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Optimizing Personal Protective Equipment Use and Infection Prevention Behaviors to Protect Healthcare Workers

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by

Kimberly Okiemute Erukunuakpor

Healthcare workers are at a significantly higher risk of exposure to infectious agents. Standard and transmission-based precautions are employed to protect healthcare workers during patient contact. Personal protective equipment and healthcare worker behavior influence the successful performance of standard and transmission-based precautions.

The three studies in this dissertation provide critical insights into personal protective equipment use and healthcare worker behavior to prevent exposure to infectious agents at the point of care. In the first study, we use patient contact simulations that incorporate viral assays and human factors analysis to determine the contribution of powered air-purifying respirator hood design to healthcare worker errors that lead to self-contamination during the use of high-level personal protective equipment. In the second study, data collected from a newly developed electronic hand hygiene monitoring system is used to identify improvements in hand hygiene behavior among healthcare workers. In the third study, we use a controlled laboratory disinfection procedure to assess the efficacy of common disinfection agents for reprocessing of elastomeric half-face respirators.

Healthcare systems rely on evidence-based methods to develop and improve infection prevention practices for healthcare workers. Therefore, this dissertation highlights crucial aspects of personal protective equipment use and healthcare worker behavior that can be optimized to successfully protect healthcare workers and provide recommendations that infection preventionists can apply to improve these areas of infection prevention.

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Healthcare Workers

by

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Optimizing Personal Protective Equipment Use and Infection Prevention Behaviors to Protect
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Author's Statement Page

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Chapter 1. Introduction

Workers spend about a quarter of their lifetime at work (1). The past few decades have seen an increase in occupational health and safety measures; however, workers continue to experience injuries and illnesses in the workplace (1). The healthcare industry is considered one of the most hazardous industries (2). Those who work in healthcare are at risk for injuries experienced in other industries in addition to illnesses caused by infectious agents. In 2019, 38 of 1000 healthcare industry workers experienced a work-related injury or illness (3).

Healthcare workers (HCWs) may become exposed to infectious agents in various ways, including patients with infectious diseases and contaminated sharps (2). HCWs may be exposed to a range of infectious agents that cause mild and treatable conditions, such as the influenza virus, to those that cause severe disease without any known treatment or cure, such as human immunodeficiency virus (HIV), Ebola virus, and severe acute respiratory syndrome coronavirus (SARS-CoV). The transmission route of infectious agents influences HCWs exposure. Improvements in handling blood samples and contaminated sharps have resulted in a decline in exposure to bloodborne pathogens, including HIV and hepatitis C (4). On the other hand, increases in exposure to airborne/droplet agents are being recorded as a result of the emergence of new agents such as SARS-CoV (5).

Several infection prevention and control methods are applied in healthcare as occupational health and safety measures to protect HCWs. Standard precautions are safety measures applied during contact with all patients. Standard precautions include hand hygiene (HH), personal protective equipment (PPE) use, and safe injection practices. However, when there is a risk of exposure to infectious agents from patients known or suspected to have an infectious disease, and standard precautions alone may be inadequate, specific transmission-based precautions must be used (5). Transmission-based precautions are additional measures combined with standard precautions for use with patients with any infections that cannot be effectively prevented solely by applying standard precautions.

The three transmission-based precautions are contact, droplet, and airborne precautions depending on the mode of transmission of the infectious agent (5). Contact precautions are precautions to prevent infections spread through direct or indirect contact with a patient or a patient's environment. Droplet precautions are applied to prevent infections spread by respiratory secretions that do not remain infectious over long distances in the environment. Airborne precautions prevent the spread of infectious agents that remain in respiratory secretions, suspended in air, over long distances. Critical to all transmission-based precautions is the use of PPE (6). PPE are barriers that protect the wearer and minimize the risk of exposure to infectious agents. Common PPE items include gloves, gowns, masks, respirators, goggles, and face shields.

For contact precautions, at the minimum, two PPE items are required – gloves and gown. HCWs are required to apply contact precautions for bacteria such as *Clostridium difficile* that spreads through environmental contamination. As the complexity of transmission of the infectious agent increases, a higher number of PPE items must be worn (5). Droplet precautions require the addition of a surgical mask to gloves and gowns. A surgical mask protects against respiratory secretions that are not small enough to be airborne. For close contact with patients known to be infected with the influenza virus, droplet precautions are recommended. Airborne precautions require the use of a respirator in addition to gloves and gowns. Respirators are designed to filter airborne particles to prevent inhalation of pathogens suspended in air. Airborne precautions are indicated for suspected or confirmed *Mycobacterium tuberculosis* cases (7).

Even more complex PPE is required for high consequence infectious diseases like Ebola virus disease, which have no known treatments and a combination of transmission routes. For such agents, a combination of contact, droplet, and airborne precautions must be applied because of transmission complexity. PPE for such high consequence infectious agents is high-level PPE, which comprises a minimum of seven items (including gloves, gowns, and respirators). In addition to PPE use, HCWs must perform standard infection prevention practices such as HH and cleaning and disinfecting surfaces around the patient (5).

The combination of PPE use with standard prevention practices such as HH should protect HCWs. However, this is not always the case. HCWs remain at high risk of infection. A recent example is the coronavirus disease 2019 (COVID-19) pandemic. For protection from exposure to SARS-CoV-2 (the virus that causes COVID-19), HCWs must apply airborne precautions and frequently perform HH with soap and water for at least 20 seconds (8). Despite these infection prevention practices performed by HCWs, the Centers for Disease Control and Prevention (CDC) reports that between February and July 2020, a total of 100,570 cases of COVID-19 were reported among HCWs, with 641 deaths (9). The cases of COVID-19 are between 3 to 11 times higher among HCW than people in the general population (10). One theory for exposure is that PPE may become contaminated with an infectious agent leading to exposure. Another view is that inadequate HH could result in exposure. The most prominent case of failure in HCW protection is that of two critical care nurses in Texas who contracted the Ebola virus from a patient (11). Despite using the required PPE, infection occurred. The route of exposure, in this case, is not well understood. Errors may have occurred while using PPE or inadequate performance of standard prevention practices (including hand hygiene and disinfecting contaminated surfaces around the patient) (11, 12). Overall, Ebola cases were between 21 to 33 times more likely among HCWs than the general population (13). All the above highlight gaps in knowledge about whether HCWs exposures to infectious agents result from errors during PPE use, lapses in standard prevention practices, or other occurrences during patient contact.

As already stated, uncertainties surround HCW exposure to infectious agents during patient contact. A significant challenge in understanding exposure is the inability to observe HCWs, during patient contact in real-time. As described in the previous paragraph, some theories relate exposure to errors while donning and doffing PPE and suboptimal prevention practices such as missing HH opportunities or washing hands for less than the required amount of time. Furthermore, the handling of contaminated PPE following doffing provides an opportunity for HCW exposure. Handling of contaminated PPE is an area of infection prevention that is currently unexplored. This dissertation's primary goals are to explore novel methods to understand HCW

exposure to infectious agents and provide recommendations to improve infection prevention practices to protect HCW.

The goals of this dissertation will be attained by performing three related studies on HCW exposures. The three studies will focus on:

- Using simulations of patient contact to quantify and map errors that lead to healthcare worker exposures during the use of high-level PPE
- Exploring the effectiveness of innovative ways of measuring and improving hand hygiene compliance to prevent exposure to infectious agents via hands
- Investigating the efficacy of disinfection practices to decontaminate personal protective equipment to prevent healthcare worker exposure

All three studies will expand our understanding of HCW exposure to infectious agents and provide novel ideas to prevent infection.

As stated previously, the two Texas nurses who became infected during the Ebola outbreak had donned the required PPE. Nevertheless, during PPE use and interaction with the patient, the occurrences that led to exposure and subsequent infection with the virus remain uncertain. The first study uses an innovative method to investigate HCW mistakes in high-level PPE use that lead to exposure to infectious agents and PPE design's contribution to susceptibility to errors. As described earlier, high-level PPE is used during the care of patients with serious communicable diseases with high fatality rates and no known treatments (14). The number of PPE items and the process of doffing PPE presents a severe exposure risk. PPE design may contribute to errors during doffing. The difficulty level for removing a PPE item may cause deviations in doffing, resulting in costly mistakes and an increased exposure risk (15). HCWs cannot be observed in real-time while interacting with patients due to exposure risk to researchers and HCWs. Simulations, where HCWs perform patient tasks in a controlled environment can be applied to address this challenge. During simulations, HCWs can be observed for errors.

The simulation approach used in this study is novel because it integrates microbiological and human factors analysis. With the combination of microbiology and human factors, specific errors in behaviors that lead to self-contamination can be linked. For simulations in this study, HCW don PPE, are exposed to surrogate microorganisms similar in structure to infectious agents, perform a patient task in the biocontainment unit where patients with serious communicable diseases receive care, and doff PPE in that area. For the entire simulation, HCW are observed for errors. Recovery of surrogate microorganisms from HCW skin or clothing is linked to errors. In observation of HCW during simulation, errors are marked as deviations from optimal behaviors.

The simulations in this study quantify and map HCW errors during high-level PPE use. Specifically, we explore three critical questions for protecting HCW that care for patients with serious communicable diseases: What kind of mistakes are most common during donning and doffing of high-level PPE? Does the design of a PPE item contribute to HCW error? Which of these errors are most likely to result in exposure to infectious agents? We provide suggestions on modifying high-level PPE use to minimize errors and infection risk with the answers to these questions.

As we attempt to prevent HCW exposure by understanding deviations in optimal behavior during high-level PPE use, there are shortcomings in the performance of basic infection prevention measures – specifically hand hygiene (HH) – among HCWs. HH compliance is low among HCW, occurring at or below 50% in most healthcare environments (16,17,18). Human factors are hypothesized to contribute to the failure in HH adherence. Forgetfulness and confusion about when to perform HH are two factors that may affect performance (16). Predictive factors may also contribute to poor performance. For example, previous studies suggest doctors have lower performance than nurses; non-intensive care unit providers have lower performance than intensive care unit providers (19,20).

Standard precautions indicate that HCWs must wash hands at critical moments such as after touching bodily fluids, between patient contact, and following glove removal (5). The WHO

clearly defined these moments in 2009. The WHO 5-moments of HH (before touching a patient; before clean/aseptic procedures; after body fluid exposure; after touching a patient; and after touching patient surroundings) is the standard for practicing HH (19). The transmission precautions described earlier all incorporate HH steps and PPE use. HH is a critical component for optimal contact, droplet, and airborne precautions and decreases HCW exposure risk. Numerous HH steps are necessary when doffing high-level PPE described in study one. Adequate HH during these steps protects the HCW and is also critical for disrupting the dissemination of high consequence infectious agents to fomites and the biocontainment unit's built environment.

For decades infection preventionists have provided evidence of the numerous benefits of HH adherence. Compliance with standard HH practice protects both patients and HCWs by interrupting transmission pathways of infectious agents. Preventing environmental dissemination of agents through adequate HH is of utmost importance in all healthcare environments. The second study investigates HH behavior among HCW by analyzing data collected using a newly developed method to observe and improve HH compliance.

Assessing improvements in HH compliance is a challenge. The 'gold standard' – direct observation – is impacted by reporting bias (21, 22). For direct observation, a trained observer monitors and records HCW HH opportunities during a defined period of a workday (23). Direct observation is time-consuming, and compliance data collected is limited to the opportunities that can be monitored by the trained observer and may not reflect actual compliance (23). Innovative ways of monitoring HH compliance have been developed to combat this challenge. One of those ways is electronic hand hygiene monitoring (EHHM) systems. EHHM systems can continually record HH events, store compliance data, capture all HH opportunities, and accurately capture compliance in a healthcare center. For comparison, over two years, 156 direct observers recorded 13808 HH opportunities (24). In contrast, one EHHM system can record over 500,000 HH opportunities in less than a year, depending on the healthcare center's size (25).

An added benefit of EHHM systems is the possibility of combining HH improvement strategies such as a voice reminder to prompt HCW when a HH event is recommended (25). However, EHHM technologies are a recent feature in hospitals; therefore, the actual effects on HH behavior is unclear. We attempt to advance knowledge on monitoring and improving HH behavior by analyzing the data from a new EHHM technology installed in two hospitals to tackle two questions. How does HH compliance change over time when EHHM is combined with other interventions? Are the changes in HH that result from EHHM use identical for different HCW groups? With the answers to these questions, we expand knowledge on the application of automated monitoring systems to successfully monitor and influence HH behavior.

In addition to errors in PPE use and inadequate standard precautions, sub-optimal handling of contaminated PPE can lead to HCW exposure. HCW handle contaminated PPE items when discarding the item or during reprocessing for reuse. Ideally, contaminated PPE items are discarded after use to reduce exposure risk. However, discarding some PPE items is not economically feasible. For example, the powered air-purifying respirator (PAPR), a high-level PPE component, costs on average about \$900 (26). Even though PAPRs may become contaminated during use, they must be reprocessed and reused.

Outside of economic reasons, shortages in PPE items leads to the need for reprocessing. The current COVID-19 pandemic has led to surges in demand and shortages in the supply of single-use N95 filtering facepiece respirator (FFR), required for airborne precautions during contact with COVID-19 patients (27, 28). An N95 respirator has a 95% filtering capacity for airborne particles. Currently, alternative N95 respirators that can be reprocessed and reused are being utilized to combat shortages in the supply of single-use N95 FFRs.

Elastomeric half-piece respirators (EHFR) are a reusable alternative to single-use FFRs. EHFRs have traditionally being used in construction and manufacturing but not healthcare. Since the introduction of EHFRs into healthcare, challenges with reprocessing (cleaning and disinfection) for reuse have arisen. Handling of contaminated EHFRs between patient encounters presents a

high exposure risk to HCWs. Because of the urgency in introducing EHFRs to healthcare, there is currently no scientific consensus on reprocessing EHFR's for reuse.

The third paper focuses on laying the foundation to guide reusable respirators' reprocessing (specifically EHFRs) to protect HCWs providing care for patients during the COVID-19 pandemic. HCWs are at the highest risk of exposure because of the high titer of virus shed by COVID-19 patients during hospitalization (29). SARS-CoV-2, the virus that causes COVID-19, is spread primarily by respiratory droplets. HCWs must perform airborne precautions when providing care for COVID-19 patients. PPE indicated for airborne precautions for COVID-19 patients should comprise a minimum of 4 items – face shield/goggles, gloves, gown, and a respirator (28). A respirator is crucial to protect HCWs providing care for COVID-19 patients to prevent exposure to respiratory droplets.

For this paper, controlled laboratory conditions are utilized to investigate the efficacy of common disinfecting agents to clean contaminated EHFRs adequately. The results from this study will inform a similar study that will be performed among HCWs providing care for COVID-19 patients in a non-controlled hospital environment. This study and the subsequent study will inform the development of standard guidelines, from the National Institute of Occupational Safety and Health (NIOSH), for disinfecting EHFRs.

All three studies in this dissertation will answer critical questions for preventing exposure among HCW. The primary objective of each study is outlined below.

Study 1 Objective:

- Using simulations, viral assays, and human factors analysis, determine the contribution of powered air-purifying respirator hood design to healthcare worker errors that lead to self-contamination during the use of high-level personal protective equipment

Study 2 Objective:

- Using data collected from a newly developed electronic hand hygiene monitoring system, identify improvements in hand hygiene behavior among healthcare workers

Study 3 Objective:

- Using a controlled laboratory disinfection procedure, assess the efficacy of common disinfection agents for reprocessing of EHFRs for reuse.

Chapter 2. Self-Contamination Risk and Failure Modes During High-Level PPE Doffing: A Comparison of Two Powered Air Purifying Respirator (PAPR) Hoods

2.1. Introduction

The 2014-2015 Ebola virus disease (EVD) outbreak refocused attention to the crucial role of high-level personal protective equipment (PPE) in protecting healthcare workers (HCW). EVD patients shed high titer of virus from blood and bodily fluids, increasing the risk of infection among HCWs during patient care (1). With a high fatality rate and lack of effective treatment, PPE remains the only protection for HCW (2). A structured protocol for PPE doffing is necessary due to the complexity of doffing PPE items (3).

A complete high-level PPE suite comprises a minimum of seven items, which include gloves, fluid-resistant aprons, coveralls, scrubs, and a powered air-purifying respirator (PAPR) or N95, head covers, and booties (Figure 2). Guided sequential doffing of items is crucial when doffing complex PPE because of HCW deviations from structured PPE doffing that increase self-contamination risk.

Simulation studies of guided sequential PPE doffing demonstrate that with a trained observer's guidance, the risk of HCW self-contamination during doffing is minimal (4, 5). Direction from a trained observer reduces the occurrence of HCW deviations from structured PPE doffing. However, PPE design may lead to HCW deviations from the doffing protocol. Such deviations, which include improper removal of certain PPE items, increase the risk of bare-skin contamination.

