REVIEW ARTICLE

COVID-19 and Keeping Clean: A Narrative Review To Ascertain the Efficacy of Personal Protective Equipment To Safeguard Health Care Workers Against SARS-CoV-2

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ABSTRACT

Identifying the optimal amount of personal protective equipment (PPE) is a formidable challenge when faced with a new contagion such as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Unequivocally, there are dangers to health care workers (and by extension, their patients, colleagues, and communities) if not enough equipment is donned to safeguard them. And yet, there are also dangers to patients, colleagues, and the community if resources are overconsumed and result in hoarding, shortages, and inequitable distribution, all of which are occurring as the worldwide coronavirus disease 2019 (COVID-19) pandemic continues.

Research to ascertain the precise PPE required to defend specifically against SARS-CoV-2 encompasses an area of active investigation that will likely remain unresolved for some time. While awaiting more definitive conclusions, we must look to past evidence to provide a reasonable basis on which protocols and policies might be refined. What follows is a narrative review of PPE efficacy and how existing evidence might apply to protecting health care workers against COVID-19. Findings are extrapolated from investigations in 4 general domains: early investigations into SARS-CoV-2, retrospective studies about severe acute respiratory syndrome coronavirus 1, prospective studies of influenza and other common respiratory viruses, and laboratory PPE studies.

Available evidence suggests that contact and droplet precautions, in addition to eye protection and standard hygiene measures, should be adequate in the vast majority of clinical settings when caring for patients with SARS-CoV-2. Adherence to guidelines promoting appropriate levels of PPE should safeguard practitioners while mitigating against resource overuse.

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Among the many uncertainties arising from the ongoing global coronavirus disease 2019 (COVID-19) pandemic are queries into the optimal form of personal protective equipment (PPE) for hospital-based practitioners, including pediatricians. What is the appropriate level of gear to don? How might we effectively protect ourselves (and by extension, our patients, our colleagues, and our communities) while caring for patients infected with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)?

Although such questions encompass an area of active investigation that will likely remain unresolved for some time, past evidence provides a reasonable basis on which we can refine protocols and policies. Many PPE-related topics were queried in the aftermaths of severe acute respiratory syndrome (SARS), caused by severe acute respiratory syndrome coronavirus 1 (SARS-CoV-1), and various influenza outbreaks. For example, in 2006, the Institute of Medicine was asked to specifically (and presciently) comment on measures "that can be taken that would permit the reuse of disposable N95 respirators in healthcare settings."[1]

Determining the right amount of protective gear is not just about safeguarding individuals; it is a matter of equity. Reports of PPE shortages are ubiquitous in domestic and international contexts.[2,3] There is hoarding, supply chains are disrupted, and low- and middle-income countries are suffering the brunt of discriminatory resource distribution.[4,5] The extent to which rich hospitals and rich countries consume resources has global implications on mortality and morality.

What follows is a narrative review about PPE efficacy and how available evidence might apply to the COVID-19 pandemic. It is organized into the classic modes of infection control (contact, droplet, and airborne precautions) and also covers issues related to the extended use of N95 respirators. The review is not intended to replace any local, national, or international guideline but rather to provide the (often corroborating) scientific rationale underlying them. Findings are extrapolated from investigations in 4 general settings: early investigations into SARS-CoV-2, retrospective studies of SARS-CoV-1, prospective studies of influenza and other common respiratory viruses, and laboratory PPE studies. Although each evidence domain has inherent limitations (primarily recall bias, potential confounding, and imperfect generalizability), together they form a composite picture from which we might surmise a reasonable approach forward.

CONTACT PRECAUTIONS

For contact-based transmission of COVID-19 to occur, a person who is infected must transfer SARS-CoV-2 directly onto another person (or indirectly via an intermediary surface [fomite]), after which the recipient would need to inoculate susceptible mucosal surfaces (eg, eyes, nose, or mouth). Additionally, contact-based transmission would only transpire if defenses against this form were not employed or not effective. These issues are explored below.

The potential for contact-based transmission of respiratory viruses has been known for 4 decades. In 1981, researchers instructed healthy volunteers to touch items (eg, countertops, toys, etc) contaminated with secretions from infants with respiratory syncytial virus (RSV) and then directed these volunteers to "gently rub the mucous membranes of their nose or eye."[6] Study participants (who never directly interacted with the infants who were infected) contracted RSV on average 6 days after exposure. When institutions acted on these findings and implemented control measures, such as cohort nursing, gowning, and gloving (without masking), nosocomial RSV rates dropped precipitously.[7] Although perhaps not generalizable, studies of RSV provide a foundation for the plausibility of contact-based transmission of respiratory viruses.

