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Role of Human Factors Engineering in Infection Prevention: Gaps and Opportunities

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Opinion statement

Human factors engineering (HFE), with its focus on studying how humans interact with systems, including their physical and organizational environment, the tools and technologies they use, and the tasks they perform, provides principles, tools, and techniques for systematically identifying important factors, for analyzing and evaluating how these factors interact to increase or decrease the risk of Healthcare-associated infections (HAI), and for identifying and implementing effective preventive measures. We reviewed the literature on HFE and infection prevention and control and identified major themes to document how researchers and infection prevention staff have used HFE methods to prevent HAIs and to identify gaps in our knowledge about the role of HFE in HAI prevention and control. Our literature review found that most studies in the healthcare domain explicitly applying (HFE) principles and methods addressed patient safety issues not infection prevention and control issues. In addition, most investigators who applied human factors principles and methods to infection prevention issues assessed only one human factors element such as training, technology evaluations, or physical environment design. The most significant gap pertains to the limited use and application of formal HFE tools and methods. Every infection prevention study need not assess all components in a system, but investigators must assess the interaction of critical system components if they want to address latent and deep-rooted human factors problems.

Introduction

To prevent healthcare-associated infections (HAIs), infection prevention and control staff and other healthcare workers must systematically identify, analyze, and evaluate factors associated with HAIs, and how these factors interact. Such factors include:

(1) people, both patients, and healthcare workers;
(2) medical devices, tools, and technologies;
(3) personal protective equipment used by healthcare workers;
(4) the physical environment; and
(5) infection prevention and control guidelines, policies, and procedures.

Human factors engineering (HFE), with its focus on studying how humans interact with systems, including their physical and organizational environment, the tools and technologies they use, and the tasks they perform, provides principles, tools, and techniques for systematically identifying important factors, for analyzing and evaluating how these factors interact to increase or decrease the risk of HAI, and for identifying and implementing effective preventive measures [1].

We reviewed the literature on HFE and infection prevention and control and identified major themes to document how researchers and infection prevention staff have used HFE methods to prevent HAIs and to identify gaps in our knowledge about the role of HFE in HAI prevention and control. To accomplish this goal, we searched, with the help of a research librarian, more than 1000 research databases including PubMed, Web of Science, Ingenta Connect, JSTOR and EBSCO to find relevant publications. This paper reports the results of this literature review.

Review findings

We categorized the studies into those that evaluated: HFE and hand hygiene promotion, behavioral science determinants of HAI prevention, the physical environment as a factor in HAI prevention, technological determinants of HAI prevention, HFE and use of personal protective equipment, and overall infection prevention topics. The paper discusses the major thematic areas in the following sections.

Human factors engineering and hand hygiene

Many studies applying HFE techniques to infection prevention and control have investigated hand hygiene practice and efforts to improve hand hygiene compliance. Many of these studies have examined how systems, the environment, cognitive factors, technology, and training affect hand hygiene adherence (Fig. 1).

Hand hygiene improvement using the systems approach

Studies have assessed whether organizational factors such as leadership, organizational support and culture [2], and coordination mechanisms (e.g., huddles), affect hand hygiene compliance. For example, Voss and Widmer [3] calculated that during a single intensive care unit (ICU) shift, 12 nurses would spend 2 h doing hand hygiene with an alcohol-based hand rub if they were 60% compliant and 4 h if they were 100% compliant. Moreover, several groups have found that healthcare workers' workload affects their hand hygiene compliance [4, 5, 6, 7•]. Lee et al. [4] conducted an observational study in nine European