Human factors research suggests that of all PPE items, deviations are most likely to occur during the removal of the PAPR head cover (PAPR hood) (6). In previous studies, the PAPR hood's inappropriate doffing posed the highest risk of spreading an infectious agent to self and surroundings in the doffing area (6, 7). HCW deviation during doffing is attributed to human error; however, PPE's design may influence human error (8). The extent to which PPE design affects human error is currently unknown. Specifically, the PAPR hood design may add to the difficulty in doffing the PAPR and subsequently lead to HCW deviations and increase self-contamination

risk. This study focuses on understanding how PAPR hood design may contribute to HCW deviations and self-contamination during the doffing of complex PPE. The study uses PPE doffing simulations, viral assays, and human factors risk analyses to quantify and compare the risk of self-contamination during the doffing of two PAPR hood designs – a one-layer and a two-layer PAPR hood.

2.2 Methods

2.2.1 PPE Doffing Simulations

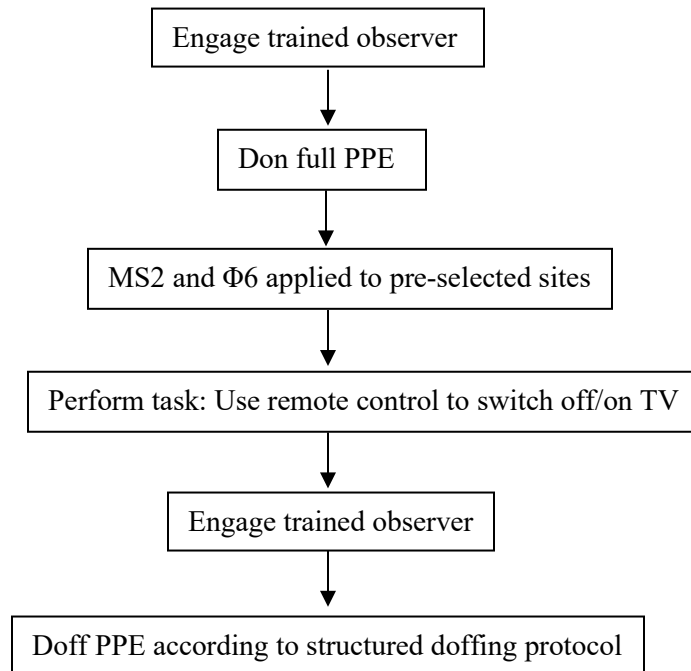
Emory University's Institutional Review Board approved all protocols. Eight participants (7 nurses and one physician) were recruited. All simulations were performed using methods described in detail elsewhere (6,7) (Figure 1). Briefly, a trained observer (TO) verbally guided participants through the donning and doffing of high-level PPE in a biocontainment unit. The same individual acted as TO for all simulations. PPE donned and doffed by participants will consist of a Tyvek suit, a fluid-resistant apron, one pair of short inner gloves, one pair of extended cuff outer gloves, a PAPR, a PAPR hood, and fluid-resistant shoe covers (Figure 2). Following donning, 5 μ L of a mixture of candidate Ebola surrogate viruses (Φ 6 an enveloped bacteriophage and MS2 a non-enveloped bacteriophage) suspended in phosphate-buffered saline (PBS) containing a fluorescent tracer (GloGerm, Moab, Utah) was applied to the top side of the PAPR hood, above the clear face shield, opposite the dominant hand.

The mean virus target titer applied to each site in 5 μ L was between 10^6 to 10^7 plaque-forming units per milliliter (PFU/ml) of PBS, approximating viral load in body fluids during the acute phase of the Ebola virus disease. To simulate actual task done during patient care, participants proceeded into the patient area in a biocontainment unit. Participants turned on/off a television facing a patient bed using a remote control placed on a bedside table in the patient area. Following the task, participants were guided through doffing using a structured doffing protocol used by the facility (Table 1). This doffing protocol has been described elsewhere by Casanova et al. (2018).

Each participant performed two simulations on two separate visits to the biocontainment unit. One simulation used a one-layer hood comprising one shroud laid over the Tyvek suit (Figure 3), while the other simulation used a two-layer hood comprising two shrouds (Figure 4). The top shroud is

laid over the Tyvek suit for the two-layer hood, while the bottom shroud is tucked into the suit. The TO guided each participant through doffing all PPE items. Steps in the structured doffing protocols used for each hood were identical except for the steps for doffing the hood (Table 1).

Figure 1: Flow Chart of Simulation



2.2.2 Virus Assay

During the doffing of PPE, inner gloves were collected for virus assay. After doffing, participants' face and hands were sampled, and scrubs were collected for virus assay. After collection, samples were placed on ice and immediately transported to the laboratory for analysis. All samples were assayed for Φ6 and MS2 using the single agar layer assay as described in Casanova et al. 2018. Viruses recovered from each site were expressed as plaque-forming units (PFU).

2.2.3 Human Factors Risk Analysis

All simulations were video recorded from different angles using three stationary cameras and one hand-held camera. A failure modes and effects analysis (FMEA) was performed as described by Mumma et al. (2018). Briefly, video recordings of simulations were reviewed to identify failure

modes (FMs), which are unique ways that a process can fail. For each simulation video, two raters independently coded the beginning and end of each doffing step and frequency of each FM using the Observer XT version 12.5 (Noldus Information Technology, Leesburg, Virginia). Interrater reliability of coding doffing steps and FMs were assessed with Cohen’s kappa. Three nurses who are experienced in doffing high-level PPE independently rated the severity of each FM using a 5-point scale, with a range from “Negligible” to “Catastrophic.” (6). Severity ratings for each FM were averaged, and the interrater reliability of the average rating assessed with the intraclass correlation coefficient. Lastly, for each FM, a risk index (RI) was obtained by scaling the raw frequencies of FMs and multiplying the scaled frequency score for each FM by its average severity rating.

2.2.4 Statistical Analysis

A McNemar’s test was used to compare the proportion of participants with contamination on face, hands, inner gloves, and scrubs using the one-layer versus the two-layer hood. A Wilcoxon rank-sum test was applied to compare the number of viruses recovered from participants’ inner gloves using the one-layer versus the two-layer hood. All statistical analyses were performed using SAS 9.4 (Cary, NC).

Figure 2: Healthcare worker in full high-level



PAPR
Hood

Image credit: ShalexOverseas

Figure 3: One-layer PAPR hood



Image credit: Hubbard Supply co. Layer 1

Figure 4: Two-layer PAPR hood



Image credit: 3M

2.3 Results

2.3.1 Viral Contamination

Eight participants completed 16 simulations. $\Phi 6$ transfer to both hands, inner gloves, and scrubs were observed for 1 participant during doffing of the one-layer hood. While doffing the two-layer hood, $\Phi 6$ transfer to scrubs was observed for 1 participant (results not shown). Table 2 presents results for MS2 transfer for both the one-layer and two-layer PAPR hoods. Overall, MS2 was detected on 10/32 sites and 5/32 sites sampled for the one-layer and two-layer hood, respectively. Contamination of hands was observed for two participants using the one-layer hood. No hand contamination was observed during the use of the two-layer hood. Inner glove contamination was observed for six participants and two participants doffing the one-layer and two-layer hood, respectively. Contamination of scrubs was slightly higher when using the two-layer (3/8 participants) compared to the one-layer hood (1/8 participants). Transfer of $\Phi 6$ or MS2 to the face was not observed for any participants.

McNemar's test revealed no statistically significant difference in the proportion of participants with contamination on at least one of the four sites sampled following each simulation (difference in proportion= 0.33, p=0.56). However, a statistically significant difference was observed in the number of MS2 virus particles recovered on participants' inner gloves using the one-layer versus the two-layer hood (one-layer median= 2.27×10^4 ; two-layer median= 0; median difference = 2.27×10^4 , p=0.03).

2.3.2 Failure Modes and Effect Analysis

The two-layer hood (Median = 143.6 seconds; Range = 98.9 – 236.7 seconds) took significantly longer to remove than the one-layer hood (Median = 24 seconds; Range = 13.6 – 41.5 seconds, p = .01). A total of 31 FMs were identified in the process for removing the two-layer hood compared to 13 FMs for the one-layer hood (Table 3), which comes from a previous risk analysis (Mumma et al., 2018). Regarding the two-layer hood, summing the risk indices of the FMs for each doffing step suggests that rolling up the outer shroud (Σ RI = 68; Step 12.6 in Table 1) and untying the torso ties (Σ RI = 39; Step 12.3 in Table 1) pose the greatest risk, with the former harboring the three riskiest of all individual FMs. Of note, our previous risk analyses of the one-layer hood (Mumma et al., 2018) suggested that disconnecting the PAPR helmet from the hood contributed most to inner glove contamination via contact between the inner gloves and face shield (e.g., “Touches face shield excessively” or “Squeezes front of face shield to remove from peg”; Table 3). However, when using the two-layer hood, HCWs largely avoided direct contact between the inner gloves and face shield by using the inner shroud to disconnect the hood from the helmet.

Table 1: Doffing Protocol

Step	Required Action	
1-11	Guided removal of bootie, outer gloves, and biohazard overall in patient room. Exit patient room and enter anteroom. Remove PAPR hood.	
	<u>One-layer Hood</u>	<u>Two-layer Hood</u>
12.1	Untie hood ties completely.	Rip and create an 8-inch piece of tape.
12.2	Grasp side of face shield and pull out snaps.	Untie top tie and tie again loosely distally.
12.3	Push face shield forward and release helmet pin.	Untie torso hood tie. Grab tie from each side around torso. Do not let go.
12.4	Grab top of hood. Pull back and then pull forward to remove PAPR hood.	Bring tie backwards and halfway over PAPR helmet.
12.5	Dispose of PAPR hood	Sanitize gloves.
12	12.6	Sanitize gloves. Grab outer PAPR shroud at shoulders roll inward toward neck neatly. Continue to roll front anterior portion into neat roll.
	12.7	n/a Grab prepared tape and tape shroud roll to visor on PAPR bottom.
	12.8	n/a Sanitize gloves.
	12.9	n/a Lift and flip inner shroud over PAPR helmet.
	12.10	n/a Starting from rear of PAPR, peel shroud off of PAPR helmet.
	12.11	n/a Peel and unsnap visor off of PAPR hood.
	12.12	n/a Dispose of PAPR hood
	12.13	n/a Sanitize gloves.
13	Remove inner gloves using beak method.	
14	Wash hands with soap and water.	
15	Remove belt, battery, and motor.	

Table 2: MS2 Virus Recovery Using One-Layer and Two-Layer PAPR Hood

Participant ID	<u>One-layer Hood</u>				<u>Two-layer Hood</u>			
	DH	Non-DH	Gloves	Scrubs	DH	Non-DH	Gloves	Scrubs
1	4	4	8.98 x 10 ⁴	10	ND	ND	1.40 x 10 ³	ND
2	ND	4	6.66 x 10 ⁴	ND	ND	ND	ND	ND
3	ND	ND	6.80 x 10 ³	ND	ND	ND	ND	ND
4	ND	ND	3.87 x 10 ³	ND	ND	ND	ND	6.60 x 10 ²
5	ND	ND	4.17 x 10 ⁴	ND	ND	ND	ND	3.00 x 10
6	ND	ND	3.86 x 10 ⁴	ND	ND	ND	45	ND
7	ND	ND	ND	ND	ND	ND	ND	1.10 x 10 ³
8	ND	ND	ND	ND	ND	ND	ND	ND

Abbreviations: DH=Dominant hand, ND=Not detected

Table 3: Failure Modes Observed During Doffing of One-Layer and Two-Layer Hood

One-layer Hood	Failure Mode(s)†	Two-layer Hood	Failure Mode(s)	S	F	RI
--	- Bumps into door [when moving from patient to anteroom] (e.g., with PAPR hood, scrub shoulder).					
12.1. Untie hood ties completely.	- Touches ties excessively. - Unsnaps hood before untying ties. - TO says “unsnap PAPR hood” before “untie PAPR hood.”	12.1. Rip and create an 8-inch piece of tape.	--			
12.2. Grasp sides of face shield and pull out snaps.	- PAPR hood contacts exposed arms. - Touches face shield excessively.	12.2. Untie top tie and tie again loosely distally.	- Difficulty untying top ties. - Retying requires multiple attempts.	2	3	6
12.3. Push face shield forward to release helmet pin.	- Squeezes front of face shield to remove from peg.	12.3. Untie torso hood tie. Grab tie from each side around torso. Do not let go.	- Drops torso tie. - Grabbing torso tie requires multiple attempts. - Begins untying torso tie before top tie was untied. - Torso ties touch coveralls. - Touches torso ties excessively with outer gloves. - Coverall sleeves touch outer shroud.	3	1	3
12.4. Grab top of hood. Pull back and then pull forward to remove PAPR hood.	- Grabs PAPR hood too far back. - Pulls PAPR hood off by grabbing near front, rather than back. - Touches PAPR hood excessively. - Drops PAPR helmet onto floor.	12.4. Bring tie backwards and halfway over PAPR helmet.*	- Back of outer shroud falls down.	4	4	15

12.5. Dispose of PAPR hood. *	<ul style="list-style-type: none"> - HCW almost hands PAPR hood to trained observer. - Trained observer's arm contacts PAPR battery cord. 	<p>12.6. Grab outer PAPR shroud at shoulders, roll inward toward neck neatly. Continue to roll front anterior portion into neat roll.</p> <p>12.7. Grab prepared tape and tape shroud roll to face shield on PAPR bottom.*</p> <p>--</p> <p>12.9. Lift and flip inner shroud over PAPR helmet.</p> <p>12.10. Starting from rear of PAPR, peel shroud off of PAPR helmet.</p> <p>12.11. Peel and unsnap visor off of PAPR hood.</p>	<ul style="list-style-type: none"> - Excessively touches outer shroud with outer gloves. - Does not roll up outer shroud completely. - Touches coveralls with outer gloves. - Touches underside of outer shroud with outer gloves. - Ties touch face shield. - Rolling up shroud requires multiple attempts. - Tape sticks to coveralls. - Taping shroud to face shield requires multiple attempts. - Grabbing tape requires multiple attempts. - Touches face shield with outer gloves. - Touches inner shroud with outer gloves. - Ties touch ground in patient room. - Unnecessarily touches ties with inner gloves. - Ties touch exposed arm. - Starts rolling inner shroud instead of peeling. - Ties touch inner shroud. - Touches inside of helmet with inner gloves. - Unsnaps before peeling. - Grabs side snaps outside of hood when unsnapping. - Peels by grabbing top of inner shroud instead of going underneath. 	<p>2 5 10</p> <p>4 5 20</p> <p>2 4 8</p> <p>3 4 11</p> <p>3 1 3</p> <p>4 4 16</p> <p>3 1 3</p> <p>2 4 9</p> <p>2 3 5</p> <p>2 1 2</p> <p>3 1 3</p> <p>3 1 3</p> <p>3 4 13</p> <p>4 3 13</p> <p>3 3 9</p> <p>3 1 3</p> <p>5 1 5</p> <p>3 1 3</p> <p>3 4 12</p> <p>3 1 3</p>
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12.12. Dispose of - PAPR hood not properly PAPR hood.*	disposed.	3	1	3
	- HCW hands PAPR hood to trained observer to dispose.	4	1	4

†From Mumma et al. (2018). *HH performed after step. S = Severity. F = Frequency. RI = Risk Index. Severity ratings are rounded to the nearest integer.

2.4 Discussion and Conclusions

The present study adds to evidence that self-contamination frequently occurs during high-level PPE doffing (5,6,7), even among highly trained HCWs and HCWs trained regularly on the use of high-level PPE. Self-contamination with an enveloped surrogate, with a close structural resemblance to the Ebola virus, was observed on hands, inner gloves, or scrubs for 1/8 HCWs using either the one-layer or two-layer PAPR hood suggesting that even with a structured protocol and a trained observer, HCWs are at risk of self-contamination with high consequence infectious agents.

The pattern of contamination for the non-enveloped Ebola surrogate MS2 during the use of the one-layer hood in the current study is similar to observations in our previous study (Casanova et al., 2018). In that study, participants donned and doffed high-level PPE (using the one-layer PAPR hood) using the same protocol as the current study, and the PAPR hood, outer gloves, and boot covers were contaminated. MS2 was recovered from inner gloves of 8/10 participants, hands of 1/10 participants, and scrubs of 2/10 participants. Based on the pattern of contamination of MS2 virus in our previous study, we concluded that the PAPR hood was the most important contributor to self-contamination, especially contamination of the inner gloves. With this study, we isolated the unique contribution of the PAPR hood to self-contamination. For all of the 8 participants, contamination was observed on hands,, inner gloves, and scrubs, reflecting the results from our previous study and supporting the conclusion that the PAPR hood is potentially the most important contributor to self-contamination particularly contamination of the inner gloves, and a high risk point during the doffing process,.

Differences in the amount of self-contamination relative to design and protocol for doffing PPE have been reported by several studies investigating various PPE ensembles (5, 9-18). Ensembles and their doffing methods are complex, and it may be challenging to isolate the contribution of individual components of the ensemble. only one of these studies compared contamination based on the design of a specific PPE item. Mana et al. evaluated contamination during doffing of two gown designs. These authors found that the gown with a design that provided more coverage and

a better fit for hands and was easier to doff resulted in lower contamination of HCWs hands, wrists, neck, and chest (11). However, Mana et al. investigated contamination during standard PPE doffing. Our study is the first to evaluate the relationship between the design of a specific PPE item and self-contamination during doffing of high-level PPE. Our study results reveal the contribution of PPE design to self-contamination during doffing of high-level PPE. The results demonstrate that the magnitude of self-contamination depends on the PPE item's design and the procedure for removing it.

