Association between the infection probability of COVID-19 and ventilation rates: An update for SARS-CoV-2 variants

Hui Dai[1], Bin Zhao[1,2] (✉)

1. Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China
2. Beijing Key Laboratory of Indoor Air Quality Evaluation and Control, Tsinghua University, Beijing 100084, China

Cover Article

Abstract

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the cause of the current coronavirus disease 2019 (COVID-19) pandemic, is evolving. Thus, the risk of airborne transmission in confined spaces may be higher, and corresponding precautions should be re-appraised. Here, we obtained the quantum generation rate (q) value of three SARS-CoV-2 variants (Alpha, Delta, and Omicron) for the Wells-Riley equation with a reproductive number-based fitted approach and estimated the association between the infection probability and ventilation rates. The q value was 89–165 h^{-1} for Alpha variant, 312–935 h^{-1} for Delta variant, and 725–2,345 h^{-1} for Omicron variant. The ventilation rates increased to ensure an infection probability of less than 1%, and were 8,000–14,000 $m^3\ h^{-1}$, 26,000–80,000 $m^3\ h^{-1}$, and 64,000–250,000 $m^3\ h^{-1}$ per infector for the Alpha, Delta, and Omicron variants, respectively. If the infector and susceptible person wore N95 masks, the required ventilation rates decreased to about 1/100 of the values required without masks, which can be achieved in most typical scenarios. An air purifier was ineffective for reducing transmission when used in scenarios without masks. Preventing prolonged exposure time in confined spaces remains critical in reducing the risk of airborne transmission for highly contagious SARS-CoV-2 variants.

1   Introduction

Since the start of global coronavirus disease 2019 (COVID-19) pandemic at the end of 2019, the risk of the airborne transmission of disease from patients' exhaled aerosols could not be ignored, especially in confined spaces (Morawska and Buonanno 2021; WHO 2021). Basic precautions were effective measures to reduce the risk, such as wearing masks, running air purifiers, and increasing the indoor ventilation rate, and people in different regions followed these measures as recommended by local authorities (Liu and Zhao 2021; Zhao et al. 2021; WHO 2022a). Considering that severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the cause of the current COVID-19 pandemic, is constantly evolving, whether the original measures still ensure a low risk of airborne transmission deserves further discussion (WHO 2022b).

The WHO named and classified SARS-CoV-2 variants based on the latest information on contagiousness, disease severity, risk of reinfection, etc. (WHO 2022d). These variants are categorized as variants of concern (VOCs), variants of interest (VOIs), and variants under monitoring (VUM). The VOC classification is based on high virus circulation, and people are most concerned about the dominant VOCs, i.e., the currently circulating VOCs. The Alpha (B.1.1.7) variant emerged in the UK and was the first announced VOC to show higher transmissibility than the ancestral strain (Burki 2021). Subsequently, the Delta (B.1.617.2) variant emerged in India and wreaked havoc around the globe (Liu and Rocklöv 2021; Volz et al. 2021; WHO 2022c). The latest global epidemiology of SARS-CoV-2 is characterized by the global dominance of the Omicron (B.1.1.529) variant that is replacing all other SARS-CoV-2 variants (Liu and Rocklöv 2022; WHO 2022c). Delta remains the only other named variant with significant reported circulation. Thus, Alpha, Delta and Omicron are the most dominant VOCs causing the fast spread of COVID-19 in past months.

Indoor/Outdoor Airflow and Air Quality

E-mail: binzhao@tsinghua.edu.cn

We have estimated the association between the airborne infection probability of the ancestral strain of COVID-19 and ventilation rates with the Wells-Riley equation, where the quantum generation rate (q) of SARS-CoV-2 was determined by a reproductive number (R_0) -based fitted approach (Dai and Zhao 2020). The approach has been proven compromised but relatively reasonable, with estimated value of q in the same range as those reported in other studies with different approaches, such as the epidemiological case back-calculation method by Lu et al. (2020) and the prediction on the basis of the emitted viral load from the mouth by Buonanno et al. (2020). However, the continuous evolution of SARS-CoV-2 leads to a continuous change in the R_0, further changing the estimated q value of COVID-19 and its infection probability. The guidance on common ventilation strategies for reducing the transmission of the ancestral strain may not be sufficient for dealing with the SARS-CoV-2 variants. Since the pandemic is ongoing with over 560 million confirmed cases globally, it is therefore urgent to update the data about the variants to face the changing epidemic situation.

