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Recent research on expiratory particles in respiratory viral infection and control strategies: A review

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1. Introduction

1.1. Background and scope of discussion

The worldwide spread of coronavirus disease 2019 (COVID-19), which is a severe respiratory disease caused by the novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has infected more than 110 million people and resulted in more than 2.4 million deaths as the end of February 2021 (World Health Organization, 2021). This poses a significant threat to human health, following other well-known pandemics that spread as a respiratory viral infection during this century, including the 2003 severe acute respiratory syndrome, 2009 H1N1 influenza pandemic, and 2013 Middle East respiratory syndrome. As a substantially more severe pandemic than has previously occurred in the world, COVID-19 also considerably hinders the development of cities and society. Therefore, to promote the construction of sustainable cities and society equipped with epidemic prevention functions (Megahed & Ghoneim, 2020; Rahmani & Mirmahaleh, 2021), there is an urgent need to seek out effective precaution and control methods against respiratory viral infection in the built environment. The success of this is critically dependent on understanding the transmission characteristics of SARS-CoV-2.

To date, plenty of evidence has shown that SARS-CoV-2 RNA or viable virus can be detected in air samples collected in the room with COVID-19 patients (Ge et al., 2020; Lednicky et al., 2020; Y. Mao et al., 2020), indicating that the virus is highly likely to be spread by expiratory particles (Fig. 1). However, the distribution of viral concentration in different-sized expiratory particles is still unclear and is generally assumed to be uniformly distributed (Mao et al., 2020). Generated from different respiratory activities such as coughing, sneezing, speaking and breathing, expiratory particles generally have a size between < 0.1 μm and 500 μm (Gralton et al., 2011). The World Health Organization (WHO) defines expiratory particles having diameters > 5 μm as droplets and < 5 μm as aerosols (World Health Organization, 2014). Aerosols can remain suspended in the air and are considered airborne. By contrast, according to Tang et al. (2021), there is no definite cut-off diameter for airborne particles because factors such as the expiratory momentum and ambient airflow could also affect the ability of a particle to remain suspended. Therefore, “droplets” are defined rather as particles that fall to the ground due to gravity and/or respiratory momentum, while “aerosols” are particles that remain suspended due to size and/or environmental influence.
environmental conditions. The WHO also regards “droplet nuclei” as a synonym for “aerosol” (World Health Organization, 2020b). However, because “droplet nuclei” explicitly refers to the residue of dried expiratory particles that result from evaporation of droplets or aerosolization of infective material (World Health Organization, 2014), they should be considered as belonging to aerosols (Tang et al., 2021).

Carried by expiratory particles, potential transmission routes for respiratory virus include contact transmission, droplet transmission, and airborne transmission (World Health Organization, 2020b). According to the World Health Organization (2014), contact transmission refers to “the spread of an infectious agent caused by physical contact of a susceptible host with people or objects.” Droplet transmission refers to “the spread of an infectious agent caused by the dissemination of droplets.” Airborne transmission refers to “the spread of an infectious agent caused by the dissemination of aerosols.” On the other hand, despite the rough classification of viral transmission routes mentioned above, the transmission characteristics of the expiratory virus from the infector to the susceptible can be very complex. Depending on different respiratory activities, the initial characteristics of expiratory particles and airflow can be quite different from each other. Moreover, after exhalation, those particles are exposed to ambient environmental conditions such as temperature, humidity, and airflow. All these factors can significantly affect the evaporation and dispersion of expiratory particles, and the viability of the virus that is contained. Therefore, to understand the transmission characteristics of SARS-CoV-2, evaluate the infection risks caused by infectious expiratory particles, and find effective control strategies, it is essential to learn the initial properties of expiratory particles and the influence of environmental factors on the virus transmission.

Meanwhile, during this COVID-19 pandemic, the detection of live viruses in feces (Wang et al., 2020) has also been reported. In addition, a simulation showed that the toilet flushing process could induce turbulent flow, which expels aerosol particles out of the bowl (Li et al., 2020), and viral RNA has been detected in aerosols and on surfaces in hospital toilets (Liu et al., 2020; Ong et al., 2020), indicating that the fecal-oral transmission route is highly likely (Hindson, 2020). To date, the fecal-oral transmission mechanism of SARS-CoV-2 has rarely been discussed; however, this transmission route should not be ignored. This review only presents relevant topics on viral infection caused by respiratory activities, considering the numerous existing studies conducted in this field.

According to the transmission routes of expiratory particles, control strategies against respiratory viral infection may be classified into close-contact (≤ 1.5 m) and long-distance (> 1.5 m) prevention methods. The distance of 1.5 m can be considered as the average threshold distance for droplet transmission (the maximum traveling distance of large droplets) during coughing and breathing (Zhang et al., 2020). General strategies such as surveillance, social distancing, quarantine, and mechanistically based strategies are examples of close-contact prevention methods. Zhang et al. (2020) classified mechanistically based strategies for

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**Nomenclature**

| Abbreviation | Description |
|--------------|-------------|
| CADR | Clean air delivery rates (m$^3$/h) |
| CFD | Computational fluid dynamics |
| CJV | Confluent jet ventilation |
| COVID-19 | Coronavirus disease 2019 |
| DV | Displacement ventilation |
| DWV | Downward ventilation |
| FFR | Filtering facepiece respirator |
| HEPA | High-efficiency particulate air |
| LJV | Impinging jet ventilation |
| MPPS | Most penetrating particle size |
| MV | Mixing ventilation |
| NaCl | Sodium chloride |
| PAC | Portable air cleaners |
| PE | Personalized exhaust |
| PIV | Particle image velocimetry |
| POV | Protected occupied zone ventilation |
| PPE | Personal protection equipment |
| PV | Personalized ventilation |
| q | Quanta emission rate (quanta/h) |
| RH | Relative humidity |
| RNA | Ribonucleic acid |
| SARS-CoV-2 | Severe acute respiratory syndrome coronavirus 2 |
| SV | Stratum ventilation |
| TBL | Thermal boundary layer |
| TVAD | Total volume air distribution |
| $v_{\text{max}}$ | Maximum velocity of expiratory flow (m/s) |
| UFV | Underfloor ventilation |
| UV | Ultraviolet radiation |
| UVGI | Ultraviolet germicidal irradiation |
| WAV | Wall attached ventilation |
| WHO | World Health Organization |

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**Fig. 1.** Expiratory particles in respiratory viral infections and the associated control strategies.
close-contact transmission into three categories according to the following transmission routes: droplet transmission (surgical masks and face shield), short-range airborne transmission (N95 respirators, personalized ventilation systems, and push-pull systems), and immediate body-surface transmission (surface disinfection, hand hygiene, and oral hygiene). By contrast, control strategies for long-range airborne transmission routes mainly include humidity and temperature control, total volume mechanical ventilation, air filtration (Xu et al., 2020), and distant fomite sterilization. This review focuses on common infection control strategies, such as masks, air distribution methods, air filtration, and disinfection methods, and suggests their potential in preventing the spread of expiratory particles and SARS-CoV-2.

1.2. Objective and paper structure

After the outbreak of COVID-19, a significant number of review papers concerning respiratory viral infections have been published. Among them, several studies set their research object on expiratory particles, such as the possible role that aerosols play in the transmission of COVID-19 (Asadi et al., 2020; Wilson et al., 2020), transmission risks of infectious droplets (Mao et al., 2020), and experimental techniques of characterizing expiratory particles (Mahjoub Mohammed Merghani et al., 2021). Compared to previous review work, this paper aims to focus on several important issues concerning the transmission of expiratory particles in the air, which have not been discussed in detail yet. Selected topics include initial characteristics of expiratory particles and airflow from different respiratory activities (Section 2), environmental influences on particle evaporation, dispersion, and viability of SARS-CoV-2 (Section 3), methods used for infection risk assessment of SARS-CoV-2, and perspective on physical distancing (Section 4), and common infection control strategies against expiratory particles or SARS-CoV-2 (Section 5). The paper structure is shown in Fig. 1.