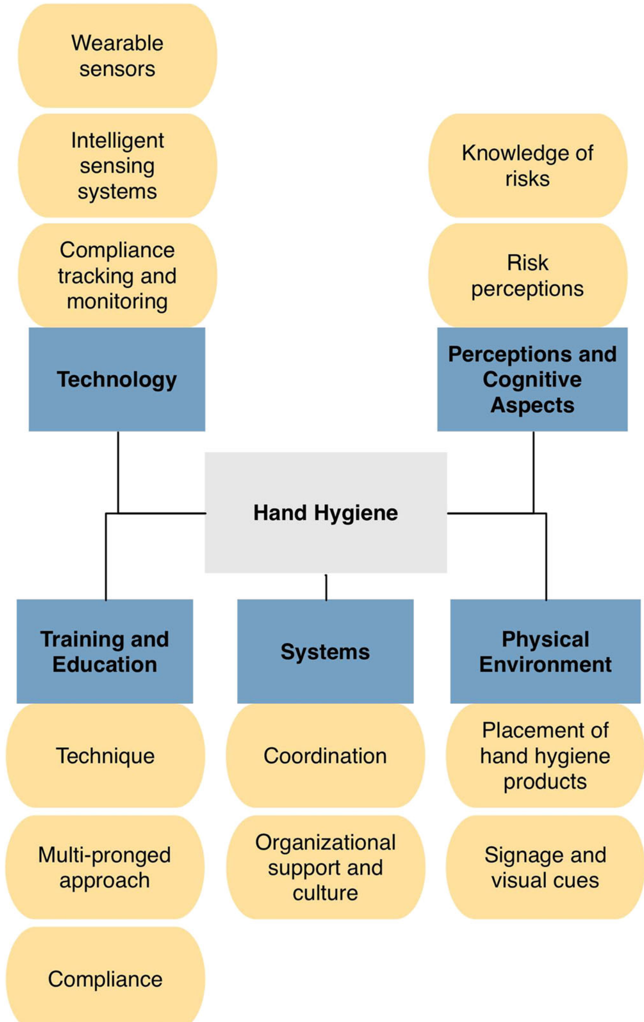

Fig. 1. Major issues addressed by studies using human factors engineering principles to assess or improve hand hygiene compliance.

countries and found that the nurses' workload, as assessed by the patient to nurse ratio, was inversely associated with compliance in the multivariable analysis. Dunn-Navarra et al. [8] found that hospitals with morning huddles were significantly more likely than other hospitals to report hand hygiene compliance rates of ≥95%, suggesting that the "organizational tools to improve teamwork, coordination, and communication" among healthcare workers may facilitate hand hygiene improvement efforts. In contrast, they found that other organizational factors did not influence hand hygiene compliance significantly [8].

Hand hygiene and the built environment

Carter et al. [9••] conducted an observational study to examine how physical layout affects hand hygiene compliance. Their multivariable analysis found that compliance was lowest when the emergency department was most crowded and was lower in "hallway care areas" than in semiprivate areas [9••]. In addition, the location of hand sanitizing products within the geographical space of the care environment significantly affects compliance [10–13]. Birnbach [12] found that dispenser location and visibility within patient rooms significantly affected hand hygiene adherence (i.e., immediately adjacent to the patient [53.8%] vs. across from the patient's bed and not clearly visible [11.5%]). Suresh et al. [14] used an ergonomic assessment tool to evaluate ICUs and 59 patient rooms for "structural ergonomic characteristics" that facilitate use of alcohol-based hand rub dispensers. They found "deficiencies in the structural layout" that could hinder use of dispensers. For example, dispensers were in locations where healthcare workers could not see or access them easily and dispensers often were in locations that did not facilitate their use within the sequence of care [14]. To address the visibility issue, Rashidi et al. [15•] and D' Egidio et al. [16] placed flashing lights to dispensers and found that hand hygiene adherence increased. However, the compliance rates during the intervention periods were still unacceptably low, 20.7 and 25.3%, respectively [16, 15•]. Healthcare workers and companies that make hand hygiene dispensers might avoid the problems described by Birnbach et al. [12] and Suresh et al. [14] or failed interventions, like that described by Rashidi et al. [15•] and D' Egidio et al. [16] if they apply the HFE principles of salience, perception and attention, and effective display design. For example, dispensers designed based on the principle of salience (e.g., bright color, unique shape, context sensitive blinking lights or audio) could help healthcare workers more easily perceive dispensers in the patient care zone, and remind them to "attend" to hand hygiene more consistently.

Hand hygiene and healthcare worker's perceptions

Behavioral modeling studies [2] and reviews of current literature on HCW's hand hygiene-related behaviors [17, 18] have shown that interpersonal factors and individual healthcare workers' characteristics affect hand hygiene compliance. For example, Pittet et al. [6] found that hand hygiene compliance was associated with a "positive attitude toward hand hygiene after patient contact," the awareness that one's hand hygiene was being observed, and the belief that one was a role model for other healthcare workers. In addition, healthcare workers' perceptions of infection risks associated with improper hand hygiene and their knowledge of hand hygiene guidelines and mechanisms of transmission can influence hand hygiene compliance [19]. McLaughlin et al. [19] found that higher levels of knowledge about hand hygiene were associated with a beneficial effect on healthcare workers' assessment of the risk that they could transfer pathogens to patients. However, they noted that only very high levels of knowledge affected the risk ratings, suggesting that very high knowledge levels may be required to improve hand hygiene compliance.

