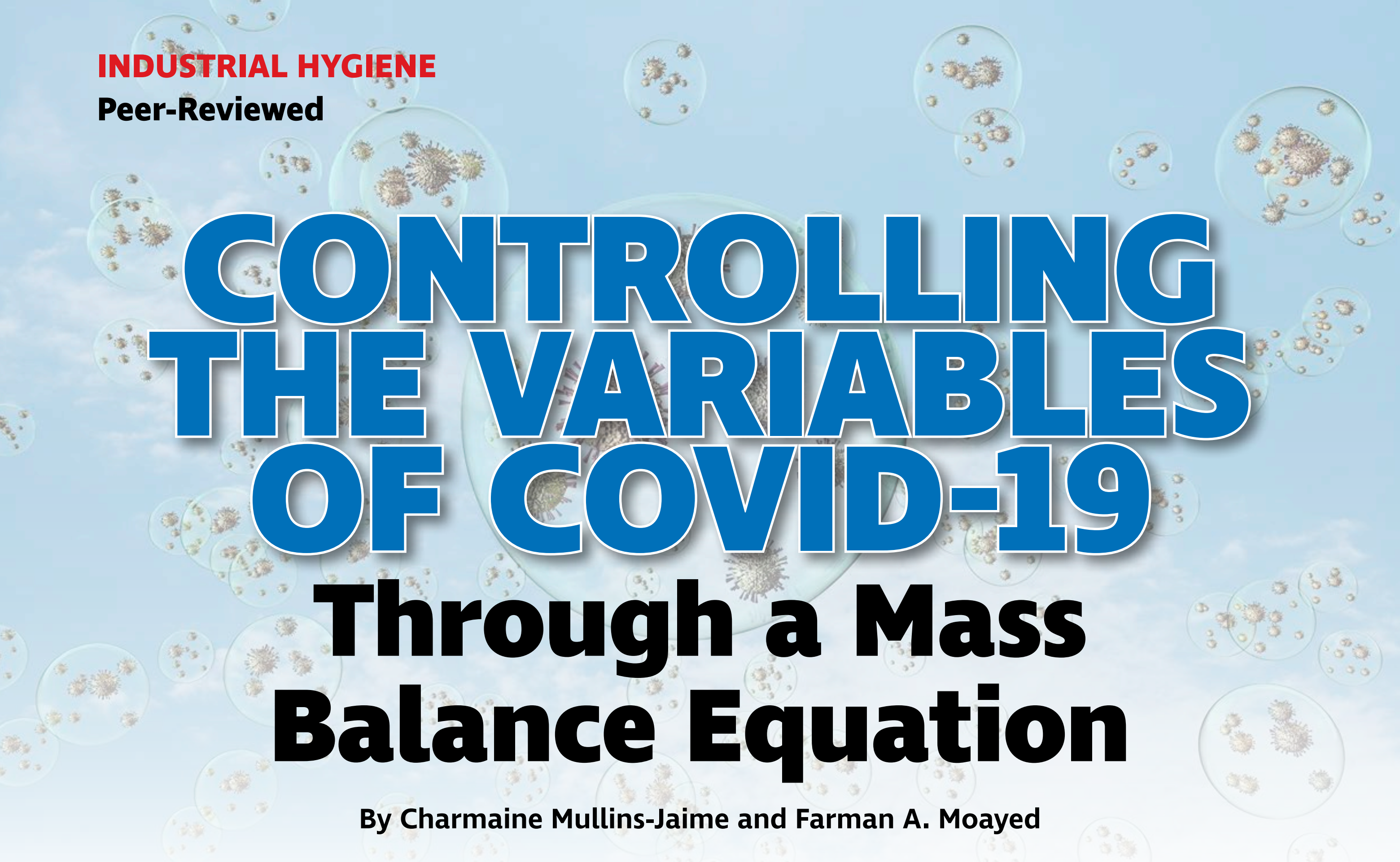


INDUSTRIAL HYGIENE

Peer-Reviewed

CONTROLLING THE VARIABLES OF COVID-19

Through a Mass Balance Equation

By Charmaine Mullins-Jaime and Farman A. Moayed

IN THE ABSENCE OF CLEAR, SUBSTANTIAL EVIDENCE backing the extent and severity of a hazard and the safety and efficacy of particular controls, occupational safety management professionals have relied on the precautionary principle and the as low as reasonably practicable (ALARP) principle to effectively manage hazards and risks.

The precautionary principle states that where serious threats to human health or ecosystems are present, acknowledged scientific uncertainty should not be used as a reason to postpone preventive measures (Martuzzi & Tickner, 2004). One has to only look at recent history to grasp the consequences of not taking stronger preventive measures amidst scientific uncertainty. Examples in recent history include millions of children who have suffered neurological damage and reduced mental capacity as a result of lead exposure and the lives lost due to asbestos exposure (Martuzzi & Tickner, 2004).

The ALARP principle comes from legal terminology "so far as is reasonably practicable" (HSE, n.d.), language that indicates onus for protecting safety and health, which can be found in safety and health legislation around the world. Doing what is reasonably practicable is doing what is within the employers' ability to do without gross disproportion between the risk and actions taken to prevent adverse consequences, where the risk is insignificant in relation to the sacrifice (HSE, n.d.).

Both the precautionary and ALARP principles attempt to understand hazards and risk and are based on ensuring robust control mechanisms that often include multiple layers of defense to control for barrier breakdowns. Occupational hygiene assessments and controls are used substantially in this endeavor to assess the presence of hazardous contaminants in both indoor and outdoor spaces, and calculations and models are used to design effective controls.

