filter removed first	Move step for heavy-loading filter removal	Removes higher-contaminated items earlier in doffing protocol
No gown	Gown sleeves freed from outer gloves	Insert step to pull gown sleeve out of the outer glove cuff	Facilitates gown removal

protocol. The results of these doffing trials are presented in Figure 3.

Following the updated protocol, no viable phages were recovered. Phage DNA was found via PCR from several locations (indicated by an X) but viable phages were unable to be recovered from these PCR-positive samples even after providing a bacterial host. This indicates that the phages moved during doffing, but these phages were likely inactivated by the alcohol-based sanitizer during hand hygiene. Even if a contamination pathway was not eliminated, the updated protocol limited those pathways to contamination on gloves where sanitation could deactivate the bacteriophages.

Deviations from the doffing protocol by HCPs could contribute to variability in the results shown in Figure 3. We analyzed footage of each HCP doffing and noted deviations from the protocol which may lead to the spread of bacteriophages (Supplementary Table 1). Several HCPs deviated from the procedure. However, these deviations did not increase contamination per the results in Figure 3.

Discussion

PPE forms the cornerstone of safety for HCPs, but for HCPs working with HCIDs, satisfactory high-containment PPE is especially important.[6] Hundreds of HCPs experienced near-miss events, infections, or death from Ebola virus disease.[7,8] Although individual pieces of equipment receive National Institute for Occupational Safety & Health approval, PPE ensembles and their doffing protocols do not. Indeed, Koh et al. wrote over twenty years ago that PPE needed to be evaluated for efficacy against infection from severe acute respiratory syndrome—this is a problem that has needed addressal for decades,[9] and later, the same call to action was issued for empirical review of Ebola PPE and ensembles.[10]

This PPE ensemble had not been assessed by empirical means. Our goal was to evaluate the ensemble and doffing protocol for possible contamination pathways and offer interventions to mitigate potential contamination. Even a slight contamination of an HCID could be a threat to HCPs (Supplementary Table 2). Thus, the aim of our interventions was to prevent viable self-contamination. We note that although other methods exist for analyzing the antiviral and disinfection qualities of PPE and its ensembles,[11,12] we elected to focus exclusively on how this ensemble performed in the transfer of pathogens.

Our first phase of this study began with an examination of a movie depicting the original protocol. The original protocol followed infection prevention best practices and was designed with disease containment in mind, but an in-depth evaluation revealed potential contamination pathways. We found from the

https://doi.org/10.1017/ice.2024.84 Published online by Cambridge University Press

HCW1-2		Recovery Location			
		Scrubs	Hands	Forearms	Inside PAPR
Origin	Critical Triangle*	---	---	X	---
	Coverall Cuffs	---	---	X	X
	Back Hood	X	---	---	---

HCW2-2		Recovery Location			
		Scrubs	Hands	Forearms	Inside PAPR
Origin	Critical Triangle	---	---	---	---
	Coverall Cuffs	---	---	X	X
	Back Hood	---	---	---	---

HCW3-2		Recovery Location			
		Scrubs	Hands	Forearms	Inside PAPR
Origin	Critical Triangle	---	---	---	---
	Coverall Cuffs	---	X	---	X
	Back Hood	X	---	---	---

Figure 3. Bacteriophage recovery after doffing personal protective equipment with the altered protocols. Experimental results of the altered doffing protocols performed by nine healthcare personnel (HCPs) with three bacteriophages initially inoculated on the powered air-purifying respirator (PAPR) Critical Triangle, coverall cuffs, and the back of the PAPR hood. An X denotes that the phage DNA from the origin location was found at that sampled location at the end of doffing via PCR. To test for viable phages below the limit of detection (1×10^2 PFU/mL) samples were incubated with a susceptible bacteria host and no viable phages were recovered from any HCP.

fluorescence testing that contamination moved through the pathways we had hypothesized onto scrubs and skin.

Fluorescence experiments, however, carry limitations.[13] Fluorescence does not reflect sanitation measures and can be visually tracked by participants. Contamination experiments with phages resolve both failings. The viruses are visually undetectable and can be inactivated via alcohol-based sanitation but pose no appreciable risk.[4,14] With the original doffing protocol, all participants had at least one contamination with at least 1800 virions present—an amount far greater than the minimum infective dose of many HCIDs (Supplementary Table 2).