Virus survival on fomite surfaces has been directly studied. Transmissible gastroenteritis virus (TGEV), a type of coronavirus that causes disease in pigs,[8] remained viable for hours on scrub fabric, gloves, and masks in laboratory conditions.[9] However, the virus inactivates with time. Two percent of the TGEV load survived on scrub fabric after 2 hours in room air; 0.2% lingered after 4 hours. Preliminary data on SARS-CoV-1 and SARS-CoV-2 corroborate viability for hours to days on surfaces, including plastic, cardboard, and stainless steel.[10]

Viral particles can be transported by touching contaminated surfaces. Transfer efficiency, the amount of virus transferred from a given surface to a fingertip after 10 seconds of contact, is humidity- and material-dependent, and in general, nonporous materials enable greater transfer. For example, MS2 bacteriophage, a single-stranded RNA virus with many research applications,[11] had low average transfer rates from cotton (0.03%) and rates as high as 67% from glass.[12] Clinically pathogenic viruses, such as rhinovirus and parainfluenza, have also successfully transferred from stainless steel to fingertips after 5 seconds of contact.[13]

High-humidity settings facilitate transfer from fomites. Transfer efficiency from stainless steel to fingertips was 6.9% in low humidity compared with 37.4% in high humidity.[12] In humid conditions, respiratory viral droplets more readily settle on surfaces and remain more stable when suspended in a liquid medium.[14] This is 1 of the reasons contact-based transmission is suspected to be the predominant form of influenza transmission in tropical climates.[15]

Defense against contact-based transmission encompasses standard measures (eg, avoiding hand-to-face contact and hand hygiene) and specific protective equipment (eg, disposable gowns and gloves). Avoiding hand-to-face contact is common sense and yet notoriously challenging. Over the course of a 2-hour lecture, medical students touched their faces on average 23 times an hour, with nearly half of the touches going to the eyes, nose, or mouth.[16] The use of gloves and/or face masks is widely theorized to decrease facial touching through psychological and physical deterrence,[17] although this hypothesis has not been specifically interrogated in formal research.

The efficacy of rigorous hand hygiene to halt contact-based spread of pathogens was demonstrated >150 years ago,[18] and recent evidence continues to support this fundamental tenet of infection control. Hygiene interventions have reduced transmission of respiratory infections in many community[19] and health care settings.[18] World Health Organization–recommended formulations of alcohol-based solutions have been specifically tested against SARS-CoV-1 and were found to be effective.[20]

Measures against contact transmission mitigated infection of health care workers (HCWs) during the 2002 SARS-CoV-1 outbreak. A pooled analysis across multiple retrospective case-control studies revealed decreased odds of contracting SARS for HCWs who frequently washed their hands (odds ratio [OR] 0.45; 95% confidence interval [CI] 0.36–0.57), wore gloves (OR 0.43; 95% CI 0.29–0.65), and wore gowns (OR 0.23; 95% CI 0.14–0.37).[21] Adherence to standardized protocols for donning or doffing PPE and participation in active training sessions decreased self-contamination in simulation studies.[22]

Taken in summation, it remains biologically and epidemiologically plausible for SARS-CoV-2 to transfer from individuals who are infected to others via direct physical contact or fomites. Transmission is dependent on multiple factors and is likely highest when occurring shortly after contact with individuals who are infected or with nonporous contaminated fomites, particularly in humid conditions. Measures against contact transmission, including avoiding hand-to-face contact, partaking in hand hygiene, and wearing gloves and isolation gowns, should protect against SARS-CoV-2 when employed effectively.

DROPLET PRECAUTIONS

Droplet-based transmission occurs when respiratory secretions containing active virus travel from a person who is infected across a short distance in the air directly onto the mucosal surface of another person. Physical contact with individuals who are infected is not necessary. The plausibility of this transmission mode has been validated through many experiments. Examples include the transfer of influenza from infected guinea pigs to susceptible counterparts in adjacent, nontouching cages[15]; the transfer of coxsackie virus from persons who were infected to those on the other side of a shared barrack separated in half by a wire barrier preventing physical contact between the study's participant groups[23]; and the transmission of rhinovirus from individuals playing poker who were infected, to others at the same table wearing restraints preventing hand-to-face touching (ie, contact-based transmission).[24]

The distance traveled by a respiratory droplet depends on multiple elements. Factors favoring shorter distances include larger droplet size ($>5\ \mu$m), slower expulsion, increased humidity, and minimal airflow away from the patient.[15,25] The Centers for Disease Control and Prevention's historical radius for droplet transmission was loosely defined as 3 ft, but after the SARS-CoV-1 outbreak, this distance was extended to 6 feet on the basis of data suggesting that medical students in Hong Kong were infected at greater rates when adjacent to (~6 ft away from) an index patient with SARS with whom they had no direct physical contact.[25,26]

In retrospective real-world observations, such as those undertaken during emerging pandemics such as SARS and COVID-19, it is often not possible to dissect whether infection occurred via contact- or droplet-based transmission. Both can occur from close-proximity interactions. However, biological plausibility, laboratory studies, and epidemiological data (described in greater detail in the next section) all imply droplet-based transmission to be a major form of SARS-CoV-2 propagation.

