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Infection risk of SARS-CoV-2 in a dining setting: Deposited droplets and aerosols

Shirun Ding, Jia Shing Lee, Mohamed Arif Mohamed, Bing Feng Ng*
School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

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ABSTRACT

Considering that safe-distancing and mask-wearing measures are not strictly enforced in dining settings in the context of SARS-CoV-2, the infection risks of patrons in a dining outlet (e.g., a cafe) is assessed in this study. The size-resolved aerosol emission rate (AER) and droplets deposition rate (DDR) on dining plates from speaking were obtained through chamber measurements and droplet deposition visualization via fluorescent imaging technique (FIT), respectively. The AER from speaking was 24698 #/min in the size range of 0.3–5.5 μm, while the DDR was 365 #/min in the size range of 43–2847 μm. Furthermore, an infection risk model was adopted and revised to evaluate the infection risk of 120 diners for a “3-h event” in the cafe. In a four-person dining setting around a rectangular table, a diner seated diagonally across an infected person posed the least infection risk due to the deposited droplets on dining plates. The deposited droplets on a dining plate were dominant in possible viral transmission as compared to the long-range airborne route when a diner shared a table with the infected person. Yet, long-range airborne transmission had the potential to infect other diners in the cafe, even resulting in super-spreading events. A fresh air supply of 12.1–17.0 L/s per person is recommended for the cafe to serve 4–20 diners concurrently to minimize infection risks due to aerosols. Current ventilation standards (e.g., 8–10 L/s per person) for a cafe are not enough to avoid the airborne transmission of SARS-CoV-2.

1. Introduction

Virus transmission via large droplets or aerosols (also known as droplet nuclei) has come under intense spotlight under the backdrop of continued resurgence of coronavirus disease 2019 (COVID-19) [1,2]. This is supported by the fact that the ribonucleic acid (RNA) of Severe Acute Respiratory Syndrome CoronaVirus 2 (SARS-CoV-2) was detected in the aerosol samples of medical staff areas and isolation rooms via polymerase chain reaction testing [3–5]. Moreover, high viral loads of SARS-CoV-2 have been detected in oral fluids of asymptomatic and symptomatic COVID-19 patients [6,7]. However, research is still needed to determine the relative contribution of large droplets or small aerosols to SARS-CoV-2 transmission in different indoor environments [8].

Social distancing, normally 1 m apart between individuals, has been recommended to prevent viral transmission via large droplets [9]. This was proposed after the initial investigations of [9,10], but the studies did not take into consideration the fact that a large proportion (of the order of 10%) of small aerosols were more likely to be responsible for the recent super-spreading events of SARS-CoV-2 [11,12]. Considering that safe-distancing and mask-wearing measures are not strictly enforced during social interactions in dining settings in the context of COVID-19, two or several persons are still allowed to talk to each other without wearing masks in between eating or drinking activities. Thus, it is critical to evaluate the infection risk of susceptible persons due to large droplets that could deposit on dining plates (i.e., a fomite) or mucosal surfaces (i.e., droplet spray transmission), or aerosols that could be inhaled by susceptible persons (i.e., airborne transmission) in speaking scenarios between eating or drinking. In a recent study, Buonanno et al. evaluated the infection risk of SARS-CoV-2 via airborne transmission for a restaurant using a proposed model [13], but the relative contribution of large droplets on dining plates or aerosols was not considered.

Human speaking contains a wide range of droplets (0.01–100 μm), and majority of them have sizes less than 5 μm [14–16]. The size boundary between large droplets and aerosols remains debatable [17–19]. Recently, the value of “100 μm” (before dehydration) was recommended to distinguish droplets from aerosols [1,8,20] based on the fact that the initial diameter of a droplet must be larger than about 10μm to have a high possibility of landing within 1 m in a typical...
indoor environment (0–0.2 m/s of air current) [20]. Early studies measured the size distribution of speech droplets using the droplet deposition method (e.g., glass slides) with subsequent imaging analysis [5,10], which is not sensitive to submicron aerosols. While recent sampling-based optical particle sizers are more sensitive for submicron aerosols [15,21,22], the measurement limit of this technique is generally less than 20 μm.