Specifically, using the two-layer hood resulted in significantly less inner glove contamination than using the one-layer hood. The most likely source of inner glove contamination is the face shield of the one-layer hood, which HCWs frequently touched when disconnecting the hood from the helmet. However, with the two-layer hood, opportunities for direct contact between the inner gloves and the face shield were significantly reduced because HCWs used the inner shroud to disconnect the hood from the helmet. The design of the PAPR hood is closely related to the protocol for removing the hood. The protocol for doffing the two-layer hood aided in reducing contact between the inner gloves and the face shield. Scrub contamination was observed for a slightly higher number of participants using the two-layer compared to the one-layer hood. However, the degree of contamination was similar. The two-layer hood has a larger surface area due to the additional shroud, which could have increased the likelihood of scrubs contacting contaminated areas on the shroud during removal. Improving the doffing protocol's design may be necessary to direct HCWs to avoid contact between the shroud and scrubs when removing the hood from the PAPR helmet.

Although there was a significant reduction in inner glove contamination, any decision to use the two-layer over the one-layer hood should consider the differences in the complexity of removal; removing the two-layer hood is far more complex than removing the one-layer hood, requiring more steps and significantly more time. Moreover, the greater complexity of the two-layer hood allows for more opportunity for failure, as evidenced by the larger number of failure modes observed for the two-layer than the one-layer hood. However, the pattern of contamination observed during the use of the two-layer hood suggests that these failure modes, although they

frequently occur during doffing, may not always lead to healthcare worker self-contamination compared to the failure modes for the one-layer hood. Lastly, problematic parts of the protocol exist, mainly when containing the outer shroud by rolling it up (and ultimately taping it to the face shield) and manipulating the ties, particularly the torso. There is a need to redesign the current doffing protocol for the two-layer to shorten the duration of removal and address the failure modes associated with rolling up the outer shroud and untying the top ties the two actions with the riskiest failure modes observed.

There are limitations in the current study. The small sample may have resulted in low power for identifying any significant differences in the proportion of self-contamination when using either the one-layer or two-layer hood. However, we identified differences in the magnitude of inner glove contamination and the number of failure modes which revealed that the one-layer hood was more likely to lead to self-contamination than the two-layer hood. Nonetheless, future studies with a larger sample size using the same simulations in the current study are necessary. Participants were not randomized during simulations; all HCWs used the one-layer hood in their first simulation then the two-layer-hood in the second simulation. The sequence of hood use may have introduced bias that increased the difference in the magnitude of self-contamination between the one-layer and two-layer designs. However, simulations were performed days apart, allowing for a wash-out period between the use of the one-layer and the two-layer hood. Further studies will benefit from randomizing HCWs to address this limitation.

In conclusion, the design of PPE items affects the amount of self-contamination and protocol deviations that occur during the doffing of the PPE item. HCWs are not always aware of soiled areas on PPE during doffing that increases the risk of self-contamination. Therefore, investigations that reveal self-infection risks are crucial. This study's results can be utilized in the decision-making process for hospitals on the type of PAPR hood to make available to HCWs who use high-level PPE to care for patients with high consequence infections. Additionally, in a situation where one type of PAPR hood is already in the stockpile of a hospital, the infection control team should focus on designing a doffing protocol or modifying an existing protocol that addresses failure modes associated with doffing that type of PAPR hood.

References

1. Kreuels, B., Wichmann, D., Emmerich, P., Schmidt-Chanasit, J., de Heer, G., Kluge, S., Sow, A., Renné, T., Günther, S., Lohse, A. W., Addo, M. M., & Schmiedel, S. (2014). A case of severe Ebola virus infection complicated by gram-negative septicemia. *New England Journal of Medicine*, *371*(25), 2394–2401.
2. Edmond MB, Diekema DJ, Perencevich EN. (2014). Ebola virus disease and the need for new personal protective equipment. *JAMA*, *312*:2495–6.
3. Guidance on Personal Protective Equipment to be Used by Healthcare Workers During Management of Patients with Ebola virus disease in US Hospitals, Including Procedures for Putting on (Donning) and Removing (Doffing). (2015). Available from: <http://www.cdc.gov/vhf/ebola/healthcare-us/ppe/guidance.html>.
4. Casanova, L., Teal, L., Sickbert-Bennett, E., Anderson, D., Sexton, D., Rutala, W. A., & Weber, D. J. (2016). Assessment of Self-Contamination During Removal of Personal Protective Equipment for Ebola Patient Care. *Infection Control & Hospital Epidemiology*, *37*(10), 1156–1161.
5. Kwon, J., Burnham, C., Reske, K., Liang, S., Hink, T., Wallace, M., Shupe, A., Seiler, S., Cass, C., Fraser, V. J., & Dubberke, E. R. (2017). Assessment of Healthcare Worker Protocol Deviations and Self-Contamination During Personal Protective Equipment Donning and Doffing. *Infection control and hospital epidemiology*, *38*(9), 1077–1083.
6. Mumma, J., Durso, F., Ferguson, A., Gipson, C., Casanova, L., Erukunuakpor, K., ... DuBose, J. (2018). Human Factors Risk Analyses of a Doffing Protocol for Ebola-Level Personal Protective Equipment: Mapping Errors to Contamination. *Clinical Infectious Diseases*, *66*(6), 950–958.
7. Casanova, L., Erukunuakpor, K., Kraft, C., Mumma, J., Durso, F., Ferguson, A., ... DuBose, J. (2018). Assessing Viral Transfer During Doffing of Ebola-Level Personal Protective Equipment in a Biocontainment Unit. *Clinical Infectious Diseases*, *66*(6), 945–949.
8. Baloh, J., Reisinger, H. S., Dukes, K., da Silva, J. P., Salehi, H. P., Ward, M., Chasco, E. E., Pennathur, P. R., & Herwaldt, L. (2019). Healthcare Workers' Strategies for Doffing Personal Protective Equipment. *Clinical infectious diseases: an official publication of the Infectious Diseases Society of America*, *69*(Supplement_3), S192–S198.

9. Lee, M., Huh, K., Jeong, J., Choi, E., Choi, J., Cho, S., & Chung, D. (2018). Adherence to Protocols by Healthcare Workers and Self-Contamination During Doffing of Personal Protective Equipment. *AJIC: American Journal of Infection Control*, 46(6), S11.
10. Chughtai, A. A., Chen, X., & Macintyre, C. R. (2018). Risk of self-contamination during doffing of personal protective equipment. *AJIC: American Journal of Infection Control*, 46(12), 1329–1334.
11. Mana, T., Tomas, M., Cadnum, J., Jencson, A., Piedrahita, C., & Donskey, C. (2018). A randomized trial of two cover gowns comparing contamination of healthcare personnel during removal of personal protective equipment. *Infection Control and Hospital Epidemiology*, 39(1), 97–100.
12. Okamoto, K., Rhee, Y., Schoeny, M., Lolans, K., Cheng, J., ... & Popovich, K. (2019). Impact of doffing errors on healthcare worker self-contamination when caring for patients on contact precautions. *Infection Control & Hospital Epidemiology*, 40(5), 559–565.
13. Osei-Bonsu, K., Masroor, N., Cooper, K., Doern, C., Jefferson, K., ... & Doll, M. (2019). Alternative doffing strategies of personal protective equipment to prevent self-contamination in the health care setting. *AJIC: American Journal of Infection Control*, 47(5), 534–539.
14. Silva, J. P. da, Pennathur, P., Salehi, H., Chasco, E., Baloh, J., ... & Abbott, L. H. (2020). Self-Contamination While Doffing Personal Protective Equipment. *Infection Control & Hospital Epidemiology*, 41(S1), s385–s386.
15. Suen, L., Guo, Y., Tong, D., Leung, P., Lung, D., Ng, M., Lai, T., ... & Yu, W. (2018). Self-contamination during doffing of personal protective equipment by healthcare workers to prevent Ebola transmission. *Antimicrobial Resistance and Infection Control*, 7(1), 1–9.
16. Tomas, M., Kundrapu, S., Thota, P., Sunkesula, V., Cadnum, J., ... & Donskey, C. (2015). Contamination of health care personnel during removal of personal protective equipment. *JAMA Internal Medicine*, 175(12), 1904–1910.
17. Zamora, J., Murdoch, J., Simchison, B., & Day, A. (2006). Contamination: a comparison of 2 personal protective systems. *CMAJ : Canadian Medical Association Journal*, 175(3), 249–254.

Chapter 3. Using Data from an Automated Monitoring System to Assess Hand Hygiene Behavior among Healthcare Workers.

3.1 Introduction

Hand hygiene (HH) is arguably the single most essential and cost-effective infection prevention measure. Healthcare workers' (HCW) routinely touch patients and environmental surfaces, providing a vehicle for pathogens to travel from patient to patient and throughout the hospital environment. HH accomplishes multiple goals. Chiefly, it prevents the transmission of infectious agents from patient to patient via HCW hands and prevents spread of organisms through the built hospital environment via hand-to-surface contact. Studies show that the excess cost of treating one healthcare-associated infection would cover HH's cost for over 3000 patient days. A 10% increase in HH among HCWs results in a 14% decrease in infection rate among patients (2, 3). In addition to spreading pathogens to patients, hand contamination also puts HCW at risk for infection through self-inoculation (1). Although HCWs' own risk of exposure and disease from commonly encountered pathogens that cause HAIs such as methicillin-resistant *Staphylococcus aureus* (MRSA) is low, there is a high risk of exposure, from hands to respiratory pathogens as has been observed in the current coronavirus disease 2019 (COVID-19) pandemic.

Despite the established relationship between HH and infection rates, and its proven ability to protect both patients and HCW from infection and intensive efforts to boost compliance rates, HH compliance in healthcare settings remains low. HH compliance rate is a measure of the number of times a HCW cleans their hands divided by the overall number of opportunities for which HH is indicated at the point of care. HH rates in hospital intensive care units, non-intensive care units, and emergency departments remain at or below 50% (4,5,6). With the poor HH performance among HCW across provider types and work environments, HH improvement remains a top priority for infection prevention in most healthcare settings. Several self-reported barriers exist that are associated with poor compliance. A lack of recognition of hand hygiene opportunities during patient care and not thinking about it/forgetfulness are two critical barriers that affect hand

hygiene compliance (5). Some other studies hypothesize that HCW type and hospital unit type are factors that act as independent predictors of compliance (7).

These self-reported barriers and factors that affect compliance need to be addressed, and HH improvements that result from addressing obstacles to HH adherence, measured. Visual cues and placing HH stations in easy-to-reach areas are some measures applied in previous studies to improve HH (8,9). However, challenges remain in accurately monitoring and measuring HH compliance. Direct observation, the gold standard for monitoring and measuring HH compliance, has several established limitations, including the Hawthorne effect and the inability to capture HH opportunities over 24 hours (10). The reliance on human observers introduces these limitations in assessing HH compliance.

Electronic HH monitoring systems have been developed to address limitations in measuring compliance (11). EHHM systems can capture significantly higher HH opportunities in a healthcare setting than human observers. Furthermore, more recently, EHHM systems equipped with verbal reminders that prompt HCWs to perform HH at indicated moments during patient contact have are available. A significant advantage of EHHM systems is the ability to record individual HH performance data without a human observer that HCWs may be aware of. Performance data fed back to HCWs can improve HH compliance. However, EHHM systems are not widely adopted in healthcare. Very few studies have examined the effect of combining EHHM technologies with HH improvement strategies on HH behavior. Primarily, there is a need to use the robust data collected from automated HH monitoring systems to detect and describe HH behavior changes among HCWs. Detecting and describing these behavior changes resulting from targeted improvement strategies, whether positive or negative, is valuable to infection prevention programs in healthcare. This paper aims to evaluate the effects on HH compliance rates of a newly developed EHHM system that combined feedback and verbal reminders for HH compliance during a 41-week intervention in 9 units (6 intensive care units and three wards) at two hospitals. Using a multilevel Poisson model, we will explore 1) the overall improvement in HH compliance over the 41-week intervention 2) the HH compliance rate variation by HCW groups over the 41 weeks, and 3) the effect on compliance rates of a verbal reminder and a verbal reminder/HH performance feedback combination using the EHHM system.

3.2 Method

3.2.1 Data collection

3.2.1.1 Electronic Hand Hygiene Monitoring System

The EHHM system used for data collection is an ultrasound-based proximity sensor – Clean Hands Safe Hands system. The CHSH system comprised of three components. The first component was badge reels that were assigned and worn by HCW during shifts. The second component was sensors attached to HH product dispensers (hand rub and soap). The third component was a network sensor mounted in each unit. Individual HCW were assigned badges with unique serial numbers. Bluetooth technology was used to transmit data for the unique serial number associated with the HCW the badge was assigned. The sensors attached to HH products detected HH opportunities when a HCW with a badge entered or left a room, then recorded HH compliance by identifying if the HH product in the dispenser was used. Also, the sensors could play an optional reminder when it detected a HCW missed a HH opportunity. The network sensor mounted in each unit allowed dispenser sensors to communicate. The communication between dispenser sensors ensured that HH compliance credit was given to the individual HCW accurately. For example, if a HCW used a hallway dispenser before entering a patient's room, the hallway and patient room dispenser communicate to give room entry HH credit to the HCW. HH was recorded as successful if the HCW cleaned their hands within the allotted time for a room. Additional data collected using the CHSH system included a timestamp when hand hygiene opportunity occurred (hour, day, week, month) and shift (night, day).

3.2.1.2 Hand Hygiene Intervention

The CHSH system was deployed in a large urban hospital (Hospital A) and a smaller community hospital (Hospital B). Nine units comprising six intensive care units and three wards were selected from both hospitals for data collection. A total of 496 HCW were assigned a badge for HH data collection. Data collection spanned 41 weeks. The intervention was a combination of individual feedback, group feedback, and voice reminders, divided into five phases for hospital A and four phases for hospital B (Table 1). For individual feedback, each HCW was provided with their personal compliance rate weekly. For group feedback HCWs were provided with the compliance

rate for the entire unit weekly. The voice reminder strategy involved playing a voice prompt on the automated system when a HCW forgot to perform HH when indicated. HCWs were further divided into two groups in Hospital A, depending on whether they received individual feedback or a voice reminder during phase 2 of the intervention (Table 1). Each phase ranged from 4 to 15 weeks for hospital A and 4 to 9 weeks in hospital B. At baseline, the CHSH system collected HH data in the background with no intervention provided to HCWs. During the intervention period, data on room mode (normal, isolation, or *Clostridium difficile*) where HH opportunity occurred and HCW group were collected.

Table 1: Hand Hygiene Interventions by Hospital

	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Duration	4 weeks	8 weeks	8 weeks	4 weeks	8 weeks	9 weeks
Hospital A Group 1	Baseline	Group feedback	Group feedback+ Individual feedback	Group feedback	Individual feedback + voice reminder	Optimize feedback and reminder process
Hospital A Group 2	Baseline	Group feedback	Group feedback+ voice reminder	Group feedback	Individual feedback + voice reminder	Optimize feedback and reminder process
	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4	
Duration	4 weeks	8 weeks	6 weeks	8 weeks	15 weeks	
Hospital B	Baseline	Test voice reminder strategies	Voice reminder	Randomize participants: Individual feedback vs. no individual feedback	Optimize feedback and reminder process	

Note: Group Feedback = Unit aggregate HH compliance rates provided to participants weekly; Individual Feedback = Individual HH compliance rates provided weekly; Voice reminder = Verbal prompt activated on CHSH system

3.2.2 Statistical Analysis

A multilevel Poisson model with HH compliance as the outcome was applied. HH compliance was measured as the count of successful HH events per week. Successful HH was defined as cleaning hands within the allotted time for an opportunity. Data collected from each hospital were analyzed separately to determine the overall rate of HH compliance. The rate was defined as the total number of successful HH events divided by the total number of HH opportunities. The model included a random effect at the individual level to account for the repeated measures of HH compliance over the 41 weeks. Bivariable and multivariable models were used to analyze HH behavior. Bivariable models included time (in weeks), intervention phase, HCW group, unit, and work shift (day vs. night) when HH opportunity occurred as independent predictors. Multivariable models included all predictors previously mentioned.

HCWs were divided into five groups to create the HCW group variable. The groups were medical providers (cardiologists, hospitalists, nurse practitioners, physician assistants, critical care providers); nurses (registered nurses); other direct care providers (phlebotomists, physical therapists, respiratory therapists, radiologists); nurse technicians; administrative/other (pharmacists, social workers, clergy, dietitians). For the models, baseline was the reference phase, the HCW group with the lowest HH compliance overall (nurse technicians) was used as reference. The reference unit in both hospitals was an ICU; in hospital A, the ICU with the lowest HH compliance (41 ICU) was used as the reference group. The night shift was the reference group for all models. An offset variable created by taking the log of all HH opportunities was included as a covariate in all models. The offset variable adjusted for the variation in the number of HH opportunities for HCW during the 41 weeks of data collection. For example, it may be that during one week of the intervention, two HCWs had 30 HH events; however, one HCW had 30 HH opportunities while the other had 100 opportunities. The offset variable adjusts for this difference in the number of opportunities between HCWs. The rate (incidence rate ratios (IRR)) of HH compliance from all models are reported.