The COVID-19 pandemic has proved challenging to businesses and governments in applying these principles to establish a safe reopening and continuity of activities. Dealing with a new virus, scientists have had to learn how it spreads and how to best control it in real time, so public health emphasis on different control mechanisms has varied as they have learned more about transmission and control. This explains the contrast in public health messaging early in the pandemic compared with current communications. In February and early March 2020, public health messaging emphasized hand hygiene, while discouraging the use of face masks as public health officials believed fomites were a greater mechanism of infection than droplet and airborne transmission. This was followed by an abrupt shift toward social distancing and the use of masks in mid-March 2020 as public health officials learned through the epidemiology that droplet, or close contact, was the more likely form of transmission.

KEY TAKEAWAYS

- **COVID-19 infection prevention guidance for general industry is largely based on preventing droplet- and fomite-based sources of infection. Prior to Jan. 29, 2021, guidance did not encourage engineering controls such as ventilation, air filtration and disinfection for many employers due to their level of risk, often based on the likelihood of employees interacting with infected persons.**
- **The CDC acknowledged that airborne transmission is also a mechanism of COVID-19 infection.**
- **Understanding the variables that determine respiratory infection in a mass balance equation and applying established controls for each variable can help employers in ensuring robust COVID-19 prevention controls.**
- **As infection rates climb or in the face of new, more infectious strains, utilizing the precautionary principle and aligning organizational objectives with ALARP (as low as reasonably practicable) are needed. Increasing the use of additional engineering controls such as improved ventilation, air filtration and disinfection in addition to vaccination, masking, social distancing, hygiene and other infection control methods is recommended to minimize the spread of COVID-19 infection and enable resilience in maintaining business activities.**

THE-LIGHTWRITER/ISTOCK/GETTY IMAGES PLUS

This initial change in messaging and subsequent further confusion on whether the virus can spread as an aerosol are likely contributing factors that have led to misconceptions among the general population about how the virus spreads and about effective prevention and control measures. While the CDC maintains that droplet transmission is the predominant mechanism of COVID-19 infections, the agency has more recently recognized airborne transmission as an additional mechanism for COVID-19 infection (CDC, 2020a). Prior to this, the general public was uninformed that, in addition to droplet and fomite transmission, the virus can also spread as an aerosol by inhaling smaller respiratory droplets and particles that travel greater distances (greater than 6 ft) and can remain suspended in the air for longer periods (typically hours) than originally anticipated (CDC, 2020a). Consequently, many recommendations for infection control for the broader public and businesses have been geared toward provisions to protect against fomite- and droplet-based transmission.

Following are the three known mechanisms of COVID-19 infection according to the CDC (2020a):

- **Fomite transmission** or contact transmission occurs through direct contact by touching an infectious person (e.g., through a handshake) or contaminated surfaces. While fomite transmission was of greater concern earlier in the pandemic, later research suggests that it is not likely a major source of transmission because, although SARS-CoV-2 can remain on inanimate surfaces for days, attempts to culture the virus from surfaces were unsuccessful (The Lancet Respiratory Medicine, 2020). This has also been more recently acknowledged by the CDC (2021) in its April 5, 2021, science brief.
- **Droplet transmission** occurs through exposure to virus-containing respiratory droplets exhaled by an infectious person. This type of transmission is most likely to occur when in close contact with an infectious person (within about 6 ft).
- **Airborne transmission** occurs through exposure to those virus-containing respiratory droplets comprised of smaller droplets and particles that can remain suspended in the air over long distances (usually greater than 6 ft) and time (typically hours).

The difference between droplet and airborne transmission is those smaller droplets and particles that can remain suspended in the air for much longer and can travel farther distances than the larger droplets, which tend to fall out of the air much more quickly and do not usually travel farther than 6 ft from the source.

According to the CDC (2020a), circumstances under which airborne transmission has occurred include enclosed spaces within which an infectious person either exposed susceptible people at the same time or to which susceptible people were exposed shortly after the infectious person had left the space; prolonged exposure to respiratory particles, often generated with expiratory exertion (e.g., shouting, singing, exercising) that increased the concentration of suspended respiratory droplets in the air space; and spaces with inadequate ventilation or air handling, allowing a build-up of suspended small respiratory droplets and particles.

Recommended Safety Protocols Before January 2021

Prior to the updated OSHA (2021) guidance posted on Jan. 29, 2021, the recommended exposure controls provided by both OSHA (2020) and the CDC's (2020b) guidance for businesses and employers focused on controls such as company sick leave and quarantine policies, process for routine self-health checks, provisions for social distancing of 6 ft per person, promotion of personal hygiene practices, routine cleaning and use of face masks.

Little emphasis was placed on the use of engineering controls such as ventilation and air disinfection outside of the healthcare setting. While the CDC (2020b) did provide recommendations for engineering controls through improved ventilation based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) "Guidance for Building Operations During the COVID-19 Pandemic," these recommendations were not encouraged by OSHA (2020) as a choice for mitigation and control in most workplaces. This is because many businesses were considered "lower risk" where routine exposure to infected persons was not expected. However, as the virus has become more prevalent in communities, many organizations have likely not reevaluated their risk of encountering infected persons and adjusted their controls accordingly.

Concerned that people will not be protected by the existing mitigations, in July 2020, more than 200 scientists published a statement calling for international bodies to recognize the potential for airborne spread of COVID-19 (The Lancet Respiratory Medicine, 2020). While the World Health Organization and CDC have since recognized airborne transmission as a source of spread, the current prevention recommendations for industry are largely based on the premise that infection occurs from large droplets and fomites that can be mitigated with separation of small distances of 6 ft, cloth face coverings, good handwashing practices and routine surface cleanings.