This work aims to measure the size-resolved droplets and aerosols from human speaking loudly, and then evaluate the infection risk of diners in a typical dining cafe based on the measurements and an infection risk model. First, the size-resolved aerosol emission rate (AER) and droplets deposition rate (DDR) from speaking were obtained through chamber measurements and droplet deposition visualization via fluorescent imaging technique (FIT), respectively. In the former, AER from speaking was obtained by an optical particle sizer (OPS, 0.3–10 μm) using a small chamber system, based on the methodology recently proposed by the authors [22]. In the latter, the deposition characteristics of large droplets on dining plates on a table, emitted from speaking, were measured via FIT with vitamin B2 as the tracer (vitamin B-2100 mg, GNC). FIT measures large droplets with an initial diameter larger than 50–100 μm (i.e., about >10–20 μm after dehydration). Vitamin B2 was found to be a feasible fluorescent tracer to measure deposited droplets in a recent study, but the droplets were generated by a nebulizer [23]. The fluorescent with the peak of about 525 nm in wavelength (visibly seen as green) is excited under 370 nm of UV light. Unlike fluorescein which has limited use in FIT due to its toxicity, vitamin B2 has been approved to be safe for consumption [24].

On the typical 4-seater rectangle dining table where the experiment was conducted, black circular plates (100% melamine) were used to provide obvious contrast between the black background and the fluorescent color from vitamin B2. The plates were positioned uniformly on the table in such a way that not only covered as much surface area as possible but also representative of where dining plates would normally be placed on a table (3 rows, A–E columns), as shown in Fig. 1A. From the speaker’s perspective, plate B1 in the bottom row corresponds to his plate. Similarly, plates B3, D3, and D1 designated the locations of listeners sitting directly opposite, diagonally opposite, and to the side of

2. Materials and methods

2.1. Experimental setup and procedure

2.1.1. Droplet deposition measurements on dining plates

As shown in Fig. 1A, the DDR (#/min) on dining plates from speaking was measured in two steps (i.e., Step 1–speaking activity and Step 2–visualization) via FIT, with vitamin B2 as the tracer (vitamin B-2100 mg, GNC). FIT measures large droplets with an initial diameter larger than 50–100 μm (i.e., about >10–20 μm after dehydration). Vitamin B2 was found to be a feasible fluorescent tracer to measure deposited droplets in a recent study, but the droplets were generated by a nebulizer [23]. The fluorescent with the peak of about 525 nm in wavelength (visibly seen as green) is excited under 370 nm of UV light. Unlike fluorescein which has limited use in FIT due to its toxicity, vitamin B2 has been approved to be safe for consumption [24].

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Fig. 1. Schematic of the experimental setup. (A) The top view of setup for measuring speech droplet deposition rates on plates of a dining table (1–3 rows, A–E columns) via fluorescent imaging technique. Three different cases were tested, as demonstrated in Step 1. The actual photos of the three different cases are shown in Fig. A1 of Appendix. The side view of the imaging setup for visualizing the droplets on a plate (Step 2). (B) The top view of a cubic stainless-steel chamber for measuring the size-resolved aerosol emission rate for the same speaking activity [22].
the speaker, respectively.

Three different cases were considered, namely Case 1—speaking straight, Case 2—speaking diagonally, and Case 3—speaking sideways. Case 1 is demonstrated in Fig. 1A where the speaker speaks directly to a listener sitting opposite the speaker. For case 2, the speaker would face plate D3 and the listener would sit diagonally opposite the speaker, as shown in Fig. A1(b) of Appendix. For case 3, the speaker would face plate D1 and the listener would sit to the side of the speaker. The speaker was a male subject in his 20s, while the listener was portrayed by a white half-toro mannequin due to biological hazard safety concerns. Under the Covid-19 restrictions imposed by the University, lab access was restricted to only research users. To avoid the possible transmission of Covid-19, only the subject who is one of the authors of this work, was tested for the 3 cases with repeats of 3 times. The subject had no history of respiratory disease or symptoms.

For the experimental procedure, before the speaking activity, the temperature and humidity of the room (53.9 m²) were set at typical values of indoor air-conditioned rooms in Singapore (23 ± 1 °C; 65 ± 5% RH). Moreover, air velocity was kept at a minimum to mimic a quiescent room during speaking with the air-conditioner turned off. All cleaned plates were affixed in place on the table and left untouched for 30 min to allow for dust and foreign particulate matter to settle on the plates. Images of each plate’s background were then captured by the visualization setup to provide a baseline. Before the speaking activity, 75 mL of high concentration of vitamin B2 solution (0.32 mg/mL) was swallowed by the speaker. This was followed by chewing 50 mg of vitamin B2 tablet for at least 20 s till the tablet was completely dissolved in the mouth. At this point, the subject’s saliva was thoroughly saturated with vitamin B2. After which, the phrase “stay healthy” was repeatedly spoken for 3 min in a loud voice (maximum 83 dB at the distance of 40 cm; average 77 dB) with 2–4 s of pause in between the phrases.

