JOURNAL OF INTERNATIONAL CRISIS AND RISK COMMUNICATION RESEARCH
ISSN: 2576-0017
2023, VOL 6, NO S4

Infection Control Measures for Health Care Workers to Prevent Airborne Infection

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Abstract

Respiratory infections pose a significant threat to healthcare workers, as evidenced by the global impact of the COVID-19 pandemic. Traditional infection control measures have been based on the assumption that most respiratory pathogens are transmitted through large respiratory droplets. However, recent advancements in aerosol science have challenged this paradigm, demonstrating that infectious aerosols are primarily composed of small particles (<5 μm) that can remain suspended in the air for extended periods. This article critically examines the scientific literature on infectious aerosols and discusses the implications for infection control practices in healthcare settings. Studies utilizing advanced sampling techniques have consistently identified pathogens such as Mycobacterium tuberculosis, Pseudomonas aeruginosa, influenza viruses, and SARS-CoV-2 in small particle aerosols generated by coughing and exhaled breath. These findings underscore the need for healthcare workers to be protected against exposure to potentially infectious aerosols, particularly when in close proximity to patients. While surgical masks offer some protection, filtering facepiece respirators and powered air-purifying respirators provide superior respiratory protection. However, the effectiveness of these devices depends on proper fit and use. Environmental controls, such as adequate ventilation and air disinfection systems, are also crucial for mitigating the risk of airborne transmission. To effectively protect healthcare workers and reduce the spread of respiratory infections, infection control strategies must be revised to address the predominance of small particle aerosols and incorporate a multifaceted approach that includes personal protective equipment, administrative controls, and environmental measures. Further research is needed to optimize protective equipment, develop rapid diagnostic tools, and better understand the factors influencing aerosol transmission dynamics.

Keywords: Infection Control, Health Care Workers, Airborne Infection

Introduction

The global outbreak of COVID-19, caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has resulted in widespread infections and fatalities, including among health-care workers (Chou et al., 2020). The pandemic has highlighted ongoing debates and discrepancies in recommendations provided by health authorities regarding the appropriate use of masks or respirators to safeguard health-care workers from infection. Over two decades ago, when personal respiratory protection for health-care workers against tuberculosis was first reviewed, the understanding of infectious aerosols was limited and based on scarce evidence. Since that time, substantial advancements have been made, with contributions from researchers across multiple disciplines generating a significant body of knowledge. This Viewpoint aims to critically examine the scientific literature concerning aerosols produced by individuals with respiratory infections and discuss how this knowledge informs the optimal utilization of masks, respirators, and additional infection-control strategies to protect health-care workers from exposure to airborne pathogens. However, this discussion does not serve as an exhaustive review of the existing literature on the use of surgical masks or respirators, as numerous comprehensive reviews have already been conducted (Bartoszko et al., 2020; Long et al., 2020).

Traditional infection control measures for respiratory pathogens have largely been based on the assumption that most respiratory infections are transmitted via large respiratory droplets, typically defined as particles larger than 5 μm in diameter. These droplets are expelled during activities such as coughing and sneezing and are believed to settle quickly onto surfaces or mucosal areas of nearby individuals. Proximity to the source of infection has frequently been used as a proxy for droplet exposure, as demonstrated by statements such as “Proximity to the index case was associated with transmission, which is consistent with droplet spread”. Airborne transmission, on the other hand, has traditionally been associated with infectious droplet nuclei that arise from the evaporation of suspended droplets, resulting in particles 5 μm or smaller. This mode of transmission has been primarily attributed to diseases such as tuberculosis and a limited number of other pathogens. Based on these premises, surgical masks have historically been recommended for protection against most respiratory infections.

Recent advancements in aerosol science have significantly altered our understanding of respiratory pathogen transmission. Emerging evidence has demonstrated that the dichotomy between "large droplets" and "airborne droplet nuclei" may oversimplify the true complexity of aerosolized particles. Respiratory activities such as talking, breathing, and coughing can generate a continuous spectrum of particle sizes, many of which remain suspended in the air for extended periods. Studies utilizing advanced aerosol measurement techniques have shown that even larger particles can desiccate into smaller, respirable sizes under specific environmental conditions, enabling them to travel farther than previously anticipated. This evolving understanding has profound implications for the design and implementation of infection-control measures, as it underscores the potential for pathogens traditionally considered to spread via droplets to also exhibit airborne transmission characteristics.