1.3. Methodology and screening criteria

In this paper, we present a selective review of recent research on expiratory particles in respiratory viral infections and the associated control strategies. We utilized Web of Science and Google Scholar to retrieve the literature and prioritize highly cited English, refereed journal articles, and focused on SARS-CoV-2 regarding the virus type analyzed in this study. Keywords used for searching papers include “expiratory particles/droplets/aerosols”, “cough/sneeze/talk/breath”, “SARS-CoV-2”, “environment/temperature/humidity/flow”, “evaporation/dispersion/viability”, “infection risks”, “physical distancing” and “control strategies/masks/air distribution/filtration/disinfection.” The transmission process of expiratory particles discussed in this study starts from the exhalation of the infector, ends in the exposure by the susceptible; phases of infectious particle generation in the respiratory tract or inhalation by the susceptible are excluded. For the time range, we have concerned mainly but not exclusively on research since January 2011 until January 2021, although studies relevant to SARS-CoV-2 are confined to years after 2019. We reviewed 117 papers, and the number of papers for each topic is shown in Fig. 1.

2. Expiratory particle and flow features

2.1. Size and number of expiratory particles

Table 1 presents previous experimental measurements on expiratory particles and flow features from different respiratory activities. Significant discrepancies remain in previous measurements of the size range of particles generated from coughing, sneezing, speaking, and breathing (Gralton et al., 2011) (Table 1). These contradictions may potentially result from individual physiological differences, various measurement technologies, and the influence of evaporation and condensation (Wei & Li, 2016). The size of these expiratory particles ranges 0.01–500 μm in healthy people and 0.05–500 μm in infected patients; therefore, it may be concluded that these respiratory activities contain droplet and airborne transmission (Gralton et al., 2011). This indicates that infection control precautions should consider both transmission routes. Moreover, the number of small particles (<1 μm) accounted for the largest proportion of exhaled particles by coughing and breathing (Fabian et al., 2008; Zayas et al., 2012) (Table 1).

In terms of the particle numbers produced in different respiratory activities, some experiments counted the total particles emitted “per cough” or “when counting 1–100 by speaking” (Chao et al., 2009; Lindsley et al., 2012), whereas others set uniform standards and measured particle numbers per liter for each respiratory activity (Wei & Li, 2016) (Table 1). However, to date, there has been no exact value for each activity. Particle numbers of each size are usually required in simulation boundary conditions or theoretical models. However, based on the uncertainty and difficulty in counting the exact particle number using the interferometric Mie imaging technique, there is doubt as to whether such direct measurement is necessary. Compared to the detailed number of total expiratory particles, the experimental value of number distribution should be more important. The number distribution and total mass of expiratory saliva (which are much easier to measure) can be used to indirectly calculate the number for each particle size. The

| Table 1 | Expiratory particle and flow features of different respiratory activities. |
|---------|--------------------------------------------------------------------------|
|         | Coughing                                                                  | Sneezing                                             | Breathing                                            |
| Size range (μm) | < 0.1–500 (Gralton et al., 2011)                                          | < 1.0–125 (Gralton et al., 2011)                      | 0.1–125 (Gralton et al., 2011)                       |
| Number distribution | 97% < 1 μm (Zayas et al., 2012)                                           | -                                                    | -                                                    |
| Particle number (total) | 947–2085 (per cough) (Chao et al., 2009)                                  | -                                                    | 112–6720 (counting 1–100) (Chao et al., 2009)        |
| Particle concentration (per liter) | 24–23,600 (Wei & Li, 2016)                                                | -                                                    | 4–600 (Wei & Li, 2016)                               |
| Mass of saliva (mg, total) | 1.1–6.7 (per cough) (Xie et al., 2009; Zhu et al., 2006)                  | -                                                    | 18.7–79.4 (counting 1–100) (Xie et al., 2009)        |
| Maximum flow velocity (m/s) | 5–22 (Female: 10.6–13.07; Male: 15.2–15.3) (Gupta et al., 2009; Scharman et al., 2016) | 4.5–100 (Nishimura et al., 2015; O’Hara, 1956; Tang et al., 2013) | 4.9–60 (Kwon et al., 2012) |
| Duration of flow expulsion (s) | 0.3–0.8 (per cough) (Bourouiba et al., 2014)                              | 0.15–0.25 (per sneeze) (Bourouiba et al., 2014; Scharman et al., 2016) | -                                                    |
| The maximum direct reach (m) | 0.3–0.7 (Nishimura et al., 2013; Tang et al., 2012)                        | 0.6–0.84 (Nishimura et al., 2013; Tang et al., 2013)   | -                                                    |
|                 |                                                                           |                                                      |                                                      |
|                 |                                                                           |                                                      |                                                      |
|                 |                                                                           |                                                      |                                                      |
average number of particles per cough from influenza-infected people was found to be higher (75,400) than the number when they had recovered (52,200); most of these particles could be inhaled easily because they were in the respirable size fractions (Lindsey et al., 2012). In another study (Asadi et al., 2019), the particle emission rate (1–50 particles per second) during speech was measured, and a positive correlation with loudness was found. However, speech super-emission was not attributable to loudness and possibly resulted from more individual physiological factors.

### 2.2. Expiratory flow velocity

It is commonly accepted that coughing, speaking, and breathing represent the descending order of maximum airflow velocity magnitude \( v_{\text{max}} \) due to different respiratory activities (Zhang et al., 2015). However, documented sneezing velocities vary widely from 4.5 to 100 m/s (Nishimura et al., 2013; O’Hara, 1956; Tang et al., 2013) (Table 1). The long-standing 100 m/s (O’Hara, 1956) was later challenged by Tang et al. (2013) because it was inferred from some basic physical principles instead of measurements from actual sneezes, and the estimated droplet velocity did not necessarily equal the airflow velocity. The inconsistency of sneezing velocities may also reflect the difficulty in measuring the sneeze at a required time, because it is not easy to create a sneeze on command compared to other respiratory activities. Therefore, more methods and experiments are needed to accurately measure sneeze velocity. In terms of velocity differences between sexes, it was found that the \( v_{\text{max}} \) of coughing and speaking of males was higher than that of females (Han et al., 2021; Kwon et al., 2012) (Table 1). Researchers found a positive linear correlation between the height of a person and their coughing and speaking velocity (Kwon et al., 2012). A comparison of the particle transmission characteristics due to different \( v_{\text{max}} \) showed that more droplet nuclei were suspended in air at a slower jet velocity; the maximum horizontal distance that a droplet could travel increased with the maximum velocity of expiratory flow \( v_{\text{max}} \) (Xie et al., 2007). \( v_{\text{max}} \) was also found to affect the dispersion of expiratory particles, whereby particles emitted from coughing were dispersed more widely than breathing (Zhang et al., 2019).

### 2.3. Duration and maximum direct reach

Gupta et al. (2009) measured the variation in flow rate at the mouth using a pneumotachograph-based spirometer, to determine the duration of a cough or sneeze ejection flow. They determined that the duration was approximately 0.3–0.8 s for a cough. Bourouiba (2016), Bourouiba et al. (2014), and Scharfman et al. (2016) used high-speed imagery to directly observe the propagation of expelled gas and liquid phases. The measured duration was approximately 0.3 s for a cough and 0.15–0.25 s for a sneeze (Table 1). These results show that coughing has a longer duration than sneezing.

Nishimura et al. (2013) defined the maximum direct reach as the distance from the mouth when the front-line particles lose momentum (equivalent to the natural convention current) or reaches an apparent plateau velocity. This reach was measured by using a digital high-vision and high-speed video system combining vector analysis by particle image velocimetry (PIV); the maximum direct reach was 0.3 m for a cough and 0.84 m for a sneeze (Table 1). Tang et al. (2012, 2013) used the shadowgraph imaging technique to measure the maximum visible distance traveled by ejecting puffs. The measured maximum direct reach was 0.7 m for a cough and 0.6 m for a sneeze (Table 1). The results obtained from these different methods show apparent disagreements. Therefore, this highlights the need for further experiments to measure the maximum direct reach of airflow emitted by different respiratory activities and a comparison between experimental methods.

