

An Overview of Usability and Ergonomics Aspects of PAPRs & EHMRS in Healthcare

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ABSTRACT

During the COVID-19 pandemic, many healthcare facilities instituted the continuous use of N95 filtering facepiece respirators to provide respiratory protection from SARS-CoV-2. These disposable, single use respirators soon were in critical shortage. However, due to their high demand and limited availability, healthcare workers were reusing them and, in some cases, had no access to supplies. This created an urgent problem since healthcare workers are continually being exposed to hazardous pathogens. Therefore, it was pertinent to find suitable replacements for N95 FFRs. Powered Air-Purifying Respirators and Elastomeric Half-Mask Respirators were and continue to be recommended by the Centers for Disease Control and Prevention for respiratory protection. These respirators and any respirator used in United States workplace settings, require National Institute for Occupational Safety and Health approval. The objective of this review is to focus on the ergonomics of these respirators in healthcare settings and documented user concerns. To achieve this, databases such as Summon, MEDLINE, Emcare, and CINAHL were used, searching key words to gather information. During this literature study, it was found that while comfort is subjective, there are documented stressors related to breathability and thermal environment that play a major role. Powered Air-Purifying Respirators have little breathing resistance and are generally cool because of the blower device. Elastomeric Half-Mask Respirators are similar to N95 FFRs, in that a hot and humid microclimate can build up inside the respirator and over time, breathing resistance can increase, an issue because they are negative pressure respirators. Powered Air-Purifying Respirators, Elastomeric Half-Mask Respirators, and N95 FFRs can impair senses, negatively affecting communication, as well as diminished field of vision with full-face respirators. Nonetheless, despite these ergonomic barriers, healthcare workers are likely to condone these issues during high-risk conditions for adequate respiratory protection. Even so, there are a considerable number of gaps in the literature on Elastomeric Half-Mask Respirators, more so than for other respirators.

Keywords: PAPR, EHMR, N95, Ergonomics, Usability, Healthcare, Respirator efficiency

INTRODUCTION

COVID-19

Over the past couple of decades, there have been multiple pandemics and epidemics, such as Severe Acute Respiratory Syndrome in 2003, Middle East Respiratory Syndrome in 2012, and Swine Flu in 2009. The most recent pandemic is the COVID-19 outbreak. COVID-19 is caused by the SARS-CoV-2 virus. This virus is spread through airborne and fomite droplets exhaled through speaking, sneezing, and

breathing. These particles range in size with diameters as small as 0.14 μm or larger than 5 μm . The particles in the smaller range, 0.1 to 1 μm , contain aerosolized live virus and include the most penetrating particle size of about 300 nm. This means they can remain in the air for longer periods as well as being least affected by removal mechanisms such as filtration (Chiang, Hanna, Lebowitz, & Ganti, 2020), making them highly contagious.

SARS-CoV-2 infects the upper and lower respiratory tract (Forouzandeh, O'Dowd, & Pillai, 2021; Bohn et al., 2020). The symptoms of this virus can vary widely. According to the European Centers for Disease Prevention and Control, 30% of cases are asymptomatic, 56% have mild symptoms that can be treated at home, 10% are moderate and need treatment in an infirmary, and 4% are severe enough to require intensive care (Pedroso, Pires, Malik, & Pereira, 2021; Mayo Clinic Staff, 2021a). People of older age and those with preexisting medical conditions are at higher risk for experiencing severe cases, which can lead to organ failure, pneumonia, and other life-threatening complications (Mayo Clinic Staff, 2021a). In addition, there are potential long-term effects primarily affecting the heart, lungs, and brain (Mayo Clinic Staff, 2021b). Imaging tests have shown there is lasting damage to the heart muscle, which can increase the risk of heart failure. Pneumonia is often associated with COVID-19, which can cause long-term breathing problems from scar tissue. COVID-19 can also cause strokes, seizures, and Guillain-Barre syndrome (Mayo Clinic Staff, 2021b). Due to these extreme consequences, it is vital to limit the spread of SARS-CoV-2, so respirators have been mandated in the healthcare industry to minimize the spread and the deposition of viral particles in the upper airways. This has led to roughly 89 million N95 Filtering Facepiece Respirators (FFRs) being needed monthly worldwide, causing a shortage often resulting in improper use, surrounding donning and doffing, storage, and reuse of these single use respirators (Chiang et al., 2020).

Healthcare Workers

Under normal conditions Healthcare Workers (HCW) commonly wear surgical or procedural masks and face shields when performing activities that would put them at risk for encountering blood-borne pathogens. Surgical masks are barriers to protect from splashes and droplets such as spit, blood, and other bodily fluids. They are also used during surgery to protect patients from medical personnel breathing into surgical sites. Due to the COVID-19 pandemic, HCWs moved to wearing respirators for prolonged periods and routine patient care activities, to protect against airborne SARS-CoV-2 viral particles. Filtering facepiece respirators, such as N95s, are designed to form a tight seal around the face, and the filtration media removes particles, such as particulates, chemicals and/or infectious pathogens, from the ambient air (National Institute for Occupational Safety and Health, 2021). While other forms of respiratory protection provide comparable, or more, protection than N95 FFRs, their designs are quite different and when used in healthcare settings can introduce ergonomic or usability concerns. Recently, a series of extensive reviews has been conducted on the added values of Powered Air-Purifying Respirators (PAPR) and Elastomeric Half Mask Respirators (EHMR) in the healthcare setting to address issues of implementation logistics and provide an overview of available systems (Greenawald et al, 2021, Haas et al., 2021). This overview focuses on the ergonomics and usability aspects of PAPRs and EHMRs in healthcare and, thus, provides a more focused overview of specific concerns with the human factors aspects of these respirators in health care settings, while still providing some basic background to allow it to be read as a stand-alone paper.

Filtering Facepiece Respirators

N95 FFRs, seen in Figure 1, fall into the category of a Filtering Facepiece Respirator (FFR). FFRs are composed of elastic straps and a facepiece. FFRs are divided into 9 classes (Electronic Code of Federal Regulations, 2021) displayed in Table I, consisting of N (not resistant to oil), R (somewhat resistant to oil), and P (strongly resistant to oil) series, available at 95%, 99%, and 99.97% filtration efficiency levels. Each has an Assigned Protection Factor (APF) of 10. APF is the "respiratory protection that a respirator or class of respirators is expected to provide" (OSHA, 2009). They are negative pressure

respirators, working by the user inhaling through the facepiece, and particulates are collected or trapped in the woven fibers to filter the airstream. They are disposable, single-use respirators (Bottino, Druley, and Ferguson, 2018).



Figure 1. Filtering Facepiece Respirator (FFR) (Echt et al., 2020).

Table I. Respirator Filter Efficiencies (Electronic Code of Federal Regulations, 2021)

Respirator	Filter Series	Efficiency Test	Efficiency
FFR	N-Series	solid sodium chloride particulate aerosol	Available in 95%, 99%, & 99.97%
	P-Series	dioctyl phthalate or equivalent liquid particulate aerosol	
EHRM	R-Series		
PAPR (loose and tight fitting)	PAPR100-N	dioctyl phthalate or Solid NaCl particulate aerosol	99.97%
	PAPR100-P		
	High Efficiency		

Powered Air-Purifying Respirators

PAPRs, seen in Figures 2 and 3 are composed of a facepiece (if a tight-fitting PAPR), hood/helmet with attached face shield and gown/shroud (if a loose-fitting PAPR), breathing tube, a high efficiency (HE) filter (in loose-fitting PAPR) or an appropriate canister or cartridge (in tight-fitting PAPR), and a blower. They are considered positive pressure respirators that work with the assistance of a battery-operated blower to provide clean, filtered air to the wearer (McCoy, Domnitz, & Liverman, 2015). The blower pulls air through an attached filter, often worn on a belt around the waist or inside a helmet, to clean the air, then delivers it to the wearer inside of the hood and face covering, at a minimum of 170 l/min, as required by NIOSH (Bottino et al., 2018). This respirator can protect against particles with the use of an HE filters. Also, with the appropriate canister or cartridge, it can protect against gases and vapors. Its APF varies depending on the construction and fit. PAPRs with a tight-fitting half facepiece have an APF of 50, while those with a tight-fitting full facepiece have an APF of 1,000. Loose-fitting PAPRs with a hood/helmet have an APF of 25 and can also have an APF of 1,000 with manufacturer test-evidence (Bottino et al., 2018; OSHA, 2009; Rowe, 2014). The APF relationship to filtration efficiency is seen in Equation 1. There are various models of PAPRs approved by NIOSH. Options with battery setup, having a single charger, or gang chargers. Then there are versions with diagnostic capabilities to alert the wearer when the battery life is low, or filter loading based on resistance to flow or that the airflow is reduced. There are also models equipped with contoured belts or head tops to aid in the weight distribution of the respirator. Along with versions with optional flow rate adjustments, offering high/medium/low variable rate of air flow, with minimum of 170 L/min. (Rowe, 2014).