Moreover, the effectiveness of surgical masks versus respirators in mitigating airborne infection risk has been a focal point of ongoing research. Surgical masks are primarily designed to protect others from the wearer's respiratory emissions and offer limited filtration efficiency for small particles. In contrast, respirators, such as N95 masks, are engineered to provide a tighter seal and higher filtration efficiency, effectively protecting the wearer from inhaling fine aerosolized particles. Despite this distinction, there has been inconsistent guidance from global health organizations on when and how each type of protective equipment should be deployed, particularly during pandemics. These inconsistencies have generated confusion and, at times, placed health-care workers at heightened risk, especially in resource-constrained settings where access to advanced protective equipment may be limited.

The role of ventilation, air purification, and other environmental controls in preventing airborne transmission is another critical component of infection control strategies. Adequate ventilation in health-care settings can dilute the concentration of airborne particles, reducing the risk of infection for both health-care workers and patients. The use of high-efficiency particulate air (HEPA) filters and ultraviolet germicidal irradiation (UVGI) systems has also been explored as adjunctive measures to enhance air quality and mitigate airborne transmission risks. These engineering controls, when combined with personal protective equipment and administrative policies, represent a comprehensive approach to minimizing the spread of airborne pathogens in health-care environments.

In summary, the growing body of evidence on respiratory aerosols challenges traditional paradigms of infection transmission and underscores the need for a multifaceted approach to infection control in health-care settings. Protecting health-care workers from airborne infections requires not only the appropriate selection and use of masks and respirators but also the integration of environmental controls, education, and consistent policy implementation. By synthesizing insights from the latest scientific literature, this Viewpoint seeks to provide actionable guidance to improve infection control measures and safeguard the health and safety of health-care workers.

Particles and Plumes

Infectious aerosols are suspensions of pathogens in airborne particles, influenced by both physical and biological principles. Particle size is the primary factor determining aerosol behavior. Particles measuring 5 μm or smaller can remain suspended in the air indefinitely under most indoor conditions unless removed by air currents or dilution ventilation. These smaller particles (<5 μm) are capable of depositing in the lower respiratory tract in humans, as well as in other species like guinea pigs, mice, and monkeys. Conversely, particles within the range of 6–12 μm primarily deposit in the upper airways of the head and neck.

Advanced imaging studies have demonstrated that aerosol plumes are generated during actions such as sneezing or coughing. These plumes contain the highest concentration of particles, which disperse over time and distance. The distance these particles travel is greater than previously understood, extending up to 7–8 m (Bourouiba, 2020). Reanalysis indicates that particles emitted by an average individual, ranging from 60–100 μm in size, fall to the ground within 2 m but can be propelled more than 6 m by sneezing. Health-care workers performing procedures near a patient's mouth—such as intubations,

bronchoscopies, or dental interventions—are at heightened risk of exposure to these aerosol plumes. These plumes encompass a broad spectrum of particle sizes (Bahl et al., 2022), raising critical questions about the presence of pathogens within the plumes and the size consistency for transmission. Research on cough aerosols and exhaled breath provides insights into these queries.

Cough Aerosol Studies

Pathogens have been consistently identified in aerosols produced by coughing from patients with respiratory infections. Studies that include methods to analyze particle size have found that pathogens are predominantly present in smaller particles (<5 μm; Table 1). Other investigations lacking particle size data have explored alternative outcomes (Acuña-Villaorduña et al., 2018) or employed methodologies incapable of providing size measurements. Infectious aerosols, which are composed of potentially pathogenic viruses, bacteria, and fungi suspended in the air, adhere to the same physical principles as other airborne particles. The biological characteristics of these pathogens influence their survival, infectivity, virulence, and related properties.

- Particle size is the key determinant of aerosol behavior.
- Small aerosol particles, defined as those smaller than 5 μm, are most likely to remain airborne for prolonged durations unless removed by air currents or ventilation. These particles also tend to deposit in the lower respiratory tract.
- Infection control guidelines have traditionally associated most respiratory infections with droplet transmission, involving particles larger than 5–10 μm. Airborne transmission has been attributed to a limited number of pathogens, such as *Mycobacterium tuberculosis*, through droplet nuclei sized 5 μm or smaller. Airborne infection isolation rooms and respirator masks have been recommended solely for preventing airborne transmission.
- These recommendations have been based on historical data and inferences. Over the last two decades, studies have directly measured particle sizes in infectious aerosols from individuals with respiratory infections, including those generated by coughing and exhaled breath.
- Research consistently demonstrates that humans produce infectious aerosols in various particle sizes, but pathogens predominantly exist in small particles (<5 μm), which are immediately respirable by exposed individuals.
- Emerging evidence suggests that severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), responsible for COVID-19, is transmitted through both small and large particle aerosols.
- These findings emphasize the necessity of protecting health-care workers from potentially infectious aerosols when working in close proximity to patients.