Throughout the speaking phase, the subject was free to swallow his saliva just like how one would normally do so while speaking. The phrase “stay healthy” was chosen because it was an efficient phrase to produce a large number of droplets and aerosols [25]. Immediately after the speaking activity, the plates were transferred in sequence to the visualization setup, and the stain marks deposited on the plates were visualized by a phone camera (Vivo V1930) accompanied with a separate UV light source (Omnichrome Spectrum 9000) in the darkroom. It is worth noting that the camera was pre-focused on a clean plate, and thus the pre-calibrated visualization setup can provide clear images under consistent conditions. Moreover, the orientation of each plate on the table was kept consistent throughout the procedure. The phone camera was used since it can easily focus on and capture the stain marks than a digital single-lens reflex camera. A yellow filter lens was attached to the camera, which provided better contrast performance than a green filter.

Finally, a MATLAB code was used to obtain the diameter and number of droplets whose maximum single-pixel (37.4 × 37.4 μm) intensity surpassed a threshold value of 53. Through several rounds of trial and error, it was observed that a threshold value of 53 in intensity can provide adequate relevant information without having corruption from background noise. Note that droplets with a geometric diameter less than 43 μm and information less than 53 of single-pixel intensity are hence not captured. The distribution of droplets on the whole table was reconstructed by combining the images of the 15 plates.

2.1.2. Chamber measurement for aerosol emission rate

It is challenging to measure the initial aerosol size distribution (ASD) at the mouth opening [26] or to capture the dynamic change in ASD from mouth to indoor air due to evaporation [27] as well as the interaction between exhaled turbulent gas cloud and air [28]. While it is important to understand the fundamental formation process of aerosols from mouth to air, it is not the focus of the current study. The authors believe that it would be more representative to measure the final size of aerosols after dehydration suspended in the chamber air from the perspective of long-range airborne transmission, rather than capturing a transient status of aerosols in the dynamic evaporating process. Therefore, in this work, the aerosols with an initial diameter less than 50 μm (i.e., about <10 μm after dehydration) suspended in the air were measured using a 0.5 m³ clean stainless steel chamber system for the same “speaking activity” (i.e., about ten “stay healthy” per minute), as shown in Fig. 1B.

In brief, a speaker spoke into the clean chamber (23 ± 1 °C, 50 ± 5% RH) for 3 min after the particle concentration (>10 nm) in the chamber is near 0 #/cm³. The size-resolved number concentration of aerosols in the chamber was sampled by an optical particle size meter (OPS, size range: 0.3–10 μm, TSI 3330) in real-time for the entire protocol. The aerosol concentration in the test chamber after 3-min speaking is about 0.15 #/cm³, which is higher than the measurement resolution of OPS (resolution: 0.06 #/cm³, 0.3–10 μm). In addition, 100-s moving average for the original data of OPS can further expand the measurable concentration limit down to 0.005 #/cm³ [22]. The chamber system, its air supply system, the experimental procedure, and data analysis have been introduced in detail in our recent study [22]. It is worth noting that the total concentration of aerosols (0.3–10 μm) from the 3-min speaking was about 0.15 #/cm³ in the chamber [22], and thus, the estimated concentration in the 53.9 m³ of room would be less than 0.001 #/cm³, which is less than the measurement resolution of the OPS. Therefore, the droplets deposited on plates and aerosols suspended in the air were measured separately.

2.2. Infection risk model

The infection risk of inhaling airborne particles in the room air or eating deposited droplets on dining plates was evaluated separately. The DDR (εDR) on a plate and AER (εAER) from speaking were used to calculate the corresponding QDR on a plate and QER of aerosols, respectively. However, considering the actual speaking behavior of individuals during dining, it is unlikely for a person to continuously speak with “high-emission-phones” loudly. The emission rate from the speaking activity was categorized as high emission rate (i.e., speaking ten “stay healthy” per minute). To avoid the overestimation of the QER and QDR, a low emission rate was also used to estimate the QER and QDR, assuming the speaker would speak one “high-emission-phone” per minute on average (i.e., speaking one “stay healthy” minute). The oral cavity represents the main entrance of SARS-CoV-2 infection [29], but the relationship between infectious dose factors and human inoculation sites (e.g., trachea and esophagus) is still unclear in the literature. A recent study found that although monkeys were infected via airborne SARS-CoV-2 with 100 times lower doses as compared to mucosa inoculation, they developed more severe respiratory disease [30]. Therefore, another recent study recommended that the infectious dose factor of large droplets should be smaller than that of aerosols by 100 times for SARS-CoV-2 [31], which has been adopted in this work.