### 2.4. Turbulent flow

Wei and Li (2015) discovered that turbulent cough airflow could facilitate the widespread dispersion of exhaled particles. Small particles (10 µm) traveled with airflow closely over a long distance, and small droplets (30 µm) were quickly transformed into droplet nuclei after exhalation and behaved similarly to small particles. The medium droplets (50 µm) were sensitive to relative humidity and could still be carried by the jet up to a certain distance even when settling. The traveling distance of large droplets (100 µm) was mostly dependent on jet outlet velocity and diameter, and Wei and Li (2015) utilized the jet model to study cough turbulence in further detail. However, Bourouiba et al. (2014) found that violent respiratory flows of coughing and sneezing are turbulent multiphase puffs rather than jets, and puff buoyancy may be impacted by the ambient conditions. VanSlieren et al. (2011) demonstrated that PIV can be used to map the flow of human coughs in vitro. However, their experimental results indicated that the human cough cannot be simplified as a typical flow field when conducting numerical simulations because of the large variance in velocity data among different subjects and trials.

### 3. Environmental influence

#### 3.1. Environmental influence on particle evaporation and dispersion

The evaporation process of expiratory particles is mainly affected by the initial properties of expiratory particles and flow and the ambient environmental conditions. This indicates that when the respiratory activity type is fixed, the environmental impact factors play a significant role in droplet evaporation.

Researchers often use different indices to evaluate the effect of particle evaporation and dispersion. These indices include time-dependent/ equilibrium droplet size, droplet evaporation/settling time, and droplet traveling distance. Some researchers (Wei & Li, 2015) have developed indices such as the “reach probability,” which aims to characterize the traveling distance of droplets within a turbulent jet. Some researchers have adopted the “droplet lifetime” (Chaudhuri et al., 2020), which refers to the smaller of the complete evaporation time and settling time; this index can describe the maximum duration a droplet can exist prior to evaporation to droplet nuclei or settlement.

Table 2 summarizes recent studies concerning the environmental influence on droplet evaporation. The most studied environmental factor is relative humidity (RH) (Ji, Qian, Ye, & Zheng, 2018; Liu, Wei, Li, & Ooi, 2017; Wei & Li, 2015). For a single droplet of different sizes, the time required for evaporation at high RH is greater than that at low RH (Wei & Li, 2015). For droplets spread in turbulent buoyant jets caused by coughing, both small (20–30 µm) and large-sized (100 µm) droplets are insensitive to RH. Small droplets evaporate into droplet nuclei soon after expiration. Large droplets are deposited on the ground, in which spreading distance is mainly determined by the jet outlet boundary. By contrast, RH has a significant effect on medium-sized (50–60 µm) droplets. At low RH, evaporation is complete prior to falling out of the jet. At high RH, some droplets are deposited out of the jet, whereas some travel long distances (Liu, Wei, Li, & Ooi, 2017; Wei & Li, 2015). Therefore, further analysis of droplet transmission by turbulent buoyant jets rather than a single droplet is important.

Compared to RH, the influence of ambient temperature and flow and has been studied less. Lea Der Chen (2020) found that when RH is below 37% and remains constant, the temperature increase is inversely related to droplet evaporation time. Conversely, when RH exceeds 37%, the temperature increase at a constant RH causes a longer evaporation time. Chaudhuri et al. (2020) conducted a parametric study and found that droplet lifetime is short at high temperatures and low RH and high at low temperatures and high RH. Ji et al. (2018) conducted a computational fluid dynamics (CFD) simulation to compare the impact of mixing and displacement ventilation. They reported that both ventilation...
systems can accelerate evaporation compared to stagnant ambient flow. Mixing ventilation accelerates droplet evaporation more because its violent turbulence causes more rapid mass transfer. Further studies are required to determine the influence of ambient temperature and flow on droplet evaporation.

Table 2 shows that theoretical or numerical analysis was conducted in most recent studies. To verify the feasibility of theoretical models, Liu et al. (2017) conducted an experiment using a droplet deposited on a Teflon-printed slide. To avoid inaccurate results caused by shape change, Chaudhuri et al. (2020) adopted acoustic levitation to suspend a droplet; this is similar to the state of real droplets in the atmosphere. Due to the many simplifications in theoretical or numerical studies, there may be inaccuracies generated in the results. For example, some researchers simplified the model by not considering crystallization and assuming that partial pressure at the droplet surface was equivalent to that of ambient air. In addition to the influence of ambient temperature, humidity, and airflow on evaporation of particles and thus on their dispersion, the ambient flow field also has a direct influence on particle dispersion. For example, thermal stratification may extend the scope of short-range airborne infections (Qian & Zheng, 2018). Zhou et al. (2017) developed a non-dimensional theoretical buoyant jet dispersion model and observed that exhaled flow could freely float upward within a thermally uniform environment, while fluctuating at a certain height in a thermally stratified environment. Based on this work, Liu et al. (2019) developed a jet integral model and reported that the lock-up phenomenon within a thermally stratified environment significantly impeded concentration decay. They also observed that the longest distance of direct exposure occurred when the breathing height of the susceptible person was at the lock-up layer in displacement ventilation. Conversely, Ai et al. (2019) found that the disturbance in horizontal ambient flow supply could strengthen the mixture of exhaled air and ambient air, thus reducing the exposure risk of close contact and making the monotonically decreasing relationship between exposure risk and separate distance unobvious. Indoor airflow patterns are typically adjusted by applying engineering control strategies; based on the complexity, the influence of different air distribution methods on the transmission of expiratory particles is specifically discussed in Section 5.2.

3.2. Influence of flow field on particle dispersion

In addition to the influence of ambient temperature, humidity, and airflow on evaporation of particles and thus on their dispersion, the ambient flow field also has a direct influence on particle dispersion. For example, thermal stratification may extend the scope of short-range airborne infections (Qian & Zheng, 2018). Zhou et al. (2017) developed a non-dimensional theoretical buoyant jet dispersion model and observed that exhaled flow could freely float upward within a thermally uniform environment, while fluctuating at a certain height in a thermally stratified environment. Based on this work, Liu et al. (2019) developed a jet integral model and reported that the lock-up phenomenon within a thermally stratified environment significantly impeded concentration decay. They also observed that the longest distance of direct exposure occurred when the breathing height of the susceptible person was at the lock-up layer in displacement ventilation. Conversely, Ai et al. (2019) found that the disturbance in horizontal ambient flow supply could strengthen the mixture of exhaled air and ambient air, thus reducing the exposure risk of close contact and making the monotonically decreasing relationship between exposure risk and separate distance unobvious. Indoor airflow patterns are typically adjusted by applying engineering control strategies; based on the complexity, the influence of different air distribution methods on the transmission of expiratory particles is specifically discussed in Section 5.2.

3.3. Environmental influence on virus viability

Based on the transmission routes of expiratory particles, studies regarding the environmental influence on virus viability are categorized into two types: those regarding droplets on the surface and those regarding suspended aerosols. SARS-CoV-2 is more stable on smooth surfaces such as plastic, stainless steel, glass, banknotes, and the outer layers of surgical masks, but less stable on printing and tissue papers, treated wood, cardboard, and copper (Chin et al., 2020; van Doremalen et al., 2020). Under common room temperature and RH conditions, SARS-CoV-2 was found to survive for up to 72 h on plastic (21–23°C, 40%) (van Doremalen et al., 2020), and infectivity was retained on respirable-sized aerosols for up to 16 h (23°C, 53%) (Fears et al., 2020). These measurements indicate that airborne and contact transmission of SARS-CoV-2 is plausible, and these risks may persist over a long period if proper infection control strategies are not implemented.

For surface-deposited droplets of SARS-CoV-2, higher temperatures were found to cause more rapid inactivation of the virus (Chin et al., 2020; Riddell et al., 2020). However, there remains a discrepancy in the influence of RH on viral viability; Biryukov et al. (2020) and Matson et al. (2020) claimed that a higher RH facilitates the decay of SARS-CoV-2, whereas Morris et al. (2020) stated that the virus has greater survivability at extremely low or high RH. This discrepancy may be caused by the limited cases and the lack of rigorous control of variables in some studies, requiring further confirmation experiments and discussions.

For SARS-CoV-2 in suspended aerosols, Smither et al. (2020) considered that aerosolized media containing the virus may influence viral stability under different RH; the virus was more stable at medium RH than in higher RH in tissue culture media, whereas the opposite result was observed in artificial saliva. Dabisch et al. (2021) found that the effect of temperature or ultraviolet (UV) radiation was much higher than that of humidity, with higher temperature and UV increasing the viral decay rate. In summary, these results also highlight the poor understanding regarding the influence of humidity on the infectivity of SARS-CoV-2 in aerosols. To date, no studies have been conducted on the infectivity variation of size-fractioned particles under different environmental conditions; such research may aid the identification of differences in viral viability in aerosols and large droplets.