Protective Measures

- Some surgical masks may offer respiratory protection compared to no mask. Filtering facepiece respirators provide superior respiratory protection than surgical masks, while powered air-purifying respirators (PAPRs) offer the highest level of protection for most health-care settings.
- Face shields can reduce exposure to and contamination from large particle aerosols but do not protect against inhalation of small particle aerosols.
- PAPRs provide integrated eye protection. However, surgical masks and other respirators require supplementary eye protection, such as face shields or goggles, to prevent infection.
- Masking patients can partially reduce infectious aerosol exposure to health-care workers but is not a replacement for physical distancing and other infection control measures.
- Aerosolization of respiratory pathogens is highly variable, partly due to the log-normal distribution of infectious aerosols, aligning with the concept of super-spreading events.
- Airborne infection isolation rooms and other infection control measures targeting airborne infections are crucial for managing highly virulent respiratory pathogens, including SARS-CoV-2.

Tuberculosis

Direct measurement of culturable cough aerosols produced by patients with tuberculosis revealed that the majority (96%) of culturable Mycobacterium tuberculosis were contained in particles smaller than 4.7 μm. In contrast, few M. tuberculosis organisms were found in large particles (e.g., >7.0 μm) or on settle plates (11% with any colony-forming units [CFU]). Furthermore, culturable cough aerosols from tuberculosis index cases were identified as the strongest predictor of new tuberculosis infections among their household contacts. A consistent observation in tuberculosis aerosol research is the substantial variability in infectious aerosol production among patients with pulmonary tuberculosis. These findings suggest that only a subset of tuberculosis patients is infectious through cough aerosols, with some individuals exhibiting high infectivity, aligning with epidemiological evidence of super-spreading events.

Additionally, M. tuberculosis has been detected in a 1.4 m^3 chamber through molecular and culture-based methods. Most of the identified particles (59%) were smaller than 3.3 μm. In the largest study of tuberculosis cough aerosols to date, nearly half of the patients with drug-resistant tuberculosis generated cough aerosols, with the highest concentrations of viable bacilli in the 2.1–4.7 μm size range, corroborating earlier findings.

Cystic Fibrosis

*Cough aerosols from patients with cystic fibrosis have been shown to contain Pseudomonas aeruginosa. The particle size distribution of these aerosols was slightly larger than that observed in tuberculosis patients. Relatively few bacteria-containing large

particles were detected on settle plates (median of 6 CFU) or in a wash of the connecting tubing (1120 CFU, 95% CI 200–6060). In a subsequent study, viable P. aeruginosa from cough aerosols was shown to travel up to 4 m and remain culturable for up to 45 minutes.

Influenza and Other Viruses

Cough aerosol studies of influenza, involving 61 patients with either influenza A or influenza B, assessed particle dispersal at distances of 1 ft, 3 ft, and 6 ft. Particles smaller than 4.7 μm were detected at all distances. At 6 ft (1.83 m), large particles (≥4.7 μm) were scarcely detected. The influenza aerosol output followed a log-normal distribution, consistent with super-spreading phenomena. Another study, utilizing a different bioaerosol sampler, identified viral RNA in cough aerosols from 38 (81%) of 47 influenza patients. Of the viral RNA detected, 35% was associated with particles larger than 4 μm, while 65% was found in particles 4 μm or smaller.

PCR assays have also detected various respiratory viruses in children and adults with upper respiratory infections. During coughing, 82% of participants produced small particles (<4.7 μm) containing viruses, compared to 57% who generated larger particles.

Exhaled Breath Aerosol Studies

Studies measuring exhaled breath aerosols consistently identified pathogens in small particles (<5 μm; Table 2). Other investigations examined exhaled breath condensates or filters or used techniques that do not provide particle size distributions, such as direct impaction onto Petri dishes or into liquid media (Lindsley et al., 2016). The majority of particles in exhaled breath were smaller than 4 μm, with a median size between 0.7 and 1.0 μm.

