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How Does the Hierarchy of Controls Integrate With the Epidemiologic Triangle to Help Address and Understand Transmission of SARS-CoV-2?

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The current novel coronavirus pandemic has highlighted widespread shortcomings in the infrastructure of medicine, and the race to find a cure has initiated what the World Health Organization has called an ''infodemic'' of misinformation, misinterpretation, rumors, and myths regarding transmission and treatment of COVID-19[1] in both the scientific literature and popular press. Health care and other essential workers have been on the frontlines of the pandemic and need effective and reliable methods to prevent occupational transmission.

The current situation is reminiscent of the HIV epidemic as it unfolded in the early 1980s. Lessons of the HIV epidemic may inform our efforts to prevent workplace transmission of COVID-19. The occupational health response to HIV unfolded over a period of years, eventually leading to a multifaceted approach including universal precautions in health care settings, safer needles, and postexposure prophylaxis that made the goal of zero cases of occupational HIV transmission increasingly achievable. Building a similar approach to eliminate occupational transmission of SARS-CoV-2 will require going beyond what is often a reductionist approach to develop an effective combination of interventions that will stop COVID-19 transmission. Combining the traditional industrial hygiene model involving the hierarchy of controls with the predominant host-agent-environment infectious disease model can help guide efforts aimed at stopping occupational transmission.

According to the traditional occupational hierarchy of controls,[2] the most effective method of preventing exposure is elimination of the hazard. This is the principle behind physical isolation. Engineering controls, a means of physical separation of the hazard from the worker include building barriers such as plexiglass screens, hands-free equipment, and proper exhaust or dilutional ventilation. Administrative controls involve institution of rules that change how workers behave, alterations in work schedules and infection control protocols. Finally, personal protective equipment that places a barrier between the worker and hazard (the principal example being respirators and other masks) are considered the least effective measure, as they are dependent on proper use by the worker every time they are worn.

The classic host–agent–environment epidemiologic triangle[3] describes how an individual may contract disease. According to this model, disease occurs when the agent that causes illness encounters a vulnerable host in a conducive environment. This model can help to understand how an outbreak takes place but does not readily inform policy about protecting workers. Conversely, the hierarchy of controls focuses on the ''environment'' branch of the epidemiologic model but does not account for the interaction between the agent and host, and thus falls short in helping understand transmission.

Figure 1 shows an integrated concept model where the hierarchy of controls serves to modify the vulnerabilities inherent in the epidemiologic model. This model is meant to provide a framework for current understanding of prevention and control that can be adapted as more data on transmission and the effectiveness of protection become available.

ELEMENTS OF COVID-19 TRANSMISSION

Agent: The ''agent'' comprises all factors related to the SARS-CoV-2 virus. Transmission of the SARS-CoV-2 agent may be through larger respiratory droplets, smaller farther-traveling airborne particles, and viable particles can be acquired through touch and transfer to mucous membrane surfaces.

COVID-19 viral transmission is thought to mainly occur from person-to-person through close contact via respiratory droplets. Respiratory droplets are generated when an infected person coughs, sneezes, sings, and talks, as well as during procedures such as endotracheal intubations. In a review of 10 studies on horizontal droplet dispersal, eight showed droplets travel more than 2 m (≈6 ft.), in some cases up to 8 m (≈26 ft.).[4]

Airborne transmission occurs by dissemination of dust or droplet nuclei (generally less than 5 μm in diameter) containing infectious agents that may be dispersed over longer distances by air currents.[5] While artificially created aerosolized SARS-CoV-2 has been shown to remain viable in the air for 3 hours,[6] there is not yet universal acceptance of airborne transmission of the virus. If small-particulate airborne transmission is critical in coronavirus spread, there are many more ramifications for infection control in health care workers, as transmission could occur to individuals who have not been in close proximity (eg, in the same room) as the infectious patient.

Host: includes both risk factors specific to the worker, such as comorbidities and immunity, and workplace procedures, including the use of personal protective equipment. The immune status of individuals and ''herd'' immunity for groups of workers will likely be important factors in determining the risk of transmission going forward. The possible development of COVID-19 vaccines will raise issues like those encountered with the seasonal influenza vaccine: cost, safety, access, efficacy in different age groups, and whether a vaccine may be mandatory or voluntary for certain groups of workers.

Personal protective equipment (PPE) includes respirators and related face coverings (surgical masks, N95 respirators), as well as gowns, gloves, shoe covers, and

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FIGURE 1. Conceptual model of factors surrounding SARS-CoV-2 transmission in healthcare settings.

goggles or other means of eye protection. The difference in performance between N95 respirators and surgical masks is related to filtration capability as well as the fit. In general, N95s protect the wearer from coronavirus aerosols, as they are designed to block at least 95% of very small (0.3 μm) test particles from inhaled air. In contrast, surgical masks block the wearer from inspiring only large particle droplets, do not effectively filter small particles and aerosols, and do not achieve a tight seal around the breathing zone.