Although evidence has shown that the stability of SARS-CoV-2 could be a function of environmental factors such as temperature, humidity, and UV, the joint effect of these factors remains unclear. Based on experimental data, Morris et al. (2020) proposed a mechanistic model to estimate the joint effect of temperature and humidity on viral viability, including SARS-CoV-2 and other enveloped viruses. This type of model can be improved in the future after addressing the discrepancies and difficulty in interpreting the existing experimental phenomena. These improvements would be significantly beneficial in the prediction of viral viability under conditions that cannot be observed.

Furthermore, in many studies, meteorological and virus epidemiological data have been used to determine the relationship between climatic conditions and the seasonality of confirmed COVID-19 cases. For example, Yao et al. (2020) focused on major Chinese cities from January to March and indicated that the communicability of COVID-19 is negatively correlated with high ozone concentrations, high
temperatures, and low RH. V et al. (2020) compared data from March to April in various Indian states and found that a decrease in RH is positively correlated with the number of confirmed cases. The dispersion characteristics of exhalatory particles and the survivability of SARS-CoV-2 in different climate conditions may potentially influence the seasonality of confirmed COVID-19 cases. However, these influences can be confounded by many other complicating factors, such as human behavior and circannual variation in immunity (Morris et al., 2020). Therefore, findings on the seasonality of COVID-19 should be interpreted with caution.

4. Infection risk assessment

4.1. Exposure risks

If the virus content of exhalatory particles is not considered, the quantification of infection risk can be simplified to the risk of exposure to exhalatory particles. Exposure risks can be assessed more easily than infection risks where there is limited knowledge of virus distribution on exhalatory particles as well as variation over time of virus viability according to environmental conditions.

As mentioned in the introduction section, droplets can only remain in the air for a short time, and thus they transmit over short distances before depositing, while aerosols can disperse over long distances and remain airborne for longer periods. The short-range transmission routes of respiratory particles include both droplet and airborne transmission, whereas the long-range transmission route of respiratory particles generally refers to airborne transmission. Therefore, the cut-off distance for “short-range” and “long-range” depends on the maximum horizontal distance that the droplets can reach. This threshold distance is determined by many factors, including the initial properties of exhalatory particles and flow, as well as ambient environmental conditions. For example, a study by Xie et al. (2007) revisited the Wells evaporation-falling curve (Wells, 1934, 1955). They found that expelled droplets could be carried by exhalatory airflow more than 3-6 m away at a velocity of 20–50 m/s (sneezing), more than 2 m away at a velocity of 10 m/s (coughing), and less than 1 m away at a velocity of 1 m/s (breathing) at room temperature and humidity conditions (20 °C, 50%).

Therefore, when a susceptible and an infected person are in close contact, with both droplet and airborne transmission, the exposure risks to exhalatory particles are expected to be higher. However, consensus on the relative contribution of each transmission route to close-contact exposure has changed several times. Traditionally, close-contact exposure is believed to be mainly due to droplet transmission (Brankston et al., 2007). Later, Liu et al. (2017) pointed out that both droplet and airborne transmission can be important for close-contact (<1.5 m) exposure to exhalatory particles. By contrast, a recent study by Wenzhao Chen et al. (2020) found that when a susceptible person is close (<2 m) to an infected person, the short-range airborne transmission contributed most to the exposure risk of exhalatory particles, while the droplet transmission only dominated when the droplets were over 100 μm at a distance within 0.2 m when talking, or 0.5 m when coughing, which is fairly negligible.

4.2. Infection risk model

The Wells-Riley and dose-response models are two common approaches for risk assessment of respiratory viral infection. The Wells-Riley model has been extensively used. It allows simple and quick evaluation, based on the quantum concept that implicitly considers the infectivity, infectious source strength, and biological decay of pathogens; the dose-response model is less frequently used because it requires information that is costly to obtain through experimental and on-site studies (Sze To & Chao, 2010; Zhang & Lin, 2020).

As for COVID-19, most infection risk models have been proposed based on the Wells-Riley model, which is shown in Equation (1) (Riley et al., 1978; Wells, 1955).

\[
P_I = 1 - e^{-\frac{Iq}{P}}
\]

where \(P_I\) is the probability of infection, \(I\) is the number of infectors, \(q\) is the quanta emission rate by one infector (quanta/h), \(p\) is the breathing rate of each susceptible person (m³/h), \(t\) is the exposure time interval (h), and \(Q\) is the room ventilation rate (m³/h).

A quantum refers to the number of infectious airborne particles required to infect a person (Wells, 1955). The Wells-Riley model assumes a spatially and temporally uniform distribution of pathogen-laden aerosols. As shown in Table 3, Buonanno et al. (2020) and Kriegel et al. (2020) integrated the time-varying quanta concentration (quanta/m³) to assess infection risk under transient conditions. Kriegel et al. (2020) also considered the time-varying viability of viruses. Zhang and Lin (2020) proposed a dilution-based evaluation method. This expansion of the Wells-Riley model can assess the airborne infection risk for both spatial and temporal resolutions. Furthermore, considering the simplification of the Wells-Riley model, the social distance index and ventilation factor (Sun & Zhai, 2020), as well as the filtration effect of masks (Dai & Zhao, 2020) were introduced to improve the prediction accuracy of the model.

To apply the Wells-Riley model to infection risk assessment effectively, many efforts have been made to determine the quanta emission.
Considering the large errors introduced in the data collection of other and vocalization (Miller et al., 2021). The these studies. Among them, the largest explicit

Summary of recent studies concerning physical distancing applied to COVID-19. Table 4

Table 4 summarizes recent studies concerning physical distancing applied to COVID-19. Feng et al. (2020) and Dbouk and Drikakis (2020a) define safe physical distance as the furthest distance that coughing droplets can reach. Both studies conducted numerical simulation and examined the significant impact of ambient wind on physical distancing. Sun and Zhai (2020) considered the infection risks from respiratory droplets. They modified the Wells-Riley model and indicated the minimum physical distance to be 1.6–3.0 m when only breathing and speaking.

Other studies calculate physical distancing by considering the infection risks from both droplets and droplet nuclei. Yang et al. (2020) utilized a dose-response model and showed that physical distancing is insufficient to control infection probability and that decreasing contact time is also important. They suggested that the contact time should be less than 8 min for a 1 m distance and 16 min for a 2 m distance from the speaking or breathing infector. Mittal et al. (2020) adopted a protection factor based on concentration decay to compare the infection risks at different physical distances. They found that when the velocity of the crossflow is much larger than that of the exhaled jet, the protection factor increases faster as the distance increases. Furthermore, buoyancy also influences the rate of increase in the protection factor. Rosti et al. (2020) conducted a numerical simulation, systematically comparing eight coughing scenarios selected from past research. They found that different initial conditions influenced the results. This again shows the necessity of further experiments on the initial properties of expiratory particles.

Due to strong evidence of the infection potential of droplet nuclei, it is inadequate to estimate a safe physical distance using only the maximum reaching distance of expiratory droplets, although this could specify the lower limit of physical distancing. Although some studies considering infection risks of expiratory particles suggested detailed physical distancing values, the viral loads assumed in these models are questionable, requiring further credible real cases or experiments on infection capability of expiratory particles carrying SARS-CoV-2.

5. Infection control strategies

5.1. Masks

According to the World Health Organization (2020a), masks used in healthcare settings include surgical masks and filtering facepiece respirators (FFR), or respirators. Surgical masks can filter 3 μm droplets, while respirators must filter 0.075 μm solid particles. Moreover, surgical masks have “an open shape and a potentially leaking structure.” By contrast, the outer edges of the FFR should seal around the wearer’s face to guarantee claimed filtration. Exhalation valves for respirators are discouraged because they “bypass the filtration function of exhaled air” (World Health Organization, 2020a).