Infection Control Measures for Health Care Workers to Prevent Airborne Infection

Pathogens in Exhaled Breath

Various viruses have been detected in exhaled breath condensates through PCR analysis, including influenza, human rhinovirus, respiratory syncytial virus, cytomegalovirus, Epstein-Barr virus, human papillomavirus, and Torque teno virus. Additionally, bacteria such as *Haemophilus influenzae*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Stenotrophomonas maltophilia*, meticillin-sensitive *Staphylococcus aureus* (MSSA), and meticillin-resistant *S. aureus* (MRSA) have been identified in exhaled breath condensates (Zheng et al., 2018). Viral and bacterial pathogens, including influenza A, respiratory syncytial virus, *S. aureus*, *H. influenzae*, *Legionella pneumophila*, and *Mycoplasma pneumoniae*, have also been isolated from the same patients. Furthermore, fungal species such as *Cladosporium*, *Alternaria*, and *Penicillium* have been detected in exhaled breath condensates from patients with asthma. In cases of exposure to patients colonized with *Pneumocystis jirovecii*, PCR identified the pathogen in the exhaled breath of two (50%) of four critically ill patients and in two (22%) of nine exposed healthcare workers.

When direct measurement of virus-containing particles in exhaled breath became possible, most influenza particles (87%) were found to be smaller than 1 μm. The

estimated generation rates of exhaled influenza particles ranged from fewer than 3.2 to 20 particles per minute. Advanced methods distinguished fine particles (≤5 μm) from coarse particles (>5 μm). In one study, influenza viral RNA was detected in the exhaled breath of 34 (92%) of 37 adults, with fine particles containing 8.8 times (95% CI 4.1–19.0) more viral copies than coarse particles. Respiratory viruses have been identified in both cough aerosols (82% of participants) and exhaled breath (81% of participants). Similar detection rates were observed for influenza, with viral RNA found in coughs (53% of participants) and breath (42% of participants). Human rhinovirus was more frequently collected from exhaled breath than from cough aerosols using a filter method. Comparative data from two studies demonstrated that influenza virus in exhaled breath is associated with smaller particles than in cough aerosols.

While three studies did not detect *Mycobacterium tuberculosis* in exhaled breath condensates, PCR assays of filters in expired air were positive in 12 (75%) of 16 mechanically ventilated tuberculosis patients. Face-mask sampling has also detected *M. tuberculosis* in exhaled breath. In one study, *M. tuberculosis*-specific RNA was found in all 15 participants who wore an N95 respirator with a sampling membrane for 5 minutes while coughing, talking, and breathing normally. Another study detected *M. tuberculosis* more frequently in face-mask samples (86%) than in sputum (21%) over 24 hours. The most likely mechanism for pathogen presence in exhaled breath is aerosol generation from the opening of collapsed bronchioles, though other theories such as vocal cord closure and vibration have been proposed (Bake et al., 2019). These mechanisms might explain transmission from asymptomatic individuals, although no definitive evidence exists for transmission through exhaled breath aerosols as most studies focus on diagnostics.

Infectious Aerosols in Room Air

Room air sampling has identified infectious aerosols, posing potential exposure risks to healthcare workers. For example, the varicella-zoster virus, one of the most contagious viruses, was detected by PCR in room air of 64 (82%) of 78 patients with varicella and nine (70%) of 13 patients with herpes zoster. Measles virus RNA was identified in particles smaller than 4.7 μm at various locations in a room occupied by a measles patient, while larger particles were positive only near the patient's head. None of the samples were positive by tissue culture (Bischoff et al., 2016).

M. tuberculosis has been detected in hospital air using PCR from settle plates and filters. In an outpatient clinic in South Africa, *M. tuberculosis* was detected by PCR in personal air samplers worn by healthcare workers in nine (36%) of 25 cases, compared to two (8.3%) of 24 stationary samplers. Influenza virus has also been detected by PCR in personal samplers worn by healthcare workers and in ambient air samples from emergency departments, with 50% of airborne virus particles measuring 4 μm or smaller. Similarly, influenza A was identified in 19% of personal samplers and 17% of stationary samplers in an urgent care clinic, where respiratory syncytial virus RNA was detected in 38% of personal samplers and 32% of stationary samplers.