The transmission by aerosols in close proximity (<1.5 m), direct physical contact with an infected person, indirect contact via other intermediate surfaces or objects (e.g., door knobs and towels), and the resuspension of deposited viruses were not considered in this study [31, 32]. It is also worth noting that Buonanno et al. have revised their original infection risk model by adopting the probability density functions of QER in more recent studies [33,34], but the original deterministic model proposed by them was used in this study [13]. It is reasonable to adopt the probability density functions of QER to predict the individual infection risk and the basic reproduction number from the perspective of a city or a country to control the pandemic [33]. The results predicted by the probabilistic model are useful for policymakers or authorities to manage different industries (e.g., the catering industry). On the other hand, the authors would like to point out that the risk assessment by a deterministic approach is also useful and straightforward for the managers of a specific restaurant and customers. For them, the possibility of infection in the worst scenarios should be made known even though the possibility is extremely low (e.g., for εDR > 10⁸ copies
2.2.1. Quanta emission rate of aerosols

The concentration of an infectious agent in the spumon is representa-
tive of the concentration in the droplets emitted during the expiratory
activities [13], considering most of the droplets originate at the front of
the mouth and to a lesser extent from the larynx [35, 36]. A quantum is
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the mouth and to a lesser extent from the larynx [35, 36]. A quantum is

The concentration of a quantum in the airborne route (e.g., SARS, SARS-CoV-2,
and influenza) [13, 33, 34, 42]. In addition, this work aims to provide a
general infection risk assessment for a dining event (e.g., 120 diners in
a small cafe-like setting (6.0 m × 6.0 m × 2.7 m³) with mixed-mode ventila-
tion, having four different air changes per hour (ACH: 1, 2, 4, or 9 h⁻¹).
A total of 20 diners were assumed to be served at any one time by a
waiter and a chef using 5 tables in the cafe. Given the size of aerosols
(<5.5 μm) allows for the effective mixing via the mechanical ventilation
or air currents in the room [40, 41], it was assumed that the quanta
concentration is homogenous in the cafe. Such an assumption may lead
to a simplification of the dispersion of viruses in a room. This assump-
tion is widely adopted in previous models to evaluate the infection
risk is other rooms [48, 49], and thus, the sum of the last three terms in Eq. (3)
is jumped into kVC(t), we arrive at Eq. (4). The quanta decay rate co-
efficient, k, is the sum of the ACH (kₐ = Q/V, min⁻¹), kᵢ (min⁻¹), and kₜ (min⁻¹) [13], as shown in Eq. (5).

C(t) can be obtained by solving the Eq. (4) assuming the QER is
constant, shown here in Eq. (6).

In (6), C(0) is the initial quanta concentration in the room at t = 0.
The derivation is provided in Appendix A.

2.2.2. Infection risk due to aerosols in a cafe-like setting

The QER (Cₚ) was used to predict quanta concentration (C(t)) in a
small cafe-like setting (6.0 m × 6.0 m × 2.7 m³) with mixed-mode ventila-
tion, having four different air changes per hour (ACH: 1, 2, 4, or 9 h⁻¹).
A total of 20 diners was assumed to be served at any one time by a
waiter and a chef using 5 tables in the cafe. Given the size of aerosols
(<5.5 μm) allows for the effective mixing via the mechanical ventilation
or air currents in the room [40, 41], it was assumed that the quanta
concentration is homogenous in the cafe. This assumption may lead

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C(t) can be obtained by solving the Eq. (4) assuming the QER is
constant, shown here in Eq. (6).

In (6), C(0) is the initial quanta concentration in the room at t = 0.
The derivation is provided in Appendix A.

2.2.3. Infection risk of deposited droplets in the cafe

The average DDR (eₐ₀, #/min) on a plate can be estimated by aver-
aging the DDR of the three cases (e₁D₀, e₂D₀, and e₃D₀), assuming
the speaker talked to the other three diners for the same duration (i.e., 20 s)
each minute.

where D₀ is the diameter of the minimum droplet and Dₚ is the diameter
of the maximum droplet deposited; A range of cₚ (0.0001–0.001) was
adopted for deposited droplets, which is smaller than that of aerosols by
100 times. cₚ is the ratio between the original droplet diameter and
wetted diameter of droplets deposited on the surface, raised to the third.
The ratio was estimated to be about 0.62 based on the 35.3° of contact
angle of the saliva droplet on the plate; cₚ ranged from 1³ to 5³ since
large droplets may be partially dehydrated.