Many studies have confirmed the importance and efficacy of masks

| Ref.         | Methodology                        | Respiratory activity       | Environment condition                  | Eligibility standard               | Physical distancing recommendations                      |
|--------------|------------------------------------|----------------------------|---------------------------------------|-----------------------------------|--------------------------------------------------------|
| Feng et al.  | Numerical simulation               | Cough/ sneeze              | Temperature: 27°C RH = 40%, 99.5%     | Little droplet reach              | Over 1.83 m due to wind convection                      |
| Dbouk & Drikakis (2020a) | Numerical simulation | Mild cough | Temperature: 20°C RH = 50% | Little droplet reach | Under 2 m with no wind; Over 2 m with parallel wind existing 1.6–3.0 m |
| Sun & Zhai (2020) | Theoretical model (Modified Wells-Riley model) | Speaking & breathing | Temperature: 0°C, 42°C | High protection factor | Decreases with strong crossflow & light plume; increases with heavy plume |
| Mittal et al. | Theoretical model                  | Breathing                  | RH = 50%                              | Infection probability under 2%    | 8 min for 1 m; 16 min for 2 m                          |
| Yang et al.  | Theoretical model (Dose-response model) | Speaking & breathing | RH = 50%                              | Infection risk under 0.63         | Conflicting results based on current knowledge         |
| Roti et al.  | Numerical simulation               | Cough                      | RH = 40%, 60%                         | Low cumulative viral load         |                                                        |
against viral respiratory infections. Zhai (2020) claimed that wearing a facial mask is necessary to beat COVID-19. Feng et al. (2020) analyzed a computational fluid-particle dynamics model and revealed that wearing facial masks, even loosely while coughing, could significantly reduce the suspension of small particles in the air. Leung et al. (2020) indicated that surgical masks could efficiently reduce the release of influenza virus particles in droplets rather than aerosols but could reduce the coronavirus virus both in large droplets and aerosols. Moreover, depending on the wearer’s activity level, filtration efficiency of surgical masks can be 44% (at rest) or 10% (in moderate activity) for 0.3–6 μm aerosols, if considering the influence of air leakage through the mask fitting gap (Konda et al., 2020).

In addition to filtering expiratory particles, masks also influence the characteristics of the expiratory flow field. As shown in Table 5, most studies have qualitatively described the features of the expiratory flow field under the influence of different masks. All types of masks can reduce the front throughflow (Dbouk & Drikakis, 2020b; Kähler & Hain, 2020; Tang et al., 2009). However, surgical and handmade masks can generate significant leakage jets, although the jet has been redirected, which causes less harm in face-to-face circumstances (Kähler & Hain, 2020; Tang et al., 2009; Viola et al., 2020). However, quantitative studies on the expiratory flow field when wearing a mask are limited. Only the distance of the filtered front throughflow has been measured using the Schlieren optical technique or PIV or simulated using CFD (Dbouk & Drikakis, 2020b; Kähler & Hain, 2020; Viola et al., 2020). Neither the velocity of the front throughflow nor the leakage flow in other directions has been measured. Considering that an increasing number of people choose to wear masks in public, the characteristics of expiratory particles and airflow when wearing a mask should be quantified.

Despite the limitations of relevant studies in this area, we can still acquire some knowledge on the usage of facial masks. A mask will not completely prevent the front dispersion of the respiratory flow; therefore, physical distancing is still essential. A greater distance is required for masks with a lower filtering efficacy. Nevertheless, when the environment is contaminated with a known source of infection, respirators are necessary. Moreover, due to the mask fitting gap, when sneezing or coughing it is advisable to use the elbow to prevent air leakage.

5.2. Air distribution methods

According to Qian and Zheng (2018), there are three key elements of ventilation that affect particle transmission: flow direction, ventilation rate, and airflow pattern. They concluded that pressure difference can be used to control the flow direction to prevent cross-infection between zones; increasing the ventilation rate is useful for reducing long-range airborne infection but might not help control short-range droplet transmission when the droplets are more influenced by gravity and exhalation velocity; the effect of ventilation rate on short-range airborne infections requires further investigation. Dai and Zhao (2020) estimated the necessary ventilation rate based on the Wells-Riley model and the reproductive number of COVID-19, as mentioned before. To control the infection probability at less than 1%, ventilation rates greater than 100–350 m³/h per infector and 1200–4000 m³/h per infector for 0.25 h and 3 h of exposure, respectively, are required; however, wearing an ordinary surgical mask could help reduce the required ventilation rate to a quarter, which is more achievable using normal ventilation modes. Considering the limitations of the Wells-Riley model, the accuracy of the suggested ventilation rate needs further discussion. Moreover, when the ventilation rate reaches a certain value, increasing the ventilation rate has no significant effect on reducing the transmission of aerosols (Zhang et al., 2019).

Ventilation systems can influence airflow patterns through different arrangements of diffusers and exhausts. Designing ventilation systems is complex, especially for large and complicated spaces. Sometimes, a combination of several air distribution methods is adopted to achieve a satisfactory environment. Therefore, here, we only summarize the basic characteristics of selected traditional and advanced air distribution methods.

5.2.1. Total volume air distribution

Total volume air distribution (TVAD) methods refer to ventilation strategies at a whole-room scale. Mixing ventilation (MV) and displacement ventilation (DV) are two traditional and principal ventilation types. MV aims to supply air at a high velocity to facilitate the mixing of the entire indoor air and dilution of contaminants, while DV aims to utilize the buoyancy force from the heat source to remove the contaminant in the breathing zone. In recent years, advanced air distribution methods have been developed and expanded based on the mechanisms of MV and DV (Cao et al., 2014; Yang et al., 2019). The characteristics of these air distribution methods for removing airborne contaminants are summarized in Table 6.

Concerning the physical mechanisms of these ventilation strategies, downward ventilation (DVW), underfloor ventilation (UFV), impinging jet ventilation (IJV), confluent jet ventilation (CJV), and wall-attached ventilation (WAV) all utilize the principle of DV in the latter process of air distribution. Except for DVW, the other four systems are all low-level air supply systems with high-velocity supplied air initially. CJV and WAV were both developed from the IJV. They deliver downstream flows with high momentum that impinge the floor, form a very thin shear layer along the floor, and reach a region further than DV. Meanwhile, all three ventilation systems can operate in heating mode. Stratum ventilation (SV) delivers clean air horizontally into the breathing zone (Lu et al., 2020), while Piston ventilation (or laminar airflow) can supply clean air vertically or horizontally across the whole room and swipe airborne virus away in a “washing effect” (Yang et al., 2019).

Table 5

Recent studies on expiratory flow field when wearing a mask.

| Ref.      | Method                        | Respiratory activities | Mask type                          | Influence on expiratory flow field                                                                 |
|-----------|-------------------------------|------------------------|------------------------------------|---------------------------------------------------------------------------------------------------|
| Tang et al. (2009) | Schlieren optical technique | Coughing               | Surgical and N95 masks            | Surgical mask can redirect the cough jet to reduce harm; N95 mask can block the formation of the jet |
| Dbouk and Drikakis (2020b) | Multiphase computational fluid dynamics | Mild coughing | Surgical mask                       | The bulk of expiratory particles will travel about 70 cm without a mask, but 35 cm with a mask; Mask efficiency will drop about 8% after 10 cough cycles |
| Kähler and Hain (2020) | Particle Image Velocimetry   | Coughing               | Mouth-and-nose cover, surgical mask, respirator | The flow resistance of masks can prevent the spread of exhaled air; Expiratory flow can leak through the edge gaps of mouth-and-nose cover |
| Viola et al. (2020) | Background oriented schlieren technique | Quiet and heavy breathing, coughing | FFP2 and FFP1 masks, a respirator, a surgical, a handmade mask | All masks can reduce the front throughflow by over 63%; Surgical and handmade masks generate significant leakage jets |
Table 6
Comparison of the efficacy of air distribution methods in removing airborne contaminants.