In a busy inner-city emergency department, influenza virus was detected in 53 (42%) of 125 personal samplers worn by 30 healthcare workers, 28 (43%) of 96 room air samples, 23 (76%) of 30 surface samples, and three (25%) of 12 respirators worn during exposure

to a confirmed influenza patient. In a separate study in a large Chinese hospital, influenza was detected in 15 (79%) of 19 air samples across all particle size ranges, with virus concentrations ranging from 3,715 to 119,371 copies per m^3. Respiratory syncytial virus was detected in room air near 22 (92%) of 24 infected infants and young children in general wards and all ten patients in intensive care units, with most of the virus contained in particles smaller than 4.7 μm. Human rhinovirus RNA has also been isolated from the air in office buildings, though specific particle sizes were not reported.

Adenovirus has been identified by PCR in air samples from various healthcare settings. In a pediatric ward in Singapore, adenovirus was detected in eight (29%) of 28 air samples (Yadana et al., 2019), while air samples from pediatric emergency departments in Taiwan showed detection rates of 18% and 36%. Additionally, adenovirus DNA was found in 21 (77%) of air samples and 78 (72%) of surface samples collected from toilets in the nephrology ward of an Italian hospital. *Mycoplasma pneumoniae* DNA was also detected in 46% of air samples taken from a pediatric outpatient department in Taiwan.

Pneumocystis jirovecii DNA has been identified in hospital room air in several studies. One study detected the DNA in 17 (57%) of 30 rooms occupied by patients with *Pneumocystis* pneumonia and in six (29%) of 21 other hospital rooms. In a subsequent study, DNA was found in air samples collected 1 meter from the heads of 15 (79.8%) of 19 patients, as well as in four (33.3%) of 12 samples taken 8 meters away. Evidence supporting nosocomial transmission of *P. jirovecii* includes positive DNA findings in four (29%) of 14 air samples and in two (22%) of nine healthcare workers exposed during bronchoscopy. Similarly, *P. jirovecii* DNA was detected in seven (47%) of 15 critical-care unit rooms, and colonies were identified in nine (8.8%) of 102 healthcare workers. Further studies confirmed DNA presence in rooms of patients with *Pneumocystis* colonies but without pneumonia (Pougnet et al., 2018).

Aerosol Data from SARS-CoV and MERS-CoV

Limited aerosol data exist from the 2003 SARS-CoV pandemic. In Toronto, air sampling with a slit sampler yielded two of ten samples positive for SARS-CoV by PCR, though these were negative by viral culture. Additionally, 28 filter samples tested negative by both PCR and culture. Retrospective studies strongly suggest airborne transmission occurred in Hong Kong during the outbreak. For MERS-CoV, viral detection was reported in seven air samples collected from dedicated MERS units in two South Korean hospitals, with all seven samples testing positive by PCR and four also positive by viral culture.

Infectious Aerosols and SARS-CoV-2

Since the onset of the COVID-19 pandemic, airborne transmission of SARS-CoV-2 has been a topic of debate. Experimental data have shown that SARS-CoV-2 retains viability for over 3 hours in aerosolized form, indicating potential airborne transmission. Although no reports on exhaled breath or cough aerosol sampling from COVID-19 patients have been published, SARS-CoV-2 has been detected in air samples from hospitals in China and the USA. In one Wuhan hospital, PCR tests were positive for 14 (35%) of 40 air samples from the intensive care unit and two (12.5%) of 16 air samples from the general

ward. SARS-CoV-2 appears transmissible through direct contact, indirect contact via contaminated objects, and aerosolized particles, though the dominant mode of transmission remains unclear.

Air sampling for SARS-CoV-2 has been negative in three studies. However, these studies involved small patient numbers in rooms with high rates of ventilation or inefficient impinger devices for sample collection. Outbreaks in settings such as nursing homes, choir practices, and correctional facilities (Wallace, 2020) resemble tuberculosis outbreaks and suggest both traditional airborne transmission and super-spreader events. Experimental studies in golden hamsters demonstrated 100% efficient aerosol transmission between caged animals, along with direct contact transmission.