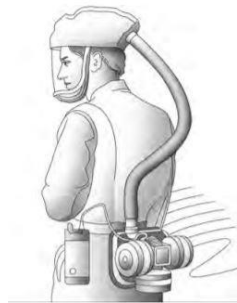


Figure 2. Loose-fitting PAPR (OSHA, 2009).



Figure 3. Hooded PAPR (OSHA, 2009).

$$Filtration\ Efficiency = \left(1 - \frac{1}{APF}\right) \times 100$$

Equation 1. Filtration Efficiency and APF Relation (Forouzandeh, O'Dowd, & Pillai, 2021).

Elastomeric Half Mask Respirators

EHMRs, as seen in Figure 4, are composed of a reusable facepiece with adjustable straps, replaceable filter cartridges, intake valves and some versions with exhalation valves (Brosseau, Jones, & Harrison, 2021; Bottino et al., 2018). EHMRs are negative pressure respirators. The respirator works by forming a seal around the nose and mouth, the user pulls in (actively inhales) filtered air from the intake valve(s), normally one on each side. Then the unfiltered exhaled air goes out through the exhalation valve, this creates unidirectional flow. These respirators have an APF of 10, comparable to N95 FFRs (Chiang et al., 2020). However, EHMRs with exhalation valves have caused hesitation for use in healthcare settings. Some believe the valve allows an asymptomatic or pre-symptomatic user to release infectious aerosols they generate into the environment. Others believe the particles released are negligible since they must travel a complex path to the valve (Brosseau et al., 2021; Chiang et al., 2020). Due to these concerns, some manufacturers developed EHMRs without exhalation valves or with filtered exhalation valves during the COVID-19 pandemic. Aside from the questions related to the exhalation valve, the reliability of EHMRs is well documented with low failure rates (Brosseau, Jones, & Harrison, 2021; McMahon et al., 2020). They have been used during COVID-19 pandemic and have protected HCWs from other respiratory diseases like tuberculosis, and H1N1 (Brosseau et al., 2021).



Figure 4. EHMR (Echt et al., 2020).

Respirator Efficiency

In the United States, a respirator must be certified by NIOSH, following 42 Code of Federal Regulations (CFR) Part 84, to be used in Occupational Safety and Health Administration (OSHA)-regulated environments. This certification details the respirator's ability to protect the human airways against airborne pathogens, assuring protection against airborne diseases (Forouzandeh et al., 2021; Gao et al., 2016; Institute of Medicine, 2015). 42 CFR Part 84 covers broad guidelines of respiratory protection. In relation to this overview, it discusses the filter element and the fit for N95 FFRs, PAPRs and EHMRs in connection to efficiency (Chen, Wang, & Yang, 2015). These respirators utilize the normal mechanical mechanisms, some additionally using electrostatic charge to capture the most penetrating aerosol particles (Martin & Moyer, 2000). However, as PAPRs and EHMRs are contaminated, the filter media becomes more effective. This is due to the particulate filters loading up with the contaminants and thus creating a more impenetrable mechanical capturing mechanism. Since SARs-CoV-2 only remains detectable on surfaces for up to 3 days, there is no need to continually change the filter (Chiang et al., 2020; 3M, 2007). Most of the replaceable filters can last up to a year if they have not been soiled or damaged and the breathing resistance remains within required limits. This continued use will however increase the breathing resistance since the airflow is being restricted. The filter options and efficiencies of PAPRs, EHMRs, and N95 FFRs are displayed in Table I (Electronic Code of Federal Regulations, 2021).

METHODS

The following electronic databases: Summon, MEDLINE, Emcare, and CINAHL were searched for peer-reviewed research. In addition, information from grey literature was obtained through the following search engines: Google Scholar, and Google. This research included published literature in English from the databases and search engines from inception to the present time. The search for records was conducted in May 2021. To be eligible for inclusion in this review, records need to address issues of usability or ergonomics in relation to PAPRs, EHMRs, or N95 FFRs. The search included empirical studies, reviews, case studies, and commentaries. From there, thematic analysis was exercised to synthesize the results. Relevant data was then acquired from each record and subjected to analysis to support a qualitative systematic review. An overview of this process is displayed in Figure 5.

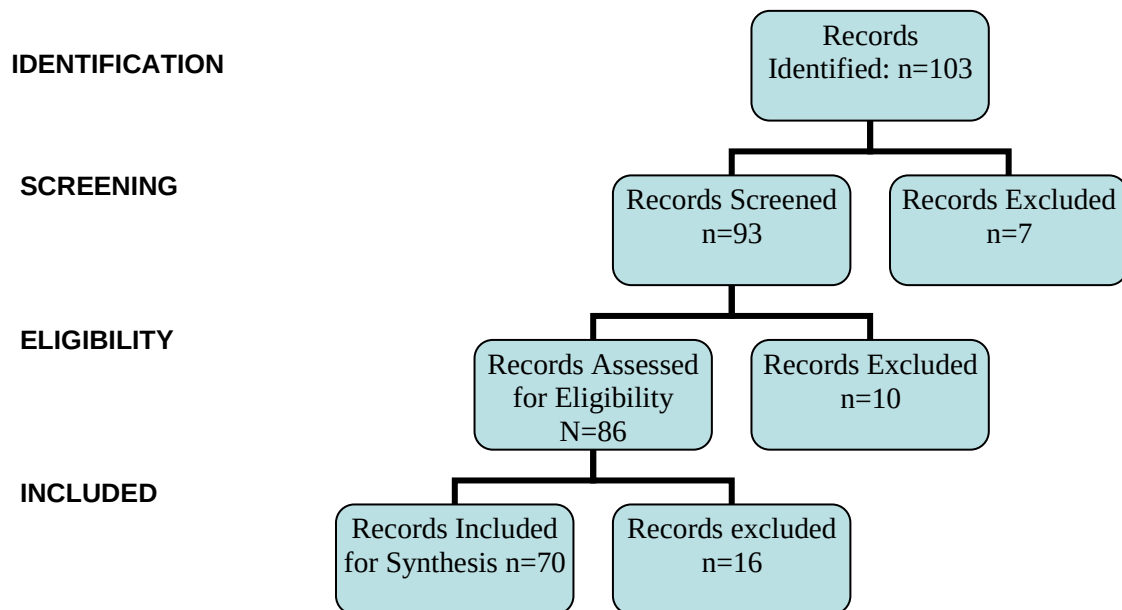


Figure 5. PRISMA flow diagram.

RESULTS

Fit

42 CFR Part 84 states that loose-fitting PAPRs do not require end user fit testing, but tight-fitting PAPRs, where a seal between the wearers face and the respirator is needed, and EHMRs, as well as N95 FFRs, require qualitative fit testing or quantitative fit testing to determine the fit factor (FF). This is essential in deciding the effectiveness of the seal on the actual wearer. Leakages negatively impact the effectiveness of the respirators. Leaks are strongly influenced by the nose and chin shape, and the presence of facial hair (Floyd, Henry, & Johnson, 2018; Gao et al., 2016). The FF can also naturally change over long periods of time, from facial scarring, dental changes, cosmetic surgery, or changes in body weight (Zhuang et al., 2016). Therefore, tight-fitting PAPRs and EHMRs are required to be fit tested annually (Chen et al., 2015; Forouzandeh et al., 2021; Gao et al., 2016). Unlike N95 FFRs where donning and doffing the respirator as few as 5-10 times can lower the FF due to the loss of strap integrity, PAPRs and EHMRs are meant to be donned multiple times (Brosseau et al., 2021; Chiang et al., 2020). Additionally, a study conducted by Lee et al. (2008), on HCW using N95 FFRs, found that while HCW may initially pass the Fit Test, after 3 months the majority tend to fail the test (Chiang et al., 2020; Lee, Takaya, Long, & Joffe, 2008). Then another study by LKP et al. (2017), stated that 4 μ m sized particles have been found inside N95 FFRs after 10 mins of physical movement (Suen, Lorna K.P., RN, MPH, PhD et al., 2017). This indicates the seal is easily lost during extended use (Chiang et al., 2020). Nonetheless, it is recommended that wearers using either of these respirators to do a seal check, a self-test every time it is worn (Regli et al., 2021).