This may have led to a misconception among organizations and the general public that fomite- and droplet-based transmission are the *only* mechanisms of infection and so, when businesses planned their policies and daily activities in response to the pandemic, they may have made permissible the removal of masks when distances beyond 6 ft were maintained or when other barriers such as plexiglass screens were provided. While plexiglass screens might be a good control for minimizing droplet transmission, they would not protect against the smaller "airborne" infectious particles that can travel distances greater than 6 ft and remain suspended in the air for hours. This would also not be a suitable recommendation as the only COVID-19 infection control and certainly not suitable if adhering to the precautionary and ALARP principles.

Current Recommended Safety Protocols

On Jan. 29, 2021, OSHA provided updated guidance to reflect the possibility of airborne transmission and recommendations that include encouraging distances of 6 ft or greater with recognition that 6-ft distances do not guarantee safety, particularly in enclosed and poorly ventilated spaces. The agency also recommends improved ventilation without any gateway criteria as part of a hierarchy of controls approach as follows (OSHA, 2021):

> - Ensure ventilation systems operate properly and provide acceptable indoor air quality for the current occupancy level for each space.
> - Increase ventilation rates when possible.
> - When weather conditions allow, increase fresh outdoor air by opening windows and doors.
> - Do not open windows and doors if doing so poses a safety or health risk (e.g., risk of falling, triggering asthma symptoms) to occupants in the building.
> - Use fans to increase the effectiveness of open windows. To safely achieve this, fan placement is important. Avoid placing fans in a way that could potentially

cause contaminated air to flow directly from one person over another. One helpful strategy is to use a window fan, placed safely and securely in a window, to exhaust room air to the outdoors. This will help draw fresh air into the room via other open windows and doors without generating strong room air currents.

- Disable demand-controlled ventilation.
- Reduce or eliminate recirculation, for example, by opening minimum outdoor air dampers. In mild weather, this will not affect thermal comfort or humidity. However, this may be difficult to do in cold or hot weather.
- Improve central air filtration to the MERV-13 (the grade of filter recommended by ASHRAE) or the highest compatible with the filter rack, and seal edges of the filter to limit bypass.
- Check filters to ensure they are within service life and appropriately installed.
- Keep systems running longer hours, 24/7 if possible, to enhance air exchanges in the building space.
- Ensure restroom exhaust fans are functional and operating at full capacity.
- Inspect and maintain local exhaust ventilation in areas such as kitchens and cooking areas.
- Use portable high-efficiency particulate air (HEPA) fan/filtration systems to help enhance air cleaning (especially in higher-risk areas such as a nurse's office or areas frequently inhabited by persons with higher likelihood of COVID-19 and/or increased risk of getting COVID-19).
- Generate clean-to-less-clean air movement by reevaluating the positioning of supply and exhaust air diffusers and/or dampers (especially in higher-risk areas).
- Consider using ultraviolet germicidal irradiation (UVGI) as a supplement to help inactivate SARS-CoV-2, especially if options for increasing room ventilation are limited. Upper-room UVGI systems can be used to provide air cleaning within occupied spaces, and in-duct UVGI systems can help enhance air cleaning inside central ventilation systems.
- If ventilation cannot be increased, reduce occupancy level in the building. This increases the effective dilution ventilation per person.

Like most safety management approaches, a robust arsenal of multilayer defenses enables organizations to prevent unwanted occurrences, in this circumstance infection, because they give organizations more resilience in the face of variability and changing circumstances. Robust defenses rely heavily on the hierarchy of controls where elimination and substitution are considered first, followed by engineering and administrative controls, and finally the use of PPE.

The American Conference of Government Industrial Hygienists (ACGIH) is an excellent resource on the assessment and control of bioaerosols. Using a simple mass balance equation to assess and control for the spread of respiratory infections can be a helpful tool in applying a hierarchy of multilayered controls to help organizations lower their risk of COVID-19 infections to ALARP levels.

The following discussion explains how the virus is transmitted and how organizations can use a steady-state equation to ensure that they are applying the precautionary and ALARP principles. It attempts to explain the existing recommended safety protocols for infection prevention in the context of controlling the variables of this mass balance equation as well as additional controls that organizations might want to consider adopting to lower their risk and insulate business continuity.

How the Virus Spreads

The droplets that are produced by breathing, talking, sneezing or coughing include different types of cells, physiological electrolytes, as well as various infectious agents such as bacteria, viruses and fungi. Such droplets are produced in different sizes. Once such droplets are produced by sneezing or coughing, droplets larger than 5 µm tend to remain trapped in the upper respiratory tract, but the ones smaller than or equal to 5 µm have the potential to be inhaled into the respiratory tract. If not inhaled, droplets larger than 5 µm usually fall to the ground because of the gravitational force and therefore transmitted only over a limited distance (e.g., less than 1 m). But the droplets smaller than 5 µm tend to remain suspended in the air for a longer period, which allows them to be transmitted over distances greater than 1 m (Atkinson et al., 2009).

Different studies have shown that the amount and size of the droplets produced by a person depend on how they are produced and that larger droplets comprise most of the total volume of the expelled respiratory droplets, for example, sneezing (as many as 40,000 droplets between 0.5 and 12 µm in size), coughing (up to 3,000 droplets smaller than 5 µm) and talking for 5 min (up to 3,000 droplets smaller than 5 µm; Atkinson et al., 2009).

The time that droplets can remain airborne, and possibly spread infectious diseases, is predominantly determined by their sizes. There are inconsistencies about the time that droplets stay airborne among published articles (Xie et al., 2009). Small droplets (< 5 µm) float on the air and are carried by the movement of air. It means that in outdoor environments, wind can carry them from higher concentration to lower concentration areas. In indoor environments, ventilation systems can determine how droplets are distributed in a building.