Supply chain problems and shortages of N95 respirators have resulted in relaxation of stricter standards for personal protective equipment for health care workers. This has resulted in differing guidelines from various regulatory and standards setting agencies. For example, the Centers for Disease Control and Prevention (CDC) initially recommended that healthcare workers be required to wear fit-tested N95 respirators when potentially exposed to patients with COVID-19 but changed course abruptly in the face of shortages to mandating N95 respirator use only when exposure to aerosol-generating procedures was expected. The US Federal Occupational Safety and Health Administration (OSHA) which recommends fit-tested N95 respirators issued temporary enforcement guidance during the pandemic that suspended the annual fit testing requirement of N95 filtering facepiece respirators.[7] Another regulatory change in response to shortages permitted extended use and limited reuse of N95 respirators, including authorization of the hydrogen peroxide vapor based Battelle decontamination system which had demonstrated efficacy in pilot studies.[8] In clinical practice, N95 extended use and reuse has been associated with a high fit test failure rate for both conventional and duckbill N95s.[9]

Some hospitals have successfully instituted use of elastomeric air purifying cartridge respirators which have advantages of ease of cleaning and reuse, improved comfort, and proven efficacy in industrial settings in controlling various types of exposure.

Environment: The ''environmental'' component encompasses three dimensions that may dictate methods of halting disease spread. Along with the patient's disease manifestation, attention to environmental factors should be directed toward administrative and engineering controls on transmission.

Increasing severity of infection as well as the types of symptoms that the index patients manifest can increase transmission. The mean viral load of severe cases is higher than that of mild cases,[10] which could increase risk of transmission through increased viral concentration in droplets, secretions, and other vehicles.[11–13] This presents a hazard in settings with direct contact of medical personnel with infected patients such as during physical examinations, procedures, and increasing duration of contact with a patient with COVID-19.[14] Aerosol generating procedures, particularly performing endotracheal intubation, increase risk of transmission.[15] One study of COVID-19 transmission in a call center in South Korea determined that duration of interaction between workers was likely the main facilitator for further spreading of the infection.[16] The US Centers for Disease Control and Prevention (CDC) has posited that 10 minutes of close exposure can be used as an operational definition.[17] Brief interactions are considered less likely to result in transmission; however, symptomatology of an infected patient and the type of interaction (eg, did the infected person cough directly into the face of the exposed individual) are also felt to be important.

There is much evidence for presymptomatic transmission, but robust evidence is less for truly asymptomatic transmission.[18] Asymptomatic individuals have tested positive for the SARS-CoV-2[19,20] and there may be viral shedding in asymptomatic patients[11] making detection and isolation of infected ''super spreaders'' difficult without frequent and widespread virus testing.

Other environmental factors that impact transmission include the use of high-efficiency air filters, ventilation, and layouts of patient care settings. A case report suggested the spread of SARS-CoV-2 virus involving three family clusters was prompted by air-conditioned ventilation in a restaurant setting,[21] indicating that ventilation may play a role in transmission. Hospital areas with natural ventilation have the highest bioaerosol concentrations whereas areas with more sophisticated mechanical ventilation systems (such as with increased air changes per hour, directional flow, and filtration systems) have the lowest total bioaerosol concentrations.[22] Administrative controls, such as testing, isolation, and quarantine policies, infection control protocols, schedule modifications, elevator distancing rules, and virtual meetings, also fall under the ''environmental'' category.

CONCLUSION

The framework presented above is one example of how current knowledge on COVID-19 transmission can be organized to reduce transmission addressing the shortcomings in the existing occupational medicine and epidemiologic models. This dual vantage point helps conceptualize the interplay between various identifiable factors and presumptive strategies, and how decisions might affect other parts of the complex system. Furthermore, it addresses shortcomings in the existing occupational medicine and epidemiologic models. The epidemiologic model can help identify the critical aspects of the three major elements (environment, agent, and host) that predict transmission of COVID-19. The hierarchy of controls, by contrast, helps to implement policies to protect workers from a hazard in the workplace which operationalizes the means to act on one or more of the arms of the epidemiologic triangle. With the exception of personal protective equipment, which is deemed the least effective strategy, the hierarchy of controls deals with modifying the environmental angle of the epidemiologic triangle. The epidemiologic model suggests that focusing on one angle of the triangle (ie, the environment) will only interrupt one factor in the chain of transmission.

Given the evolving nature of our understanding of SARs-CoV-2, no framework can be fully comprehensive, and it is possible that the future research will change this framework entirely. One limitation is that this framework is not as simple as application of one of preceding models alone. As we have learned from the experience of the HIV epidemic, a multifaceted approach is needed to address a new viral hazard in the workplace. A sound understanding of the interplay between risk factors and potential controls can help inform policies such as an infectious disease prevention standard that effectively applies the precautionary principle[23] to protect workers in hospitals and other industries as we attempt to treat the already-infected, form safe return-to-work policies, and attempt to halt transmission of the virus going forward.

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