To suit an abundance of people, PAPRs, EHMRs, and N95 FFRs are designed to be either one size fits all or have more than one size to fit varied face shapes and sizes. Fit is aided by EHMRs and tight fitting PAPRs having facepieces or mouthpieces equipped with adjustable head harnesses that provide tension and pressure over the face to maintain the seal. N95 FFRs are constructed to have nose

clips to aid in that facial seal. All three types of respirators are designed with the end-use in mind, this allows for individuals with safety goggles or corrective lenses to use the respirators, along with ensuring against any restriction of movement by the wearer (Electronic Code of Federal Regulations, 2021). These features not only affect protection but usability. The ergonomics behind all three types of respirators is what should dictate if they can be used in healthcare.

Comfort

The efficiency of PAPRs and EHMRs are better than N95 FFRs, so the aspects to focus on are usability and ergonomics. The protection and comfort levels of respirators need to be balanced. Comfort is the “state of physical ease and freedom from pain or constraint” (Oxford University Press). It can influence job performance, compliance, and the duration of work cycles from HCWs (Powell, Kim, & Roberge, 2017), with increased discomfort decreasing HCW compliance (Roberge et al., 2013). While comfort is subjective, several factors influence the wearer's experience. These include breathing resistance, weight, temperature, humidity, facial pressure, cardiopulmonary effects, and exertion (Chen et al., 2015; Shenal, Radonovich, Cheng, Hodgson, & Bender, 2012).

For EHMRs, the study by Harber et al. (2009) and one by Or et al. (2018) suggest that N95 FFRs are likely more tolerable when evaluated in simulated work environments. EHMRs have been reported to have nasal discomfort and respirator heaviness (Harber et al., 2009; Or, Chung, & Wong, 2018). Regarding PAPRs compared to N95 FFRs, weight is one of the principal comparisons. Nonetheless, the study conducted by Powell et al. (2017), found that the additional stressors of PAPRs had no significant impact on cardiopulmonary variables like blood oxygen saturation, transcutaneous oxygen measurement, heart rate, or breathing rate. They found that this holds true at a low-moderate work rate of over 1-hour (Powell et al., 2017). However, subjective measures of comfort were not examined.

Specific comfort stressors related to respiratory protective devices include CO₂ retention, heat stress, and impaired senses. These factors play a major role in the HCW's tolerance to wearing respiratory protection. The idea that human performance decreases as a respirator's capability increases is observed across literature. This is attributed to respirators causing discomfort, somatic complaints, interference with duties, and diminishing communication (Johnson, 2016). James et al. (1984) performed an in-lab study on the effects of half and full facepiece, cartridge-type, air-purifying respirators under heat and work conditions. They found that a full facepiece respirator imposed significant physiological strain, in comparison to half facepiece respirators. Then a study by Zelnick et al. (1994), on the visual field loss while wearing full-face respiratory protection (specifically a military M-17 protective field mask, a North model 7600-8A full-face respirator, and a 3M Easi-Air model 7800/M full-face respirator) observed that full-face respirators obscure portions of the visual field. However, these respirators are tight-fitting full-face respirators which are seldom used by HCWs. Additionally, a study by Zimmerman et al. (1991), where subjects wore a disposable dust mask, a rubber half-mask with high efficiency particulate air cartridges, and a full-facepiece airline respirator while performing simulated work tasks, noted that cognitive performance decreases when wearing a full facepiece respirator. While these studies do not compare N95 FFRs to PAPRs or EHMRs, they examine the common usability concerns related to wearing respirators.

Additionally, execution of everyday tasks is also affected by wearing a respirator. The wearer cannot eat, drink, or touch their face when wearing a respirator. HCWs particularly might be affected if they are in tight spaces because bumping the respirator against something could break the seal, and the construction of the respirator could interfere with using some equipment; for example, it would be impossible to use a stethoscope when HCWs are properly wearing a hooded tight-fitting PAPR because their ears are covered. Utilizing digital stethoscopes that transmitted via Bluetooth, such as the Littman 3200, Omni-Steth, could solve this problem, but these are significantly more expensive than traditional stethoscopes. Another tool that would be difficult to use is an otoscope when wearing a full facepiece respirator due to the wearer's eyes being covered by a visor that may obscure their view (Johnson, 2016). There are also conflicting opinions on cognitive performance while wearing respirators. Multiple studies in the 1990s have shown that there is no change in cognitive performance, but a later study has stated that

there is a significant effect on cognitive performance (AlGhamri, Murray, & Samaranayake, 2013; Chen et al., 2015; Loibner, Hagauer, Schwantzer, Berghold, & Zatloukal, 2019). Caretti et al. (1999) found that when performing cognitive tasks, such as choice reaction, serial addition/subtraction, logical reasoning, and serial reaction there were no significant cognitive performance changes with or without a respirator. The study by Zimmerman et al. (2007) showed similar results. They used standardized Miller Analogy, Graduate Record Examination (GRE) logical, GRE analytical tests, and Hypothesis test to measure cognitive performance. However, a later study by AlGhamri et al. (2013) using the Serial Sevens Test to evaluate cognitive performance, found that the rate of errors increases with full-face, negative-pressure respirators compared with no respirator.

Breathability

Increased breathing resistance adds a physiological burden causing respiratory fatigue and impaired physical work capacity (Chen, Yang, Wang, & Gong, 2016). The NIOSH certification limits of inspiratory and expiratory filter resistance in non-powered, air purifying particulate respirators are 35- and 25-mm H₂O pressure, respectively, at an air flow of 85 l/min. This includes EHMRs and N95 FFRs. Since EHMRs are negative pressure respirators, breathing could potentially become difficult. However, if the pressure drop is within limits, it is considered tolerable (Roberge et al., 2013). NIOSH also has certification limits for tight-fitting PAPRs. It varies depending on the type, but for inhalation it ranges from 50-70 mm H₂O pressure, and for exhalation the resistance must be less than 20 mm H₂O pressure (NIOSH, 2018). Nonetheless, since PAPRs are positive pressure respirators, there are fewer issues with breathing resistance. It is generally not a problem if the user is not hyperventilating, which could cause the respiratory flow rate to exceed the blower flow rate which would then cause inspiratory resistance (Gao et al., 2016; Johnson et al., 2005). While the positive pressure works for inhaling, it works against exhaling. At rest without a respirator, exhaling is a passive activity. However, when a PAPR is worn, depending on design it may behave like any other air purifying respirator, making exhaling an active activity, requiring the user to push out the air (Johnson et al., 2005). These breathing resistances have been documented to have minimal effects on the wearer. A study was conducted by Roberge et al. (2013), where subjects underwent treadmill exercise while wearing respirators with various filter resistances. They found that under low to moderate conditions there is no significant difference perceived by the wearers in energy expenditure at the different filter resistances.