The amount of saliva (in the form of droplets) produced by sneezing, coughing, talking and breathing can be different. The average volume of saliva for these activities are 1,000, 100, 10 and 1 nL, respectively (Evans, 2020). Regardless of the volume of the saliva produced, it contains the COVID-19 virus if expelled from an infected person. The viral load of COVID-19 in such droplets is still unknown, however, considering the existing data regarding the viral load of similar viruses (e.g., influenza, SARS-CoV-1, SARS-CoV-2, MERS), it can be assumed that the viral load for COVID-19 is approximately 1,000 virions/m^3 (Hewett & Ganser, 2017; Lelieveld et al., 2020, Riediker & Tsai, 2020).

The Steady-State Equation

Using a steady-state equation where *C* is the expected number of cases, and *S* is the number of susceptible persons, the number of cases among susceptible persons is proportional to the average number of infectious droplet nuclei in a room and the probability the particles will be inhaled (Macher et al., 1999). A steady-state concentration is reached if a source generates infectious agents at a constant rate and the particle removal rate remains constant. Concentration of droplet nuclei is directly proportional to the number of infectious people present (*I*) and the generation rate of infectious agents (*q*; infectious doses/hour or quanta/hour). The concentration of infectious agents is directly inversely proportional to the rate of droplet nuclei dilution and removal by room ventilation (*Q*) expressed

TABLE 1
ESTIMATED VIRAL LOAD OF COVID-19 BY ACTIVITY

Estimated viral load of COVID-19 in saliva produced by four different activities.

Activity	Volume of saliva (nL)	Period or frequency	Viral load (virions/min)
Breathing	1	1 min	103
Talking	10	1 min	104
Coughing	100	1 cough/min	105
Sneezing	1,000	1 sneeze/min	106

TABLE 2
ESTIMATED CONCENTRATION OF INFECTIOUS PARTICLES BY SETTING

Estimated concentration of infectious particles based on given social settings.

Social setting	Condition	Concentration (virions/m³)
Small office	One symptomatic person present	3,778.7
	One asymptomatic person present	112
Classroom	Two symptomatic persons present	7,557.3
	Two asymptomatic persons present	224
Gym	Two symptomatic persons present	7,557.3
	Two asymptomatic persons present	224
Restaurant	Four symptomatic persons present	15,114.7
	Four asymptomatic persons present	448

TABLE 3
PURGING TIME TO REDUCE INFECTIOUS PARTICLES BY SETTING

Purging time to reduce infectious particles to below desired concentration based on given social settings.

Social setting	Condition	Room volume (m³)	Purging time
Small office	One symptomatic person present	180	76 min (1.3 hr)
	One asymptomatic person present		51 min (0.8 hr)
Classroom	Two symptomatic persons present	300	135 min (2.2 hr)
	Two asymptomatic persons present		93 min (1.5 hr)
Gym	Two symptomatic persons present	300	270 min (4.5 hr)
	Two asymptomatic persons present		185 min (3.1 hr)
Restaurant	Four symptomatic persons present	800	382 min (6.4 hr)
	Four asymptomatic persons present		269 min (4.5 hr)

TABLE 4
ESTIMATED PROBABILITY OF INFECTION BY SETTING

Estimated probability of infection based on given social settings.

Social setting	Condition	Exposure time	Exposure dose (virions)	Probability of infection
Small office	One symptomatic person present	480 min (8 hr)	18,138	1.0
	One asymptomatic person present		538	0.42
Classroom	Two symptomatic persons present	90 min (1.5 hr)	6,802	1.0
	Two asymptomatic persons present		201	0.18
Gym	Two symptomatic persons present	90 min (1.5 hr)	34,008	1.0
	Two asymptomatic persons present		1,008	0.64
Restaurant	Four symptomatic persons present	120 min (2 hr)	18,138	1.0
	Four asymptomatic persons present		538	0.42

as room air changes per hour, ACH or m³/hour, or other means of particle inactivation (e.g., filtration, ultraviolet disinfection). The chance of exposed persons becoming infected is directly proportional to the volume of air they inhale p m³/hour and their exposure time t (hours).

Equation 1:

$$C = S(1 - e^{-x})$$

where:

C = expected number of new cases

S = number of exposed susceptible persons

x is defined in the following equation:

Equation 2:

$$x = \frac{Iqpt}{Q}$$

where:

I = number of sources of infectious aerosols

q = quanta or generation rate of infectious agents (infectious doses/hour or quanta/hour)

p = breathing rate for exposed person (m³/hour)

t = exposure time (hours)

Q = ventilation rate (ACH or m³/hour)

Employers may defer to this model to control the number of potential infections in their organizations by applying mitigating controls to each variable in the equation. For example, if 25 people occupy a 300 square meter office space for approximately 8 hr, and the community case rate is 5% and everyone in the room is from the same community or one with an equal case rate, then I will be 1.25, or 1 infected person. Assuming the room is ventilated at a rate of 0.5 air changes per hour, the infected person generates 2 quanta per hour and susceptible persons breathe at a rate of 1 cubic meter per hour, you can expect C to be 2.43, or approximately 2 new cases. Following the ALARP principle, the objective is to ensure that C remains below 1. To do this, the employer could triple the ventilation rate to 1.5 ACH to reduce expected new cases, or it can restrict the number of people in the space to 12 and ensure that the space is ventilated at a rate of 1 air change per hour or more to bring the expected new case rate to below 1.

In the preceding scenario, quanta was assumed to be 2 infectious dose per hour; however, the infectious dose is not known for most human infections. Among other factors, it varies depending on the virulence of the pathogen and host resistance. Chance also affects who becomes infected because particles may be diluted and unevenly distributed. By chance, some people may inhale more of the infectious particles than others. Based on Poisson's law of chance, Wells created the term "quantum" or quanta to represent the required dose of infectious particles to create infection in the host (Macher et al., 1999). However, by using the amount of the liquid and the viral load and by making a few basic assumptions, it is possible to estimate the concentration of virions in different indoor social settings and calculate the probability of transmission. The model discussed here was developed based on the following assumptions:

- The viral load of COVID-19 is 1,000 virions/nL saliva like similar viruses (e.g., influenza, SARS-CoV-1, SARS-CoV-2, MERS).