Lutze et al. [20••] found that physicians and nurses working in ICUs believed that hand hygiene prevents transmission of pathogens. However, nurses perceived the risk reduction to be greater than did physicians, and nurses' rated their knowledge of the guidelines higher than physicians rated their own knowledge. The belief that hand hygiene substantially reduced the transmission risk was associated with high response efficacy (the extent to which a person believes that a recommended response is effective), behavioral intention (a person's assessment of the likelihood that she will engage in a specific behavior), and self-efficacy (a persons' assessment of his ability to execute specific behaviors), but not with self-rated knowledge. On the basis of these results, Lutze et al. [20••] concluded that both educational measures and skills training are needed to improve hand hygiene compliance and that physicians may require special attention.

Hand hygiene, data monitoring technology and compliance

To date, most hospitals that monitor hand hygiene compliance have had human observers collect the data. However, human observers capture only a small percentage of the possible hand hygiene opportunities and they are susceptible to the Hawthorne effect [21••]. Automated systems are now available that continuously monitor hand hygiene compliance and, thus, provide data for higher percentage of hand hygiene opportunities and likely minimize the Hawthorne effect. Automated systems providing instant feedback may help increase compliance [22]. However, few studies have assessed whether they actually increase compliance [23••]. Automated systems also have the potential to produce standardized data for a hand hygiene metric that could be compared within or across healthcare facilities over time [21••]. Conway [21••] recently reviewed significant HFE issues associated with implementation of automated hand hygiene monitoring systems. We will discuss some of the issues in the following paragraphs.

Currently, automated systems range from devices recording each time a dispenser is used to fully automated systems recording all hand hygiene opportunities, providing feedback or reminders to healthcare workers, and responding to the healthcare workers' actions [23••, 24, 25]. Results of studies comparing compliance as measured by human observers and by automated systems have varied. For example, Sharma et al. [26] evaluated nearly 1400 hand hygiene-related events recorded by an automated system and by human observers. They found that the details of the observations differed for 38% of the events. They postulated that the discrepancies may have been due to the "distance between the observer and the event" and the clinic's level of busyness [26]. Swoboda et al. [27] found that hand hygiene compliance assessed by observers was 20% (±2%) higher than that assessed by the electronic monitoring system. They attributed this in part to the fact that the observers monitored compliance for healthcare workers only whereas the system monitored compliance for all persons entering the room. In contrast, Filho et al. [28] evaluated an automatic system and found a 92% (95% confidence interval [CI], 90%–95%) overall concordance with an intraclass correlation coefficient of 0.87 (95% CI, 0.77–0.92) when comparing the electronic system and human observers. Morgan et al. [22] conducted a quasi-experimental study and found that electronic dispenser counts increased significantly but directly observed compliance did not after monthly feedback of compliance data was introduced. They concluded that automatic systems might be more sensitive to changes in hand hygiene compliance and, thus, may assess results of an intervention more accurately than human observers, whereas, human observers provide information (e.g., was hand hygiene done at the appropriate time) necessary for those designing behavioral interventions to improve hand hygiene compliance [29, 22].

In the future, sophisticated intelligent sensing compliance monitoring systems may provide additional benefits. For example, these systems may be able to determine when healthcare workers are doing tasks that require hand hygiene after the task is complete, remind healthcare workers to do hand hygiene, and, provide timely feedback to healthcare workers on their hand hygiene compliance [29]. Additionally, intelligent sensing and monitoring systems could help us identify factors such as healthcare worker job classifications, "situations, locations, and specific times" associated with low hand hygiene compliance [29]. This information could help staff design effective interventions to improve compliance.

Current automatic systems have limitations. In 2014, Dawson et al. [30••] published a review of 19 systems and found that none were fully fit for purpose (FFP) with respect to monitoring, measuring, and providing feedback for all 5 hand hygiene moments specified by the World Health Organization (WHO). Fifteen systems were FFP for moment 1 (before touching a patient) and 14 were FFP for moment 4 (after touching a patient). Only 3 were FFP for moment 5 (after touching the patient's surroundings) and none were FFP for moments 2 and 3 (before a clean or aseptic procedure and after doing a task with a risk of exposure to body fluids) [30••]. Many current systems do not provide information about contextual factors or work flow such as who enters the room (e.g., staff vs. visitors), the number of people entering a room (e.g., one person entering a room vs. a group of people entering together), or the reason people enter the room (e.g., doing patient care vs. asking the patient a question) [31, 23••, 22]. In addition, "sensor networks record hand hygiene events within a defined care area" and miss those that occur outside that area [23••]. Automatic systems also create issues regarding patient and healthcare worker confidentiality and privacy [32, 21••, 33].

Conway [21••] recently reviewed significant HFE issues associated with implementation of automated hand hygiene monitoring systems. She noted that the system must "minimize disruption to the physical structure and to clinician workflow" and fit with the "organization's culture and budget." Leaders must obtain "buy-in" from front–line workers and address their concerns about data accuracy and about "how the data will be used." Leaders also must provide hand hygiene data to healthcare workers such that they can use the data to improve compliance [21••].