The primary measures against droplet-based transmission include remaining a safe distance away from individuals who are infected (commonly considered to be 6 ft but would depend on specific clinical contexts) and/or donning facial protection (surgical mask [not an N95 respirator] and eye protection) to block physical entry of particles onto susceptible mucosa.[25] The efficacy of such measures is presented in the next section to allow for a direct comparison between PPE against droplet and airborne transmission.

AIRBORNE PRECAUTIONS

In contrast to droplet-based transmission, airborne transmission occurs when patient secretions containing infective viral particles travel long distances (>6 ft) and enter the respiratory tract of susceptible individuals. Airborne (or aerosolized) particles are generally small ($<5\ \mu$m) and dry (desiccated) and thus able to remain suspended in air and travel on currents great distances before settling on persons, the ground, or atop objects.[25]

Measures to protect against airborne transmission include environmental controls (eg, specialized air handling) and provider gear (eg, N95 respirator).[25] When fit tested to ensure a proper seal on the user's face, an N95 respirator blocks 95% of nonoily particles as small as 0.3 μm.[27] Although droplet and airborne precautions are generally operationalized in a dichotomous manner, emerging data suggest a continuum between these 2 modes of transmission based on both host and environmental factors.[14] For example, despite containing large particles that theoretically should not travel far, the gas cloud formed by sneezing has been demonstrated to transit beyond 20 ft.[28]

A number of recent studies provoked concern that SARS-CoV-2 may infect via airborne mechanisms. In laboratory conditions entailing a rotating drum maintained under strict temperature control (22°C) and humidity parameters (65%), the virus survived in the air for hours.[10] Additionally, researchers in Wuhan, China, and Nebraska discovered that SARS-CoV-2 RNA was present in air samples of wards and ICUs housing patients with COVID-19.[29,30] The presence of viral RNA as detected by polymerase chain reaction assays, however, does not necessarily mean those particles can successfully infect others. Virus viability (or infectivity), measured by inoculating a tissue culture and examining subsequent cell death, was not assessed in the Wuhan study and was not detected in any samples from the Nebraska study.[29,30]

The question thus remains: Are airborne precautions necessary to care for patients with COVID-19, or will droplet precautions suffice? While ongoing investigations continue to uncover how SARS-CoV-2 behaves in real-world clinical settings, a review of past evidence provides 4 relevant points.

First, substantial evidence indicates that the predominant modes of transmission for respiratory viruses are through droplet and contact mechanisms, not airborne means. In a separate study arm of the aforementioned research into RSV communicability, none of the volunteers who sat in the examination room without a mask 6 ft away from an infant who was infected contracted the disease.[6] Studies of influenza reveal far greater transmission from person to person in close-contact settings.[31,32] Contact tracing in a Canadian hospital noted SARS-CoV-1 infections in HCWs among only those who touched the index patient, with the exception of 1 HCW for whom no clear etiology was identified.[33]

Emerging data from SARS-CoV-2 similarly corroborate a propensity for close-contact (ie, contact or droplet) transmission.[34] In a review of 1286 contacts of 391 individuals with COVID-19 in Shenzhen, China, increased odds of transmission were observed in settings where contacts spent considerable time in close proximity with individuals who were infected.[36]

Second, both retrospective and prospective data suggest contact and droplet PPE are adequate protection in most clinical contexts. In another SARS-CoV-1 contact tracing study involving 254 HCWs (13 of whom contracted SARS) exposed to 11 index case patients in Hong Kong, 0 of 51 staff workers who wore a surgical mask were infected, as were 0 of 92 workers who wore an N95 respirator.[37] Both were protective, although the study did not include any index case patients receiving nebulized therapies.

Prospective data corroborate this general finding. A trial of Canadian nurses randomly assigned to wear fit-tested N95 respirators or surgical masks (even during nebulized treatments) during influenza season revealed nearly identical rates of laboratory-confirmed influenza between the 2 arms, and the authors concluded that surgical masks were noninferior.[38] A similarly designed prospective study in outpatient settings across the United States over multiple years revealed the same: there was no significant difference in the incidence of laboratory-confirmed influenza and other respiratory illnesses (including common coronavirus strains) in HCWs wearing N95 respirators compared with those wearing surgical masks.[39]