In the present study, we estimated the association between the infection probability of three SARS-CoV-2 variants (Alpha, Delta, and Omicron) and ventilation rates. We followed the method proposed by Dai and Zhao (2020) to obtain the q value of the three dominate variants. Afterwards, we applied the Wells-Riley equation to re-evaluate the relationship between the ventilation rate and airborne infection probability of COVID-19 caused by these three SARS-CoV-2 variants. Furthermore, we estimated the effect of wearing masks of different efficiencies and running air purifiers on reducing the infection probability.

2 Method

2.1 Wells-Riley equation

We employed the following Wells-Riley equation (Riley et al. 1978) for scenarios without wearing masks or running air purifiers:

$$P = \frac{C}{S} = 1 - e^{-Iqpt/Q} \tag{1}$$

where: P is the probability of infection; C is the number of cases of infection; S is the total number of susceptible people in the space; I is the number of sources of infection, which is set to 1 to consider cases where one infector present; q is the quantum generation rate of airborne infection produced per infector per hour; p is the pulmonary ventilation rate of each susceptible person, in m³/h, which is 0.3 m³/h when people are sitting or participating in light indoor activities (Duan et al. 2013); t is the exposure time, in h; Q is the

ventilation rate of the room, in m³/h.

If indoor personnel wear masks, the filtering effect of the mask is equivalent to increasing the ventilation rate of the room. Both the ordinary medical surgical mask and N95 mask show a high filtration efficiency of more than 60% for aerosols in the submicron range and almost 100% for aerosols in the supermicron range, the two ranges to which SARS-CoV-2 most commonly adheres (Liu and Zhao 2021). Considering the influence of air leakage, the filtration efficiency can be set as 50% for ordinary medical surgical masks and 90% for N95 masks on virus-laden aerosols (Davies et al. 2013; Leung et al. 2020; Duncan et al. 2021). We then changed Eq. (1) as:

$$P = \frac{C}{S} = 1 - e^{-Iqpt(1-\eta_I)(1-\eta_S)/Q} \tag{2}$$

where η_I is the inhalation filtration efficiency and η_S is the exhalation filtration efficiency. We also considered the dilution effect of the air purifier on the viruses, accounting for cases where the existing ventilation systems do not provide adequate ventilation rates or are not suitable for wearing masks (Dai and Zhao 2022). In these cases, the Wells-Riley equation could be changed to:

$$P = \frac{C}{S} = 1 - e^{-Iqpt/(Q+CADR)} \tag{3}$$

where $CADR$ (clean air delivery rate) is the amount of virus-free air the purifier can provide per hour, in m³/h. The value was set to 361 m³/h based on a previous survey of 100 best-selling air purifiers on major Chinese online shopping websites (Zhao et al. 2020).

When indoor personnel are wearing masks and the air purifier is running simultaneously, we further changed the Wells-Riley equation to:

$$P = \frac{C}{S} = 1 - e^{-Iqpt(1-\eta_I)(1-\eta_S)/(Q+CADR)} \tag{4}$$

2.2 The reproductive number-based fitting equation

To obtain the q value of COVID-19, the most critical parameter for estimating the infection risk of viruses, we have proposed a reproductive number-based fitting approach. The estimated result has been validated in other studies with different approaches, and the accuracy of the method was proven to be satisfactory (Dai and Zhao 2020). The curve is fitted from five respiratory diseases with known values of R_0 and q. The principle of obtaining the q of COVID-19 is based on real-time-published R_0 of COVID-19, so it can be applied to SARS-CoV-2 variants as well as the ancestral strain. Therefore, we further used the validated fitted curve

to estimate the q for the SARS-CoV-2 variants. The fitted equation is as follows (Dai and Zhao 2020):

$$q = A + B_1 \times R_0 + B_2 \times R_0^2 \qquad (5)$$

where $A = -30.27958 \pm 26.07$, $B_1 = -44.81536 \pm 12.34048$, and $B_2 = 19.67934 \pm 0.62317$.