Hand hygiene, training and education

Results of several studies [30••, 34–36] suggest that multimodal programs including education and training together with feedback of compliance, effective reminders, and supportive organizational and system factors are necessary to improve hand hygiene compliance. A study by Widmer et al. [37] found that training improved both hand hygiene technique, as measured by the $\log_{10}$ reduction in bacterial colony forming units and hand hygiene compliance. Stewardson et al. [38••] found that a device using video-measurement technology and immediate feedback significantly improved the number of WHO-recommended "poses" healthcare workers used during hand hygiene. However, Kwok et al. [39] found that an automated hand hygiene training system used by 79% of clinicians was not associated with improved hand hygiene compliance. Gluck et al. [40] found that international medical graduates had lower hand hygiene compliance than American graduates during a standardized patient encounter. These investigators suggested that one should consider where physicians went to medical school when designing interventions, such as "intern orientation and clinical education," to improve hand hygiene behaviors [40].

Several studies have shown that signs (i.e., reminders) alone or in combination with feedback of hand hygiene compliance data do not increase compliance [41, 42, 43•]. However, Reisinger et al. [43•] found that a sign "using messages focused on patient consequences and gain-framed language" was associated with higher absolute compliance compared with other theoretically derived signs, suggesting that the "specific type of messaging strategy" might affect the efficacy of hand hygiene poster campaigns.

Infection prevention and human factors engineering: Other topics

Investigators have used human factors engineering principles to address several other infection prevention issues, including: cognitive aspects of infection prevention, design of the physical environment, technology and tools, and design and use of personal protective equipment (PPE; Fig. 2). We briefly discuss these studies in this section.

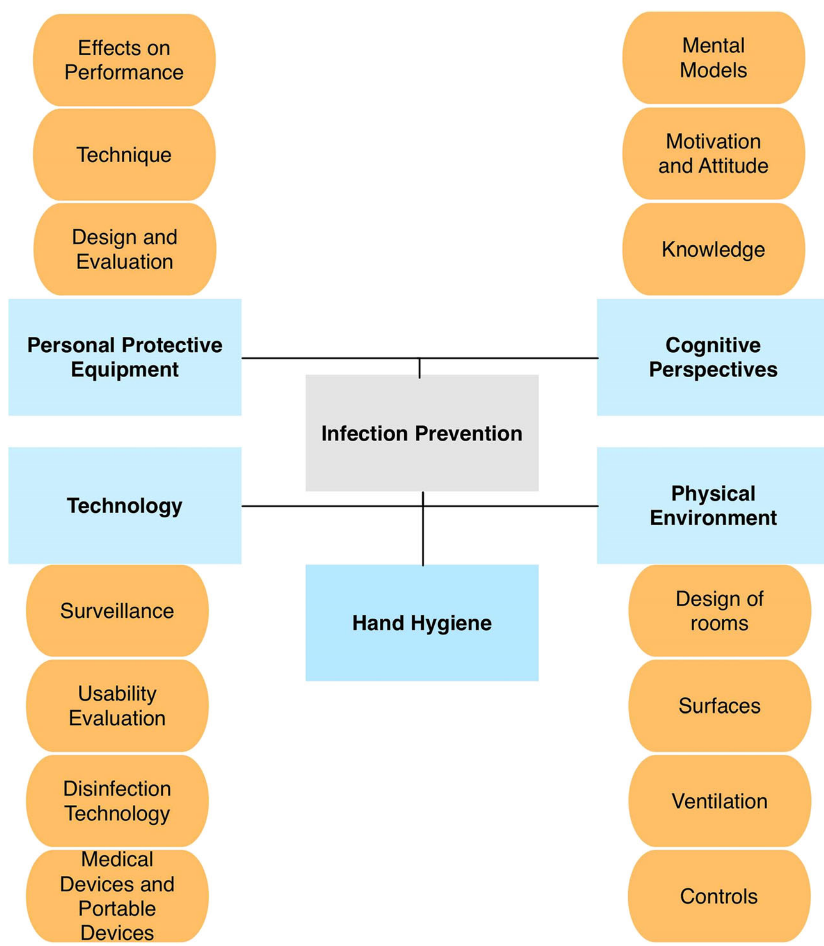

Fig. 2. Major themes in infection prevention and human factors engineering.