Another matter to examine is CO₂ retention, the byproduct of respiration. In normal conditions, a room's CO₂ levels are 300-400 ppm. At these levels, there are no known side effects. However, above 1,000 ppm cognitive functions may start to be affected and at higher levels could become toxic to the body. Personal breathing characteristics, for example slow/deep vs. fast/shallow, can affect the CO₂ accumulation within the respirator. PAPRs and EHMRs are within NIOSH limits for short-term, 15-minute exposure of 30,000 ppm (Rhee et al., 2021). However, HCWs are likely wearing their respirators for longer periods. So HCW's conditions should be compared to NIOSH limits for the long-term, 8-hour exposure threshold limit of 5,000 ppm, in which case EHMRs, and N95 FFRs may exceed NIOSH limits. Due to their high air flow it is unlikely that PAPRs would exceed this limit, but this might need to be studied as well. The NIOSH 8-hr defined as the the 8-hour time-weighted average and is treated as the equivalent to a single uniform exposure over 8-hour, making it more representative of an average 8-hour work shift. However, an observational study by Rebmann et al. (2013), found that HCWs wearing an N95 FFR for 12-hour showed CO₂ elevations that were not clinically important. Additionally, a study conducted by Bansal et al. (2009) comparing the physiological impacts of N95 FFRs and Half-Mask respirators during simulated work conditions such as stocking shelves and sorting bolts, found that most people can physically tolerate both respirators during low to moderate physical tasks (Roberge et al., 2013).

Thermal Environment

Temperature also plays an important role in user's comfort. Elevated temperature allows evaporation to occur more quickly, so the moisture expelled from breathing and talking, along with the

sweat produced from the rise in temperature, work to create a humid environment within the respirator. This, in addition to the ambient temperature heat, causes discomfort, specifically on the facial skin. The metabolic heat produced is determined by the workload of the HCW. The overall thermal strain, however, is not only dictated by the surrounding environment but also by the wearer's garments. So, if HCWs are required to wear other personal protective equipment (PPE), such as gowns and gloves, their thermal strain is expected to increase. Also, at rest or during light exertion people normally breathe through their nose, which produces less expired heat into the environment because some of that expelled heat is reclaimed by vasculature and mucosal surfaces of the nasal passages and paranasal sinuses. However, during strenuous activities, people are more likely to switch to mouth breathing. This results in an increase of expired heat into the microclimate and increased respiratory flow rate (Roberge, Kim, & Coca, 2012).

PAPRs, EHMRs, and N95 FFRs all negatively impact respiratory and dermal mechanisms of thermoregulation by impairing convection, evaporation, and radiation processes from the body to the environment (Roberge et al., 2012). EHMRs and N95 FFRs can create humid microclimates within the respirator, different from the ambient air (Chen, C., Lin, & Wei, 2017; Shenal et al., 2012; Johnson, 2016; Lin & Chen, 2019), close to core body temperature and relative humidity of nearly 100%. This can affect the face seal because the skin is now wet, and causes general discomfort. Nonetheless, when EHMRs are equipped with an exhalation valve, that heat can be released into the surrounding environment (Lin & Chen, 2019). The accumulated heat in N95 FFRs has the potential to increase breathing resistance because the sweat build-up can block the pores of the respirator (Kim, Wu, Powell, & Roberge, 2016). Unlike N95 FFRs and EHMRs, PAPRs have been known to help cool the face and evaporate sweat due to their high air flow (Johnson, 2016).

While hot temperatures are unfavorable, cold conditions can also lead to several problems, causing fogging in facepieces which can impede vision. Some full facepiece respirators are designed to eliminate fogging by being equipped with nose cups and fog proof lenses, but they are not always effective. Additionally, the cold can cause issues with facial seals, and the valves sticking within PAPRs and EHMRs (Johnson, 2016).

Having tolerable thermal environments and breathability is beneficial since the comfort of PPE makes HCWs more likely to comply with OSHA regulations (Or, Chung, & Wong, 2018). A survey conducted by Mitchell et al. (2012) on vaccination, illness, absenteeism, and PPE, found that the key factors associated with HCW compliance are availability of PPE, work experience, comfort, and feeling of protection. In this study, HCWs in intensive care units and influenza wards were more compliant with wearing N95 FFRs than other work locations. Wearers who reported feeling comfortable wearing an N95 FFR were also significantly more compliant. Similar views are observed in the survey by Baig et al. (2010) on HCW opinions of respirator use. The results showed that HCWs want respirators to be more comfortable, interfere less with breathing, and to diminish heat buildup.

Communication

Another matter to examine is the impaired communication, which plays a part inter-professionally and within patient-clinician interaction (Marler & Ditton, 2021). Communication is crucial to the quality of a patient's care and safety. Facepiece respirators such as Tight-fitting PAPRs, EHMRs and N95 FFRs can interfere with visual cues during listening and speaking, attenuate sound transmission, and reduce intelligibility. Hooded and Loose-fitting PAPRs allow the wearer's mouth to be visible so when communicating such that the receiver can see the words the wearer is mouthing. However, PAPR's attached blower can be loud, affecting the wearer's ability to communicate (Hines, Oliver, Gucer, & McDiarmid, 2020; Round & Isherwood, 2021). The shield on the respirator also interferes with sound transmission. This can be addressed with the use of microphones in the respirator, as available in some models on the market. Another contributing factor to speech intelligibility is the thickness of the materials used to construct the respirators. With thicker materials it is harder for sound to transmit through because material blocks and absorbs more sound waves (Xu et al., 2021).

Anecdotally, HCWs wearing PAPRs have difficulty communicating. In 1990, HCWs rejected a proposal from NIOSH to implement the use of PAPRs during the Tuberculosis outbreak. The HCWs thought it may frighten patients, reduce the perception of empathy towards patients, and thus limit patient communication (Hines, Oliver, Gucer, & McDiarmid, 2020; Nelson, 1992; Round & Isherwood, 2021). Yet, in a study by Udayasiri et al. (2007), where HCWs performed resuscitation procedures, a task where verbal communication is required while wearing PPE with full-face respirators, there were no adverse physiological effects, or impacts on performance (Round & Isherwood, 2021).

Additionally, there are several Speech Intelligibility Testing Methods. The American National Standards Institute uses the Diagnostic Rhyme Test, the Phonetically Balanced Word List, and the Modified Rhyme Test (MRT) in their standards. The MRT is a speech discrimination test, that is also used by NIOSH when deciding whether a Chemical, Biological, Radiological, and Nuclear (CBRN) Air-Purifying Respirator (APR) and PAPRs can be used occupationally. It determines the overall performance rating of the listener. A study by Radonovich et al. (2009) found that without any respirator users received a score of 90% on the MRT. When a PAPR was worn, the score decreased to 79% and when wearing an EHMR it went to 72%. All of these results are considered passing scores by NIOSH since they are greater than 70% (NIOSH, 2007). While this test is useful for everyday speech, in discriminating between words like “pen” and “hen”, the test does not include terminology specific to healthcare (Radonovich, Yanke, Cheng, & Bender, 2009).

Vision

Diminished vision related to acuity and range are notable facets affected by wearing full facepiece respirators (Johnson, Dooly, Sahota, Coyne, & Benjamin, 1997; Shenal et al., 2012). The Johnson et al. (1997) study showed that visual acuity when wearing a full facepiece respirator worsened by 75% on the Snellen chart lines, seen in Figure 6. During this test, a person covers one eye, stands 6 meters away, and reads the chart starting at the top with the largest symbols and continues to read down the chart. Then the lowest row the person can correctly read dictates their visual acuity in that eye. The poor level of visual acuity can be attributed to doing light work and foggy lenses (Chen et al., 2015; Johnson et al., 1997). There is also a study done by Zelnick et al. (1994), showing that visual field loss is another variable affected and directly correlated with the design characteristics of the respirator. So, the model of the respirator dictates the visual range of the wearer and diminished vision negatively affects task performance. This is demonstrated in a study by Johnson et al. (1994) where subjects wore respirators with lenses at varying levels of visual acuity. They concluded that during console-monitoring and hand-eye-coordination tasks, performance decreased with decreasing visual acuity.

There are potentially dangerous implications of HCWs experiencing impaired vision. The care they administer can be negatively impacted. In the United States, over 100,000 people are injured each year due to medication errors (Food and Drug Administration, 2019). A great portion of this can be attributed to patients with visual impairments that misread storage, dosing, and administration instructions (Taylor, Sheridan, & Faber, 2016). However, HCWs experiencing diminished vision could have a larger risk as they are responsible for reading medical charts, prescribing medications, and delivering dosages of medication so the error could be detrimental or even fatal to patients.