3.3 Results

3.3.1 Aggregate Hand Hygiene Compliance

A total of 1,149,328 HH opportunities were recorded from 496 participants in both hospitals, with an overall HH performance of 47%. Overall, HH performance was 49% and 44% in hospital A and hospital B, respectively (Table 1). In hospital A, compliance was low at baseline (37%). Compliance was highest in hospital A following implementation of a combination of feedback and voice reminder strategies which occurred in phase 2 (53%), phase 4 (54%), and phase 5 (55%). In hospital B, overall compliance at baseline was 32%. Compliance was higher at phase 4 (51%) when a combination of feedback and voice reminder strategies were implemented than a voice reminder only (phase 1 and 2) or feedback only (phase 3). Regarding weekly improvements, baseline compliance in the first week in hospital A was 36%, then increases to 60% by the final week in phase 5 (fig 1). Compliance was lower in the first week in hospital B (32%) than in hospital A (fig 2). Within phase 1, compliance increases steadily, peaking at approximately 40% by the end of phase 1 (fig 2). By the end of phase 4, compliance increases to approximately 54% (fig 2).

In both hospitals, HH opportunities were highest among nurses and lowest among administration staff 9 (Table 1). Compliance was highest among medical providers and lowest among nurse technicians (Table 1). Compliance ranged from 47% (baseline) to 74% in the final week of phase 5 among medical providers in hospital A and from 43% (baseline, week 4) to 77% in the final week of phase 4 hospital B (fig 3, fig 4). For all weeks observed, compliance among nurse techs remained consistently below 40% in hospital A and hospital B. Administration staff in hospital B recorded significantly higher compliance than nurses (fig 4).

The medical wards in hospital A recorded lower compliance than the ICUs (Table 1). In hospital B, the ICU had lower compliance (36%) than the medical ward (46%). In both hospitals, compliance during the night shift was lower than the day shift (Table 1).

3.3.2 Multilevel Poisson Regression Analysis

Results from the adjusted and unadjusted models are represented in table 3. Over the 41 weeks, HH compliance increased by approximately 1% for a week difference in time in both hospitals. In

unadjusted models, the HH compliance rate increased significantly at every phase compared to baseline. In hospital A, the rate of HH compliance compared to baseline was lowest in phase 1 (IRR =1.15, 95% CI = 1.12, 1.19, $p<.001$) when feedback alone was implemented, and highest in the final phase of the intervention, phase 5 (IRR =1.47, 95% CI = 1.43, 1.52, $p<.001$) during which the feedback and a voice reminder strategies were improved (Table 3). A similar pattern is observed in hospital B, where the final phase recorded the highest compliance rate (IRR =1.60, 95% CI = 1.51, 1.69, $p<.001$) compared to baseline. However, the lowest compliance rates were observed in phase 1 (IRR =1.32, 95% CI = 1.24, 1.41, $p<.001$) and phase 2 (IRR =1.33, 95% CI = 1.26, 1.42, $p<.001$) when voice reminders alone were implemented (Table 3). After adjusting for time, HCW group, hospital unit, and shift, the compliance rate in all intervention phases remained higher compared to baseline but were slightly lower than in unadjusted models.

Compliance rates from the models varied by HCW group in both hospitals. We found statistically significant differences in compliance rate among other healthcare worker groups compared to nurse techs (table 3). After adjusting for covariates, compliance rates in hospital A decreases while those in hospital B increase among other HCW groups compared to nurse techs. The rate among medical providers was 1.40 (95% CI: 1.34,1.46, $p<.001$) in hospital A and 2.10 (95% CI: 1.98, 2.23, $p<.001$) in hospital B, after adjusting for covariates. Among nurses, the rate of compliance in hospital A was 1.19 (95% CI: 1.16, 1.22) and 1.64 (95% CI: 1.58, 1.70) in hospital B.

In hospital A, the ICUs performed better than the medical wards. Compared to the ICU with the lowest compliance rate (41 ICU), significantly lower compliance rates were observed in the medical wards (31 floor and 41 floor) in both unadjusted and adjusted models (Table 3). In hospital B, the ICU recorded a significantly higher HH compliance rate compared to the medical ward in unadjusted (IRR =1.29, 95% CI: 1.24, 1.34, $p<.001$) and adjusted (IRR =1.43, 95% CI: 1.38, 1.48, $p<.001$) models. HH compliance was slightly higher during the day shift compared to the night shift in both hospitals. However, after adjusting for covariates, the difference in hospital A's compliance rate during the day shift compared to the night shift was not statistically significant.

Table 2: Aggregate HH performance by intervention phase, healthcare worker group, unit, and shift.

	Hospital A			Hospital B		
	Events	Opportunities	Compliance	Events	Opportunities	Compliance
Overall	364,473	742,326	49%	180,682	407,002	44%
Intervention						
Baseline	34,602	92,407	37%	13,759	43,552	32%
Phase 1	67,587	156,590	43%	34,789	82,466	42%
Phase 2	87,429	163,508	53%	24,518	58,727	42%
Phase 3	37,184	77,115	48%	37,182	83,149	45%
Phase 4	65,063	121,247	54%	70,434	139,108	51%
Phase 5	72,608	131,459	55%	-	-	-
Group						
Medical Providers	18,840	31,255	60%	12,128	19,113	63%
Nurses	278,323	554,098	50%	118,188	248,233	48%
Nurse Techs	43,330	108,182	39%	26,369	85,946	31%
Other DCP	20,527	39,401	52%	19,648	46,547	42%
Admin	4,453	9,390	47%	4,349	7,163	61%
Unit						
3 ICU	-	-	-	25,535	73,032	35%
3 Medical	-	-	-	155,147	333,970	46%
11 ICU	34,008	59,516	57%	-	-	-
31 ICU	58,145	95,457	61%	-	-	-
41 ICU	28,624	60,352	47%	-	-	-
71 ICU	76,436	151,245	51%	-	-	-
31 Floor	83,258	197,555	42%	-	-	-
41 Floor	39,740	98,045	41%	-	-	-
PICU	44,262	80,156	55%	-	-	-
Shift						
Night	101,489	216,248	47%	68,861	164,567	42%
Day	262,984	526,078	50%	111,821	242,435	46%

*DCP= Direct Care Providers

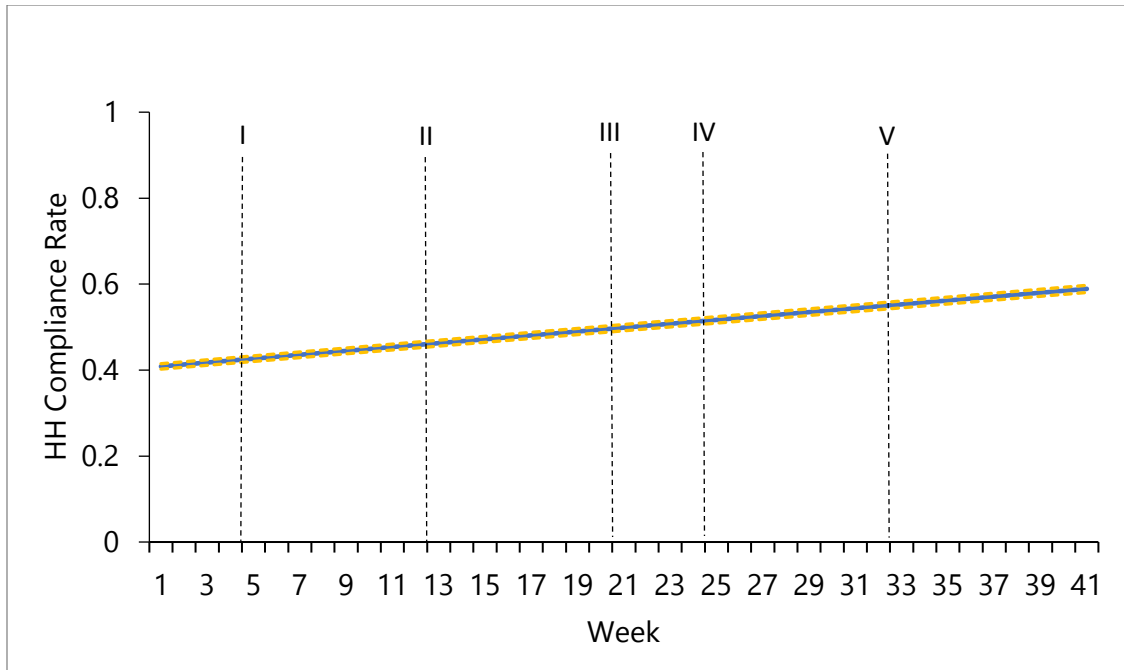


Fig 1. Trend plot depicting HH compliance rate and 95% CI in hospital A. The vertical dashed lines indicate when each phase of the intervention occurred.

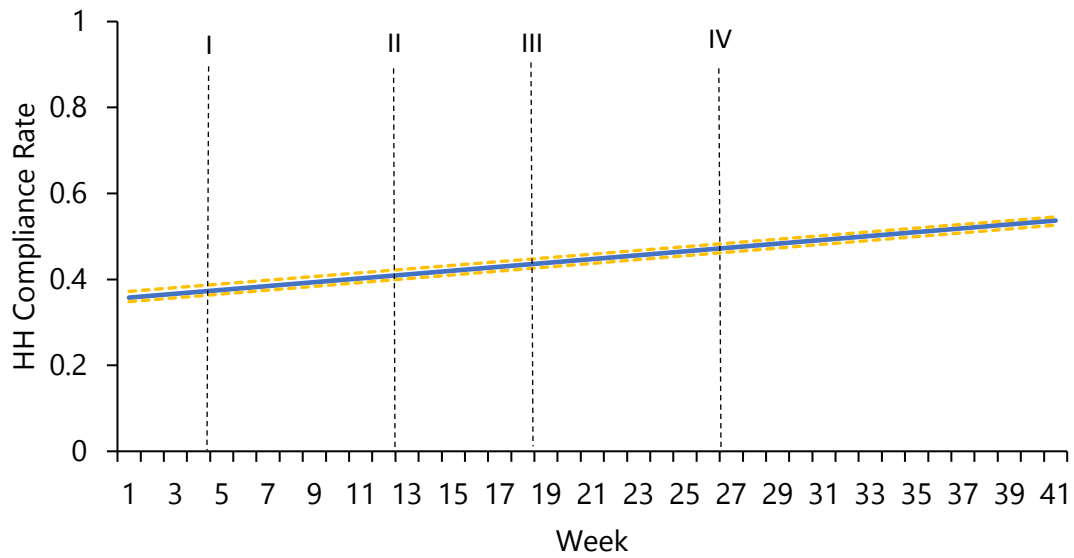


Fig 2. Trend plot depicting HH compliance rate and 95% CI in hospital B. The vertical dashed lines indicate when each phase of the intervention occurred.

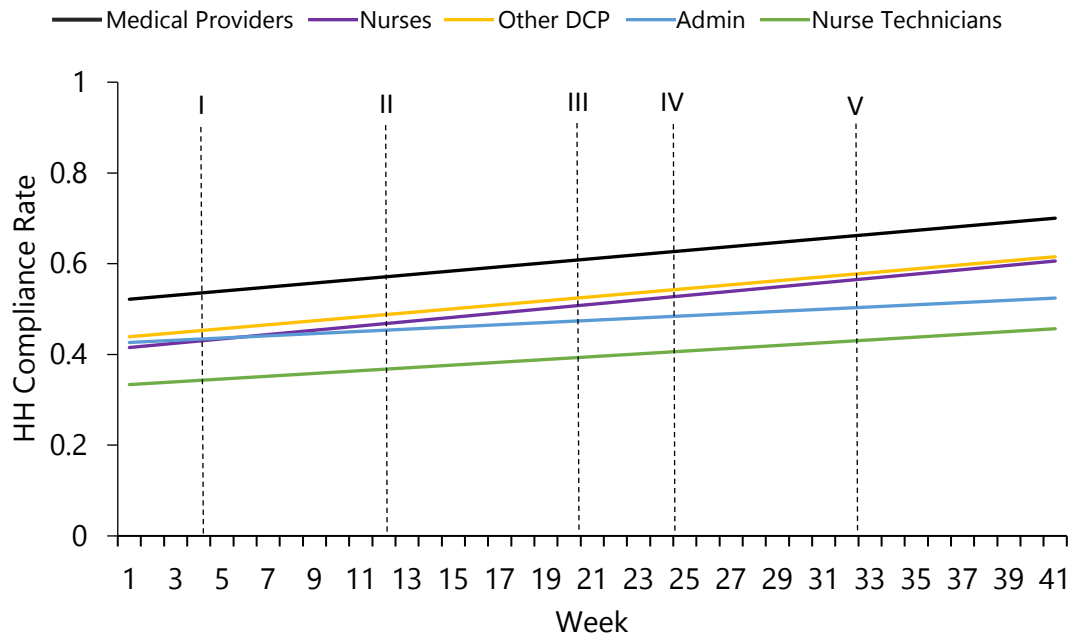


Fig 3. Trend plot depicting HH compliance rate by HCW group in hospital A. The vertical dashed lines indicate when each phase of the intervention occurred.

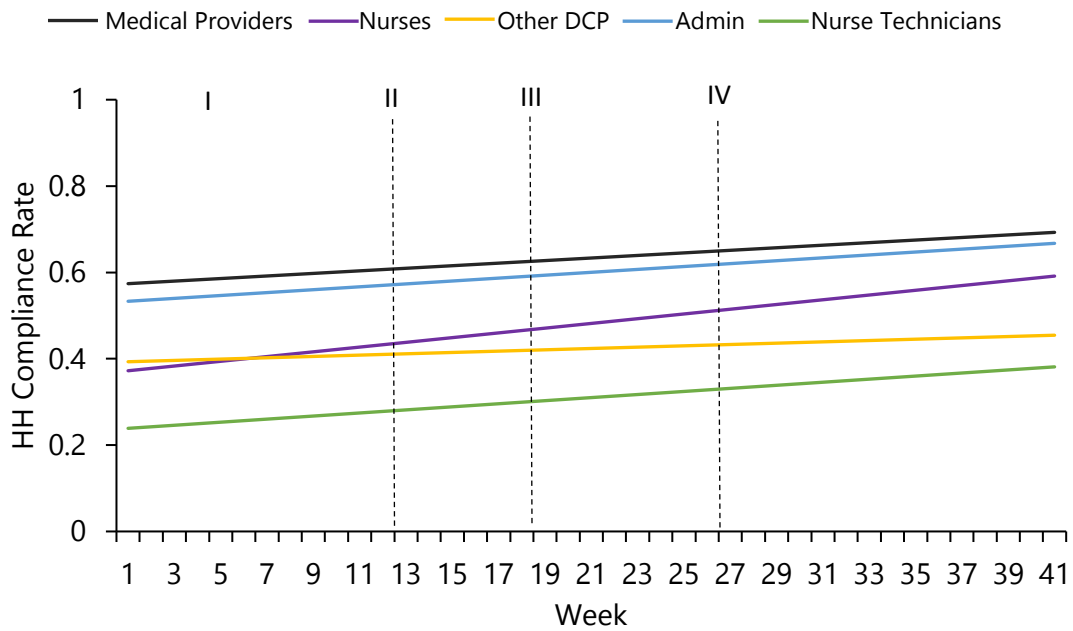


Fig 4. Trend plot depicting HH compliance rate by HCW group in hospital B. The vertical dashed lines indicate when each phase of the intervention occurred.

Table 3: Multilevel Poisson regression analysis for modeling hand hygiene compliance (dependent variable) as a function of time (in weeks), healthcare worker group, intervention phase, unit, and shift (independent variables).