Revising the Paradigm of Infectious Aerosols

Evidence indicates that infectious aerosols encompass a wide range of particle sizes, which is consistent across different studies, methods, and pathogens. Contrary to traditional guidelines suggesting respiratory infections primarily involve large droplet transmission, small particle aerosols predominate. These particles do not require prolonged time for desiccation and are immediately respirable. Such findings call for an update to current infection control guidelines, a need that was first proposed nine years ago.

The assumption that close proximity defines droplet spread is flawed, as small particle aerosols are most concentrated near patients and dissipate with distance. Epidemiological data on tuberculosis transmission highlight this gradient, with higher transmission risk in closer proximity to the source case. For example, individuals sharing a bed with a tuberculosis patient are at greater risk of infection than those sharing the same room, while people in different rooms have even lower risk. An outbreak linked to an aerosol-generating device used to clean a tuberculous abscess showed a similar gradient of infection risk, with higher rates of tuberculin reactivity in rooms nearest the source case.

Physical distancing reduces transmission risk from both large and small particles, although small particles can travel farther. Transmission variability among respiratory pathogens appears to depend more on biological factors—such as emitted inoculum size, pathogen survival during aerosolization, and airborne transport—than on the physical size of emitted particles. Environmental factors, including air movement, temperature, humidity, and host defenses, also play significant roles in transmission dynamics.

Implications of Infectious Aerosol Data for Infection Control Practices

Given the high volume of patients in healthcare environments, healthcare workers face frequent exposure to highly infectious cases. This exposure may result in cumulative inhaled doses of pathogens, potentially leading to infections, although the role of this mechanism in the pathogenesis of COVID-19 remains uncertain. Infection control measures may not only decrease the likelihood of infection but also reduce the inhaled inoculum size, which has been associated with disease severity in influenza (Hemmink et al., 2016) and other diseases. This is particularly significant for small particle aerosols,

as demonstrated in a foundational study where 1 μm aerosols of *Bacillus anthracis* caused greater mortality in animals compared to 12 μm aerosols.

Masks Versus Respirators

Modeling studies and simulated workplace protection studies in the United States have highlighted the benefits of various types of respirators, while showing minimal to no protection from surgical masks. Research in the United Kingdom found that surgical masks reduced exposure to inert aerosols by a factor of two, whereas filtering facepiece respirators reduced exposure by a factor of 100 or more. For influenza aerosols, surgical masks reduced exposure by an average factor of six, though the reduction varied widely from 1.1 to 55 times, depending on the mask design.

Randomized trials have produced mixed results regarding the efficacy of N95 respirators compared to surgical masks in reducing respiratory illnesses. Two trials found no significant benefit (Radonovich et al., 2019), while two others showed protective effects of N95 respirators. However, none of these trials implemented quantitative fit testing, and two trials reported unexpectedly low failure rates (1.1–2.6%) for N95 respirators, contrasting with a 60% failure rate observed in a panel study using the same respirators. These findings suggest potential issues with the fit-testing processes used.

The effectiveness of filtering facepiece respirators depends on their fit, as face-mask leaks are a primary vulnerability. Operational research on fit testing for healthcare workers remains limited. The variability among filtering facepiece respirators means it may be more beneficial to use a respirator model with inherently good fit characteristics than a poorly fitting model that has passed a fit test. While some surgical masks provide adequate protection, their lack of certification or regulation as respiratory protection devices makes it difficult to identify the most effective options. Research is urgently needed in this area. Face shields have demonstrated efficacy in reducing inhalation exposures to aerosols with a median diameter of 8.5 μm by 96% and reducing surface contamination of filtering facepiece respirators by 97%. However, for smaller particles of 3.4 μm, the reduction in inhalation exposures was only 23%.

Masks to Prevent Transmission from the Wearer

Although surgical masks offer limited protection against inhaled pathogens, they play a role in protecting healthcare workers when worn by patients. For instance, placing surgical masks on patients with multidrug-resistant tuberculosis reduced transmission to guinea pigs by 56%. Similarly, masking patients with cystic fibrosis decreased *Pseudomonas aeruginosa* air contamination by 8% (Wood et al., 2018). In influenza studies, surgical masks reduced the quantity of viral RNA in small particles by 2.8 times and in large particles by 25 times. Surgical masks effectively reduced large droplets (>5 μm) of seasonal coronaviruses from three of ten patients to none of 11 ($p=0.09$) and small aerosols (<5 μm) from four of ten patients to none of 11 ($p=0.04$). Additionally, masks reduced influenza droplets from six of 23 patients to one of 27 ($p=0.04$), although the reduction in influenza small aerosols (<5 μm) was not statistically significant. Increasing

evidence supports the use of masks to reduce SARS-CoV-2 transmission in community and healthcare settings (Prather et al., 2020).