| Ventilation type                | Mechanism                                                                                           | Advantages & Applications                                              | Limitations                                                                 |
|--------------------------------|-----------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Mixing ventilation (MV)        | The diffuser introduces air at high velocity to facilitate mixing of the indoor air near the ceiling level (Bolashikov & Melikov, 2009) | Can create a uniform indoor environment to achieve thermal comfort (Yang et al., 2019) | Can enhance the dispersion of airborne contaminants, occupants may be exposed to infectious particles regardless of source location; Low energy efficiency |
| Displacement ventilation (DV)  | Slightly cooler air (cooler than ambient air) is delivered at floor level at low velocity, moving upwards and entrained by flows generated from heat sources, finally extracted at ceiling height (Bolashikov & Melikov, 2009) | Can minimize indoor mixing, ideally keeps contaminant away from the breathing zone; Natural or mechanical DV can be alternatives of the negative pressure ventilation for makeshift hospitals (Bhagat & Linden, 2020) | Cannot be used in heating mode to avoid full mixing; With intensive heat sources, the supplied air penetrates limited distance; Thermal stratification lock up phenomena can increase the dispersion distance of exhaled jet (Qian & Zheng, 2018) |
| Downward ventilation (DWV)     | Cooler air is supplied from a ceiling diffuser with low velocity, giving a downward flow. The local flow pattern can be similar to DV or MV depending on the distribution position of downward flow (Nielsen et al., 2010) | When the downward flow is supplied to areas outside the occupied zone with exhausts at a high location, this system can remove warm aerosols as per DV, and handle a high flow rate without causing high velocity, which is suitable for hospital wards (Nielsen et al., 2010) | When the downward air is supplied towards the occupied zone with thermal buoyancy, this system will operate like MV, and facilitate the dispersion of airborne contaminants throughout the space (Qian et al., 2008) |
| Underfloor ventilation (UFV)   | Cooler clean air is delivered at floor level with higher velocity through many diffusers. The air undergoes good mixing within the occupied zone, then starts to lift upwards similar to DV (Yang et al., 2019) | Can facilitate rapid mixing of air in the occupied zone, with the space above the occupied zone stratified to prevent the return of contaminants; Close to occupants for easy control | The high-speed supply jet promotes resuspension of particles from the floor and into the breathing zone (Bolashikov & Melikov, 2009) |
| Impinging jet ventilation (IJV) | A jet of air is supplied downwards with high momentum at a certain height, then strikes and spreads over the floor, forming a very thin shear layer with a far reach. The exhaust is generally near the ceiling level (Karimipanah & Awbi, 2002; Yang et al., 2019) | Fresh air can be delivered directly to the occupied zone due to thermal stratification; Heated air can be supplied in winter, which has sufficient momentum to overcome the buoyancy force generated by heat sources (Yang et al., 2019) | Because of the discomfort of the draught, the application is suggested in scenarios where occupants remain in fixed positions (Haghshenaskashani & Sajadi, 2018) |
| Confluent jet ventilation (CJV) | Circular jets are delivered in parallel directions in the same plane, coalescing at a certain distance downstream and moving as a single jet (Cho et al., 2008) | Confluent jets have slower velocity decay than other jet forms due to less entrainment of the ambient air, therefore the momentum is conserved better and the confluent jets can penetrate further in the occupied zone (Andersson et al., 2018) |  |
| Wall attached ventilation (WAV) | Fresh air is delivered from the linear slot inlet, attached to the sidewall or column surface due to the Coanda effect, moving downwards, impinging and spreading over the floor (Li et al., 2019) | Can be used in both cooling and heating mode; Simple to install (Li et al., 2019) |  |
| Stratum ventilation (SV)       | Clean air is delivered horizontally, forming the lowest air temperature and highest air velocity at the breathing zone (Lu et al., 2020) | Forms a fresh air layer and reduces contaminant concentration in the breathing level (Lu et al., 2020) | Supplied air temperature and contaminant source position can affect the performance of SV (Tian et al., 2010) |

Air is delivered vertically or horizontally across the whole room at low velocity and Large energy consumption due to high air change rate;
Strictly speaking, Protected occupied zone ventilation (POV) is not a type of TVAD, as it separates the indoor space into several subzones through downward-plane jets with low turbulence, which can effectively reduce short-range cross-infection (Cao et al., 2014). Moreover, other types of air distribution methods can be combined with the POV in each subzone to achieve better ventilation efficacy (Yang et al., 2019).

5.2.2. Personalised ventilation and personalised exhaust

To control the microenvironment around each occupant, personalised ventilation (PV) and personalized exhaust (PE) are commonly used. Compared with TVAD, these systems are effective in cleaning polluted air locally and from the source, can be controlled by occupants individually or self-respond to physiological signals, be quickly modified to suit requirements, and reduce energy consumption (Melikov, 2016).

PV delivers fresh air to the breathing zone of occupants directly, and therefore, the interactions between PV airflow and this microenvironment should be carefully considered (Xu et al., 2020). The distance between the exposed individual and PV terminal, as well as the relative position of the PV terminal, infected individual, and susceptible individual, are both important factors affecting infection exposure risks (Xu et al., 2020). It has been widely documented that PV could reduce cross-infection risks when used by the exposed individual; however, the use of PV by the infected individual should be avoided owing to its further dispersion of exhaled infectious particles (Ai et al., 2019). Another important factor that influences the cross-infection risk is the air volume of the PV. When occupants are at a close distance, PV only protects against infection with a high ventilation efficacy in the inhalation zone by reducing the entrainment of infectious flow and by being operated with a higher clean air volume (Xu et al., 2020). As higher velocity might cause discomfort, an intermittent PV system that balances thermal comfort and good air quality is proposed (Assaad et al., 2018). Dynamic PV airflow could cause a higher exposure risk than constant PV airflow due to higher turbulence intensity (Xu et al., 2020). Furthermore, the penetration of the PV jet into the thermal boundary layer (TBL) was not found as challenging as expected; the interaction between the PV airflow and the TBL alters the airflow distribution in the breathing zone and affects the inhaled air quality, and this should be carefully monitored (Xu et al., 2018).

PE works by extracting air locally (Yang et al., 2014). Either top-PE or shoulder-PE shows excellent performance in reducing infection risks of airborne transmission when used by an infected individual (Yang et al., 2015b). However, PE can cause the under-pressure problem, if the contaminated air is expelled from the room without being balanced with the supply airflow (Yang et al., 2014).

When comparing the efficacy of PV and PE, the single use of a PE system for the infected individual performed better than the single use of a PV system for the susceptible individual (Yang et al., 2015b). When combining these two solutions, the additional installation of a PE system for the susceptible individual can facilitate the clean PV flow to reach the breathing zone; this improvement of inhaled air quality can be better achieved under the background ventilation of DV than MV (Yang et al., 2014). On the other hand, when the infected individual uses the PE system, the PV used by the susceptible individual can increase or reduce the exposure risks, depending on many influential factors (Yang et al., 2015b). According to the above studies, layouts and operating modes of the PV and PE, positions of people, and ambient environmental factors, might influence the efficacy of the PV and PE systems. Therefore, as suggested by Ai and Melikov (2018) as well, further systematic investigation of different scenarios is needed.

Because PV and PE affect the air around individuals, both droplet and airborne transmission of the virus should be considered. Past studies utilized tracer gas to simulate the expiratory particles to investigate the airborne transmission performance (Yang et al., 2014, 2015a, 2015b). Some recent studies have utilized nebulizers to generate particles in the size range of breathing or talking (C. Xu et al., 2020; J. Xu, Fu, & Chao, 2020). Further studies are required to assess the control of droplet transmission by PV and PE during violent respiratory activities, such as coughing and sneezing, which generate larger droplets with different size distributions.

5.2.3. Occupancy-aided ventilation

Most existing ventilation systems are designed to be energy-efficient under non-pandemic conditions. When the airborne transmissibility of a certain type of virus is extremely high, like the SARS-CoV-2, the ventilation rate of the system may be insufficient to dilute the concentration of viral aerosols. In this case, reducing occupancy can reduce the risk of infection by reducing virus from the source. Based on this principle, Melikov et al. (2020) proposed an improved control strategy in which occupants were asked to leave the ventilated room at set intervals. The ventilation should be in operation before any occupant enters the room. Short room occupation times with long breaks are recommended. However, this occupancy-aided ventilation may reduce work productivity. Therefore, Zhang et al. (2021) further optimized the occupancy schedule to maximize the total duration of normal occupancy, balancing low airborne infection risks and work productivity. Despite the innovation of occupancy-aided ventilation, there are limitations such as potential corridor blockage, simplification of work productivity evaluation, assumption of uniform virus distribution, and difficulty in obtaining infector numbers (Zhang et al., 2021), and further research is required.
5.3. Air filtration

Air filtration is another method that can assist in reducing the indoor virus concentration when the existing ventilation system cannot provide an adequate air change rate. A temporary anteroom with air filtration devices could help remove virus particles and convert a general patient room into an isolation space (Mousavi et al., 2020). Air filtration methods are divided into in-duct devices (filters) and portable (stand-alone) air cleaners. In-duct devices work for the entire house but function only during the operation of the air-handling system where they are installed (Chen, Zhang, & Zhang, 2005). Portable air cleaners (PACs) can be operated and positioned in a room with the flexibility to target the problem areas and have received increasing attention in recent years.