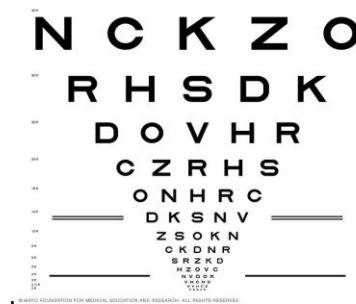


Figure 6. Snellen Chart (Mayo Clinic, 2021).

Implementation

Implementation of PAPRs and EHMRs seems feasible since their tolerability is equivalent or better in comparison to N95 FFRs. Nevertheless, there are other factors to consider for accepted use. There needs to be appropriate storage that protects the respirators from damage, contaminants, dust, sunlight, extremes of temperature, moisture, and chemicals. Users also need to follow OSHA's and manufacturers' instructions for storage, cleaning, and disinfecting (Lawrence et al., 2017). Along with an established sanitation process, there needs to be a scheduled filter changeout and replacement filters readily available (Hines et al., 2019b). This will allow users to change filters once they expire, when they become soiled or damaged, or when a HCW finds it inordinately difficult to inhale or exhale. There should also be training on the proper donning and doffing of these devices, which is regularly supervised to confirm appropriate technique and compliance (Petsonk & Harber, 2020).

Another issue to be addressed is the significant cost difference with PAPRs and EHMRs compared to N95 FFRs. Long term it would be cost-effective to use EHMRs and PAPRs since they are both reusables, but the initial cost would be great (Khoo, Leng, Ibrahim, & Lim, 2005). PAPRs specifically have a high cost because of the rechargeable or replaceable batteries required (Licina & Silvers, 2021). There are also the continual costs to replace hoods, gowns, and filters. Even so, the use of EHMRs has been seen to cost 10 times less per month than disposable N95 FFRs, and the cost-benefit continues to increase the longer they are used (Chalikonda et al., 2020). Based on that, it is presupposed a similar trend would eventually be seen with PAPRs.

Interposed breaks from wearing a respirator also need to be put in place. A study in 2012 by Shenal et al., surveyed HCW's comfort while wearing one of the follow respirators when delivering care to patients: Medical Mask; Duckbill N95; Cup N95; Cup N95 + Exhalation Valve; Cup N95 + Medical Mask; Cup N95 + Exhalation Valve + Medical Mask; Half-face Elastomeric Respirator; and Powered Air-Purifying Respirator. This study found that HCWs who are accustomed to wearing respirators for brief periods are not willing to wear them for a full 8-hour work shift even with breaks. However, in a study by Hines et al. (2019a), they surveyed HCWs on their acceptance of PAPRs and EHMRs. During this study, they observed that HCWs are more willing to tolerate respirators when in a high-risk scenario, like caring for patients with aerosol-transmissible diseases.

Users from Underrepresented Populations

There have also been reports showing that HCWs from Black, Asian, and minority ethnic (BAME) communities are disproportionately affected by COVID-19 (Regli, Sommerfield, & Ungern-Sternberg, 2021). In an observational cohort study that assessed the risk of COVID-19 among HCWs by Nguyen et al. (2020), authors found that compared to non-Hispanic white HCWs, BAME HCWs are more likely to work in high-risk clinical settings such as inpatient hospitals and nursing homes. They are also more likely to be assigned to care for patients with suspected or documented cases of COVID-19. Moreover, data released by the National Health Service in England showed that of the COVID-19 fatalities in HCWs, 63%

were of BAME ethnicity, which is disproportionate to the 13% population of the BAME in England (Kirby, 2020). A similar trend is seen in the general public of the United States, where African Americans represent 33% of COVID-19 hospitalizations, while only making up 18% of the population (Garg et al., 2020). Another suspected cause for these communities being disproportionately affected are preexisting conditions. These minority groups have a greater frequency of hypertension, diabetes, and coronary heart disease. These conditions are thought to increase the severity of COVID-19 (O'Hearn et al., 2021; Kirby, 2020). As well, in a survey by the British Medical Association, it was found that BAME HCWs feel pressured to treat patients in high-risk environments even without adequate protection. The Centers for Disease Control and Prevention also recently stated that there were other factors contributing to the increase in positive cases of COVID-19 in BAME communities (cf. <https://www.cdc.gov/coronavirus/2019-ncov/community/health-equity/race-ethnicity.html>). One such factor is that BAME groups are more likely to live in densely populated areas. Another reason is that they are more likely to work service jobs where exposure is increased (Kirby, 2020). Currently, available literature does not seem to suggest any significant difference for these groups on physiological or ergonomic effects. There are some reports on anthropometric differences, yet respirator design solutions that aim to cover the United States population as a whole should also address any such issues. Education on respirators for frontline HCWs in these BAME communities that are not traditionally wearing them due to availability may facilitate better use and reduction of issues with usability and discomfort.

Adverse Effects

While HCW acceptance and implementation are possible, there are drawbacks that include a number of adverse effects not limited to the ones listed. There is an increased chance of falls attributed to vision impairment, hearing problems, and postural stability (Chiou & Keane, 2016). Additionally, individuals with disorders related to intrathoracic airflow obstruction will likely have difficulty adapting to the use of all types of respirators (Harber et al., 2010). Panic-prone individuals are also likely to experience greater discomfort than others, thus reducing their tolerance to wearing respirators (Perna, Cuniberti, Daccò, Nobile, & Caldirola, 2020). There are also potential health issues that may arise. Some literature suggests the continued use of respirators can affect the immune system. Immune systems are highly adaptive so reducing the exposure of normal microbes can lead to underdevelopment, in turn leaving the individual susceptible to immune system attacks from bacteria and viruses (Ahmed et al., 2020). Another risk is associated with Qualitative Fit testing using Denatonium Benzoate, which has caused severe asthmatic reactions in some people (Youakim, Sami, MD, MSc, FRCP, 2007). Other than these issues, PAPRs and EHMRs are effective and well documented.

CONCLUSIONS

The enacting of the use of PAPRs and EHMRs in place of N95 FFRs in healthcare is achievable. Using these respirators would require facilities to provide appropriate storage that protects the respirators, along with having an established schedule for filter changeout and replacement filters readily available. There would also need to be standardized sanitation methods. While these actions may seem cumbersome, if a healthcare facility already has respiratory protection programs in place for N95 FFRs, these new processes can readily be adopted (Lawrence et al., 2017; Hines et al., 2019b).

Moreover, PAPRs are a suitable replacement for N95 FFRs in healthcare. Like N95 FFRs, PAPRs are produced to NIOSH, 42 CFR Part 84 specifications (Forouzandeh et al., 2021; Gao et al., 2016; Institute of Medicine, 2015). Their APF varies between 25, 50, and 1000, depending on the construction and fit, all of which are higher than N95 FFRs APF of 10 (Bottino et al., 2018; Rowe, 2014). The seal of tight-fitting PAPRs also lasts longer than N95 FFRs, and only requires a fit test once a year. (Chen et al., 2015; Forouzandeh et al., 2021; Gao et al., 2016) Additionally, loose-fitting PAPRs do not require end user fit testing and so would be a sensible option for individuals with facial hair or facial

anthropometries who would have trouble passing a fit test (Floyd, Henry, & Johnson, 2018). Therefore, it can be inferred that PAPRs are efficient tools to protect users.

The usability and ergonomics of PAPRs are exemplary as well. PAPRs are positive pressure respirators so there are few issues with breathing resistance (Gao et al., 2016; Johnson et al., 2005). The blower used does create some general concern because of the added weight and noise. Nevertheless, it has been found that the weight bears no significant impact on cardiopulmonary variables (Powell et al., 2017). The noise level of PAPRs is being continually improved. The Maxair and 3M Versaflo PAPRs produce noise levels below 65 dBA, a decrease compared with older PAPRs with noise levels greater than 70 dBA. The communication issue has been addressed with the use of microphones in the respirator. Implementing microphones could also positively affect the results on the MRT, which is currently 79% (Radonovich et al., 2009). When wearing these full-face respirators, vision is often diminished, particularly the acuity and range (Johnson, Dooly, Sahota, Coyne, & Benjamin, 1997; Shenal et al., 2012). Additionally, the thermal environment does not affect PAPRs as much. These respirators are known to help cool the face and evaporate sweat due to the constant flow of clean air through the hood or mask.