Variable	Hospital A		Hospital B	
	Unadjusted IRR	Adjusted IRR	Unadjusted IRR	Adjusted IRR
Time (in weeks)	1.01 (1.01, 1.01)	1.01 (1.01, 1.01)	1.01 (1.01, 1.01)	1.01 (1.01, 1.01)
Intervention				
Baseline	Reference		Reference	
Phase 1	1.15 (1.12, 1.19)	1.10 (1.06, 1.14)	1.33 (1.26, 1.42)	1.26 (1.19, 1.34)
Phase 2	1.43 (1.38, 1.47)	1.26 (1.19, 1.33)	1.32 (1.24, 1.41)	1.18 (1.09, 1.28)
Phase 3	1.29 (1.24, 1.34)	1.09 (1.01, 1.18)	1.42 (1.33, 1.50)	1.23 (1.11, 1.35)
Phase 4	1.43 (1.39, 1.48)	1.18 (1.07, 1.29)	1.60 (1.51, 1.69)	1.35 (1.18, 1.54)
Phase 5	1.47 (1.43, 1.52)	1.12 (0.99, 1.26)	-	-
Group				
Nurse Technicians	Reference		Reference	
Medical Providers	1.54 (1.47, 1.61)	1.40 (1.34, 1.46)	2.07 (1.94, 2.20)	2.10 (1.98, 2.23)
Nurses	1.28 (1.25, 1.32)	1.19 (1.16, 1.22)	1.55 (1.49, 1.61)	1.64 (1.58, 1.70)
Other DCP	1.33 (1.27, 1.39)	1.19 (1.15, 1.24)	1.37 (1.30, 1.45)	1.50 (1.43, 1.58)
Admin	1.21 (1.12, 1.31)	1.08 (1.00, 1.16)	1.98 (1.80, 2.17)	2.14 (1.96, 2.34)
Unit				
3 ICU	-	-	Reference	
3 Medical	-	-	1.29 (1.24, 1.34)	1.43 (1.38, 1.48)
41 ICU	Reference		-	-
31 Floor	0.89 (0.86, 0.92)	0.90 (0.87, 0.93)	-	-
41 Floor	0.86 (0.83, 0.89)	0.89 (0.86, 0.93)	-	-
11 ICU	1.19 (1.14, 1.24)	1.19 (1.15, 1.24)	-	-
31 ICU	1.28 (1.24, 1.33)	1.27 (1.23, 1.32)	-	-
71 ICU	1.07 (1.03, 1.11)	1.06 (1.03, 1.10)	-	-
PICU	1.15 (1.11, 1.20)	1.15 (1.11, 1.20)	-	-
Shift				
Night	Reference		Reference	
Day	1.03 (1.01, 1.05)	1.01 (1.00, 1.03)	1.09 (1.05, 1.12)	1.05 (1.03, 1.08)

3.4 Discussion and Conclusions

Our model results show a significant improvement in HH compliance for each week of the intervention in both hospitals. However, our results also show that the compliance improvement strategy, HCW group, the type of unit, and the shift when a HH opportunity occurred are significant predictors of compliance. The greatest gains in HH compliance were observed during phase 2, 4, and 5 in hospital A and phase 4 in hospital B, when individual feedback or group feedback were combined with voice reminder strategies. We found that overall compliance was significantly better among medical providers compared to other HCW groups. Overall, HCWs in the ICUs in hospital A recorded better compliance rates than those in the medical wards. In contrast, compliance in the medical ward was greater than in the ICU in hospital B. The effect of work shift on the overall rate in HH compliance was low compared to other predictors.

This study's primary aim was to use data collected using an EHHM system to evaluate improvements in HH compliance in two hospitals. Using direct observers for monitoring compliance is labor-intensive, records <1% of HH opportunities, and is prone to significant bias. The EHHM system used in this study collected HH data continuously over the 41 weeks, addressing some of the shortcomings in monitoring through direct observation. The EHHM system is unique because it provided individualized HCW data by assigning badges to individual HCWs. This allowed for the estimation of overall HH improvement while accounting for individual variation in compliance.

One study reported that installing an EHHM system in the absence of interventions may improve compliance (12). The weekly compliance during baseline data collection in this study is consistent with other previous studies that found that installing an automated system without additional interventions failed to produce HH improvements (13-15). Baseline compliance levels in both hospitals were similar to those in other published studies (16-18). Introducing weekly individual or group performance feedback and voice reminders were associated with an overall compliance rate that was up to 1.35 times (hospital B, phase 4) baseline rates, corresponding to an increase of

approximately 19 percentage points which was slightly lower than found in previous studies that applied similar improvement strategies (18,19).

Assessing compliance during each phase of the intervention, we did not observe a significant difference when comparing the effect of a voice reminder alone to feedback alone on compliance in both hospitals. A review of previous studies suggests there are differences in the effect of feedback compared to voice reminders (20). Venkatesh et al. recorded an increase in HH rate four times higher than baseline (approximately 34 percentage points change) within three months of implementing electronic alerts that reminded HCWs to wash their hands when an opportunity was missed (21). Venkatesh et al. used a prerecorded voice prompt ('please wash your hands'), similar to that used in the current study (21). Marra et al. tested a real-time daily compliance feedback strategy and observed a 16 percentage points increase in compliance over seven months (22). However, these improvement strategies were not tested on the same population of HCWs as we did in this study and may explain the difference in results. Overall, the phases where individual or group feedback and voice reminders were combined produced higher improvement rates, this included the final intervention phase in both hospitals. In the final phase, the rate of compliance was 1.12 times and 1.35 times the rate at baseline, after adjusting for covariates, in hospital A and hospital B respectively. These results are consistent with other studies that show multimodal strategies produce significantly higher compliance rates than a single intervention (23).

We found that being a medical provider was associated with higher compliance than being a registered nurse. Medical providers, especially physicians, are considered to have poor compliance (24). The higher compliance rates reported among nurses are based on studies that rely on direct observation and may explain the difference in our findings (7, 25, 26). To date, collecting individual HH data relies on direct observation because most automated systems are designed to collect aggregate data at the unit level (27).

Current reports suggest that HCWs in ICUs have poor hand hygiene performance (28, 29). A possible reason is that the higher number of indicated HH opportunities in an ICU, due to the high risk of healthcare-associated infection among immunocompromised patients, produces lower compliance (30). The authors of these studies, however, conceded that direct observation might have influenced adherence to HH. The pattern of compliance in hospital B conforms with the possible reason for lower compliance in a hospital unit. In hospital B, HCWs in the medical ward had a significantly higher number of opportunities and reported lower compliance rates than the medical unit. On the other hand, ICUs in hospital A recorded a higher number of opportunities and compliance rates than the medical units. Conclusive evidence remains to be presented that supports lower compliance among HCWs in ICUs due to the reasons already mentioned.

Few studies have evaluated the effect of time of day on compliance. Venkatesh et al. demonstrated a compliance rate that was two times higher during the day within the first month of HH monitoring using an automated system (21). However, during the implementation of electronic alerts within the following three months, the differences in compliance between the day and night shift declined (21). Our study results follow the same pattern, compliance was slightly better during the day than at night, but this effect was not substantial. There is evidence that compliance may significantly decline over a work shift as HCWs may pay less attention to infection prevention behaviors as hours worked increases (31). These findings suggest that examining HH compliance within shifts may be a better measure than between shifts. Additionally, future studies may consider exploring these within shift differences with data from an automated system.

Data were collected continuously for 41-weeks (10 months), a more extended period than most other studies, and the use of an automated system allowed for capturing robust HH data. The feedback and verbal reminder interventions were designed as single and multimodal strategies to test their individual and combined effects. We examined HH compliance using a multilevel Poisson model with an offset that accounted for the individual variation in HH opportunities. Because data were collected at the individual level, we are able to examine the differences in the effect of our intervention strategies on HCW groups. Our study would have been strengthened if

our models controlled for HCW length of experience in healthcare, previous training on HH competencies, patient census, and patient-to-nurse ratio, all factors that affect compliance. Future studies may consider controlling for these factors in models that assess HH compliance. Without data on the incidence of healthcare-associated infections during the time of the intervention, we were unable to associate HH improvements to infection prevention among patients or HCWs. However, previous studies have consistently reported declines in infection rates associated with improving compliance (32). Automated systems provide robust data but are limited to capturing HH performance at room entry and exit, covering two out of the five moments defined by the WHO – before touching a patient and after touching patient surroundings (WHO moments 1 and 5). Therefore, with this data, we cannot describe HH behavior during three critical points (WHO moments 2, 3, and 4) during patient contact.

In summary, hand hygiene prevents exposure to infectious agents among patients and HCWs. This study provides much-needed information on HH improvement at a larger scale than can be provided by direct observation. The automated system used in this study performed well in capturing individual HH events and opportunities and allowed individual variability in assessing compliance. We observed significant gains in HH compliance that were attributable to the improvement strategies applied in this study. Therefore, we conclude that automated systems are a valuable tool for changing HH behavior. We recommend that automated systems, feedback, or voice reminders should not be considered as stand-alone interventions, instead be combined for optimal changes in HH behavior. HCWs responded differently to the strategies used in this study, particularly medical providers. Future studies may consider tailoring evidence-based interventions to target compliance among specific HCW groups. Finally, it will be essential to examine the sustainability of HH behavior changes in the weeks and months following the end of intervention strategies.

References

1. Phan, L., Maita, D., Mortiz, D., Bleasedale, S., Jones, R. & the CDC Prevention Epicenters Program. (2019). Environmental Contact and Self-contact Patterns of Healthcare Workers: Implications for Infection Prevention and Control. *Clinical Infectious Diseases*, 69 (3), S178–S184.
2. Brown, S., Lubimova, A., Khrustalyeva, N., Shulaeva, S., . . . O'Rourke, E. (2003). Use of an Alcohol-Based Hand Rub and Quality Improvement Interventions to Improve Hand Hygiene in a Russian Neonatal Intensive Care Unit. *Infection Control and Hospital Epidemiology*, 24(3), 172-179.
3. Sickbert-Bennett, E., DiBiase, L., Willis, T., Wolak, E., Weber, D., & Rutala, W. (2016). Reduction of Healthcare-Associated Infections by Exceeding High Compliance with Hand Hygiene Practices. *Emerging Infectious Diseases*, 22(9), 1628-1630.
4. McGuckin, M., Waterman, R., & Govednik, J. (2009). Hand hygiene compliance rates in the United States--a one-year multicenter collaboration using product/volume usage measurement and feedback. *American Journal of Medical Quality*, 24(3), 205–213.
5. Pittet, D. (2000). Improving Compliance with Hand Hygiene in Hospitals. *Infection Control and Hospital Epidemiology*, 21(6), 381.
6. Haas, J. & Larson, E. (2008), Impact of Wearable Alcohol Gel Dispensers on Hand Hygiene in an Emergency Department. *Academic Emergency Medicine*, 15: 393-396.
7. Buffet-Bataillon, S., Leray, E., Poisson, M., Michelet, C., . . . & Cormier, M. (2010). Influence of job seniority, hand hygiene education, and patient-to-nurse ratio on hand disinfection compliance. *Journal of Hospital Infection*, 76(1), 32–35.
8. Deyneko, A., Cordeiro, F., Berlin, L., Ben-David, D., Perna, S., & Longtin, Y. (2016). Impact of sink location on hand hygiene compliance after care of patients with *Clostridium difficile* infection: a cross-sectional study. *BMC infectious diseases*, 16, 203.
9. Nevo, I., Fitzpatrick, M., Thomas, R. E., Gluck, P. A., Lenchus, J. D., Arheart, K. L., & Birnbach, D. J. (2010). The efficacy of visual cues to improve hand hygiene compliance. *Simulation in healthcare: journal of the Society for Simulation in Healthcare*, 5(6), 325–331.

10. Masroor, N., Doll, M., Stevens, M., & Bearman, G. (2017). Approaches to hand hygiene monitoring: From low to high technology approaches. *International Journal of Infectious Diseases*, 65, 101–104.
11. Pong, S., Holliday, P., & Fernie, G. (2018). Effect of electronic real-time prompting on hand hygiene behaviors in health care workers. *AJIC: American Journal of Infection Control*, 46(7), 768–774.
12. Dyson, J., & Madeo, M. (2017). Investigating the use of an electronic hand hygiene monitoring and prompt device: influence and acceptability. *Journal of infection prevention*, 18(6), 278–287.
13. Conway, L. J., Riley, L., Saiman, L., Cohen, B., Alper, P., & Larson, E. L. (2014). Implementation and Impact of an Automated Group Monitoring and Feedback System to Promote Hand Hygiene Among Health Care Personnel. *The Joint Commission Journal on Quality and Patient Safety*, 40(9), 408–417.
14. Kwok, Y. L. A., Juergens, C. P., & McLaws, M.-L. (2016). Automated hand hygiene auditing with and without an intervention. *AJIC: American Journal of Infection Control*, 44(12), 1475–1480.
15. Edmonds-Wilson, S., Pelz, R., & Moore, L. (2016). Electronic Hand Hygiene Monitoring with a Complementary Improvement Program Significantly Increases Hand Hygiene Rates. *AJIC: American Journal of Infection Control*, 44(6), S6–S7.
16. Sahud, A., Bhanot, N., Narasimhan, S., & Malka, E. (2012). Feasibility and effectiveness of an electronic hand hygiene feedback device targeted to improve rates of hand hygiene. *Journal of Hospital Infection*, 82(4), 271–273.
17. Al Salman, J., Hani, S., de Marcellis-Warin, N., & Fatima Isa, S. (2015). Effectiveness of an electronic hand hygiene monitoring system on healthcare workers' compliance to guidelines. *Journal of Infection and Public Health*, 8(2), 117–126.
18. Boyce, J., Laughman, J., Ader, M., Wagner, P., Parker, A., & Arbogast, J. (2019). Impact of an automated hand hygiene monitoring system and additional promotional activities on hand hygiene performance rates and healthcare-associated infections. *Infection Control and Hospital Epidemiology*, 40(7), 741–747.

19. Knepper, B., Miller, A., & Young, H. (2020). Impact of an automated hand hygiene monitoring system combined with a performance improvement intervention on hospital acquired infections. *Infection Control and Hospital Epidemiology*, 41(8), 931–937.
20. Srigley, J., Gardam, M., Fernie, G., Lightfoot, D., Lebovic, G., & Muller, M. (2015). Hand hygiene monitoring technology: a systematic review of efficacy. *Journal of Hospital Infection*, 89(1), 51–60.
21. Venkatesh, A., Lankford, M., Rooney, D., Blachford, T., Watts, C., & Noskin, G. (2008). Use of electronic alerts to enhance hand hygiene compliance and decrease transmission of vancomycin-resistant *Enterococcus* in a hematology unit. *AJIC: American Journal of Infection Control*, 36(3), 199–205.
22. Marra, A., Sampaio Camargo, T., Magnus, T., Blaya, R.,& Edmond, M. (2014). The use of real-time feedback via wireless technology to improve hand hygiene compliance. *AJIC: American Journal of Infection Control*, 42(6), 608–611.
23. Luangasanatip, N., Hongsuwan, M., Limmathurotsakul, D., & Cooper, B. (2015). Comparative efficacy of interventions to promote hand hygiene in hospital : systematic review and network meta-analysis. *BMJ: British Medical Journal*, 351.
24. Squires, J., Linklater, S., Grimshaw, J., Graham, I., Sullivan, K., ... & Suh, K. (2014). Understanding Practice: Factors That Influence Physician Hand Hygiene Compliance. *Infection Control and Hospital Epidemiology*, 35(12), 1511–1520.
25. Pan, A., M., Mondello, P., Posfay, K. , Catenazzi, P., Grandi, A., ... & Carnevale, G. (2007). Hand Hygiene and Glove Use Behavior in an Italian Hospital. *Infection Control and Hospital Epidemiology*, 28(9), 1099–1102.
26. Zerr, D., Allpress, A., Heath, J., Bornemann, R., & Bennett, E. (2005). Decreasing hospital-associated rotavirus infection - A multidisciplinary hand hygiene campaign in a children's hospital. *Pediatric Infectious Disease Journal*, 24(5), 397–403.
27. Boyce, J. M. (2019). Current issues in hand hygiene. *AJIC: American Journal of Infection Control*, 47(Supplement), A46–A52.
28. Rosenthal, V., McCormick, R., Guzman, S., Villamayor, C., & Orellano, P. (2003). Effect of education and performance feedback on handwashing: The benefit of administrative support in Argentinean hospitals. *AJIC: American Journal of Infection Control*, 31(2), 85–92.

29. Pittet, D., Simon, A., Hugonnet, S., Pessoa-Silva, C., Sauvan, V., & Perneger, T. (2004). Hand hygiene among physicians: performance, beliefs, and perceptions. *Annals of Internal Medicine*, 141(1), 1–8.
30. World Health Organization. (2009). WHO Guidelines on Hand Hygiene in Health Care: First Global Patient Safety Challenge Clean Care Is Safer Care. Geneva: Available from: <https://www.ncbi.nlm.nih.gov/books/NBK144013/>
31. Dai, H., Milkman, K. L., Hofmann, D. A., & Staats, B. R. (2015). The Impact of Time at Work and Time Off From Work on Rule Compliance: The Case of Hand Hygiene in Health Care. *Journal of Applied Psychology*, 100(3), 846–862.
32. Knepper, B., Miller, A., & Young, H. (2020). Impact of an automated hand hygiene monitoring system combined with a performance improvement intervention on hospital acquired infections. *Infection Control & Hospital Epidemiology*, 41(8), 931–937.

Chapter 4. Disinfection of Reusable Elastomeric Respirators Using Common Healthcare Disinfection Wipes

4.1 Introduction

Between February and July 2020, a total of 100,570 cases of coronavirus disease 2019 (COVID-19) was reported among healthcare workers, with 641 deaths (1). Current evidence suggests that respiratory droplets are the primary transmission mode (2); several studies have demonstrated exposure to COVID-19 through airborne viral particles (3,4,5). To prevent respiratory exposure to COVID-19, the CDC recommends an N95 filtering facepiece respirator (FFR), face shield/goggles, gloves, and gown personal protective equipment (PPE) for health care workers (HCWs) during contact with COVID-19 patients (6). Respirators are critical in protecting healthcare workers who are in direct contact with COVID-19 patients. Close contact with patients can result in exposure to high concentrations of SARS-CoV-2; a study by Wölfel et al. (2020) showed that those hospitalized with COVID-19 shed on average 7×10^6 copies/mL of viral RNA in oral fluid while exhibiting symptoms (7).