To simplify our risk evaluation, it was assumed that a person only
consumed the food on his plate on that specific (e.g., plate B3 by the diner
talking directly opposite the speaker). The dining activity took 30 min (T = 30
min) for all persons, and the food with the deposited droplets was
consumed uniformly during the whole period. The infection risk of a
susceptible person by consuming the deposited droplets on his dining
plate can be evaluated by Eq. (9):

where n is the estimated number of people infected in the room; nₛ is the
number of susceptible people exposed for a period T (minute) in the
room; C(t), with t representing time, is the time-resolved quanta con-
centration in the room (quanta cm⁻³); q is the inhalation rate of a
normal person (generally 9000 cm³/min for a person standing still [13]).

C(t) in the Wells-Riley equation can be calculated using the dynamic
particle-number-balance model (assuming well-mixed conditions in the
room) [46]. This is given as:

where V is the volume of the room considered (cm³); Cₚ(t) is the quanta
concentration flowing into the room from another room via central air
conditioning and ventilation system. Q is the volume flow rate of air, in
and out of the room (cm³/min) via mechanical ventilation. kₗ is the total
quanta loss coefficient, including the effects of gravitational deposition,
wall losses, etc. The half-life of airborne aerosols from speaking in
stagnant air (23 ± 1 °C, 50 ± 5% relative humidity) was measured to be
87 min [22], thus kₗ is calculated as 0.47 h⁻¹ (0.0078 min⁻¹). k₁ is the viral
inactivation and 0.63 h⁻¹ (0.0105 min⁻¹) was used based on the
airborne SARA-CoV-2 half-life (1.1 h) [47].

Cₚ is negligible without considering the transport of virus from
another room [48,49], and thus, the sum of the last three terms in Eq. (3)
is jumped into kVC(t), we arrive at Eq. (4). The quanta decay rate co-
efficient, k, is the sum of the ACH (kₐ = Q/V, min⁻¹), kᵢ (min⁻¹), and kₜ (min⁻¹) [13], as shown in Eq. (5).

C(t) can be obtained by solving the Eq. (4) assuming the QER is
constant, shown here in Eq. (6).

In (6), C(0) is the initial quanta concentration in the room at t = 0.
The derivation is provided in Appendix A.
3. Results and discussion

3.1. Deposition characteristics of speech droplets on dining plates

The characteristics of droplets and aerosols will be shown and discussed in this section, followed by an evaluation of the infection risk of SARS-CoV-2. The speech droplets were observed to follow a conical deposition pattern (~90°), the majority of which landed along the direction of the speaking, with a small fraction landing to the sides, as shown in Fig. 2. The large droplets from speaking were able to travel and deposit within and over 1 m in this dining setting. All repeated tests of the three cases showed similar results (Fig. A2 of Appendix). The average count for the total number of deposited droplets was 1095 from the 3-min speaking activity (i.e., 365 min⁻¹). Another study also reported a similar emission rate of large droplets (90–800 μm) from speaking (354 min⁻¹) [31]. Separately, the face of the mannequin, used in this study to represent a listener, was inspected using UV light to find traces of fluorescent droplets after the speaking activity. Qualitatively, more droplets were deposited on the listener’s face (including lips) for Case 3 (speaking sideways) because of the shortest distance between the speaker and listener, as demonstrated in Fig. A5. It has been reported through numerical simulations that the contribution of large droplets to infection risk is appreciable only for distances well below 0.6 m [31].

The size distribution of droplets deposited on the plates for the Case 1 (speaking straight) is shown in Fig. 3. It was found that the median and mean of the 936 droplets (43–2155 μm) were 381 and 421 μm, respectively. Similar results were observed for the repeated tests of the three cases (Fig. A2 of Appendix). Moreover, the ratio of the large to small droplets was denoted at the bottom-right corner of each square; a value larger than 1 indicates that a larger ratio of “large droplets” was present in that region. It was found that “large droplets” dominated areas that are furthest away from the speaker, especially in row 5 or column E where the ratio of large-to-small droplets generally exceeded 1 (see Fig. 2). This suggests that the “large droplets” played a more important role in the long-range deposition as compared to the “small droplets”. One of the possible reasons is that the initial velocity of the “large droplets”, once ejected from the mouth, was larger than that of the exhaled turbulent gas cloud, which was filled with “small droplets”. Surprisingly, a larger ratio of “small droplets” is deposited at regions near the speaker (e.g., plate B1 for Case 1). One of the possible reasons is that the initial velocity of the “small droplets” should be lower than that of “large droplets” based on their formation mechanisms, the stretching and break-up of saliva filaments, or large droplets [50]. Another possible reason is that the “small droplets” tended to lose their forward momentum rather quickly once ejected from the mouth due to the impact of exhaled turbulent gas cloud with indoor air [28].