EHMRs however, do bring up some concerns because of the gaps in research related to them. Similar to N95 FFRs and PAPRs, EHMRs are produced to NIOSH, 42 CFR Part 84 specifications (Forouzandeh et al., 2021; Gao et al., 2016; Institute of Medicine, 2015). EHMRs APF of 10 is more comparable to N95 FFRs APF of 10 (Bottino et al., 2018; Rowe, 2014). The seal of the EHMRs may easily be lost during extended use, but it still only requires a fit test annually and should be fit checked with each donning (Chen et al., 2015; Forouzandeh et al., 2021; Gao et al., 2016). Nonetheless, compared to N95 FFRs where donning and doffing as few as 5-10 times can lower the FF (Brosseau et al., 2021; Chiang et al., 2020), it can be gathered that the fit factor of EHMRs is maintained with reuse, and filtration efficiency is comparable N95 FFRs when using N95 filters.

The usability of EHMRs varies. There have been reports stating there is general discomfort when wearing EHMRs, compared to N95 FFRs (Harber et al., 2009; Or, Chung, & Wong, 2018), and because it is a negative pressure respirator the breathing resistance is a concern. However, if the pressure drop is within limits of 35 mm H₂O during inspiratory and 25 mm H₂O during expiratory parts of the breathing cycle, it is considered tolerable (Roberge et al., 2013).

The thermal environment is one of the key issues for EHMRs. Heat accumulates on the inside of the respirator creating a microclimate with humidity near saturation and temperature close to skin temperature, similar to what happens with N95 FFRs (Chen, C., Lin, & Wei, 2017; Shenal et al., 2012; Johnson, 2016; Lin & Chen, 2019). With EHMRs, though some are designed with an exhalation valve so a portion of the heat can release, there should be further studies to understand the magnitude of the heat loss, especially with longer wear times as it may strengthen negative effects on cognitive and sensory performance (Lin & Chen, 2019). EHMRs also impair senses, parallel to the ways N95 FFRs affect them (Marler & Ditton, 2021).

Visual cues during listening and speaking are limited, sound transmission is attenuated, and speech intelligibility is reduced with EHMRs (Hines, Oliver, Gucer, & McDiarmid, 2020; Round & Isherwood, 2021). Currently, EHMRs resulted in 72% on the MRT (Radonovich et al., 2009). New research may be considered to evaluate the respirators (EHMR and PAPR) for HCWs specific language as opposed to the generic language used in the MRT. Additionally, the application of speech diaphragms in EHMRs may also improve the speech intelligibility when wearing these devices.

There is also room for further investigation of both PAPRs and EHMRs. The concentration of CO₂ produced holds some worry because while PAPRs and EHMRs are within limits for short-term, 15-minute exposure of 30,000 ppm HCWs are likely wearing their respirators for longer periods (Rhee et al., 2021). So HCW's conditions should be compared to NIOSH limits for the long-term, 8-hour exposure threshold limit of 5,000 ppm, in which case EHMRs and N95 FFRs may exceed NIOSH limits. PAPRs are unlikely to exceed these NIOSH limits due to their high air flow rates. The NIOSH 8-hr defined as the 8-hour time-weighted average and is treated as the equivalent to a single uniform exposure over 8-hour, making it more representative of an average 8-hour work shift. Cold conditions can also affect PAPRs and EHMRs, by generating problems with the facial seals when rubber on the facepieces stiffen, and also making the valves stick (Johnson, 2016). This could be improved by looking into other materials for

construction. PAPRs airflow can cause discomfort in at low temperature by it blowing over the face. The other major worry of PAPRs and EHMRs are the initial costs. Over time, the respirators will likely be cost-effective because of their reusability (Khoo, Leng, Ibrahim, & Lim, 2005).

This literature study identified other gaps in the research, such as on the use of hospital instrumentation. There is no documentation on how well or how much of the hospital equipment HCWs can use while wearing EHMRs or PAPRs. For example, when wearing a hooded PAPR it would be difficult to use tools like a standard stethoscope that require open access to one's ears. Such tools would need to be adapted or modified leading to additional (significant) cost. HCWs would also not be able to complete lab work that requires viewing a microscope if a full facepiece respirator is worn. So, it is questionable whether HCWs can perform all their duties while wearing PAPRs and EHMRs (Powell, Kim, & Roberge, 2017; Youakim, Sami, MD, MSc, FRCP, 2007).

HCWs from underrepresented groups and minorities have been reported to suffer from higher incidence rates of COVID-19. The literature does seem to confirm that, but rather than specific physiological or ergonomics aspects, the difference seems to be related to socio-economic circumstances, leading to generally higher exposures and possibly higher pre-existing conditions. These issues will require a broad systemic approach to achieve effective reduction, but good education on respirators and associated hazards for frontline HCWs are very likely to have a benefit to this population. Based on this information, the authors conclude that PAPRs are suitable replacements for N95 FFRs. Regardless of any perceived barriers, HCWs are likely to tolerate these respirators, particularly in high-risk scenarios (Hines et al., 2019a) where the needs for protection are known and understood. There may be some benefit in obtaining a better understanding (i.e., studying) of the acceptance and appreciation of respirators over time during actual work (with actual hazards), as opposed to just evaluating respirators under lab conditions. Furthermore, there may be a need for such field studies in realistic (hazard-based) work conditions that focus on ergonomics and usability differences between N95 FFRs, EHMRs, and PAPRs to further support the notion that these products are just as good in practice, whereas they have significant long-term commercial benefits.

There are anecdotal reports that user acceptance increases, and discomfort decreases when the PPE is perceived to protect the wearer against actual existing hazards. Wearers under such conditions seem to 'habituate' to the protective equipment, leading to an effective reduction of discomfort complaints (Ahmed, Harker, & Edirisinghe, 2020; Hines et al., 2019a; Shenal, Radonovich, Cheng, Hodgson, & Bender, 2012). More research may come out on that topic after the COVID-19 pandemic, but may also be actively pursued to support better education of HCWs. Education on and habituation of wearing respirators and their function may help obtain better acceptance of respirators and consequently better compliance in wearing them.