•An asymptomatic person spreads the virus only by talking (20%) and breathing (80%).

•A symptomatic person spreads the virus by talking (20%), breathing (80%), sneezing (five sneezes per hour) and coughing (five coughs per hour). A symptomatic person is expected to create more virions than an asymptomatic person, as they would be expected to cough and sneeze several times per hour, which can produce more droplets.

•The model uses steady-state concentration (it does not differentiate between highly infectious and low infectious individuals).

•The airflow of the ventilation system is assumed to be 1,500 m^3/hr constantly.

•The safety factor (K) of the ventilation system is considered to be 1.0 (perfect design).

•Persons occupying the space are not wearing masks.

•People in the room have not been inoculated.

To start the model, it is necessary to estimate the viral load for the main activities that contribute to the spread of the virus. Table 1 represents the viral load of COVID-19 in saliva produced by four different activities.

The concentration of airborne virus produced by a symptomatic and asymptomatic person (as assumed above) can be estimated as 3,779 virion/m^3 and 112 virion/m^3 respectively using Equation 3.

Equation 3:

$$Concentration = \frac{Viral\ load\ \left(\frac{virion}{min}\right)}{Ventilation\ air\ flow\ \left(\frac{m^3}{min}\right)}$$

where:

Viral load = q or quanta, generation rate of infectious agents

Ventilation airflow = Q or ventilation rate m^3/hour/60

Table 2 demonstrates the social settings that were considered in this model. The concentration of the virus was estimated for each setting under two separate conditions: 1. if only symptomatic people are present; and 2. if only asymptomatic people are present.

The concentration values estimated in Table 2 are based on steady-state assumption (i.e., the breathing, talking, coughing, sneezing rates and the airflow of ventilation are constant). At the end of the day, the purging method can be used to reduce the concentration of virus in the environment (Plog & Quinlan, 2012). The purging time for each social setting and condition was estimated in Table 3 using Equation 4.

Equation 4:

$$Time = -\frac{Volume\ of\ the\ room\ (m^3)}{Ventilation\ air\ flow\ \left(\frac{m^3}{min}\right)} \times \ln\left(\frac{Desired\ concentration\ \left(\frac{virions}{m^3}\right)}{Estimated\ concentration\ \left(\frac{virions}{m^3}\right)}\right)$$

The desired concentration of virus should be much less than the infective dose of the virus, which is currently unknown for COVID-19. In this model, it was assumed to be 0.1 virion/m^3, which is 1/10,000th of the infective dose D50 of SARS-CoV-2 suggested by Lelieveld et al. (2020) in their model. Viral load estimation is based on assumptions found in recent literature on COVID-19, however, viral load can be higher or lower depending on a host of variables including dose response relationships specific to individuals and circumstances (Van Damme, et al., 2021) and the type of COVID-19 variant (Mahase, 2020).

For each social setting described, it is possible to estimate the probability of infection using Equations 2 and 3. To estimate the exposure dose, the breathing rate was assumed to be 0.01 m^3/min for all social settings except for gym, in which the breathing rate was assumed to be 0.05 m^3/min due to heavy physical activities. The exposure times were assumed to be 8, 1.5, 1.5 and 2 hr for small office, classroom, gym and restaurant settings, respectively.

Equation 5:

$$Exposure\ dose = Concentration\ \left(\frac{virions}{m^3}\right) \times Breathing\ rate\ \left(\frac{m^3}{min}\right) \times Exposure\ time\ (min)$$

Equation 6:

$$P(infection) = 1 - e^{\left(-\frac{Exposure\ dose}{D50}\right)}$$

As shown in Table 4, the probability of infection increases exponentially whenever there are symptomatic unmasked people in the given social settings. The smallest probability was estimated for a classroom with two asymptomatic people present. Although the probability of infection is smaller for given social settings with asymptomatic people present, the challenge is that the number of such people in any given setting is practically unknown unless everyone in the room is tested.

Recommendations

While the models discussed are not appropriate for brief exposures to infected persons, as they are not likely to create steady-state conditions, it is reasonable to expect longer duration exposures to infected persons to meet the steady-state assumptions (Macher et al., 1999), making a mass balance model a useful tool for controlling airborne infections in indoor spaces where occupancy tends to remain constant (e.g., manufacturing facilities, office spaces, classrooms). Safety professionals and industrial hygienists may defer to the steady-state equation in anticipation of potential respiratory infections in their organizations and direct mitigation efforts toward each of the variables in the equation to reduce the likelihood of infection.

Following are recommendations for mitigation and prevention for each variable of the mass balance equation considering the hierarchy of controls (Figure 1, p. 36).