Third, although airborne transmission may not be a primary mechanism of transmission, viral spread through small-particle aerosolization is plausible in certain clinical contexts. Air samples obtained from rooms of patients with laboratory-confirmed H1N1 revealed that certain aerosol-generating procedures, such as bronchoscopy, increased the quantity (although not statistically significant) of small particles containing the virus.[40] In a systematic review of SARS-CoV-1 studies, the OR of contracting SARS for HCWs performing or being exposed to tracheal intubation, relative to those not exposed to the procedure, was 6.6 (95% CI 4.1–10.6).[41] Data on nebulized therapies were mixed, as was the case for a number of other clinical interventions, including high-flow oxygen.[41] This general lack of evidence has left public health authorities unable to enumerate a validated list of aerosol-generating procedures for COVID-19.[42]

Fourth, the amount of airborne virus can be mitigated through physical and environmental controls. For example, the amount of small-particle aerosolized virus in patients with influenza and common coronavirus strains substantially decreased when patients who were infected wore a face mask.[43,44] Source control through masking may not be possible in young children. In a systematic review of face mask use at mass gatherings, 11 years was identified as the youngest age studied[45]; the Centers for Disease Control and Prevention does not recommend face coverings for anyone $<$2 years of age.[46] Provider-based physical barriers, including face shields,[1] may also decrease the potential for aerosolized particles to be transferred to an HCW.

In summary, current evidence suggests that use of contact and droplet precautions is an adequate protection against SARS-CoV-2 in most clinical contexts, and physical controls can decrease the load of airborne virus. There are situations (such as intubation) during which additional precautions are warranted, but routine use of N95 respirators outside of high-risk settings is not supported by the current evidence base.

EXTENDED USE OF N95 RESPIRATORS

Current PPE shortages and the resultant need for institutions to extend the use of heretofore disposable N95 respirators has put many at unease. Concerns have been raised as to whether these respirators might be teeming with viral particles, increasing the propagation of disease.

In 2014, Fisher and Shaffer[47] from the National Institute for Occupational Safety and Health identified 4 reassuring properties related to extended respirator use. First, most viral particles are trapped in the middle, not external, surface of the mask. Dissecting influenza-laden masks infected in laboratory settings revealed that nearly 70% of viral particles were present in the middle layer, which typically has electrostatic properties that trap the virus there.[48] Second, as previously mentioned, the virus inactivates with time. Laboratory studies of TGEV demonstrated that 15% of a viral load on the surface of an N95 respirator survived after 2 hours in room air, whereas ~ 0.1% lingered after 24 hours.[9] Third, only a small fraction of viral particles are transferred onto fingertips when any particular surface is touched. There have been no studies on viral transfer specifically from N95 respirators to the finger, but transfer efficiency was low (0.3%) from polyester to the fingertip,[12] the material used for the shell of most N95 respirators.[49] Finally, even during a forceful cough, only a small fraction of viral particles are transferred back into the air. During laboratory cough simulations, at most, 0.2% of the mask's viral load was reaerosolized.[50]

Another concern is that extended respirator use may impact the mask's inherent ability to protect the user in terms of filtration or fit. Again, there are some reassuring features to note, as described by the

National Institute for Occupational Safety and Health.[47] First, when masks were continuously loaded (with flow rates of 85 L/minute) for 5 straight hours, filtration efficiency remained >97%.[51] Second, the fit test is a good test. Simulation of 3 10-minute patient encounters (obtaining vital signs, wound dressing change, intravenous care) revealed that initial mask fit was predictive of mask fit during care tasks.[52] However, fit can decrease with each re-use. When laboratory participants were asked to don or doff respirators 20 times consecutively (keeping the N95 respirator on for 2 minutes each time), there was decreasing fit with each re-use, with only 60% passing the fit test on the 20th use.[53] This is one of the reasons extended use (keeping the respirator on) is generally recommended over reuse (on, off, on). Another reason is the donning and doffing process requires a seal check each time, meaning that hands touch the mask more with each re-use.

Other studies have revealed general physiologic tolerance of extended respirator use, although such investigations have been conducted in healthy young adults without comorbid conditions.[54,55] In summary, N95 respirators have a number of technical features that, alongside the implementation of administrative and environmental controls, mitigate the potential for viral disease propagation during extended use.

CONCLUSIONS

Identifying the optimal amount of PPE is a daunting challenge when faced with the outbreak of a new contagion, such as SARS-CoV-2. Unequivocally, there are dangers to HCWs (and by extension, their patients, colleagues, and communities) if not enough equipment is donned to safeguard them. And yet, there are also dangers to patients, colleagues, and communities if scarce resources are overconsumed and/or result in hoarding, shortages, and inequitable distribution, as is currently occurring while the COVID-19 pandemic continues.

A review of currently available evidence suggests that contact and droplet precautions, in addition to eye protection and standard hygiene measures, are adequate in the vast majority of clinical settings when caring for patients with SARS-CoV-2. Adherence to guidelines[56] promoting appropriate levels of PPE should safeguard practitioners while minimizing resource overuse.

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