3.2. Quanta deposition rate on a plate

QDR on a plate was estimated based on the DDR for the “high emission rate” and “low emission rate” of speaking, as shown in Fig. 4A. Comparing the three cases, the QDR on the plate D3 in Case 2 (QDR = 0.13) was significantly less than that of plate B3 in Case 1 (QDR = 0.91) and the plate D1 in Case 3 (QDR = 1.82) for the “high emission rate”. Therefore, it can be deduced that the infection risk of a diner sitting diagonally opposite the infected speaker was the lowest. This is followed by the cases where the diner is sitting directly opposite and next to the speaker in a two-persons dining scenario using a rectangular table. Based on the QDR in Fig. 4A, the lowest infection risk of a diner, when dining with a virus carrier for 30 min, was about 33% (total quanta = 0.4, see Fig. A4 in Appendix) in Case 2 for the “low emission rate” in two-
diagonally) and Case 3 (speaking sideways) cases with repeated tests are shown in the Fig. A2 of Appendix.

To evaluate the four-persons dining scenario with the rectangular table, the average QDR of the three cases (i.e., $c_q$) under different viral loads of the speaker from $10^3$ to $10^8$ copies per mL was calculated based on the average QDR (Fig. 4 B). The infection risk of all three diners were near 100% when the viral load was higher than or equal to $10^8$ copies mL$^{-1}$ under all combinations of the infectious dose factors and DDRs. This is because the total quanta deposited on any plate (B3, D1, or D3) for 30 min was larger than 6 (i.e., 99.75% of infection risk) when the viral load was higher than or equal to $10^8$ copies mL$^{-1}$. Correspondingly, the reproduction number of the “3-h event” was about 3 when the viral load was higher than or equal to $10^8$ copies mL$^{-1}$, as shown in Fig. 5B.

The average viral load of SARS-CoV-2 reported or adopted varied from $10^3$ to $10^7$ copies per mL$^{-1}$ for B1.1.7 variant [52], $10^5$ to $10^7$ copies per mL$^{-1}$ [34], to $10^7$ copies per mL$^{-1}$ [33]. For the Omicron variant, viral loads were primarily reported to range from $1.41 \times 10^4$ to $1.65 \times 10^8$ (mean $4.16 \times 10^7$) copies per mL of swab eluate, with the highest averages (mean $6.69 \times 10^7$) on day 4 after symptom onset [53]. In this work, the viral loads in the sputum of COVID-19 patients loads of the infected speaker is demonstrated in Fig. 4B. It was found that the average QDR on plate D3 was also lowest among the three plates, suggesting the infection risk of the listener sitting diagonally opposite the speaker was also lowest in the four-persons dining scenario. Interestingly, there was a negligible difference in the average QDR between sitting straight and sitting sideways for a diner in the four-persons dining scenario. Note that the evaporation of droplets deposited was not considered for large droplets and the QDR would increase by 1–125 times if the losses from the evaporation of the droplets were considered in Fig. 4 [25].

### 3.3. Infection risk of diners in a cafe due to deposited droplets

For the deposited droplets, the infection risk, shown in Fig. 5A, of the three diners sharing a table with the infected speaker in the cafe for 30 min, was calculated based on the average QDR (Fig. 4B). The infection risks of all three diners were near 100% when the viral load was higher than or equal to $10^8$ copies mL$^{-1}$ under all combinations of the infectious dose factors and DDRs. This is because the total quanta deposited on any plate (B3, D1, or D3) for 30 min was larger than 6 (i.e., 99.75% of infection risk) when the viral load was higher than or equal to $10^8$ copies mL$^{-1}$. Correspondingly, the reproduction number of the “3-h event” was about 3 when the viral load was higher than or equal to $10^8$ copies mL$^{-1}$, as shown in Fig. 5B.

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were regarded to mainly range from $10^4$ to $10^8$ copies mL$^{-1}$, with an average viral load of $7 \times 10^6$ copies per mL$^{-1}$ adopted [51]. As shown in Fig. 5A, the infection risks were considerable for the range of $10^4$ to $10^8$ copies mL$^{-1}$, increasing from near 0–100% under different combinations of infectious dose factors and DDRs.

### 3.4. Quanta emission rate of aerosols

The size-resolved AER obtained in the chamber measurement is shown in Table 1. The number of aerosols generally increased with the decrease of the particle diameter. The AER in the size range of 0.3–5.5 μm (24698 min$^{-1}$) was much larger than the DDR (365 min$^{-1}$) by 68 times for the same “speaking activity”. In another study, the emission rate was reported to be ~19800 min$^{-1}$ in the size range of 0.3–20 μm for the “aah” vocalization [27]. Also, the ratio of AER (14916 min$^{-1}$) to droplet emission rate (354 min$^{-1}$) was calculated to be 42 times based on the results in another study [31].