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REFERENCES

- 3M. (2007). Why and when to replace your 3M filters. Retrieved from <https://multimedia.3m.com/mws/media/447121O/filter-change-out-brochure.pdf>.
- Ahmed, J., Harker, A., & Edirisinghe, M. (2020). COVID-19: Facemasks, healthcare policies and risk factors in the crucial initial months of a global pandemic. *Medical Devices & Sensors*, 3(6), n/a.
- AlGhamri, A. A., Murray, S. L., & Samaranyake, V. A. (2013). The effects of wearing respirators on human fine motor, visual, and cognitive performance. *Ergonomics*, 56(5), 791-802.
- Baig, Aliya S., MPH, MSN, Knapp, C., PhD, Eagan, A. E., RN, & Radonovich, L. J., MD. (2010). Health care workers' views about respirator use and features that should be included in the next generation of respirators. *American Journal of Infection Control*, 38(1), 18-25.
- Bottino, B., Druley, K., & Ferguson, A. (2018). NIOSH publishes guide on air-purifying respirator selection. Chicago: National Safety Council.
- Brosseau, L. M., Jones, R. M., & Harrison, R. (2021). Elastomeric respirators for all healthcare workers. *American Journal of Infection Control*, 49(3), 405-406.
- Caretti, D. M. (1999). Cognitive performance and mood during respirator wear and exercise. *American Industrial Hygiene Association Journal*, 60(2), 213-218.
- Centers for Disease Control and Prevention. (2013). Severe acute respirator syndrome. Retrieved from <https://www.cdc.gov/sars/about/index.html>
- NIOSH (2018). National Personal Protective Technology Laboratory. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2018-141
- Chalikonda, S., Waltenbaugh, H., Angelilli, S., Dumont, T., Kvasager, C., Sauber, T., . . . Diaz-Garcia, R. (2020). Implementation of an elastomeric mask program as a strategy to eliminate disposable N95 mask use and reesterilization: Results from a large academic medical center. *Journal of the American College of Surgeons*, 231(3), 333-338.
- Chen, C., Lin, Y., & Wei, H. (2017). O081 change in respiratory heat flows in response to wearing half-mask respirators in hot-and-humid environment. *Occupational and Environmental Medicine*, 74, A22.
- Chen, Y., Wang, J., & Yang, Z. (2015). The human factors/ergonomics studies for respirators: A review and future work. *International Journal of Clothing Science and Technology*, 27(5), 652-676.
- Chen, Y., Yang, Z., Wang, J., & Gong, H. (2016). Physiological and subjective responses to breathing resistance of N95 filtering facepiece respirators in still-sitting and walking. *International Journal of Industrial Ergonomics*, 53, 93-101
- Chiang, J., Hanna, A., Lebowitz, D., & Ganti, L. (2020). Elastomeric respirators are safer and more sustainable alternatives to disposable N95 masks during the coronavirus outbreak. *International Journal of Emergency Medicine*, 13(1), 39. doi:10.1186/s12245-020-00296-8
- Echt, A., Coffey, C., Earnest, S., Novakovich, J., Garza, E., Breloff, S. & Soias-Moral, C. (2020). A guide to respirators used for dust in construction. Retrieved from <https://blogs.cdc.gov/niosh-science-blog/2020/08/17/respirators-construction/#:~:text=A%20reusable%20half-mask%2C%20negative-pressure%20respirator%2C%20consists%20of%20a,ensure%20a%20tight%20fit%20to%20the%20wearer%E2%80%99s%20face.>
- Electronic Code Of Federal Regulations. (2021). 42 CFR part 84.
- Floyd, E. L., Henry, J. B., & Johnson, D. L. (2018). Influence of facial hair length, coarseness, and areal density on seal leakage of a tight-fitting half-face respirator. *Journal of Occupational & Environmental Hygiene*, 15(4), 334-340.
- Food and Drug Administration. (2019). Working to reduce medication errors.
- Forouzandeh, P., O'Dowd, K., & Pillai, S. C. (2021). Face masks and respirators in the fight against the COVID-19 pandemic: An overview of the standards and testing methods. *Safety Science*, 133, 104995.
- Gao, S., McKay, R. T., Yermakov, M., Kim, J., Reponen, T., He, X., . . . Grinshpun, S. A. (2016).

- Performance of an improperly sized and stretched-out loose-fitting powered air-purifying respirator: Manikin-based study. *Journal of Occupational and Environmental Hygiene*, 13(3), 169-176.
- Haas, E.J., Greenawald, L.A., Furek, A., D'Alessandro, M.M. (2021) Using Public Feedback about the use of Elastomeric Half Mask Respirators to Inform a National Deployment Study within Health Settings. *Journal of the International Society for Respiratory Protection*, Vol. 38, No. 2, 2021, In Press.
- Harber, P., Bansal, S., Santiago, S., Liu, D., Yun, D., Ng, D., . . . Wu, S. (2009). Multidomain subjective response to respirator use during simulated work. *Journal of Occupational and Environmental Medicine*, 51(1), 38-45.
- Harber, P., Santiago, S., Bansal, S., Liu, Y., Yun, D., & Wu, S. (2010). Respirator physiologic impact in persons with mild respiratory disease. *Journal of Occupational and Environmental Medicine*, 52(2), 155-162.
- Hines, S. E., Brown, C., Oliver, M., Gucer, P., Frisch, M., Hogan, R., . . . McDiarmid, M. (2019a). User acceptance of reusable respirators in health care. *American Journal of Infection Control*, 47(6), 648-655.
- Hines, S. E., Brown, C., Oliver, M., Gucer, P., Frisch, M., Hogan, R., . . . McDiarmid, M. (2019b). Storage and availability of elastomeric respirators in health care. *Health Security*, 17(5), 384-392.
- Hines, S. E., Oliver, M. S., Gucer, P., & McDiarmid, M. A. (2020). Self-reported impact of respirator use on health care worker ability to perform patient care. *American Journal of Infection Control*, 48(12), 1556-1558.
- Chiou, S. S., & Keane, P. R. (2016). Influence of personal protective equipment use on fall risk. CRC Press
- James, R., Dukes-Dobos, F., & Smith, R.(1984). Effects of respirators under heat/work conditions. *American Industrial Hygiene Association Journal*, 45(6), 399-404.
- Johnson, A. T. (2016). Respirator masks protect health but impact performance: A review. *Journal of Biological Engineering*, 10(4), 4.
- Johnson, A. T., Dooly, C. R., & Brown, E. Y. (1994). Task performance with visual acuity while wearing a respirator mask. *American Industrial Hygiene Association Journal*, 55(9), 818-822.
- Johnson, A. T., Dooly, C. R., Sahota, M. S., Coyne, K. M., & Benjamin, M. B. (1997). Effect of altered vision on constant load exercise performance while wearing a respirator. *American Industrial Hygiene Association Journal*, 58(8), 578-582.
- Johnson, A. T., Mackey, K. R., Scott, W. H., Koh, F. C., Chiou, K. Y. H., & Phelps, S. J. (2005). Exercise performance while wearing a tight-fitting powered air purifying respirator with limited flow. *Journal of Occupational and Environmental Hygiene*, 2(7), 368-373.
- Katlin Taylor, P., RPh, Dan Sheridan, M., RPh, & and Melinda Faber, R N. (2016). Low vision = high risk for medication errors. *Nursing*, 46(1), 65-66.
- Khoo, K., Leng, P., Ibrahim, I. B., & Lim, T. (2005). The changing face of healthcare worker perceptions on powered air-purifying respirators during the SARS outbreak. *Respirology (Carlton, Vic.)*, 10(1), 107-110.
- Kim, J., PhD, Wu, T., MS, Powell, J. B., MS, & Roberge, Raymond J., MD, MPH. (2016). Physiologic and fit factor profiles of N95 and P100 filtering facepiece respirators for use in hot, humid environments. *American Journal of Infection Control*, 44(2), 194-198.
- Kirby, T. (2020). Evidence mounts on the disproportionate effect of COVID-19 on ethnic minorities. *The Lancet Respiratory Medicine*, 8(6), 547-548.
- Lawrence, C., Harnish, D. A., Sandoval-Powers, M., Mills, D., Bergman, M., & Heimbuch, B. K. (2017). Assessment of half-mask elastomeric respirator and powered air-purifying respirator reprocessing for an influenza pandemic. *American Journal of Infection Control*, 45(12), 1324-1330.
- Lee, M. C., Takaya, S., Long, R., & Joffei, A. M. (2008). Respirator-Fit testing: Does it ensure the protection of healthcare workers against respirable particles carrying pathogens? *Infection Control and Hospital Epidemiology*, 29(12), 1149-1156.
- Licina, A., & Silvers, A. (2021). Use of powered air-purifying respirator(PAPR) as part of protective equipment against SARS-CoV-2-a narrative review and critical appraisal of evidence. *American*