Behavioral science and infection prevention and control interventions

Infection prevention experts are investigating the utility of applying methodologies and theories from behavioral sciences to infection prevention interventions [5]. Aside from studies done to improve hand hygiene compliance, most publications addressing social cognitive determinants of infection prevention behavior, including mental models, review the behavioral concepts and theories and then use them as a framework for describing possible multimodal interventions [5, 44••, 45, 46, 47]. In his Lowbury Lecture, Didier Pittet [5] discussed cognitive determinants, such as knowledge, motivation, threat perception, expectations regarding outcomes (attitude; perceived efficacy of an intervention), perceived ability to accomplish a task (self-efficacy), and social pressure (perceived views of important persons or groups), that may affect the efficacy of infection prevention measures. He also asserted that further studies should be done in different populations to identify key determinants of infection prevention behavior and methods for modifying these behaviors.

In a recent paper, Sax and Clack [44••] discussed how healthcare workers' concepts of reality (i.e., mental models) may determine whether they implement good infection prevention practices. Sax and Clack [44••] noted that mental models are "internal images, gathered through experience and observations to collectively form an internal representation of the individual's understanding of the world . . . .". People use mental models as they interpret new observations and make predictions. However, mental models may not be complete or accurate representations of reality and, thus, might prevent people, including healthcare workers, from implementing beneficial practices. Sax and Clack [44••] proposed two ways to help healthcare workers create mental models that would facilitate infection prevention: (1) providing healthcare workers with experiences that optimize their "mental models regarding infection prevention and control"; (2) "designing the workplace so that it aligns with existing mental models" and facilitates safe practices. Given that microbial pathogens and the effect of hand hygiene on microbial counts are not visible to the eye and the contamination event and a related HAI are separated in time, healthcare workers may have difficulty creating correct mental models about HAI and preventive measures. Thus, Sax and Clack [44••] recommended creating educational experiences that help healthcare workers "see" the invisible, such as simulations with fluorescent markers to demonstrate how healthcare workers' hands and clothes become contaminated during patient care, and creating policies, such as the WHO's 5 moments for hand hygiene, that enable healthcare workers to know exactly when a specific behavior is required. Sax and Clack [44••] also suggested that designers, who understand healthcare workers' mental models, might be able to incorporate "cues that trigger automatic behavior," such as tape on the floor to indicate where the patient-care zone starts and ends, to improve infection prevention behavior.

In addition, infection prevention staff and other clinicians may be able to facilitate long-term compliance with infection prevention guidelines, policies, and procedures if they understand how healthcare worker's cognitive limitations and capabilities affect their ability to comply and then write guidelines and policies and design procedures that minimize the cognitive demands associated with compliance. These demands include the conscious attention needed to do specific infection prevention tasks, the effort required to do these tasks, distractions in the environment, and overall workload. Alvarado et al. [48] used a human factors and ergonomics task analysis to assess the process of placing central venous catheters with ultrasonic guidance [49]. They found that physicians inserting these catheters were often interrupted to address issues unrelated to placing the catheters. Some interruptions caused “breaks in the primary task” and likely increased the physicians’ cognitive load by forcing them to shift their attention from their task to unrelated issues and preventing them from formulating “a complete and coherent picture of the task at hand.” [48, 49] In addition, organizational policies and practices can further strain healthcare workers’ cognitive abilities. For example when staffing levels decrease, individual healthcare worker’s workloads increase [50], which may cause these healthcare workers to eliminate steps they consider to be extra or unnecessary (i.e., take short cuts), including steps that decrease the infection risk.

Physically designing the care environment

The physical environment can substantially affect healthcare workers’ ability to implement good infection prevention measures and the physical environment itself can limit or enhance the risk of transmission. For example, healthcare workers participating in focus groups conducted by Lavender et al. [51•] noted that hand hygiene products were often placed in inconvenient or in inconsistent locations and some patient rooms did not have sinks that staff could use. In addition, numerous outbreaks of organisms such as the Coronavirus that caused Severe Acute Respiratory Syndrome (SARS) [52, 53], *Pseudomonas aeruginosa* [54], and *Legionella pneumophila* [55], in healthcare facilities have been associated with faulty design. To help prevent outbreaks and cross transmission to individual patients, persons designing new healthcare facilities or renovating and maintaining existing facilities must ensure that the physical spaces and facility design and maintenance efforts facilitate infection prevention efforts. For example, the design team must ensure that the materials used for surfaces such as walls, floors, furniture, and equipment can be cleaned and disinfected adequately such that environmental contamination and the risk of cross transmission are minimized [56].

Trudel et al. [57••] studied how the design of products and the environment in a neonatal ICU might undermine infection prevention efforts. They found multiple defective designs including high touch/contact items that were difficult to clean and maintain (e.g., door handles), spaces and objects that required “physical and cognitive effort to navigate, use or maintain,” (e.g., surfaces or equipment that could be cleaned only if healthcare workers contorted their bodies), and designs that did not remind staff when and how to perform specific infection prevention measures [57••].