The particle-removal performance of air filtration devices is evaluated by the clean air delivery rate (CADR), which is the product of the single-pass efficiency and airflow rate. According to particle filtration efficiency, air filters are divided into four types, which is pre filter, medium filter, high-efficiency particulate air (HEPA) filter and ultra-low particulate air filter (Liu et al., 2017). Among these, HEPA filters have shown excellent performance in removing expiratory aerosols and are most widely adopted in the market. As shown in Fig. 2, they have at least 99.97% efficiency for removing particles in the range of 0.15 to 0.2 μm, which is the most penetrating particle size (MPPS) due to the combined effect of different mechanisms of particle capture (Christopherson et al., 2020). Experiments by Qian et al. (2010) found that a common HEPA-filter PAC could reach an effective air change rate (dividing CADR by room volume) from 2.7 to 5.6 1/h in the ward with a size of 109 m³. However, regarding the efficacy of PAC on removing viral particles, several assumptions have been made in studies to date, such as neglecting the influence of particle evaporation and loss of particle infectiousness, assuming a constant rate of influenza emission, and using NaCl particles as an analog to the viral particles (Zuraimi et al., 2011). Thus, further research on the suitability of these assumptions is required. Moreover, the purification performance of an air cleaner can degrade over time. Pei et al. (2020) showed that the standard cumulative clean mass test in a laboratory using cigarette smoke did not represent the actual dust loading capacity and that using the initial CADR value could overestimate the daily purification capability. Therefore, the authors proposed a new PAC service life evaluation method that considers decay in actual applications.

PACs usually discharge cleaned air with strong momentum, and it was found that the HEPA filter PAC could produce global air mixing indoors at high speeds (Qian et al., 2010). Moreover, flow interaction between other momentum sources (e.g., ventilation systems) and PAC could play a significant role in indoor air cleaning. Thus, the parameters and positioning of a variety of momentum sources should ensure a good air circulation cycle to enhance air purification efficacy (Zhang et al., 2010). When airborne particles were distributed uniformly indoors, the flow rate had the greatest impact on the indoor particle concentration, and the position of the air cleaner affected the particle concentration at low volumetric flow rates; little difference was found between the effects of horizontal and upward ejection (Jim et al., 2016). By contrast, under non-uniform aerosol distributions, caused by smoking and coughing, the position of the air cleaner significantly impacted the particle concentration, which was also affected by the expiratory airflow velocity and the orientation of the air cleaner (Chen et al., 2017). When the PACs were applied in wards, Mousavi et al. (2020) found that if only one machine was used, the optimal placement was close to the patient’s bed, and if two machines were used, the optimal placement was on either side of the plastic division wall between the isolation space and the anteroom. From previous studies, we can learn that the contaminant sources, sinks and airflow can significantly affect the PAC efficacy in removing indoor viral contaminants. Thus, further systematic studies concerning the influence of the position, orientation, and flow rate of air cleaners are needed. Moreover, the influence of expiration characteristics under different respiratory activities, purifying efficacy under different ventilation systems, and purifying efficacy with the interaction of multiple air cleaners also warrant further study.

5.4. Disinfection

Compared to filtration, which refers to the removal of virus particles from airstreams passing through the filter, disinfection methods focus on the inactivation of viruses circulating in the air or depositing on surfaces. Possible COVID-19 disinfection technologies include ultraviolet germicidal irradiation (UVGI), electrostatic spraying, disinfectant fogging, ozone generators, plasma, photocatalytic disinfection, and heat sterilization (Chen & O’Keeffe, 2020; Tysiä-Miśta et al., 2020).

Among the disinfection methods mentioned above, the chemical-free technology of UVGI is most widely used. UV radiation is classified into UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm) based on wavelength, among which UV-C shows optimum germicidal effects, and disinfects microbes by damaging their nucleic acid (Reed, 2010). To achieve a valid inactivation efficiency, the UV-C dose (the irradiance delivered to microbial cells multiplied by the exposure time), intrinsic microbial characteristics, and target medium (air or surface) characteristics should be considered (Raeiszadeh & Adeli, 2020). A recent study showed that, similar to other human coronaviruses, SARS-CoV-2 can effectively be inactivated by UV-C radiation as well (Hellingsloh et al., 2020). On the other hand, excessive exposure to UV-C can also damage human skin and eyes, as well as degrade some materials (Raeiszadeh & Adeli, 2020). Therefore, in the UV-C dose, a balance between disinfection efficiency and the potential harm to human health or surfaces is needed. Further research, standardized protocols of optimum UV-C doses, and optimization of the system design in different settings are required.

UVGI technology has been applied in many scenarios for different purposes, such as in-duct and cooling coil systems, upper-room, UV barriers, lower-room, recirculating or air cleaning units, area disinfection systems, disinfection chambers, and UV-C wands (Chen & O’Keeffe, 2020). Thus far, upper-room UVGI may provide the most practical option owing to its safe distance from occupants. As shown in Fig. 3, this system utilizes the entire upper room as a disinfection chamber, as well as the rising warm air from the human body, with the ceiling fan assuring good mixing, and the shielding sufficiently protecting occupants below (Nardell, 2016). The upper-room UVGI system indicates the potential of combining UVGI and mixing ventilation in the future.

![Image](https://via.placeholder.com/150)
6. Discussion

6.1. Characteristics of expiratory particles and flow from different respiratory activities

Expiratory particle and flow features of different respiratory activities are summarized to provide quick references for further experiments and boundary conditions of numerical analysis. Due to many influential factors (e.g., individual physiological differences, various measurement technologies, particle evaporation and condensation, health status), experimental measurements so far cannot determine the explicit size range and number of expiratory particles for each respiratory activity. However, the number of particles under 1 μm was found to occupy the largest proportion, indicating a significant threat of airborne transmission. The maximum velocity of expiratory airflow can also be influenced by individual physiological differences such as gender and height. It can affect the number of aerosols suspending in the air and the maximum horizontal distance that a droplet can travel (Xie et al., 2007). Among different respiratory activities, the data of sneezing characteristics are scarce and inconsistent with each other, because of the difficulty of creating a sneeze on command during experiments. In the future, to improve the database on characteristics of expiratory particles and airflow from different respiratory activities, there is still a lot of work to be done.

6.2. Environmental influence on evaporation and dispersion of expiratory particles

Environmental factors such as humidity, temperature and airflow can influence the dispersion of expiratory particles by influencing their evaporation. For a single droplet of different sizes, the evaporation time at a high RH was greater than that at a low RH (Wei & Li, 2015). For droplets spread in turbulent buoyant flow, the trajectories of small (20–30 μm) and large (100 μm) sized droplets were insensitive to RH; RH significantly affects medium-sized (50–60 μm) droplets (Liu, Wei, Li, & Ooi, 2017; Wei & Li, 2015). Further research should consider the turbulent buoyant flow when discussing the influence of RH on the spread of expiratory droplets. The influence of temperature on droplet evaporation was found to be affected by RH. More violent turbulence in the ambient flow field can facilitate evaporation (Ji et al., 2019). In the future, more studies are needed on the influence of ambient temperature and flow on droplet evaporation. Considering the current methodologies used to study the impact of environmental factors, experimental studies should attempt to suspend droplets in the air; more efforts should be made to refine theoretical models, such as considering the composition of expiratory droplets.

The flow field in the ambient environment can also directly influence the dispersion of expiratory particles. The lock-up phenomena in thermal stratification may extend the scope of short-range airborne transmission (Liu et al., 2019; Zhou et al., 2017). Disturbance in the horizontal airflow supply can strengthen the mixture of expiratory flow and ambient air, thus reducing the exposure risks of close contact (Ai et al., 2019). Engineering control strategies, such as ventilation and air cleaners can reduce long-range airborne transmission through positive intervention with indoor airflow patterns.