The recommended and most widespread respiratory protection in healthcare is the single-use N95 FFRs (6). Single-use N95 FFR is ideal because HCWs discard the respirator after each patient encounter, reducing the risk of repeated handling of a contaminated respirator. The current pandemic has led to a shortage in the supply of single-use N95 FFRs (8), which have forced HCW to reuse single use FFRs. Because they are not designed to be reused, there are currently no standard or manufacturer-recommended disinfection protocols. Disinfection of single-use FFRs poses a challenge because it is not clear whether different disinfecting agents harm the integrity of these respirators (9), and disinfection methods must be evaluated on a case-by-case basis to determine if they affect the filtration efficacy of FFRs. A second challenge with reusing FFRs is a potential loss of fit following multiple uses (10). The face seal of a respirator that fits on the first use may become loose over time, leading to inadequate protection (10).

There are currently two alternatives to single-use respirators. These are the elastomeric half-face respirators (EHFRs) and powered air-purifying respirators (PAPRs). EHFRs have historically been

used in manufacturing and construction, where workers are exposed to high amounts of particulate matter such as lead dust (11). EHFRs were considered for use in healthcare settings after the shortages in disposable masks experienced following the H1N1 pandemic in 2009 (11). Between 2009 and 2019, only two hospitals have implemented respiratory programs that use EHFRs exclusively or primarily (11). The advantage of EHFRs over single-use FFRs is that they are designed to be reused. EHFRs can be cleaned and disinfected and will not lose fit over multiple uses. However, because EHFRs were not intended for healthcare, there is currently no scientific consensus and no standardized or rigorously evaluated methods exist for effectively disinfecting these respirators to ensure healthcare worker safety during reuse (11). Of significant concern is the lack of evidence on what type of disinfection of EHFRs is necessary to protect against self-contamination that may occur during repeated donning and doffing over multiple patient encounters. Three studies to date have investigated the cleaning and disinfection of EHFRs; these studies focused on eliminating the influenza virus from the surface of EHFRs (12,13,14).

As more hospitals consider introducing the use of EHFR, particularly for HCWs who care for COVID-19 patients, effective disinfection protocols to reduce the risks of reuse between patient encounters need to be validated and included in respiratory protection programs that use EHFRs. The disinfection protocols need to eliminate contamination of the surfaces of respirator components by SARS-CoV-2 and other infectious agents routinely encountered in healthcare. The goal of this study is to measure the effectiveness of a standardized procedure for the disinfection of EHFRs using wipes with disinfection agents commonly found in healthcare. Disinfectants were tested on EHFRs contaminated with two bacteriophages as surrogates for SARS-CoV-2 and two bacterial representatives of hospital-acquired pathogens.

4.2 Methods

4.2.1 Infectious Agents

Each set of elastomeric respirators (model RU8500; Honeywell) (Figure 1) was contaminated with four infectious agents obtained from the American Type Culture Collection (ATCC). The four agents were two viruses – bacteriophages Phi6 and MS2, one gram-negative bacteria – *Pseudomonas aeruginosa*, a common gram-negative hospital acquired pathogen, and one spore-forming bacteria – *Bacillus atrophaeus*, a surrogate for spore-forming hospital acquired

pathogens such as clostridium perfringens. These infectious agents were suspended in trypticase soy broth (TSB) at a concentration of 10^7 to 10^8 plaque-forming units per milliliter (PFU/ml) for Phi6 and MS2 and colony-forming units per milliliter (CFU/ml) for *Pseudomonas aeruginosa* and *Bacillus atrophaeus*. Respirators were inoculated with 50 μ L of each infectious agent on four predetermined areas (Figure 1) and allowed to dry at room temperature for 30 minutes.

4.2.2 Disinfecting Wipes

Following drying, each set of 3 respirators were disinfected using 1 of 4 disinfection wipes containing commercially available EPA approved hospital disinfectants. These disinfection agents were 0.5% hydrogen peroxide (Oxivir[®] Tb Wipes; Virox Technologies Inc.), 0.76% didecyldimethylammonium chloride (a quaternary ammonium compound (QAC) plus 7.5% ethanol plus 15% isopropanol (CaviWipes1; Metrex Research), 0.4% Benzalkonium Chloride (a QAC) (The Big Ones; Allegro Industries), and 0.9% Sodium Chloride plus Benzalkonium Chloride (Hyg ea Sterile Saline Wipes; Professional Disposables International, Inc.). Each set of respirators were cleaned with disinfectant wipes using a standard cleaning procedure (Table 1). Immediately after the cleaning procedure, EHFRs were allowed to sit for the indicated contact time for each disinfection agent. Contact times were 1 minute for 0.5% hydrogen peroxide, 1 minute for 0.76% didecyldimethylammonium chloride (a quaternary ammonium compound (QAC) plus 7.5% ethanol plus 15% isopropanol, 2 minutes for 0.4% Benzalkonium Chloride. There was no indicated contact time for the saline wipes (0.9% Sodium Chloride plus Benzalkonium Chloride). The respirators were allowed to sit for 2 minutes following disinfection with the saline wipes based on the contact time for 0.4% Benzalkonium Chloride. Inoculation and disinfection procedures for each infectious agent and disinfection wipe combination were performed in triplicate.

4.2.3 Recovery Experiments

After the required contact time for each disinfection agent, recovery of infectious agents was performed using a polyester swab premoistened with phosphate-buffered saline (PBS). The areas previously inoculated were brushed ten times with the premoistened swab using back and forth

and zig-zag motions. Swabs were then suspended in a standard volume of PBS. The suspension was vortexed for 30 seconds. A standard volume of the suspension was plated directly on trypticase soy agar (TSA) plates to recover *Pseudomonas aeruginosa* and *Bacillus atrophaeus* spores, incubated overnight at 37°C, then plates examined and counted. Phi6 and MS2 in suspension were enumerated using the single agar layer plate method that applies bacteriophage hosts *Pseudomonas syringae* and *Escherichia coli* Famp.

4.2.4 Statistical Analysis

The concentration of the recovered infectious agent was calculated in CFU/ml and PFU/ml, Reduction by disinfection was expressed as $\log_{10}(N_r/N_i)$ where N_r is the concentration of the infectious agent recovered from the respirator at time r (after required contact time) and N_i is the concentration of the infectious agent in the inoculum placed on the respirator before disinfection (time i). A one-way analysis of variance (ANOVA) and t-tests were used to compare the mean number of times each organism was recovered from a site. A t-test was used to compare the mean \log_{10} reduction for each organism/wipe combination. All analyses were performed using GraphPad Prism (GraphPad, San Diego, CA).

Figure 1: Honeywell RU8500 Series Elastomeric Respirator

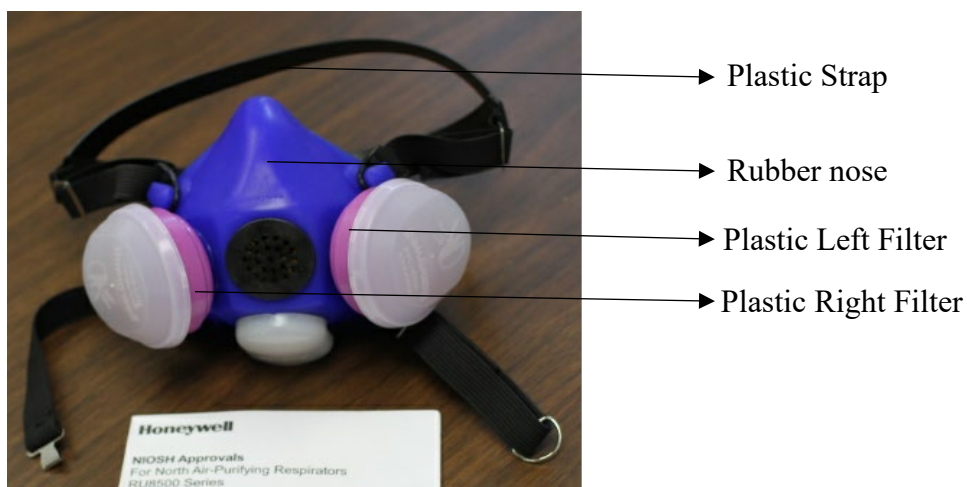


Table 1: Respirator Cleaning Procedure

Step	Required Action
1.	Grab head strap close to strap knob attached to silicon nose
2.	With one wipe, clean the top half of the nose area, fold wipe over and clean the same surface, then discard wipe
3.	With a new wipe, clean the left filter, fold wipe over and clean the right filter, then discard wipe
4.	With a new wipe, clean the lower half of the area, fold wipe over and clean the same surface, then discard wipe
5.	Wipe a new wipe, clean the bottom strap, fold wipe over and clean the top strap
6.	Repeat step 5 with a new wipe
7.	Allow respirator to air dry for wipe manufacturers recommended disinfection contact time

4.3 Results

4.3.1 Organism Recovery from EHFR Surface

A total of 192 respirator surfaces (4 per respirator) were sampled in 48 disinfection experiments. Organisms were recovered from 89% of EHFR surfaces using the Saline+QAC wipe for cleaning (Table 2). Disinfecting with the QAC+Alcohol wipe resulted in the least number of surfaces with contamination (Table 2). Organisms were more likely to be recovered from the plastic left filter and plastic right filter than the rubber nose and plastic strap. Comparing all wipes using ANOVA, there was a significant difference in the mean number of surfaces with any organism recovery. There was a significant difference in the mean number of surfaces with recovery when using hydrogen peroxide compared to the QAC+Saline for disinfection (mean difference= -8, p=0.01). Disinfecting with QAC+Alcohol compared to QAC+Saline resulted in a significant difference in the number of surfaces with any organism recovery (mean difference= -8, p=0.01). The difference in the number of surfaces with any organism recovery comparing QAC only to hydrogen peroxide (mean difference = -4, p=0.23) and QAC+Alcohol (mean difference = -5, p=0.23) was not statistically significant.

4.3.2 Log Reduction on EHFR Surface

The mean log reduction for all disinfection agents by infection agent is presented in table 3. All organisms demonstrated approximately a 4- \log_{10} to 8- \log_{10} reduction following disinfection. The efficacy of each disinfection agent to remove and/or inactivate organisms varied by organism type. Overall, organism recovery was highest from the plastic left filter and lowest from the plastic strap (figures 2-5).

Phi6 was highly susceptible to all disinfection agents (table 3, figure 2). Phi6 was recovered from all surfaces following disinfection with Saline+QAC (figure 2) and demonstrated a mean \log_{10} reduction of 6.7 ± 0.9 .

Susceptibility to disinfection agents varied for MS2. Infectious MS2 recovery from all EHFR surfaces was observed following disinfection with all agents (figure 3). Mean \log_{10} reduction for MS2 was highest using hydrogen peroxide (6.6 ± 0.24) and lowest using Saline+QAC (4.4 ± 0.10) (table 3). The \log_{10} reduction observed for MS2 was higher using hydrogen peroxide compared to QAC+Alcohol (mean log reduction difference = 1.6, 95% CI: 0.5, 2.7, $p = 0.01$). Disinfecting with QAC only resulted in a higher mean \log_{10} reduction for MS2 compared to Saline+QAC (mean difference = 1.7, 95% CI: 0.8, 2.6, $p < 0.01$).

Pseudomonas aeruginosa was highly susceptible to disinfection with hydrogen peroxide and QAC+Alcohol (table 3, figure 4). Recovery of *Pseudomonas aeruginosa* was least likely from the plastic strap compared to the other surfaces of the EHFR (figure 4). Disinfection with QAC only demonstrated a higher mean log reduction (6.8 ± 0.19) compared to Saline+QAC (5.6 ± 0.41), however the difference in \log_{10} reduction was not significant (mean difference = 1.1, 95% CI: -0.5, 2.9, $p = 0.14$).

Bacillus atrophaeus spores were least susceptible to all disinfection agents. Recovery of viable *Bacillus atrophaeus* spores from all EHFR surfaces was observed following disinfection with all agents (figure 5). Log reduction for *Bacillus atrophaeus* spores ranged from 4.2 ± 0.04 (Saline+QAC) to 5.7 ± 0.39 (hydrogen peroxide). The mean log reduction for *Bacillus atrophaeus* spores was higher following disinfection with hydrogen peroxide compared to

QAC+Alcohol; however, the difference was not statistically significant (mean difference = 1.3, 95% CI: -0.5, 3.1, p =0.11). QAC only demonstrated a slightly higher log reduction compared to Saline+QAC; however, the difference was not statistically significant (mean difference = 0.1, 95% CI: -0.1, 0.3, p =0.31).

Table 2: Number of Surfaces with Any Organism Recovery by Disinfection Agent

Disinfection Agent (Wipe)	N (%)
Hydrogen Peroxide (Oxivir [®] Tb)	13 (27)
QAC+Alcohol (CaviWipes1)	11 (23)
QAC only (The Big Ones)	30 (63)
Saline+QAC (Hyg�a Sterile)	43 (89)

Note: 48 surfaces per disinfection agent

Table 3: Mean Log Reduction Values by Organism/Disinfection Agent

Disinfection Agent (Wipe)	Organism			
	Phi6 [†]	MS2 [†]	<i>Pseudomonas aeruginosa</i> [†]	<i>Bacillus atrophaeus</i> spores [‡]
Hydrogen Peroxide (Oxivir [®] Tb)	>LRV	6.6 ± 0.24	>LRV	5.7 ± 0.39
QAC+Alcohol (CaviWipes1)	>LRV	4.9 ± 0.32	>LRV	4.4 ± 0.42
QAC only (The Big Ones)	*	6.1 ± 0.36	6.8 ± 0.19	4.3 ± 0.06
Saline+QAC (Hyg�a Sterile)	6.7 ± 0.9	4.4 ± 0.10	5.6 ± 0.41	4.2 ± 0.04

LRV = log reduction value, *single data point, no mean calculated; [†]log reduction limit = 10⁸; [‡] log reduction limit = 10⁷