The size and physical layout of a patient room determines how many patients can be cared for safely in the space and how effectively healthcare workers can navigate the space [57••, 58]. Several studies have suggested that roommates of patients infected or colonized by organisms such as methicillin-resistant *Staphylococcus aureus* [59, 60] vancomycin-resistant enterococci [60], or *Clostridium difficile* [60] are at higher risk than other patients of acquiring these organisms. A review by Ulrich et al. [58] found that HAI rates were usually lower in single-patient rooms than in multi-patient rooms. Ulrich et al. [58] also stated that single-patient rooms are easier to clean and that “single rooms with a conveniently located sink or alcohol-gel dispenser” may facilitate hand hygiene compliance compared with multi-bed rooms, where it is easy to go from patient to patient without doing hand hygiene.

A well-designed ventilation system can limit spread of organisms transmitted via airborne or droplet spread [58, 61]. Contaminated ventilation systems and those without adequate filtration or other design flaws have been the source of numerous outbreaks of infection in healthcare facilities [62–64]. Engineering controls, such as HEPA filters and ultraviolet (UV) lights, can prevent contamination of ventilation systems and may be required for air handling systems in specific hospital areas [65]. Knibbs et al. [66] modeled the effect of ventilation rates on the risk of influenza, tuberculosis, and rhinovirus infection in a lung function laboratory, an emergency department negative-pressure isolation room, and an outpatient consultation room. The air-exchange rates in the lung function laboratory and the isolation room "limited infection risks to 0.1%–3.6%" but the influenza risk for persons entering an outpatient consultation room after an infectious patient "departed ranged from 3.6% to 20.7%," depending on how long the person occupied the room [66]. In addition, door type can affect the efficacy of the air handling system. For example, Julian Tang et al., [67] used water-tank models "fitted with programmable door-opening and moving human figure motions" to compare the effect of four different door designs on the ability to prevent air leakage from airborne isolation rooms. In their model, sliding doors had the lowest risk of air leakage and double-hinged doors had the highest risk of leakage and, thus, of transmission [67]. Luongo et al. [68] recently reviewed the literature on the association between ventilation systems and infection and concluded that we need well-designed observational and intervention studies that describe the characteristics of heating, ventilation, and air conditioning (HVAC) systems and measure both airborne exposures and disease outcomes.

Technology use in infection prevention and control

Many healthcare facilities have implemented "no-touch" technologies, such as hydrogen peroxide vapor or mist and UV light, for room disinfection. Each system has its own advantages and disadvantages [69•, 70•]. In general, these technologies can decrease surface contamination over large areas and they address some limitations of traditional methods in that they help disinfect hard to reach surfaces, and they often do not create toxic byproducts [71–73]. Moreover, they reduce microbial contamination substantially [69•, 70•] and they have been used to control outbreaks in healthcare facilities [69•]. Studies to date have demonstrated that hydrogen peroxide vapor significantly decreased acquisition of any multidrug-resistant organism [74•], that UV-C use was associated with a significantly decreased incidence of *C. difficile* infections [75], and that terminal room decontamination enhanced with both bleach and UV-C light significantly decreased the risk of acquiring a target organism (i.e., MRSA, VRE, or *C. difficile* multidrug-resistant *Acinetobacter*) [45]. However, these technologies are expensive and they increase the time needed for terminal room disinfection. Furthermore, hospitals should consider human factors issues associated with these technologies before implementing them [71].

The National Health Safety Network (NHSN) is supporting the development of algorithms for computerized detection of HAI [76]. Nevertheless, the results of surveys done between 2008 and 2013 found that only 23–56% [77–79] of respondents were using automated systems for HAI surveillance, despite well-documented benefits, including a 61% decrease in the time spent on surveillance

[80] and improved implementation of isolation precautions [81]. Some infection prevention programs may have continued to do surveillance manually because their facilities did not have electronic medical records (EMR), their EMR had substantial limitations, the EMR provider did not have an HAI surveillance package, or their administration did not provide funding. However, Hebden [82•] postulated that some infection prevention programs may have been reluctant to implement electronic surveillance because of ambiguity [83] related to tasks, responsibilities, methods, expectations, and exceptions [82•]. For example, infection preventionists might experience task ambiguity because they have limited experience retrieving, managing, validating, and analyzing electronic data. In addition, infection preventionists transitioning from manual to computerized surveillance must change their workflow to fit automated surveillance processes and they will have a substantial learning curve. Consequently, Hebden [82•] recommended that formal qualitative studies be done to assess the role such human factors have in impeding implementation of electronic surveillance programs [82•].