Size-resolved QER was estimated based on the three factors including the AERs, the viral loads, and the infectious dose factors ($c_q$), as demonstrated in Fig. 6. For clarity, the color scale of the QER was set as 0–1 in Fig. 6. Indication of danger by yellow or red color and a super-spreader were shown in the red zone where QER was equal to or greater than 1. Even though a wide range of viral loads ($10^5$–$10^8$ RNA copies mL$^{-1}$) were considered [37,38], the viral loads in the sputum of COVID-19 patients mainly ranged from $10^4$ to $10^8$ copies mL$^{-1}$ [51], as indicated between two white dash lines in Fig. 6. It was found that the QER was generally larger for the larger aerosols, even though the number of smaller aerosols (e.g., 12982 for 0.4 μm of aerosols) was much more than that of larger aerosols (e.g., 73 for 5.5 μm of aerosols). The largest QER was observed when $c_q = 0.1$ for a high emission rate case (refer to the red zone between the two white dash lines in Fig. 6A). In the case where $c_q = 0.01$ and emission rate is low, the blue zone in Fig. 6B significantly increased, especially in the typical viral load range of $10^4$–$10^8$ copies mL$^{-1}$.

### 3.5. Infection risk of diners in a café due to aerosols

The estimated quanta concentration of aerosols in the cafe and the corresponding infection risk of a diner as a function of time are shown in Fig. 8. No person was infected via the airborne route in most of the exposure scenarios, as shown by the blue safe zone (i.e., $R_{00} < 1$) in Fig. 8. The most dangerous situation is shown in Fig. 8A for the combination of the $c_q = 0.1$ and the “high emission rate”. The reproduction number could be larger than 1, even resulting in the super-spreading event ($R_{00} > 10$) between the two white dash lines, as shown in Fig. 8A. In contrast, the reproduction number was less than 1 between the two white dash lines for the combination of $c_q = 0.01$ and the “low emission rate”, as shown in Fig. 8B.

Also, the reproduction number decreased with the increase in ventilation. For example, the reproduction numbers significantly decreased from 7.0 (ACH: 1 h$^{-1}$) to 1.5 (ACH: 9 h$^{-1}$) at the viral load of $10^7$ copies mL$^{-1}$ in Fig. 8A. Moreover, the viral load also had a tremendous effect on the reproduction number. For instance, the reproduction number was higher than 10 (i.e., super-spreading event) if the infected person was a super-spreader with a viral load of $10^{30}$ copies mL$^{-1}$, even under sufficient fresh air supply (i.e., 8–10 L/s per person) based on the most standards [55,56]. Although the sufficient fresh air supply can effectively avoid the airborne transmission of SARS-CoV-2 in most of the scenarios, it is not enough to cope with a super-spreader who tends to speak with a high viral load ($>10^9$ copies mL$^{-1}$) and large infectious dose factor ($c_q = 0.1$). For instance, for the “high emission rate”, the ACH for the cafe should be higher than 150 h$^{-1}$ to avoid new infection at the high viral load of $10^8$ copies mL$^{-1}$.

For the three diners who shared the same table with the virus carrier, the infection risk due to aerosols was less than 2% under the viral load of $10^8$ copies per mL$^{-1}$, and the corresponding reproduction number was less than 1 under different combinations of infectious dose factors and AERs (see Figs. 7 and 8). However, the infection risk of the diner due to the deposited large droplets on a dining plate (6%–100%) was significantly higher than that due to aerosols under the same conditions (see Fig. 5A). This is because the total quanta inhaled by a diner in the cafe during 30 min of the period were much lower than that deposited on a plate. In summary, the deposited droplets on a dining plate, as compared to the long-range airborne transmission, were dominant in the possible viral transmission from the infected speaker to the other 3 diners who shared the same table with the speaker. Even so, it was the aerosols that had the potential to lead to a super-spreading event in the cafe. For the short-range airborne transmission, in another study, the infection risk was estimated to be less than 10% for a 0.8-m distance between the susceptible person and a SARS-CoV-2 virus carrier, with an exposure time of 15 min [31].