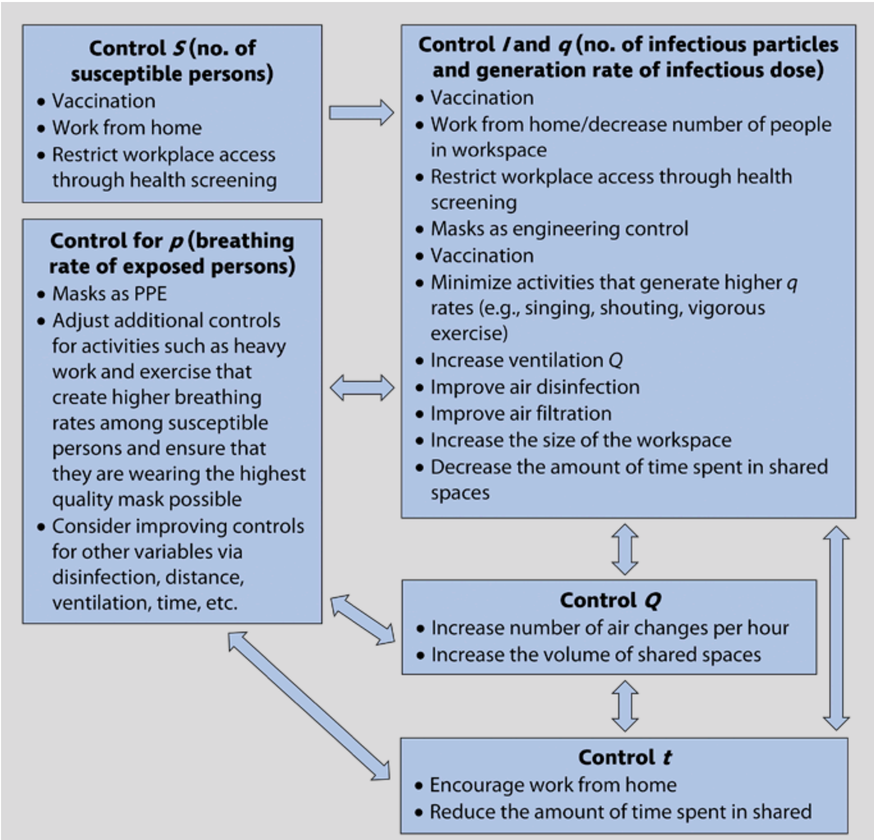
Reduce the number of susceptible sources (*S*). Immunization will reduce the number of susceptible people within the organization, as inoculated persons are no longer susceptible to the worst effects of the virus. So, as vaccines become readily available, encouraging vaccination can influence both the *I* and *S* variables at the top tier as an ***eliminating*** control. Mitigation efforts aimed at controlling this variable focus on the top tier of the hierarchy of controls by seeking to ***eliminate*** the sources of infection in the workplace by restricting people's access to the workplace if they have been exposed to the virus. This is done through routine health screenings, COVID-19 testing, contact tracing and policy that ensures that symptomatic and exposed people stay home. Other measures for minimization including limiting in-person gatherings and the number of people occupying the workspace as they reduce both the number of susceptible persons in the workplace (*S* value) and *I* value as it reduces the number of possible sources of infection.

Control the number of infectious sources (*I*). Immunization, when readily available, will also reduce *I* value and are part of that top tier of controls aimed at eliminating infectious sources, assuming that inoculated people cannot be infectious. While it is not yet well established, there is preliminary evidence indicating that vaccines reduce and even prevent transmission (Levine-Tiefenbrun, 2021; Lipsitch & Kahn, 2021). However, additional research is needed to confirm viral load reduction capabilty of all vaccines available.

Other controls include those described on restricting workplace access through screening. Based on the anticipated num-

FIGURE 1

CONTROLLING THE VARIABLES OF THE STEADY-STATE EQUATION FOR INFECTIOUS BIOAEROSOLS



(Macher et al., 1999). A recent study showed UV-C light can inactivate more than 99.9% of SARS-CoV-2 viral particles deposited over the filtering material of N95 masks and stainless-steel surfaces (Sabino et al., 2020). Air disinfection with upper-room germicidal UV-C light fixtures is a well-established tool in infection control. An observational study during the 1957 influenza pandemic reported that patients housed in hospital wards with upper-room UV-C had an infection rate of 1.9%, compared to an infection rate of 18.9% among patients housed in wards without UV-C; however, the germicidal effect of UV-C seems to be dependent on the relative humidity of the air, with UV-C effectiveness against influenza virus decreasing with increasing relative humidity (Sabino et al., 2020). According to ACGIH's *Bioaerosols: Assessment and Control*, to gain the benefit of irradiation without overexposure for personnel, germicidal lamps can be placed in the ductwork of HVAC systems or in entryways and halls of shared spaces where people do not spend significant amounts of time (Macher et al., 1999).

Air filtration is also critical. The CDC and ASHRAE recommend improving central air filtration to the MERV-13 or the highest compatible with the filter rack, sealing edges of the filter to limit bypass and checking filters to ensure that they are within service life and appropriately installed (CDC, 2020a).

ber of sources of infection, for example, community case rate is 5% and 25 people from that same community are occupying a space, one might expect *I* to = 1.25. Based on the other variables in the equation and following the ALARP principle, one would consider additional controls to lower the *I* value, such as ***substitution*** of face-to-face encounters with virtual meetings and ***administratively*** through reducing the number of people allowed to occupy the space.

Reduce the number of infectious particles people release (*q*). This is where use of masks plays a critical role. Masks when worn properly versus other face coverings such as face shields are better equipped to catch large respiratory droplets before they become droplet nuclei because they capture the droplets at the source. The use of masks in this variable of the equation serves more as an ***engineering*** control than PPE, as they are intended to minimize the hazard at the source.

Considering the different quantities of infectious particles released by various activities and adjusting additional controls is another way to lower the risk of infection. In noisy work environments, where people are expected to shout to be heard or in large classrooms where teachers must speak loudly, it is expected that carriers will emit higher amounts of infectious particles than during other activities such as talking or breathing, so these workplace factors should be considered as aspects that might raise the *q* values and, in turn, the risk. Some mitigating controls could include noise reduction or providing microphones and audio equipment to eliminate the need to shout.