6.3. Environmental influence on the viability of SARS-CoV-2 and seasonality of COVID-19

At room temperature and RH, SARS-CoV-2 can survive for up to 72 h on plastic (21–23°C, 40%) (van Doremalen et al., 2020), up to 16 h in aerosols (23°C, 53%) (Fears et al., 2020). This indicates that airborne and contact transmission of SARS-CoV-2 is plausible, and risks can last for long periods. For droplets deposited on surfaces, higher temperatures were found to cause faster inactivation of SARS-CoV-2, but a discrepancy still exists in the influence of RH on virus stability. For different-sized aerosols, the influence of humidity on the infectivity of SARS-CoV-2 is also unclear. Therefore, further studies with rigorously controlled variables regarding the influence of humidity on viral viability are required. In addition, further improvements can be made to models that show the joint effect of environmental factors, to improve the prediction of virus viability under varying conditions.

The seasonality of confirmed COVID-19 cases may be affected by the evaporation and dispersion characteristics of expiratory particles, as well as the survival ability of SARS-CoV-2, under different climate conditions. However, other factors such as human behavior and circannual variation (Morris et al., 2020) in immunity can also influence the seasonality of COVID-19.

6.4. Exposure risks of expiratory particles and infection risks of SARS-CoV-2

The cut-off distance for “short-range” and “long-range” transmission routes of expiratory particles depends on the maximum horizontal distance that the droplets can reach. This threshold distance is influenced by many factors, including the initial properties of expiratory particles and airflow, as well as ambient environmental conditions. The maximum horizontal distance can be up to 3–6 m at a velocity of 20–50 m/s (sneezing) (Xie et al., 2007). The long-range exposure risk of expiratory particles generally results from airborne transmission. Moreover, a recent study showed that airborne transmission also contributes the most to the short-range exposure risk of expiratory particles (Chen et al., 2020). This shows that airborne transmission route plays a critical role in both short-range and long-range transmission of expiratory particles.

Most infection risk assessment methods for airborne transmission of SARS-CoV-2 have been proposed and expanded based on the classic Wells-Riley model, in which the determination of the quanta emission rate (q) (quanta/h) value is significant. The q value is influenced by many factors, such as different respiratory activities and activity levels (Buonanno et al., 2020). Moreover, considering the different methods adopted and different scenarios considered in relevant studies, the q value varies considerably in different studies. So far, we can only obtain an upper limit q value of approximately 1000 under common speaking and singing scenarios using the back-calculated method. In the future, more studies concerning the determination of q values under different scenarios are needed. Moreover, further studies on the infection risk assessment methods for droplet and contact transmission are also required.
6.5. Determination of safe physical distance and consideration of safe contact time

Many influential factors, such as initial properties of expiratory droplets and flow, viral load, infectious dose, and environmental influence on expiratory particles and virus viability, make it difficult to determine safe physical distancing. It is inadequate to estimate a safe physical distance based only on the maximum reaching distance of expiratory droplets because strong evidence has shown the potential infectiousness of aerosols. Meanwhile, considering the short-range airborne transmission, a safe contact time is also significant (Yang et al., 2014). In the future, to obtain a more reasonable safe physical distance and contact time, the relationship between exposure risks and infection risks must be established, by determining the infection capability of expiratory particles carrying SARS-CoV-2. Therefore, further studies on dose-response models are needed.

6.6. Influence of masks on expiratory particles and flow, and associated wearing suggestions

All types of masks can reduce the front flow, but air leakage in other directions can occur when wearing surgical and handmade masks. If air leakage is considered, the aerosol filtration efficiency of surgical masks can be 44% when the wearer is at rest, or 10% when the wearer is in moderate activity (Konda et al., 2020). Greater physical distance is required for masks with larger fitting gap and lower filtering efficiency, and respirators are necessary in the presence of a known infection source. To prevent airflow leakage, the use of the elbow is recommended during violent respiratory activities. In the future, further quantitative studies on the expiratory flow field when wearing a mask are needed.

6.7. Air distribution methods and occupancy-aided ventilation

Ventilation, which usually refers to total volume air distribution, is the most used engineering control strategy against airborne transmission of respiratory virus. Ventilation rate is an important index to evaluate the effectiveness of contaminant removal through ventilation systems. However, the appropriate ventilation rate depends on the development of suitable infection risk assessment models. The efficacy of ventilation is also influenced by the airflow pattern, especially in large and complex spaces. Mixing ventilation (MV) and displacement ventilation (DV) are two traditional ventilation types creating different airflow patterns. Most advanced air distribution methods are based on the mechanism of DV for expansion, given the high effectiveness of DV in removing viral contaminants. In the future, with the development of CFD technology, designing airflow patterns will become more convenient.

Personalized ventilation (PV) and personalized exhaust (PE) are two air distribution methods targeting at the microenvironment around human body. Generally, PV is used by the susceptible, while PE is used by the infector to prevent cross-infection (Ai et al., 2019; Yang et al., 2015a). The combination of PV and PE for the susceptible individual can further enhance the penetration of PV airflow to the breathing zone (Yang et al., 2014). In the future, a more systematic investigation of PV and PE effectiveness in different conditions, as well as the study of their influence on controlling droplet transmission, is needed.

Occupancy-aided ventilation, which is a type of source control method, aims to reduce the airborne infection by managing the indoor occupancy (Melikov et al., 2020). The adopted occupancy schedule should balance short occupancy duration and work productivity. In the future, studies should address problems such as potential corridor blockage, simplified evaluation of work productivity, assumption of homogeneous virus distribution, and difficulty in obtaining infector number (Zhang et al., 2021).

6.8. Supplementary infection control strategies for total volume air distribution

When total volume air distribution methods cannot provide sufficient air change rate due to heating or cooling requirements, potential air purifying strategies such as air filtration and disinfection can be implemented for infection control.

Air filtration aims to remove expiratory particles from airstreams passing through the filter. The HEPA filters are most widely used among common air filters, with the particle filtration efficiency of up to 99.97% (Christopherson et al., 2020). Flow interaction between other momentum sources and HEPA-filter portable air cleaners (PACs) can significantly influence indoor air purifying efficacy (Zhang et al., 2010). In the future, further systematic studies on the influence of the layouts and operation parameters of PACs are needed. Moreover, the influence of expiration characteristics under different respiratory activities and different airflow patterns on the purifying efficacy need to be discussed.

Disinfection aims to directly inactivate virus circulating in the air, among which the chemical-free ultraviolet germicidal irradiation (UVGI) is now the most widely used. The UV-C dose should balance disinfection efficiency and the potential harm to human health or surfaces. The upper-room UVI system could present a safe option (Nord, 2016), which also shows a potential of combination with mixing ventilation. In the future, standardized protocols of appropriate UV-C dose, as well as the system design for SARS-CoV-2 disinfection, are needed.

7. Conclusion

In this study, the characteristics of expiratory particles and airflow, environmental influence on particle transmission and virus viability, infection risk assessment methods and common control strategies are critically reviewed. The primary conclusions of this review are as follows:

1) Expiratory particle and flow features of different respiratory activities obtained from experiments are summarized. Discrepancies still exist in some measurement results, and data on some respiratory activities are limited. Therefore, further research is required in terms of measuring methodologies.

2) Ambient environmental factors influence the transmission of expiratory particles by affecting their evaporation and dispersion. The RH significantly influences the evaporation of medium-sized (50–60 μm) droplets. A lower RH contributes to faster evaporation. However, there is limited research on the influence of ambient temperature and flow on expiratory particle evaporation. Higher temperatures accelerate the inactivation of SARS-CoV-2 both on surfaces and in aerosols. However, the influence of RH on virus viability requires further research.

3) Airborne transmission is found to be a significant route in both short- and long-range virus transmission. The Wells-Riley model and its expansions are widely used to predict the infection risks of airborne SARS-CoV-2 transmission. Further efforts to calculate a more accurate quanta emission rate (g), as well as to assess the suitability of applying the expanded Wells-Riley model in other transmission routes, are needed. For a safe physical distance, the maximum reaching distance of expiratory droplets can determine the lower limit, but the infection potential of aerosols should be considered in future studies.

4) Based on scientific analysis, suggestions for mask usage during the pandemic are offered. Further studies on expiratory particle and airflow features when wearing a mask are needed. As for engineering control strategies, traditional and advanced air distribution methods, from the total volume scale to microenvironment scale, are introduced and compared. Moreover, as promising complementary of