### 3.6. Recommendations

To avoid the possible viral transmission from speech due to the large droplets deposited on the dining plates, sitting diagonally opposite an infected person was recommended in the two-persons or four-persons dining scenario with a rectangular table. Even so, the estimated infection risk due to the deposited droplets when dining with a virus carrier for 30 min was extremely high regardless of sitting arrangement, as shown in Fig. 5A. Recommendations, based on aerosols, can be decided upon by looking at viral loads, emission rates, and the infectious dose factor. Fig. 9 shows the recommendations, for aerosols, based on the relatively higher infectious dose factor ($c_q = 0.1$), large viral load ($c_v = 10^8$ copies mL$^{-1}$), and the “low emission rate”. The reproduction number of the “3-h event” in the cafe is demonstrated in Fig. 9A when concurrently serving a different number of diners. The minimum ACH of 2.7 h$^{-1}$ (the corresponding minimum fresh air supply: 12.1 L/s per person), 5.5 h$^{-1}$ (14.8), 8.3 h$^{-1}$ (16.0), 11.1 h$^{-1}$ (16.6), and 13.9 h$^{-1}$ (17.0) were sufficient to make the $R_{00}$ less than 1 for serving 4, 8, 12, 16, and 20 diners concurrently, respectively. The recommended range of

| Table 1 | Measured size-resolved aerosol emission rate ($R_{00}$, #/min) of the “speaking activity” in the chamber measurement [22], as shown in 12 size bins. |
|---------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Particle diameter (μm) | $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ | $D_6$ |
| (μm)       | (0.4) | (0.6) | (0.83) | (1.25) | (1.75) | (2.25) |
| $D_7$ | 12982 | 4533 | 2924 | 929 | 1608 | 835 |
| (#/min)   | --- | --- | --- | --- | --- | --- |
| Particle diameter (μm) | $D_7$ | $D_8$ | $D_{10}$ | $D_{11}$ | $D_{12}$ |
| (μm)       | (2.75) | (3.5) | (4.5) | (5.5) | (---) |
| $D_8$ | 428 | 292 | 94 | 73 | 73 | 10 |
| (#/min)   | --- | --- | --- | --- | --- | --- |
fresh air supply (12.1–17.0 L/s per person) for this cafe is higher than the values required (8–10 L/s per person) by most standards [55,56] for restaurants and recommendations (10 L/s per person) of World Health Organization (WHO) [57]. Furthermore, the maximum number of diners allowed concurrently for different sizes of cafes (50–190 m³) with a specific ACH was recommended in Fig. 9B. For example, the upper limit is 14 diners concurrently in a 150 m³ cafe with an ACH of 5.9 h⁻¹, as illustrated in Fig. 9B. Also, for the “high emission rate”, the ventilation rate must be extremely high (150 h⁻¹) for the cafe to avoid new infection as discussed in Fig. 8A, and thus the administrative measures (e.g., no loud and frequent speaking) would be more effective than the existing mechanical ventilation systems.

4. Conclusions

The present study provided a methodology to measure the size-resolved AER and DDR from speaking activities in a dining setting through chamber measurements and droplet deposition visualization via the FIT, respectively. Vitamin B2 that is used in FIT for visualizing the presence of deposited speech droplets proved to be feasible. For aerosols, a chamber test system was provided to measure the final size of aerosols after dehydration, rather than capturing a transient status of aerosols in the dynamic evaporating process. The emission rate of aerosols (0.3–5.5 μm) was larger than that of deposited droplets (~43–2847 μm) by 68 times. These measurements are important for researchers to evaluate the infection risk of SARS-CoV-2 in indoor environments.

Furthermore, an infection risk model was adopted and revised to evaluate the infection risk of 120 diners for a “3-h event” in a cafe. It was found that in a four-persons dining setting with a rectangular table, sitting diagonally opposite an infected person posed the least infection risk.
risk due to deposited droplets on dining plates, followed by sitting directly opposite and then to the side. The deposited droplets on dining plates were dominant in the possible viral transmission when a diner shared a table with the infected person as compared to the long-range airborne route, while the airborne transmission via aerosols had the potential to infect other diners in the cafe, even resulting in a super-spreading event. The infection risk of diners by aerosols in close proximity (also known as short-range airborne transmission) should be considered in the future research. The fresh air supply of 12.1–17.0 L/s per person was recommended for the operation of the cafe for serving 4–20 diners concurrently to avoid new infection due to the long-range airborne transmission of SARS-CoV-2. This suggests that current ventilation standards (e.g., 8–10 L/s per person) for restaurants are not enough to avoid the airborne transmission of SARS-CoV-2. The findings are useful for researchers and engineers to design new ventilation systems in the future, and for the managers, standards makers, and policymakers to consider stricter mitigation measures (e.g., higher ventilation level, the number of customers, and the volume of the room) for catering industry including restaurants, bars, cafes, and teahouses.

Data availability statement

The data are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Shirun Ding: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. Jia Shing Lee: Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. Mohamed Arif Mohamed: Investigation, Writing – review & editing. Bing Feng Ng: Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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