An additional control to reduce the presence of infectious particles is through air filtration and disinfection. Use of UVGI can be effective in controlling the spread of viruses, however, placement and intensity of these lamps must be balanced with the need to protect people from harmful ultraviolet radiation

Reduce exposure time (*t*). Sharing the same breathing space with an infected person does not require the two people to be present in the same room at the same time if contaminated air can move between spaces or be distributed by mechanical ventilation system (Macher et al., 1999). Among factors for controlling the time required for a susceptible person to receive an infectious dose are the number of organisms needed to cause the infection and the air concentration of the infectious organism (Macher et al., 1999). The concentration of infectious particles in the air is dependent on the number of sources *I*, number of infectious particles released *q*, which we have already established as predominantly controlled by face masks, through immunization when available and assuming that inoculated people cannot shed infectious particles, and by restricting access to the workplace if exposed as ***eliminating*** controls for *q* and finally by the ventilation *Q* in the space. Reducing the amount of time workers must spend together is a critical ***administrative*** control and the duration of many face-to-face interactions can be shortened or ***substituted*** for virtual interaction.

Increase ventilation (*Q*). Ventilation is a much underrecognized and underutilized control mechanism in the COVID-19 pandemic outside the healthcare setting. However, local exhaust or dilution ventilation rates *Q* that dilute and remove the infectious particles from the air can be an effective engineering control mechanism and should be considered wherever reasonably practicable as part of a precautionary principle and ALARP approach. *Q* values can be influenced by both increasing the volume of space utilized in shared spaces and increasing the number of air changes per hour. Ventilation rates of 7.5 L/s (15 ft^3/min) of outdoor air per person are recommended to reduce the likelihood of airborne transmission of contagious diseases (Macher et al., 1999). For controlling the spread of tuberculosis, the recommended ventilation rates are higher, at 16.5 L/s (35 ft^3/min). There has been no recommended ventilation rate for COVID-19 as of the writing of this article; however, it has since been established that like tuberculosis, SARS-CoV-2 airborne transmission without direct contact is possible (Anderson et al., 2020; Lu et al., 2020; Meyerowitz, 2021; Zhang et al., 2021). If adhering to the ALARP and precautionary principle, some organizations may opt to adjust their ventilation rates to the most stringent ventilation rate practicable.

Consider the breathing rate of susceptible persons (*P*). While it may be impracticable to control for the breathing rate of individuals, considerations for the breathing rate are needed as prompts to make additional improvements that reduce the values of the other variables in this equation. One might consider that those working in manual labor, exercising or performing other laborious indoor work will be taking in larger volumes of air and, in turn, larger volumes of infectious particles, and, therefore, additional adjustments to other elements of the equation may be necessary to lower the risk. The predominant control used for this variable is the use of face masks as a form of PPE. While cloth face masks might be effective protection against larger droplets, to protect against smaller infectious particles people should opt to use a finer particulate filtering facepiece such as an N95 or higher if available and if demand for these masks can be supplied without creating a burden of risk to healthcare workers by prohibiting their ability to access them first.

The calculations shown in Tables 2 through 4 (p. 34) show concentration of infectious particles, required purge time and probability of infection based on no controls such as masking or ventilation. The calculations in Tables 5 through 7 (p. 38) consider the impact of some of the controls discussed on these variables.

Effect of Airflow of Ventilation

If only the airflow increases from 1,500 m^3/hr (25 m^3/min) to 2,500 m^3/hr (42 m^3/min) and no other control methods are implemented (e.g., mask wearing and exposure time), the concentration of infectious particles (Table 5, p. 38), the purging time (Table 6, p. 38) and the probability of infection (Table 7, p. 38) will be reduced accordingly.

Effect of Wearing Masks

If mask wearing is the only control method implemented in each scenario while airflow remains at 1,500 m^3/hr and exposure time remains the same, the concentration (Table 5, p. 38), purging time (Table 6, p. 38) and probability of infection (Table 7, p. 38) will be reduced accordingly. It is assumed that the size of droplets produced by coughing/sneezing is as small as 0.5 µm or larger (Atkinson et al., 2009) and that people use a commercially available surgical face mask. Studies show that surgical masks can capture 75% of such particles (Howard et al., 2021).

Effect of Reducing Exposure Time

If reduction in exposure time is the only control method implemented in each scenario while airflow remains at 1,500 m^3/hr and people do not wear masks, the only thing that will change is the probability of infection (Table 7, p. 38). The reduction in exposure time in each social setting is based on the following assumptions:

- People work in hybrid format to reduce their exposure time by 50% in small office and classroom.
- Enforce a 45-min limit for workout in the gym.
- Enforce no dine-in in restaurant and only allow carryout with a maximum 20-min waiting time.
- Breathing rates remain the same.
- Size of the rooms remain the same.

Combined Effect of All Three Control Methods

If all three control methods are implemented in the given scenarios, the probability of infection can be reduced significantly (Table 7, p. 38). Tables 5 through 7 (p. 38) are a side-by-side comparison of how each control method in comparison to a no-control condition, can affect the concentration of infectious particles, as purging time and probability of infection.

It is important to note that Tables 5 and 6 (p. 38) do not show effects of reduction in exposure time and are shown as not applicable. Table 5 calculates infectious particle concentration and Table 6 calculates the time it will take to purge the infectious particle concentration. Noninfected people do not contribute to the concentration of infectious particles or to the need to purge the air so it does not matter whether uninfected people stay in a room 1 hr or 10 min; they will not contribute to the number of infectious particles in the air. However, the effects of reducing exposure time are shown in Table 7 (p. 38) because reducing time spent indoors around infected people will dramatically lower the probability of transmission and infection.

Conclusion

The calculations in this article are based on established industrial hygiene formulas used to measure and control respiratory viruses. However, estimations and assumptions have been made on infectious dose, viral load and efficacy of controls such as masks based on recent literature on the subject in an attempt to quantify and explain the role of each variable in infection control. Empirical quantification on effectiveness of controlling the variables presented in this article would be a result of prospective studies conducted over a longer period, which is outside the scope of this article.