Technology may not enhance infection prevention efforts. Verhoeven et al. [84] used HFE principles to evaluate the usability of a website that provided a guideline on MRSA control. Semi-structured interviews revealed that healthcare workers rated the website's usability, design, and relevance positively but they questioned the website's credibility and preferred to depend on their own knowledge and experience, or a peer's knowledge. Additionally, they perceived "high work pressure" to be a barrier to website use [84]. The study by Verhoeven et al. [84] and the review by Hebden [82•] highlight the value of doing human factors evaluations to uncover barriers to implementation of infection prevention measures, which are often hidden and difficult to resolve.

Technology, including medical devices, computers used to access the EMR, and communication devices (e.g., cell phones, and tablets) can be contaminated [85–87]. Recent outbreaks of carbapenem-resistant *Enterobacteriaceae* related to contaminated duodenoscopes [88] and outbreaks of hepatitis B associated with blood glucose monitoring devices illustrate this point. Investigations of outbreaks associated with duodenoscopes have identified a number of human factors issues, including breaches in cleaning protocols, defects in the endoscopes, and the inherent difficulty in cleaning and disinfecting these complicated devices [88, 89]. Investigations of hepatitis B outbreaks also identified substantial human factors issues, including healthcare workers taking short cuts (did not clean and disinfect blood glucose meters between patients) and violating infection control principles (comingling contaminated and clean equipment and supplies and using single-patient finger stick devices on multiple persons) [90, 91].

Designing and using personal protective equipment

For centuries, healthcare workers have used special clothing and equipment to protect themselves from infectious diseases. Yet, we still lack basic information about the efficacy of most PPE items, optimal removal (doffing) procedures, and optimal methods for educating staff and assessing their competence [92]. PPE, particularly gloves, became important in the 1980s as healthcare workers sought to protect themselves from exposure to bloodborne pathogens, particularly hepatitis B and human immunodeficiency virus. Problems with PPE and PPE use became apparent during epidemics of SARS in 2003 and novel H1N1 influenza in 2009 [93–101]. Unfortunately, lessons learned from these outbreaks did not lead to sustained improvements in PPE designs or practices. Consequently, during 2014 hundreds of healthcare workers in West Africa died of Ebola because they either lacked PPE, their PPE was inadequate, or their PPE was difficult to doff safely. Moreover, PPE that was impermeable to infected fluids was extremely uncomfortable and hampered healthcare workers' ability to care for patients [102].

Well-designed PPE should protect healthcare workers from contaminating themselves and their clothes with patients' body fluids and infectious agents, facilitate correct donning, allow healthcare workers to work effectively and comfortably, and facilitate safe removal. The nature of the patient's illness and the healthcare tasks will determine if healthcare workers need one PPE item (e.g., mask, respirator, or gloves) or need an entire ensemble (mask, face protection, gown, gloves, and boots). Additionally, some healthcare workers (e.g., bedside nurses) may don and doff PPE many times during a workday. Furthermore, PPE designs are not standardized and PPE items and doffing protocols were not designed or tested based on human factors principles. Thus, one should not be surprised that healthcare workers' knowledge [103–106] about proper PPE use and their use of PPE [107, 108, 103, 106, 109–114] are suboptimal and that they contaminate themselves when they doff PPE [115–122].

Zellmer et al. [123••] observed healthcare workers removing PPE and found that only 17% removed and disposed PPE correctly. The errors Zellmer et al. [123••] observed suggested that healthcare workers likely did not know the proper order for removing PPE and that they were unaware of contaminating themselves when they use improper removal methods like rolling their gowns or gloves against their clothes or bare hands. Thus, education to improve PPE removal must help healthcare workers remove PPE items in the correct sequence and also identify subconscious actions that increase their risk of self-contamination. In addition, results of a study by Swanhorst et al. [124•] demonstrated that pictures of a proper removal sequence, which allowed healthcare workers to visualize the process, together with a written protocol helped healthcare workers don and doff a complex PPE ensemble properly.

Recent studies demonstrate the importance of using human factors principles when designing and evaluating PPE to better match the PPE to the healthcare workers' needs and limitations, their tasks, and the environmental constraints. For example, study by AlGharmri et al. [125] found that full-face, negative pressure respirators impaired users' motor, visual, and cognitive abilities and were associated with an increased error rate. Strauch et al. [126] put tabs on respirator straps to help healthcare workers remove these devices safely. The investigators noted that "use of the tabs was not intuitive." Nevertheless, healthcare workers thought respirators with tabs were easier to remove than those without tabs and they were significantly less likely to contaminate themselves with a tracer when removing the respirators with tabs than those without tabs. These results suggest that the tabs may be a good addition to respirator straps but healthcare workers must be taught to use them properly [126].