Challenges in Assessing Infectious Aerosols

A major limitation in infectious aerosol studies is the heavy reliance on PCR results, with relatively few studies evaluating the viability of pathogens using cell cultures or other methods. Viability assessment is inherently challenging, as aerosolization from the respiratory tract subjects pathogens to various stresses that diminish their viability, often defined as the ability to be cultured. Indoors, desiccation is the predominant stressor, though factors such as temperature, radiation, oxygen, ozone, and associated reaction products can damage viral lipids, proteins, and nucleic acids. Additionally, aerosol sampling itself introduces mechanical trauma, desiccation, and post-sampling injuries during extraction processes.

While PCR assays are logistically simpler than cell culture methods, they do not measure viability. For example, although influenza virus was successfully sampled directly onto cell culture monolayers in the laboratory, this method proved impractical for transport to and from clinical sites due to the sensitivity of cells to spillage and pH stresses. These limitations, combined with the physical inefficiencies of air samplers, suggest that most infectious aerosol data likely underestimate the actual exposures faced by healthcare workers.

Continuous breathing by infectious individuals generates aerosols around the clock, yet no data exist on potential circadian variations or rhythmic patterns in output. Coughing, which is often sporadic and paroxysmal, has been studied in terms of 24-hour frequency, but its association with aerosol production remains unclear. Only one study has examined the relationship between cough aerosol production by tuberculosis index cases and subsequent infections in exposed contacts. Notably, there is no evidence of respiratory infections being transmitted exclusively via large respiratory droplets or fomites. While a subset of patients may act as super-spreaders, no diagnostic tests are currently available to reliably identify them. Consequently, all patients with respiratory pathogens must be considered potentially infectious.

Discussion

This analysis underscores the need to reevaluate infection control guidelines to address the dominance of small particles within infectious aerosols. Protective equipment for healthcare workers, ranging from surgical masks to filtering facepiece respirators and powered air-purifying respirators, offers varying degrees of protection. While such equipment is essential for close-contact encounters, its limitations highlight the need for enhanced administrative controls. These include the rapid identification and isolation of infectious patients, as well as the development of effective vaccines and treatments.

The evidence reviewed supports the recognition of aerosol (i.e., traditional airborne) transmission of SARS-CoV-2 (Somsen et al., 2020). This recognition could promote the adoption of advanced environmental control measures, such as improved dilution and directional ventilation systems. Air disinfection using ultraviolet germicidal irradiation has shown promise, particularly in congregate settings like nursing homes.

Furthermore, expanding research into respirator fit testing and surgical mask efficacy could significantly enhance protection for healthcare workers. Current practices must also integrate comprehensive environmental controls to mitigate the risk of airborne transmission. Strengthened infection control measures are crucial for safeguarding healthcare workers and reducing morbidity and mortality in future outbreaks. This requires a multidisciplinary approach encompassing engineering, public health, and clinical expertise to address the multifaceted challenges posed by infectious aerosols.

Conclusion

The growing body of evidence on infectious aerosols highlights the need to revise traditional infection control practices in healthcare settings. Research has demonstrated that small particle aerosols are the primary contributors to airborne transmission of respiratory pathogens, including SARS-CoV-2. Protective equipment, such as filtering facepiece respirators and powered air-purifying respirators, remains a critical line of defense for healthcare workers. However, the limitations of these devices emphasize the necessity of incorporating advanced administrative and environmental controls. These measures include improving diagnostic capabilities, implementing effective isolation protocols, and utilizing engineering solutions like enhanced ventilation and air disinfection systems.

Infection control strategies must evolve to address the complex and dynamic nature of respiratory aerosol transmission. Future research should focus on optimizing personal protective equipment, developing rapid diagnostic tools for identifying highly infectious individuals, and understanding the biological and environmental factors influencing aerosol transmission. By adopting a multifaceted approach, healthcare systems can better protect their workers, reduce transmission risks, and improve preparedness for current and future infectious disease outbreaks. Recognizing the critical role of airborne transmission and implementing robust measures can significantly reduce morbidity and mortality, safeguarding both healthcare professionals and the broader community.

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