Figure 2: Phi6 Mean Log Reduction Values by Surface Disinfected

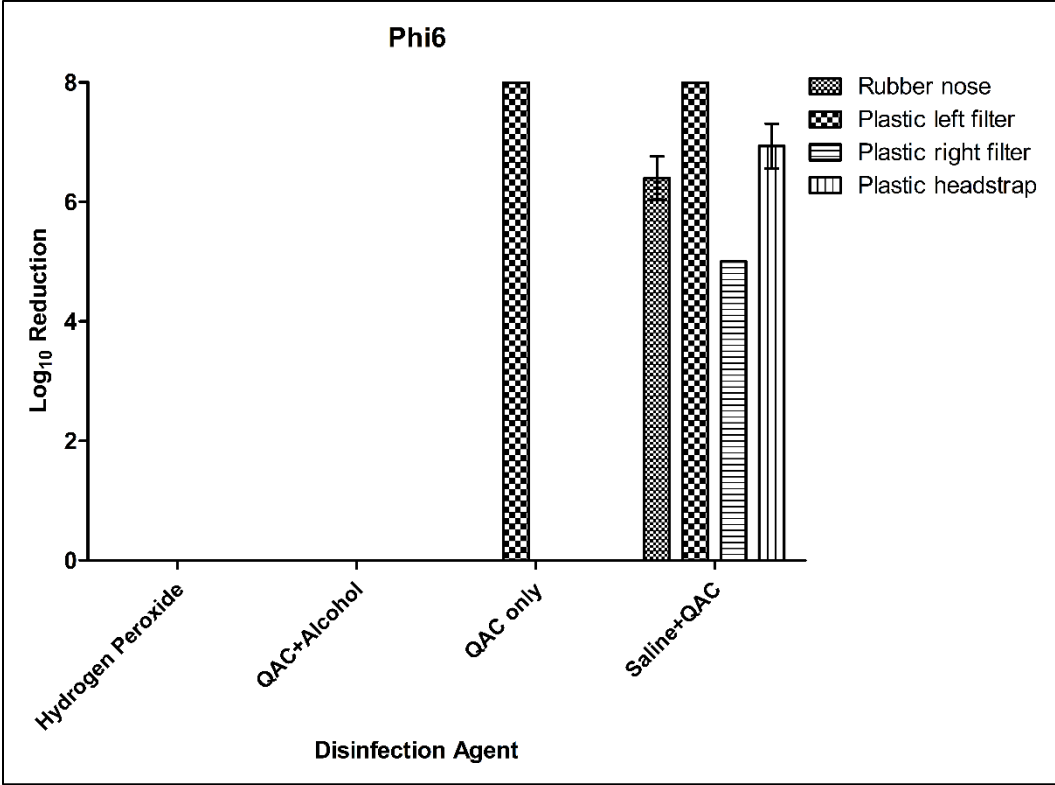


Figure 3: MS2 Mean Log Reduction Values by Surface Disinfected

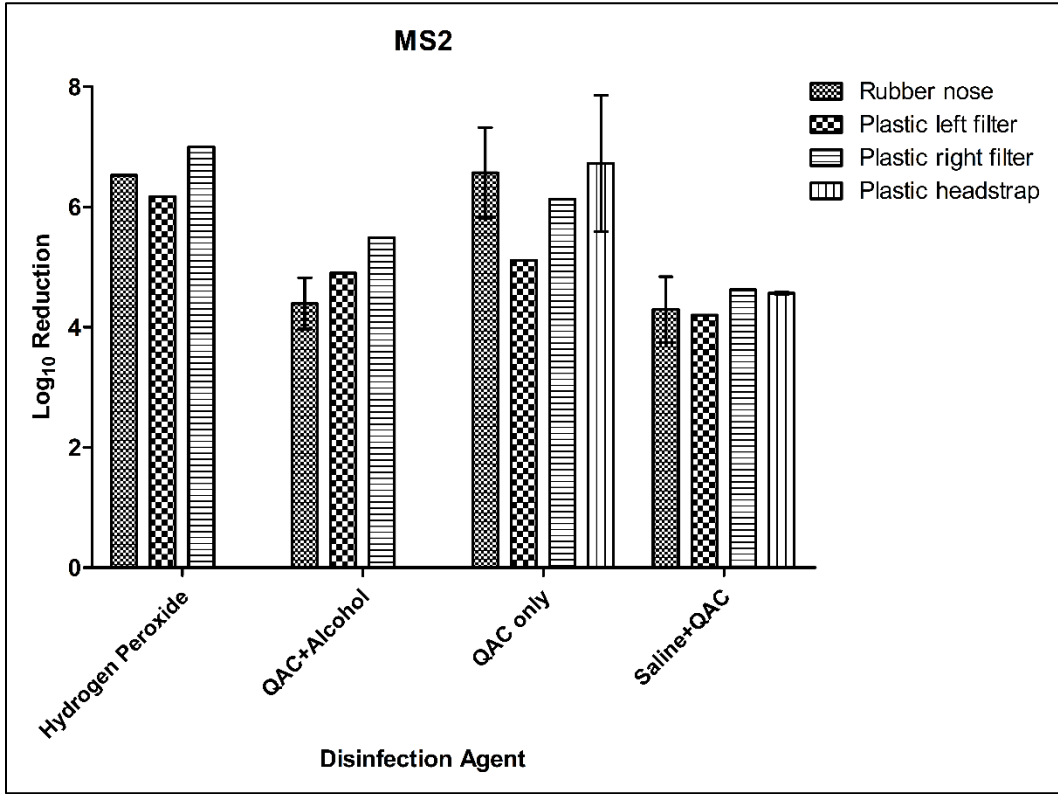


Figure 4: *Pseudomonas aeruginosa* Log Reduction Values by Surface Disinfected

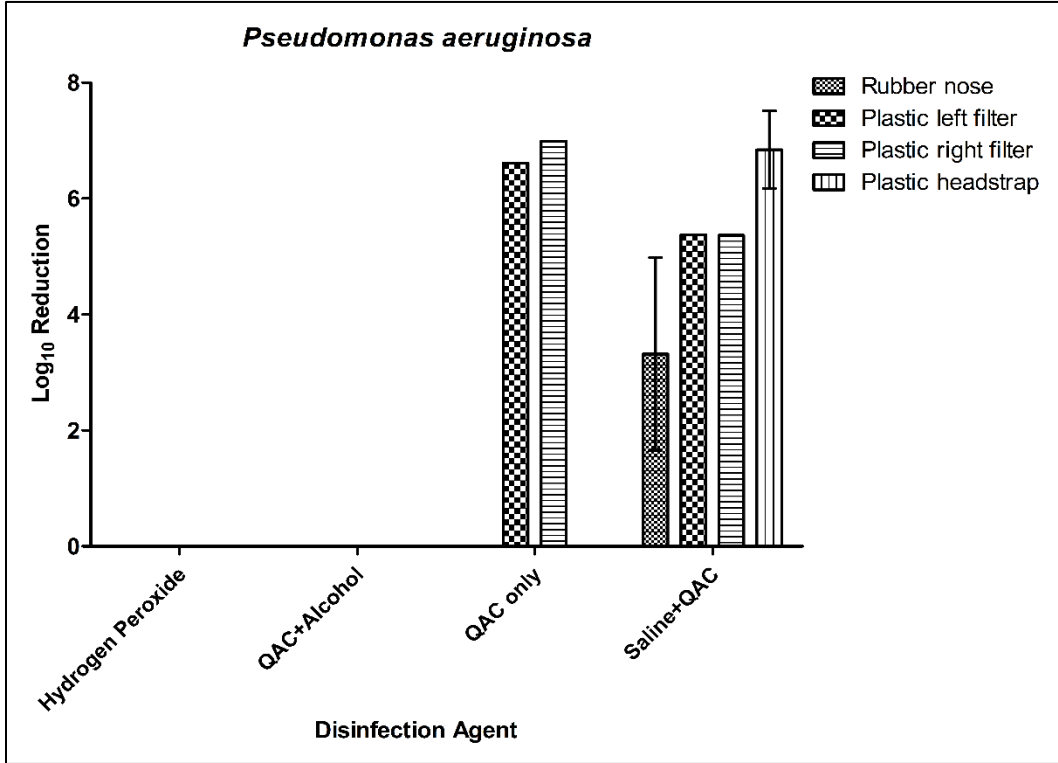
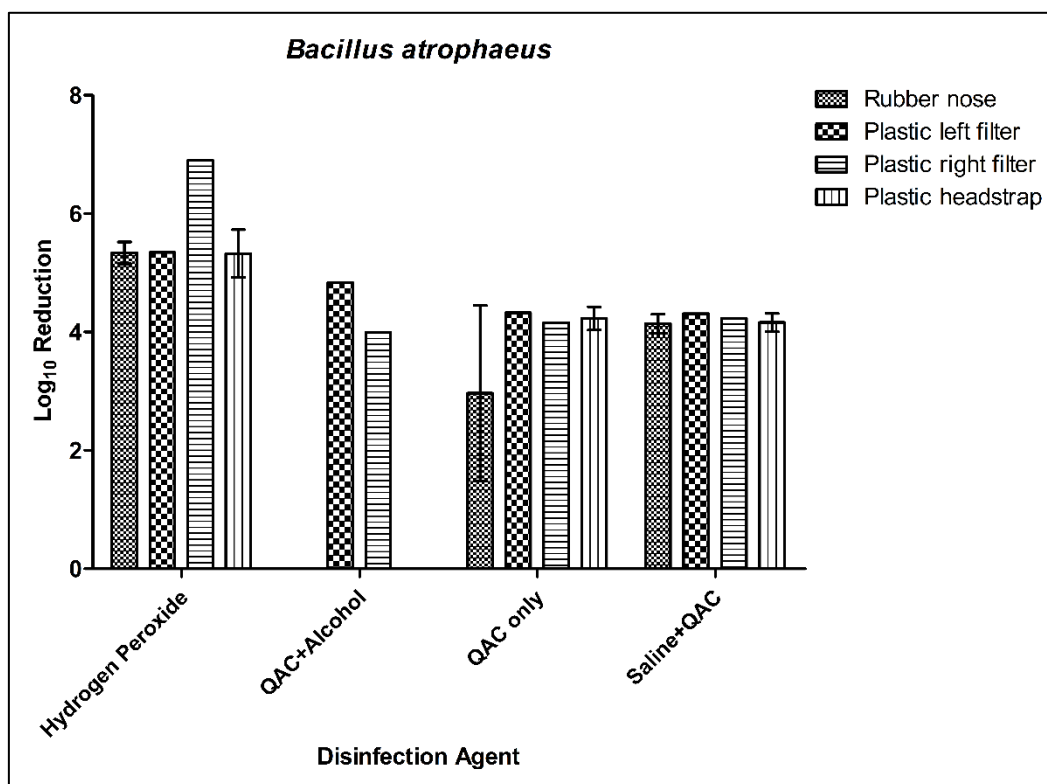


Figure 5: *Bacillus atrophaeus* Log Reduction Values by Surface Disinfected



4.4 Discussion and Conclusions

This study demonstrates the efficacy of four wipes containing common commercially available EPA approved hospital disinfection agents to decontaminate EHFRs for reuse. All disinfection agents tested produced a 4- log₁₀ to 8- log₁₀ reduction in the burden of infectious organisms on the respirator. The type of organism on the respirator influenced the efficacy of the disinfection agent. The results show that hydrogen peroxide was the most efficacious in decontaminating EHFRs soiled with any of the organisms tested, followed by QAC+Alcohol and the QAC only agent. Saline+QAC produced the least activity against all organisms.

Hydrogen peroxide has been reported to have good virucidal, bactericidal, and sporicidal properties (15-18). In the current study, following disinfection of EHFRs with 0.5% hydrogen peroxide, Phi6 (an enveloped virus with the closest structural resemblance to SARS-CoV2) and the bacterial agent *Pseudomonas aeruginosa* were undetectable on all sampled areas on the respirator, demonstrating an 8-log₁₀ reduction overall for both organisms. Similar to our results

are those from a previous study using a 0.5% hydrogen peroxide disinfectant solution and 1-minute contact time that demonstrated a 4- \log_{10} reduction in infectivity of enveloped viruses and 6- \log_{10} reduction in bacterial agents, including *Pseudomonas aeruginosa* on plastic inoculated with 10^4 and 10^6 viable organisms respectively (17,18). Furthermore, one of these studies found that hydrogen peroxide activity against non-enveloped viruses was similar to the elimination of MS2 in this study (18). Hydrogen peroxide was not completely effective at eliminating the spores of *Bacillus atrophaeus*; however, previous evidence shows a higher concentration of hydrogen peroxide and longer contact time is required to be effective against bacterial spores (20).

QACs are effective at inactivating bacteria and enveloped viruses. However, the efficacy of alcohol as a disinfection agent largely depends on the concentration. One study reported complete inactivation of SARS-CoV-2 following 1-minute contact with 0.1% didecyldimethylammonium chloride (21). The same study showed that 20% ethanol could not inactivate SARS-CoV-2, but at 30%, complete inactivation was observed (21). The combination of 0.76% didecyldimethylammonium chloride/7.5% ethanol/15% isopropanol (QAC+Alcohol) proved efficacious in eliminating Phi6 and *Pseudomonas aeruginosa* from soiled EHFRs. The performance of QAC+Alcohol against Phi6 is similar to those found during disinfection of EHFRs contaminated on the exterior surface with an enveloped human virus, the influenza virus (12). The influenza virus was not recovered by culture from any EHFRs treated with a quaternary ammonium chloride/ isopropanol wipe, similar to the QAC+Alcohol wipe used in this study (12). The activity of QAC+Alcohol was suboptimal against MS2 and the spores of *Bacillus atrophaeus*. QACs and alcohols have been shown to produce weak activity against non-enveloped viruses and lack sporicidal activity (22-25).

The activity of 0.4% benzalkonium chloride (QAC only) against Phi6 and *Pseudomonas aeruginosa* was satisfactory. Although Phi6 and *Pseudomonas aeruginosa* were detected on the plastic filters, the \log_{10} reduction from those disinfection experiments was $>7\log_{10}$. Our results differ from previous studies regarding the activity of benzalkonium chloride against enveloped viruses. These studies reported $<3\log_{10}$ reduction in human CoV 229E following disinfection

with benzalkonium chloride (26, 27). The differing results may be due to the differences in benzalkonium chloride concentration (0.4% in this study vs. 0.05-0.2% in other studies). However, it is important to note that there is currently insufficient evidence to support the effectiveness of benzalkonium chloride to eliminate SARS-CoV-2 and other enveloped viruses (28-30).

The Saline+QAC wipes used in this study contained 0.9% sodium chloride/benzalkonium chloride; the combination of Saline and a QAC produced minimal activity against all organisms, particularly MS2 and *Bacillus atropheus* spores. A high titer of all organisms remained on all surfaces on EHFRs after treatment with Saline+QAC..

From our data, organism recovery was dependent on the area of the EHFRs sampled. Organisms were less likely to be recovered from the plastic strap and rubber nose than the plastic left filter and plastic right filter. Our results differ from those of two other studies that found no difference in detecting viable influenza virus from non-porous surfaces (plastic and rubber) on EHFRs following a combination of cleaning and cleaning/disinfection processes (13, 14). The difference in results is most likely due to variation in disinfection agents and cleaning/disinfection processes. Whereas our study tested alcohol, QAC, and saline wipes, these studies tested a bleach wipe and cleaning with water and detergent.

The strengths of our study are the range of organisms and ability to follow extensive log reductions, up to 8log₁₀; therefore, with our results, we show that these disinfection agents are efficacious in eliminating virus titers in the range of those that may be shed by COVID-19 patients (7). Furthermore, we challenged these disinfection agents with a representative range of infectious agents typically encountered in healthcare. If EHFRs are routinely used in healthcare, respiratory agents are not the only contaminants of concern. Common hospital acquired pathogens are still present in the healthcare environment during respiratory disease outbreaks, and still pose risks of contamination when EHFRs are touched and handled during patient care and our results showed that the disinfection agents performed well to decontaminate EHFRs for bacteria as well as viruses.

There are several limitations present in this study. These results are from laboratory-controlled experiments; therefore, there may be differences in the effectiveness of the disinfection agents under uncontrolled environmental conditions. The next step with this research is to apply the disinfection methods among HCWs who use EHFRs for providing care to COVID-19 patients. Second, the number of wipes used to disinfect each respirator was high; five wipes were used to ensure the surfaces of each wipe were used once on the respirator. Five wipes per respirator may not be feasible in a healthcare setting with a limited supply of disinfection wipes. A lower number of wipes may produce the same results as this study if each wipe's surfaces are used no more than once on the respirator. Third, our method is limited to the disinfection agents tested; therefore, more studies are needed to test other disinfection agents in wipes, including those QACs not tested in this study, bleach wipes, and other recommended disinfection agents indicated for use in healthcare (31). Finally, our method was used on one type of EHFR, the Honeywell RU8500 Series Elastomeric Respirator. Application of our disinfection methods to other types/brands of EHFRs is needed to establish a broader applicability of our methods.

In summary, our study found that common disinfection agents in wipes are suitable for decontaminating heavily soiled EHRFs to prevent respiratory exposure to infectious agents among HCWs. Reusable EHFRs are a viable alternative to single-use N95 FFRs for HCW protection during the current COVID-19 pandemic. Disinfecting EHFRs for optimal protection of HCWs during care of patients with COVID-19 is critical. The disinfecting procedure for EHFR reuse needs to provide equal protection as single-use FFRs. Therefore, disinfection methods for EHFRs should produce complete elimination of any organisms on the respirator. As more healthcare systems introduce EHFRs to protect HCWs during the care of patients under airborne precautions, there are factors related to disinfection of EHFRs that need to be considered. These include the choice of disinfection agent and the type of infectious agent. Some disinfection agents such as hydrogen peroxide are not recommended for certain brands of EHFRs (32). The infectious agent(s) of concern, such as an enveloped vs. non-enveloped virus, and the risk of respiratory reactions among HCWs should drive disinfection agent choice. Extended exposure to some disinfection agents such as QACs has been associated with triggering asthma and COPD development (33). The methods tested in this study can be applied to inform the development of EHFR disinfection

procedures in healthcare systems. As we continue to investigate the best measures to protect HCWs during the current pandemic, more studies are needed to develop robust standardized protocols for effective point-of-care disinfection of EHFRs.

References

1. Hughes, M., Groenewold, M., Lessem, S., Xu, K., Ussery, E., ,.....Stuckey, M. (2020). Update: Characteristics of Health Care Personnel with COVID-19 - United States, February 12 to July 16, 2020. *MMWR: Morbidity & Mortality Weekly Report*, 69(38), 1364–1368.
2. Centers for Disease Control (CDC). (2020). Scientific Brief: SARS-CoV-2 and Potential Airborne Transmission. Retrieved October 24, 2020 from <https://www.cdc.gov/coronavirus/2019-ncov/more/scientific-brief-sars-cov-2.html>.
3. Brlek, A., Vidovič, Š., Vuzem, S., Turk, K., & Simonović, Z. (2020). Possible indirect transmission of COVID-19 at a squash court, Slovenia, March 2020: case report. *Epidemiology and infection*, 148, e120.
4. Cai, J., Sun, W., Huang, J., Gamber, M., Wu, J., & He, G. (2020). Indirect Virus Transmission in Cluster of COVID-19 Cases, Wenzhou, China, 2020. *Emerging Infectious Diseases*, 26(6), 1343-1345.
5. Lu J., Gu J., Li K. COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020. *Emerging Infectious Diseases*, 26:1628–1631.
6. Centers for Disease Control. (2020). *Interim Infection Prevention and Control Recommendations for Healthcare Personnel During the Coronavirus Disease 2019 (COVID-19) Pandemic*. Retrieved October 24, 2020 from <https://www.cdc.gov/coronavirus/2019-ncov/hcp/infection-control-recommendations.html>.
7. Wölfel, R., Corman, V., Guggemos, W., Seilmaier, M., Zange, S.,.....Wendtner, C. (2020). Virological assessment of hospitalized patients with COVID-2019. *Nature* **581**, 465–469.
8. Noguee, D., & Tomassoni, A. (2020). Covid-19 and the N95 respirator shortage: Closing the gap. *Infection control and hospital epidemiology*, 41(8), 958.
9. Centers for Disease Control (CDC). (2020). *Implementing Filtering Facepiece Respirator (FFR) Reuse, Including Reuse after Decontamination, When There Are Known Shortages of N95 Respirators*. Retrieved October 24, 2020 from https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe_strategy/decontamination-reuse-respirators.html.