- Journal of Infection Control, 49(4), 492-499.
- Lin, Y., & Chen, C. (2019). Thermoregulation and thermal sensation in response to wearing tight-fitting respirators and exercising in hot-and-humid indoor environment. *Building and Environment*, 160, 106158.
- Loibner, M., Hagauer, S., Schwantzer, G., Berghold, A., & Zatloukal, K. (2019). Limiting factors for wearing personal protective equipment (PPE) in a health care environment evaluated in a randomised study. *PLoS One*, 14(1), e0210775.
- Marler, H., & Ditton, A. (2021). "I'm smiling back at you": Exploring the impact of mask wearing on communication in healthcare. *International Journal of Language & Communication Disorders*, 56(1), 205-214.
- Martin, S. B., & Moyer, E. S. (2000). Electrostatic respirator filter media: Filter efficiency and most penetrating particle size effects. *Null*, 15(8), 609-617.
- Mayo Clinic. (2021). Visual acuity test. Retrieved from <https://www.mayoclinic.org/tests-procedures/eye-exam/multimedia/visual-acuity-test/img-20006168>
- Mayo Clinic Staff. (2021a). Coronavirus disease 2019 (COVID-19). Retrieved from <https://www.mayoclinic.org/diseases-conditions/coronavirus/symptoms-causes/syc-20479963>
- Mayo Clinic Staff. (2021b). COVID-19 (coronavirus): Long-term effects. Retrieved from <https://www.mayoclinic.org/diseases-conditions/coronavirus/in-depth/coronavirus-long-term-effects/art-20490351>
- McCoy, M.A., Domnitz, S.B., Liverman, C.T., Institute of Medicine. 2015. The Use and Effectiveness of Powered Air Purifying Respirators in Health Care: Workshop Summary. Washington, DC: The National Academies Press. <https://doi.org/10.17226/18990>.
- McMahon, K., Balakrishnan, V., Check, R., Kelly, B., Rivard, L., Pester, J., . . . Jeanmonod, R. (2020). 336 the pragmatic use of industrial elastomeric respirators in health care practice during the COVID-19 viral pandemic. *Annals of Emergency Medicine*, 76(4, Supplement), S129-S130
- Institute of Medicine (2015). The use and effectiveness of powered air purifying respirators in health care. Washington, D.C: National Academies Press.
- Mitchell, R., MHSc, Ogunremi, T., MSc, Astrakianakis, G., PhD, Bryce, E., MD, Gervais, R., MD, Gravel, Denise, BScN, MSc, . . . Weir, Christine, BScN, MSc. (2012). Impact of the 2009 influenza A (H1N1) pandemic on canadian health care workers: A survey on vaccination, illness, absenteeism, and personal protective equipment. *American Journal of Infection Control*, 40(7), 611-616.
- Garg S, Kim L, Whitaker M, et al. Hospitalization Rates and Characteristics of Patients Hospitalized with Laboratory-Confirmed Coronavirus Disease 2019 — COVID-NET, 14 States, March 1–30, 2020. *MMWR Morb Mortal Wkly Rep* 2020;69:458–464. Nelson, H. (1992). USA: Objections to protective respirators. *The Lancet (British Edition)*, 340(8827), 1088.
- Greenawald, L.A., Haas, E.J., D'Alessandro, M.M., (2021) Elastomeric Half Mask Respirators: An Alternative to Disposable Respirators and a Solution to Shortages during Public Health Emergencies. *Journal of the International Society for Respiratory Protection*, Vol. 38, No. 2, 2021, In Press.
- NIOSH. (2007). Determination of communication performance test for speech conveyance and intelligibility of chemical biological radiological and nuclear full-facepiece air purifying respirators standard testing procedure.
- O'Hearn, M., Liu, J., Cudhea, F., Micha, R., & Mozaffarian, D. (2021). Coronavirus disease 2019 hospitalizations attributable to cardiometabolic conditions in the united states: A comparative risk assessment analysis. *Journal of the American Heart Association*, 10(5), e019259. doi:10.1161/JAHA.120.019259
- Or, P. P., Chung, J. W., & Wong, T. K. (2018). A study of environmental factors affecting nurses' comfort and protection in wearing N95 respirators during bedside procedures. *Journal of Clinical Nursing*, 27(7-8), e1477-e1484.
- OSHA. (2009). Assigned protection factors for the revised respiratory protection standard. Washington, D.C.: U.S. Dept. of Labor, Occupational Safety and Health Administration.

- Oxford University Press. (n.d.). Comfort. In Oxford Advanced Learner's Dictionary. Retrieved December 2, 2021, from https://www.oxfordlearnersdictionaries.com/us/definition/english/comfort_1
- Perna, G., Cuniberti, F., Daccò, S., Nobile, M., & Caldirola, D. (2020). Impact of respiratory protective devices on respiration: Implications for panic vulnerability during the COVID-19 pandemic. *Journal of Affective Disorders*, 277, 772-778.
- Petsonk, E. L., & Harber, P. (2020). Respiratory protection for health care workers: A 2020 COVID-19 perspective. *American Journal of Industrial Medicine*, 63(8), 655-658.
- Powell, J. B., Kim, J., & Roberge, R. J. (2017). Powered air-purifying respirator use in healthcare: Effects on thermal sensations and comfort. *Journal of Occupational & Environmental Hygiene*, 14(12), 947-954.
- Radonovich, L. J., Yanke, R., Cheng, J., & Bender, B. (2009). Diminished speech intelligibility associated with certain types of respirators worn by healthcare workers. *Journal of Occupational and Environmental Hygiene*, 7(1), 63-70.
- Rebmann, Terri, PhD, RN, CIC, Carrico, Ruth, PhD, RN, CIC, & Wang, J., PhD. (2013). Physiologic and other effects and compliance with long-term respirator use among medical intensive care unit nurses. *American Journal of Infection Control*, 41(12), 1218-1223.
- Regli, A., Sommerfield, A., & Ungern-Sternberg, B. S. (2021). The role of fit testing N95/FFP2/FFP3 masks: A narrative review. *Anaesthesia*, 76(1), 91-100.
- Rhee, M. S. M., Lindquist, C. D., Silvestrini, M. T., Chan, A. C., Ong, J. J. Y., & Sharma, V. K. (2021). Carbon dioxide increases with face masks but remains below short-term NIOSH limits. *BMC Infectious Diseases*, 21(1), 354.
- Roberge, R. J., Jung-Hyun, K., Powell, J. B., Shaffer, R. E., Ylitalo, C. M., & Sebastian, J. M. (2013). Impact of low filter resistances on subjective and physiological responses to filtering facepiece respirators. *PLoS One*, 8(12), e84901.
- Roberge, R. J., Kim, J., & Coca, A. (2012). Protective facemask impact on human thermoregulation: An overview. *The Annals of Occupational Hygiene*, 56(1), 102-112.
- Round, M., & Isherwood, P. (2021). Speech intelligibility in respiratory protective equipment - implications for verbal communication in critical care. *Trends in Anaesthesia and Critical Care*, 36, 23-29.
- Rowe, G. (2014). Clearing the air about PAPRs: All about using a powered air-purifying respirator. *Chilton's Industrial Safety & Hygiene News*, 48(5), 46.
- Shenal, B. V., Radonovich, L. J., Cheng, J., Hodgson, M., & Bender, B. S. (2012). Discomfort and exertion associated with prolonged wear of respiratory protection in a health care setting. *Journal of Occupational and Environmental Hygiene*, 9(1), 59-64.
- Suen, Lorna K.P., RN, MPH, PhD, Yang, L., PhD, Ho, Suki S.K., RN, MSc, Fung, Keith H.K., RN, MPhil, Boost, M. V., PhD, Wu, Cynthia S.T., RN, PhD, . . . O'Donoghue, M., PhD. (2017). Reliability of N95 respirators for respiratory protection before, during, and after nursing procedures. *American Journal of Infection Control*, 45(9), 974-978.
- Udayasiri, R., Knott, J., McD Taylor, D., Papson, J., Leow, F., & Hassan, F. A. (2007). Emergency department staff can effectively resuscitate in level C personal protective equipment. *Emergency Medicine Australasia*, 19(2), 113-121.
- Xu, S., Simons, J., Yorio, P., Rottach, D., Zhuang, Z., & Radonovich, L. (2021). Speech intelligibility test methodology applied to powered air-purifying respirators used in healthcare. *Null*, 18(1), 28-34.
- Youakim, Sami, MD, MSc, FRCP. (2007). Adverse reactions associated with respirator fit testing of healthcare workers in british columbia, canada: A review of compensation claim cases. *Archives of Environmental & Occupational Health*, 62(4), 197-200.
- Zelnick, S. D., McKay, R. T., & Lockey, J. E. (1994). Visual field loss while wearing full-face respiratory protection. *American Industrial Hygiene Association Journal*, 55(4), 315-321.
- Zhuang, Z., Bergman, M., Brochu, E., Palmiero, A., Niezgoda, G., He, X., . . . Shaffer, R. (2016). Temporal changes in filtering-facepiece respirator fit. *Journal of Occupational and Environmental Hygiene*, 13(4), 265-274.
- Zimmerman, N. J., Eberts, C., Salvendy, G., & McCabe, G. (1991). Effects of respirators on performance of physical, psychomotor and cognitive tasks. *Ergonomics*, 34(3), 321-334.