Prior to January 2021, workplace hazard mitigation and control provided by the CDC and OSHA including social distancing (1 to 2 m; 3 to 6.5 ft), surface cleaning and disinfection, handwashing and other strategies of good hygiene have been promoted as being far more important than any control related to HVAC systems. However, more recent evidence shows that there is risk of transmission from smaller bioaerosol droplets 5 to 10 µm that remain suspended in the air for longer periods and are capable of spreading further distances. This has also been corroborated by investigations of cases between people who were not in direct or indirect contact, indicating airborne transmission was the source of infection (The Lancet Respiratory Medicine, 2020), which would require additional controls such as provisions for social distancing measures greater than 6 ft, face coverings capable of filtering smaller particle size such as N95 respirators, and the growing importance of ventilation (Chirico et al., 2020; Lu et al., 2020; Morawska et al., 2020).

Masks, restricting access to the workplace if exposed and social distancing are predominant controls to prevent COVID-19 infection and are an absolute necessity to lower infection rates during the pandemic, however, airborne transmission is still possible. Considering the mass balance equation on how respiratory infections spread and ensuring a hierarchical blanket of controls aimed at each variable in the equation is a better approach to lower the risk of COVID-19 infection in the workplace.

TABLE 5
ESTIMATED CONCENTRATION OF INFECTIOUS PARTICLES BY SETTING & CONTROL SCENARIO

Estimated concentration of infectious particles based on given social settings and control scenarios.

		Concentration (virions m^3)				
Social setting	**Condition**	**No control**	**Control of airflow**	**Face mask**	**Reduction in exposure time**	**Two control methods combined**
Small office	One symptomatic person present	3,778.7	2,267.2	944.7	NA	566.8
	One asymptomatic person present	112	67.2	28.0		16.8
Classroom	Two symptomatic persons present	7,557.3	4,534.4	1,889.3	NA	1,133.6
	Two asymptomatic persons present	224	134.4	56.0		33.6
Gym	Two symptomatic persons present	7,557.3	4,534.4	1,889.3	NA	1,133.6
	Two asymptomatic persons present	224	134.4	56.0		33.6
Restaurant	Four symptomatic persons present	15,114.7	9,068.8	3,778.7	NA	2,267.2
	Four asymptomatic persons present	448	268.8	112.0		67.2

TABLE 6
PURGING TIME TO REDUCE INFECTIOUS PARTICLES TO BELOW DESIRED CONCENTRATION BY SETTING & CONTROL SCENARIO

Purging time to reduce infectious particles to below desired concentration based on given social settings and control scenarios.

		Purging time (min)				
Social setting	**Condition**	**No control**	**Control of airflow**	**Face mask**	**Reduction in exposure time**	**Two control methods combined**
Small office	One symptomatic person present	76	44	66	NA	37.3
	One asymptomatic person present	51	28	41		22.1
Classroom	Two symptomatic persons present	135	78	119	NA	67.2
	Two asymptomatic persons present	93	52	76		41.9
Gym	Two symptomatic persons present	270	155	236	NA	134.4
	Two asymptomatic persons present	185	104	152		83.8
Restaurant	Four symptomatic persons present	382	220	337.3	NA	192.6
	Four asymptomatic persons present	269	152	225		125.0

TABLE 7
ESTIMATED PROBABILITY OF INFECTION BY SETTING & CONTROL SCENARIO

Estimated probability of infection based on given social settings and control scenarios.

		Probability of infection				
Social setting	**Condition**	**No control**	**Control of airflow**	**Face mask**	**Reduction in exposure time**	**Three control methods combined**
Small office	One symptomatic person present	1.0	1.0	0.99	1.0	0.74
	One asymptomatic person present	0.42	0.28	0.13	0.24	0.04
Classroom	Two symptomatic persons present	1.0	0.98	0.82	0.97	0.40
	Two asymptomatic persons present	0.18	0.11	0.05	0.10	0.02
Gym	Two symptomatic persons present	1.0	1.0	1.0	1.0	0.92
	Two asymptomatic persons present	0.64	0.45	0.22	0.40	0.07
Restaurant	Four symptomatic persons present	1.0	1.0	0.99	0.95	0.36
	Four asymptomatic persons present	0.42	0.28	0.13	0.09	0.01

The use of engineering controls such as improved ventilation, filtration and air disinfection should be considered as necessary additional layers of mitigation in light of the more recent knowledge of airborne transmission as a cause of infection in some cases, rising community spread and more infectious strains.

New and more infectious SARS-CoV-2 strains pose more challenges to communities and businesses weary from the pandemic. However, the principles of how infectious respiratory viruses spread and can be controlled remain the same. As vaccines become available and communities and business begin to ease off of restrictions, or even before widespread vaccine administration as people become fatigued with the restrictions and possibly less vigilant of safety precautions, now is a good time to introduce additional infection prevention controls into the workplace by increasing the use of engineering controls that are known to be effective in minimizing exposures.

These recommendations are not to be interpreted as a replacement for existing controls but an addition to the existing prevention efforts. As the virus spreads, the likelihood of encountering an infectious person increases and the amount of infectious particles in indoor spaces also increases. Additional layering of engineering controls may be necessary to reduce the risk and may prove to be a more viable long-term solution for businesses to conduct their day-to-day activities.

The ALARP and precautionary principles promote multilayer defenses. Adding bioaerosol engineering controls to the arsenal of COVID-19 precautions could provide businesses more resilience to community case rate spikes and render more capability to withstand and even thrive amidst any new strains or future airborne public health events. **PSJ**

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