10. Bergman, M., Viscusi, D., Zhuang, Z., Palmiero, A., Powell, J., & Shaffer, R. (2012). Impact of multiple consecutive donnings on filtering facepiece respirator fit. *American journal of infection control*, 40(4), 375–380.
11. Liverman, C., Yost, O., Rogers, B., & Clever, L. (2019). *Reusable Elastomeric Respirators in Health Care : Considerations for Routine and Surge Use*. National Academies Press.
12. Subhash, S., Cavaiuolo, M., Radonovich, L., Eagan, A., Lee, M., Campbell, S., ... (2014). Effectiveness of Common Healthcare Disinfectants against H1N1 Influenza Virus on Reusable Elastomeric Respirators. *Infection Control and Hospital Epidemiology*, 35(7), 894.
13. Lawrence, C., Harnish, D., Sandoval-Powers, M., Mills, D., ... & Heimbuch, B. (2017). Assessment of half-mask elastomeric respirator and powered air-purifying respirator reprocessing for an influenza pandemic. *AJIC: American Journal of Infection Control*, 45(12), 1324–1330.
14. Heimbuch, B. & Harnish, D. (2019). Research to Mitigate a Shortage of Respiratory Protection Devices During Public Health Emergencies (Report to the FDA No. HHSF223201400158C). Applied Research Associate, Inc. Retrieved October 19, 2020 from https://www.ara.com/sites/default/files/MitigateShortageofRespiratoryProtectionDevice_2.pdf.
15. Rutala, W., & Weber, D. (2019). Disinfection, sterilization, and antisepsis: An overview. *American Journal of Infection Control*, 47S, A3–A9.
16. Song, X., Vossebein, L., & Zille, A. (2019). Efficacy of disinfectant-impregnated wipes used for surface disinfection in hospitals: a review. *Antimicrobial Resistance and Infection Control*, 8(1), 1–14.
17. Lin, Q., Lim, J., Xue, K., Yew, P., Owh, C., Chee, P., & Loh, X. (2020). Sanitizing agents for virus inactivation and disinfection. *View* (2688-268X), 1(2), 1.
18. Omidbakhsh, N., & Sattar, S. (2006). Broad-spectrum microbicidal activity, toxicologic assessment, and materials compatibility of a new generation of accelerated hydrogen peroxide-based environmental surface disinfectant. *AJIC: American Journal of Infection Control*, 34(5), 251–257

19. Ríos-Castillo, A., González-Rivas, F., & Rodríguez-Jerez, J. (2017). Bactericidal Efficacy of Hydrogen Peroxide-Based Disinfectants Against Gram-Positive and Gram-Negative Bacteria on Stainless Steel Surfaces. *Journal of Food Science*, 82(10), 2351–2356.
20. Sagripanti J, & Bonifacino A. (1996). Comparative sporicidal effect of liquid chemical germicides on three medical devices contaminated with spores of *Bacillus subtilis*. *American Journal of Infection Control*, 24(5), 364–371.
21. Xiling, G., Yin, C., Ling, W., Xiaosong, W., Jingjing, F., Fang, L... & Yan., X. (2021). In vitro inactivation of SARS-CoV-2 by commonly used disinfection products and methods. *Scientific Reports*, 11(1), 1–9.
22. Gehrke, C., Steinmann, J., & Goroncy-Bermes, P. (2004). Inactivation of feline calicivirus, a surrogate of norovirus (formerly Norwalk-like viruses), by different types of alcohol in vitro and in vivo. *Journal of Hospital Infection*, 56(1), 49–55.
23. Doultree, J. C., Druce, J. D., Birch, C. J., Bowden, D. S., & Marshall, J. A. (1999). Inactivation of feline calicivirus, a Norwalk virus surrogate. *Journal of Hospital Infection*, 41(1), 51–57.
24. Weber, D., Sickbert-Bennett, E., Gergen, M., Rutala, W. (2003). Efficacy of Selected Hand Hygiene Agents Used to Remove *Bacillus atrophaeus* (a Surrogate of *Bacillus anthracis*) From Contaminated Hands. *JAMA, Journal of the American Medical Association*, 289(10), 1274–1277.
25. Yim, J., Song, K., Kim, H., Bae, D., Chon J., & Seo, K. (2021). Effectiveness of calcium hypochlorite, quaternary ammonium compounds, and sodium hypochlorite in eliminating vegetative cells and spores of *Bacillus anthracis* surrogate. *Journal of Veterinary Science*, 22(1):e11.
26. Wood, A., & Payne, D. (1998). The action of three antiseptics/disinfectants against enveloped and non-enveloped viruses. *Journal of Hospital Infection*, 38(4), 283–295.
27. Sattar, S. A., Springthorpe, V. S., Karim, Y., and Loro, P. (1989). Chemical disinfection of non-porous inanimate surfaces experimentally contaminated with four human pathogenic viruses. *Epidemiology and Infection*, 102(3), 493–505.
28. Kampf, G., Todt, D., Pfaender, S., & Steinmann, E. (2020). Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. *Journal of Hospital Infection*, 104(3), 246–251.

29. Schrank, C., Minbiole, K., & Wuest, W. (2020). Are Quaternary Ammonium Compounds, the Workhorse Disinfectants, Effective against Severe Acute Respiratory Syndrome Coronavirus-2? *ACS Infectious Diseases*, 6(7), 1553–1557.
30. Centers for Disease Control. (2020, May 17). *Hand hygiene recommendations: Guidance for Healthcare Providers about Hand Hygiene and COVID-19*. Retrieved March 18, 2021 from <https://www.cdc.gov/coronavirus/2019-ncov/hcp/hand-hygiene.html>.
31. Rutala, W., & Weber, D. (2019, May 1). Guideline for Disinfection and Sterilization in Healthcare Facilities, 2008. <https://www.cdc.gov/infectioncontrol/pdf/guidelines/disinfection-guidelines-H.pdf>
32. 3M Personal Safety Division. (2021, March 1). *Cleaning and Disinfecting 3M Reusable Elastomeric Half and Full Facepiece Respirators following Potential Exposure to Coronaviruses*. <https://multimedia.3m.com/mws/media/1793959O/cleaning-and-disinfecting-3m-reusable-respirators-following-potential-exposure-to-coronaviruses.pdf>
33. Dumas, O., Varraso, R., Boggs, K., Quinot, C., Zock, J... & Camargo, C. (2019). Association of Occupational Exposure to Disinfectants With Incidence of Chronic Obstructive Pulmonary Disease Among US Female Nurses. *JAMA Network Open*, 2(10), e1913563.

Chapter 5. Dissertation Summary

Overall, the three studies presented provide new insights into critical aspects of protecting healthcare workers from exposure to infectious agents at the point of care as well as reducing risks of provider-to-patient transfer of pathogens. All three studies focus on providing novel recommendations for optimizing HCW behavior and PPE use. The first study used a simulation method that combined microbiological and human factors analysis to determine the errors that occur when HCWs use complex high-level PPE to prevent exposure to high consequence infectious agents such as the Ebola virus. Specifically, we demonstrate that the PAPR hood design, which protects the head and neck of the HCW, influences failure modes and self-contamination. A greater number of failure modes were observed for the two-layer hood, and it took longer to doff than the one-layer hood. However, self-contamination was greater for the one-layer hood. We recommend that the PPE item that provides less risk for self-contamination be made available to HCWs. If a design is already available in the stockpile, infection preventionists should improve the donning and doffing procedure. This is closely related to the design of the PPE item and influences the risk of exposure.

While the design of PPE items is important, human behavior plays a central role in all the infection risks studied here. For example, a PPE item's design will not successfully protect HCWs without adequate hand hygiene (HH). As demonstrated by our simulation approach to PAPR use, having effective methods for studying and observing key behaviors is crucial to designing effective interventions. In the second study, we determine HH adherence using data collected using a newly developed automated system. The automated system collected individualized data that allowed for accounting for individual variation in HH adherence. HH adherence improved steadily over the 41 weeks of data collection and was influenced by several factors. In both hospitals examined, bundling improvement strategies were more effective at improving adherence than single strategy interventions. We show that adherence is influenced by the healthcare professional group, hospital unit, and time of day. However, the effect of HCW group on adherence was more concrete than hospital unit and time of day. We highlight that medical providers in this study responded well to the intervention strategies used to improve HH and demonstrated the highest adherence levels than

other HCW groups. More research is needed to establish the influence of the type of hospital unit and time of day.

Optimal HH adherence is an effective measure for HCW protection during the current coronavirus disease 2019 (COVID-19) pandemic. Nevertheless, HH alone cannot prevent other exposure pathways, such as respiratory exposure, for HCW at the point of care. In the third study, we examine decontamination methods for elastomeric half-face respirators (EHFRs) using four disinfection agents commonly available in healthcare. We demonstrate that hydrogen peroxide wipes performed best in disinfecting heavily soiled EHFRs compared to alcohol and quaternary ammonium compounds (QACs), using a standard disinfection procedure. However, we recommend that before deciding on the type of disinfection agent to be used by HCWs, infection preventionists need to account for the type of infectious agent and the type/brand of EHFR.

In conclusion, HCWs are at an increased risk of exposure to infectious agents compared to workers in other occupations and the general population. Infection prevention and control programs rely on evidence-based methods to provide adequate protection for HCWs. PPE use and HCW behavior are crucial aspects of infection prevention that, when optimized, provide a safer work environment for HCWs. Further studies are needed to explore the influence of other PPE items (gowns and gloves) designs on infection risk, HH improvement strategies that combine automated systems, and PPE decontamination methods to provide more robust evidence-based results to inform HCW protection.

References for Chapter 1

1. US Department of Human and Health Services (2020, October 8). *Occupational Health and Safety*. <https://www.healthypeople.gov/2020/topics-objectives/topic/occupational-safety-and-health>
2. Joseph, B. & Joseph, M. (2016). The Health of the Health Care Workers. (2016). *Indian Journal of Occupational & Environmental Medicine*. 20(2): 71-72.
3. US Department of Labor, Bureau of Labor Statistics (2020, November 4). Incidence rates of nonfatal occupational injuries and illnesses by industry and case types. https://www.bls.gov/iif/oshwc/osh/os/summ1_00_2019.htm
4. Do, A., Ciesielski, C., Metler, R., Hammett, T., Li, J., & Patricia L. Fleming. (2003). Occupationally Acquired Human Immunodeficiency Virus (HIV) Infection: National Case Surveillance Data During 20 Years of the HIV Epidemic in the United States. *Infection Control and Hospital Epidemiology*, 24(2), 86–96.
5. Siegel, J., Rhinehart, E., Jackson, M., & Chiarello, L. (2007). 2007 Guideline for Isolation Precautions: Preventing Transmission of Infectious Agents in Health Care Settings. *AJIC: American Journal of Infection Control*, 35(10), S65–S164.
6. Williams, V., Leis, J., Trbovich, P., Agnihotri, T., Lee, W., Joseph, B., ... & Powis, J. (2019). Improving healthcare worker adherence to the use of transmission-based precautions through application of human factors design: a prospective multi-centre study. *Journal of Hospital Infection*, 103(1), 101–105.
7. Centers for Disease Control. Guidelines for preventing the transmission of Mycobacterium tuberculosis in healthcare settings, 2005. *MMWR Recommendations and Reports* 2005;54(17):1-141.
8. Centers for Disease Control. (2020, May 17). Hand Hygiene Recommendations: Guidance for Healthcare Providers about Hand Hygiene and COVID-19. <https://www.cdc.gov/coronavirus/2019-ncov/hcp/hand-hygiene.html>
9. Hughes, M., Groenewold, M., Lessem, S., Xu, K., Ussery, E.,, Stuckey, M. (2020). Update: Characteristics of Health Care Personnel with COVID-19 - United States, February 12 to July 16, 2020. *MMWR: Morbidity & Mortality Weekly Report*, 69(38), 1364–1368.

10. Nguyen, L., Drew, D., Graham, M., Joshi, A., Guo, C.-G., Ma, W., ... Chan, A. T. (2020). Risk of COVID-19 among front-line health-care workers and the general community: a prospective cohort study. *The Lancet. Public Health*, 5(9), e475–e483.
11. Liddell, A., Davey, R., Mehta, A., Varkey, J., Kraft, C., & Uyeki, T. (2015). Characteristics and Clinical Management of a Cluster of 3 Patients with Ebola Virus Disease, Including the First Domestically Acquired Cases in the United States. *Annals of internal medicine*, 163(2), 81–90.
12. Centers for Disease Control and Prevention (2014, October 24). CDC tightened guidance for U.S. healthcare workers on personal protective equipment for Ebola. <https://www.cdc.gov/media/releases/2014/fs1020-ebola-personal-protective-equipment.html>.
13. World Health Organization (2015, May 31). Health Worker Ebola Infections in Guinea, Liberia, and Sierra Leone: A Preliminary Report. <https://www.who.int/csr/resources/publications/ebola/health-worker-infections/en/>.
14. Edmond MB, Diekema DJ, Perencevich EN. (2014). Ebola virus disease and the need for new personal protective equipment. *JAMA*, 312:2495–6.
15. Mumma, J., Durso, F., Ferguson, A., Gipson, C., Casanova, L., Erukunuakpor, K., ... DuBose, J. (2018). Human Factors Risk Analyses of a Doffing Protocol for Ebola-Level Personal Protective Equipment: Mapping Errors to Contamination. *Clinical Infectious Diseases*, 66(6), 950–958.
16. McGuckin, M., Waterman, R., & Govednik, J. (2009). Hand hygiene compliance rates in the United States--a one-year multicenter collaboration using product/volume usage measurement and feedback. *American Journal of Medical Quality*, 24(3), 205–213.
17. Pittet, D. (2000). Improving Compliance with Hand Hygiene in Hospitals. *Infection Control and Hospital Epidemiology*, 21(6), 381.
18. Haas, J. & Larson, E. (2008), Impact of Wearable Alcohol Gel Dispensers on Hand Hygiene in an Emergency Department. *Academic Emergency Medicine*, 15: 393-396.
19. World Health Organization. (2009). WHO Guidelines on Hand Hygiene in Health Care: First Global Patient Safety Challenge Clean Care Is Safer Care. Geneva: Available from: <https://www.ncbi.nlm.nih.gov/books/NBK144013/>

20. Buffet-Bataillon, S., Leray, E., Poisson, M., Michelet, C., & Cormier, M. (2010). Influence of job seniority, hand hygiene education, and patient-to-nurse ratio on hand disinfection compliance. *Journal of Hospital Infection*, 76(1), 32–35.
21. Kohli, E., Ptak, J., Smith, R., Taylor, E., Talbot, E., & Kirkland, K. (2009). Variability in the Hawthorne effect with regard to hand hygiene performance in high- and low-performing inpatient care units. *Infection control and hospital epidemiology*, 30(3), 222–225.
22. Dhar, S., Tansek, R., Toftey, E., Dziekan, B., Chevalier, T., & Kaye, K. (2010). Observer Bias in Hand Hygiene Compliance Reporting. *Infection Control and Hospital Epidemiology*, 31(8), 869-870.
23. Masroor, N., Doll, M., Stevens, M., & Bearman, G. (2017). Approaches to hand hygiene monitoring: From low to high technology approaches. *International Journal of Infectious Diseases*, 65, 101–104.
24. Honeycutt, M., Linam, W., Gilliam, C., Wisdom, C., & Deshpande, J. (2014). Successful Development of a Valid Direct Observation System to Measure Healthcare Professional Hand Hygiene Utilizing Multiple Trained Volunteers. *AJIC: American Journal of Infection Control*, 42(6), S137.
25. Pong, S., Holliday, P., & Fernie, G. (2018). Effect of electronic real-time prompting on hand hygiene behaviors in health care workers. *AJIC: American Journal of Infection Control*, 46(7), 768–774.
26. Liverman, C., McCoy, M., Domnitz, S., & Institute of Medicine (U.S.). (2015). *The Use and Effectiveness of Powered Air Purifying Respirators in Health Care: Workshop Summary*. National Academies Press.
27. Noguee, D., & Tomassoni, A. J. (2020). Covid-19 and the N95 respirator shortage: Closing the gap. *Infection control and hospital epidemiology*, 41(8), 958.
28. Centers for Disease Control. (2020). Interim Infection Prevention and Control Recommendations for Healthcare Personnel During the Coronavirus Disease 2019 (COVID-19) Pandemic. Retrieved from <https://www.cdc.gov/coronavirus/2019-ncov/hcp/infection-control-recommendations.html> Accessed 10/24/2020.
29. Wölfel, R., Corman, V., Guggemos, W., Seilmaier, M., Zange, S.,.....Wendtner, C. (2020). Virological assessment of hospitalized patients with COVID-2019. *Nature* **581**, 465–469.

References for Images in Chapter 2

1. ShalexOverseas (n.d). Retrieved from:
<https://www.shalexoverseas.com/wecare/blog/project/high-risk-prevention-kit/>
2. Hubbard Supply co. (n.d) Retrieved from:
<https://www.hubbardsupply.com/2528873/product/3m-051131-07037-h-series-hood-with-collar-standard-for-use-with-3m-belt-mounted-powered-air-purifying-respirator-papr-and-supplied-air-respirator-systems-white>
3. 3M (n.d). Retrieved from: https://www.3m.com/3M/en_US/company-us/all-3m-products/~/3M-Versaflo-Hood-Assembly-with-Inner-Shroud-Premium-Head-Suspension-S-657-1-EA-Case/?N=5002385+3294753631&rt=rud