We next offered an assortment of interventions. Modifications were made not only to reduce contamination by contact but also to make doffing easier. Reducing discomfort for HCPs may reduce deviations from a protocol, reducing contamination. The result of these changes manifested in the phage experiment with the updated protocol. In the second phage experiment, we did not recover a viable population of phage on any of the nine HCPs. Through PCR, we found phage DNA in several locations, indicating that the phages were inactivated by the use of alcohol-based sanitizer during the doffing. Phages that may have contaminated several locations were routed through pathways that included successful hand sanitation. Moreover, updates to the protocol eliminated intermediate contamination locations present in the original doffing protocol, which would have re-contaminated the HCP at later doffing steps. These results were observed despite deviations from the protocol by the HCPs during their doffings. The protocol, built to include redundancies and reduce events of contamination, allowed for small deviations without self-contamination.

This study does contain limitations. The original contamination was deliberately placed according to the fluorescent test with the intention of revealing contamination pathways. Thus, we cannot wholly capture contamination that would occur in a clinical setting – instead, we show how specific contamination can be tracked and eliminated through specific procedures. Further studies are needed to capture how contamination may move throughout a clinical environment, on PPE and otherwise. We further note that phages are only proxies. Using HCIDs for studies such as this is not ethical, but accordingly, we are closely approximating how they would function in a clinical setting through phages.

With the initial PPE ensemble and doffing protocol, contamination occurred that would have endangered the individual HCP and the community at large had it occurred with a dangerous pathogen. Through modifications of both protocol and equipment, the doffing protocol was successfully improved from initially incurring dangerous amounts of contamination to eliminating viable contaminants in all cases. These tests did not pose a great financial burden. Excluding PPE costs, each trial cost less than $45 USD, and our interventions were modest. Based on our results, validation of other healthcare PPE protocols by quantitative methods such as those we employed here is both logistically feasible and informative. No hospital procedure is designed for failure, but with empirical validation, those procedures can ensure they provide necessary protection.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/ice.2024.84

https://doi.org/10.1017/ice.2024.84 Published online by Cambridge University Press

Data availability statement. All data generated for this manuscript are available in the manuscript or its supplementary material.

Acknowledgments. We thank the other members of the Levin Lab, particularly Joshua Manuel and Bruce Levin, for their advice and assistance. We also Jessica Carag and Darryl Grant for their help with revising this manuscript.

Author contributions. Conceptualization: CSK, JSM, BAB.
Methodology: JBV, JM, JT, JSM, KBB, BAB.
Investigation: JSM, APS, KBB, BAB.
Visualization: APS, KBB, BAB.
Funding Acquisition: CSK, JMM.
Project Administration: CSK, JBV.
Supervision: JSM, BAB.
Writing – Initial Draft: CSK, JT, JSM, APS, KBB, BAB.
Writing – Review & Editing: CSK, JMM, JBV, JM, JT, JSM, APS, KBB, BAB.

Financial support. This work was supported by funds from the US National Institute of General Medical Sciences [grant number R35GM136407 to Bruce R. Levin]; the US National Institute of Allergy and Infectious Diseases [grant number U19AI158080-02 to Bruce R. Levin]; and the Centers for Disease Control and Prevention [grant number NU38CK000481 to Joel M. Mumma]. The funding sources had no role in the design of this study and will not have any role during its execution, analysis, interpretation of the data, or drafting of this report. The content is solely the responsibility of the authors and does not necessarily represent the official views of the Centers for Disease Control and Prevention.

Competing interests. The authors have no potential conflicts of interest to declare.