Knowledge gaps and implications for future

Our literature review found that most studies in the healthcare domain explicitly applying HFE principles and methods addressed patient safety issues not infection prevention and control issues. In addition, most investigators who applied human factors principles and methods to infection prevention issues assessed only one human factors element such as training, technology evaluations, or physical environment design. The most significant gap pertains to the limited use and application of formal HFE tools and methods. Human factors engineers have developed, tested, and validated rigorous formal techniques and tools in numerous domains. However, investigators assessing usability and those assessing the physical environment were the only ones who used rigorous HFE methods to address infection prevention issues. Moreover, few investigators have evaluated the interaction among human factors variables [57••] as described by the systems engineering initiative for patient safety (SEIPS) model. This model posits that people (e.g., healthcare workers) interact in a system that includes other people, the tasks they are doing, the organization (e.g., healthcare facility), the environment, and the available technology and tools [127, 128]. Pressure or change in one portion of the system causes pressure or change in the other portions. Thus, if people designing infection prevention interventions do not take into account the effect the intervention has on all portions of the system, the interventions are likely to be ineffective. For example, if well-designed, usable hand hygiene technology is placed in a location where healthcare workers cannot see it or access it, the device will not promote use. If this device is placed where healthcare workers can see it and access it easily but they have not been trained to use it or trained when to use it, the device is unlikely to increase compliance.

Every infection prevention study need not assess all components in a system, but investigators must assess the interaction of critical system components if they want to address latent and deep-rooted human factors problems. For example, a task analysis might identify details about how and when healthcare workers do or do not practice hand hygiene, the number of hand hygiene opportunities in different clinical settings, barriers intrinsic to the hand hygiene process, inefficiencies in current workflow patterns, and design flaws that discourage healthcare workers from doing hand hygiene. Given this information about the overall system, infection prevention investigators together with frontline staff may be able to create and implement solutions that increase hand hygiene compliance and improve clinical workflow.

Numerous infection prevention studies have found that changing healthcare workers' behavior is very difficult. Yet few investigators or infection prevention specialists have explored how to use design to promote effective infection prevention behaviors. For example, few studies address questions such as "Can we 'design out' barriers to compliance or could we 'design in forcing functions or strong cues,' that would direct healthcare workers to do the task properly?"

Human factors engineers have developed, tested, and implemented design principles to help humans change their behavior [129, 130]. For example, the proximity compatibility principle [131, 132] indicates that related products or functions should be linked by location, function, color coding, or other characteristics to direct attention and guide behavior. Examples relevant to infection prevention could include placing alcohol hand rub dispensers conveniently in the patient care area and marking the floor to demarcate clearly the patient care zone from the non-patient care zone.

HFE usability principles indicate that processes and products should be designed such that they minimize the cognitive effort healthcare workers must exert to comply or to use the product appropriately. These principles suggest that infection prevention interventions are more likely to be successful if the procedures require minimal cognitive effort and if they become automatic. Examples pertinent to infection prevention include providing central venous catheter placement kits that include each item needed to maintain sterility during placement and developing simple interventions to prevent interruptions during sterile procedures.

Ergonomic design principles indicate that equipment, technology, and processes should be designed to fit the users' cognitive and physical capabilities and limitations. Thus, PPE should be designed to accommodate healthcare workers' physical limitations and should be provided in sizes that facilitate patient care and healthcare worker protection. Nevertheless, manufacturers or hospitals often provide isolation gowns in a few sizes and they rarely make accommodations for healthcare workers with limited mobility. Consequently, some healthcare workers wear gowns that are too big and limit their dexterity, others wear gowns that do not provide adequate coverage, and those with limited shoulder mobility may be unable to don isolation gowns properly or to remove them without contaminating themselves.

User-centered design principles indicate that users should be included in the design, development, and evaluation phases for policies, procedures, equipment, and technology to ensure that users can use the final product in their work environment to accomplish the desired goals without causing unintended negative consequences. User-centered design principles can help infection prevention staff, administrators, or investigators develop policies, procedures, equipment, and technology that enable healthcare workers to care safely and effectively for patients without adversely affecting patient-care processes or care itself. In addition, healthcare workers may be less likely to balk when required to adopt new practices, equipment, or technology if they were included in the processes leading to the required change.

Summary

Infection prevention researchers and specialists have begun using HFE principles and methods to improve infection prevention. Yet, numerous infection prevention practices have been refractory to significant improvement and new problems and issues arise continuously as patient populations, procedures, treatments, equipment, and technology change. To ensure that their efforts are effective, infection prevention specialists and researchers should collaborate with human factors engineers and use the full complement of human factors principles and methods.

Compliance with Ethical Standards

Conflict of Interest
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Human and Animal Rights and Informed Consent
This article does not contain any studies with human or animal subjects performed by any of the authors.

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- • Of importance
- •• Of major importance

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