References

1. Centers for Disease Control and Prevention NCfEaZIDN. Division of Healthcare Quality Promotion (DHQP). Guidance on Personal Protective Equipment (PPE) To Be Used By Healthcare Workers during Management of Patients with Confirmed Ebola or Persons under Investigation (PUIs) for Ebola who are Clinically Unstable or Have Bleeding, Vomiting, or Diarrhea in U.S. Healthcare Settings, Including Procedures for Donning and Doffing PPE. Accessed 25 April.
2. Casanova LM, Erukunuakpor K, Kraft CS, *et al.* Assessing viral transfer during doffing of Ebola-level personal protective equipment in a biocontainment unit. *Clin Infect Dis.* 2018;66(6): 945–949.
3. Kwon JH, Burnham CD, Reske KA, *et al.* Assessment of healthcare worker protocol deviations and self-contamination during personal protective equipment donning and doffing. *Infect Control Hosp Epidemiol.* 2017; 38(9):1077–1083.
4. Burke KB, Berryhill BA, Garcia R, *et al.* A methodology for using Lambda phages as a proxy for pathogen transmission in hospitals. *J Hosp Infect.* 2023;133:81–88.
5. Kropinski AM, Mazzocco A, Waddell TE, Lingohr E, Johnson RP. Enumeration of bacteriophages by double agar overlay plaque assay. *Methods Mol Biol.* 2009;501:69–76.
6. MacIntyre CR, Chughtai AA, Seale H, Richards GA, Davidson PM. Uncertainty, risk analysis and change for Ebola personal protective equipment guidelines. *Int J Nurs Stud.* 2015;52(5):899–903.
7. World Health O. *Ebola Response Roadmap Situation Report.* World Health Organization; 2014.
8. Houlihan CF, McGowan CR, Dicks S, *et al.* Ebola exposure, illness experience, and Ebola antibody prevalence in international responders to the West African Ebola epidemic 2014–2016: A cross-sectional study. *PLoS Med.* 2017;14(5):e1002300.
9. Koh D, Lim MK, Chia SE. SARS: health care work can be hazardous to health. *Occup Med (Lond.).* 2003;53(4):241–243.
10. Sprecher AG, Caluwaerts A, Draper M, *et al.* Personal protective equipment for filovirus epidemics: a call for better evidence. *J Infect Dis.* 2015;212(Suppl 2):S98–S100.
11. Xue X, Coleman CM, Duncan JD, *et al.* Evaluation of the relative potential for contact and doffing transmission of SARS-CoV-2 by a range of personal protective equipment materials. *Sci Rep.* 2022;12(1):16654.
12. Pfuderer L, Stark WJ, Grass RN. Synthetic microbial surrogates consisting of lipid nanoparticles encapsulating DNA for the validation of surface disinfection procedures. *ACS Appl Bio Materials* 2023;6(3):1252–1259.
13. Hall S, Poller B, Bailey C, *et al.* Use of ultraviolet-fluorescence-based simulation in evaluation of personal protective equipment worn for first assessment and care of a patient with suspected high-consequence infectious disease. *J Hosp Infect.* 2018;99(2):218–228.
14. Burke KB, Berryhill BA, Garcia R, *et al.* Using Lambda phages as a proxy for pathogen transmission in hospitals. *medRxiv* 2022;2022.09.09. 22279770.
15. Franz DR, Jahrling PB, Friedlander AM, *et al.* Clinical recognition and management of patients exposed to biological warfare agents. *JAMA* 1997;278(5):399–411.
16. Vetter P, Fischer WA, 2nd, Schibler M, Jacobs M, Bausch DG, Kaiser L. Ebola virus shedding and transmission: review of current evidence. *J Infect Dis.* 2016;214(suppl 3):S177– S184.
17. Suess T, Remschmidt C, Schink SB, *et al.* Comparison of shedding characteristics of seasonal influenza virus (sub)types and influenza A(H1N1)pdm09; Germany, 2007–2011. *PLoS One* 2012;7(12):e51653.
18. Yezli S, Otter JA. Minimum infective dose of the major human respiratory and enteric viruses transmitted through food and the environment. *Food Environ Virol.* 2011;3(1):1–30.
19. Musisi E, Sessolo A, Kaswabuli S, *et al.* High Mycobacterium tuberculosis bacillary loads detected by tuberculosis molecular bacterial load assay in patient stool: a potential alternative for nonsputum diagnosis and treatment response monitoring of tuberculosis. *Microbiol Spectr.* 2022;10(1):e0210021.
20. Sakamoto K. The pathology of mycobacterium tuberculosis infection. *Vet. Pathol.* 2012;49(3):423–439.
21. SeyedAlinaghi S, Karimi A, Mojdeganlou H, *et al.* Minimum infective dose of severe acute respiratory syndrome coronavirus 2 based on the current evidence: a systematic review. *SAGE Open Med.* 2022;10: 20503121221115053.
22. Oh M-D, Park WB, Choe PG, *et al.* Viral load kinetics of MERS coronavirus infection. *N Engl J Med.* 2016;375(13):1303–1305.
23. Frey SE, Newman FK, Yan L, Belshe RB. Response to smallpox vaccine in persons immunized in the distant past. *JAMA* 2003;289(24): 3295–3299.
24. Price PA, Jin J, Goldman WE. Pulmonary infection by *Yersinia pestis* rapidly establishes a permissive environment for microbial proliferation. *Proc Natl Acad Sci.* 2012;109(8):3083–3088.
25. Kolodziejek AM, Hovde CJ, Minnich SA. Yersinia pestis Ail: multiple roles of a single protein. *Front Cell Infect Microbiol.* 2012;2:103.