3 Results

3.1 Quantum generation rate of SARS-CoV-2 variants

A comparison of the ancestral strain and the studied three SARS-CoV-2 variants based on the validated fitted curve is shown in Figure 1. Table 1 shows the q values increased to 89–2,345 h^{-1} for the three variants, which were much larger than 14–48 h^{-1}, the value of the ancestral strain (Dai and Zhao 2020).
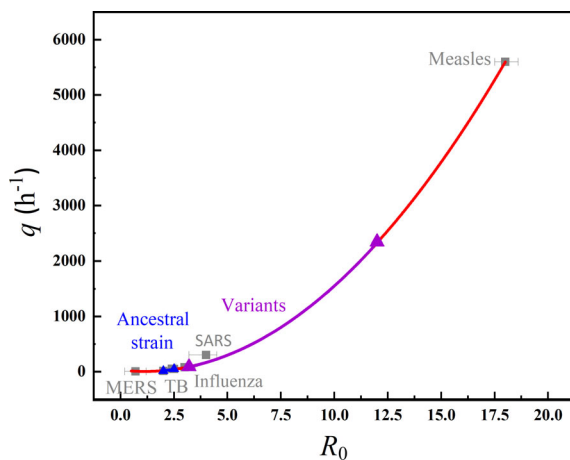

Fig. 1 The estimated quantum generation rate (q) of SARS-CoV-2 variants

3.2 Association between infection probability and ventilation rate

3.2.1 Infection probability

The association between the infection probability and ventilation rate for the SARS-CoV-2 variants with one infector in a confined space is shown in Figrues 2–5. A ventilation rate larger than what is commonly applied is required to ensure an infection probability of less than 1% for a susceptible person. For the Alpha variant, a ventilation rate of 650–1,200 m^3 h^{-1} was required for 0.25 h of exposure, while a ventilation rate of 8,000–14,000 m^3 h^{-1} was required for 3 h of exposure [Figures 2 (1) (2)]. For the Delta variant, ventilation rates of 2,200–6,800 m^3 h^{-1} and 26,000–80,000 m^3 h^{-1} were required for 0.25 h and 3 h of exposure, respectively [Figures 3 (1) (2)]. For the Omicron variant, 5,400–17,000 m^3 h^{-1} and 64,000–250,000 m^3 h^{-1} for 0.25 h and 3 h of exposure were required, repectively [Figures 4 (1) (2)]. Figure 5 further shows that, without any additional measures, the Alpha variant requires a ventilation rate approximately four times more than the ancestral strain, while the Delta and Omicron variants require approximately 20 times and 50 times greater ventilation rates, respectively.

If the infector and susceptible person wore ordinary medical surgical masks with a filtration efficiency of 50%, the required ventilation rate was reduced to about 1/4 of the original values, which was less effective for reducing the infection probability for the Delta and Omicron variants [Figures 3–4 (3) (4)]. If N95 masks with a filtration efficiency of 90% were worn, the ventilation rate was further reduced to about 1/100 of the original values, i.e., 6.5–12 m^3 h^{-1} for 0.25 h of exposure and 80–140 m^3 h^{-1} for 3 h of exposure for the Alpha variant [Figures 2 (5) (6)], 22–68 m^3 h^{-1} for 0.25 h of exposure and 260–800 m^3 h^{-1} for 3 h of exposure for the Delta variant [Figures 3 (5) (6)], and 54–170 m^3 h^{-1} and 640–2,500 m^3 h^{-1} for 0.25 h and 3 h of exposure, respectively, for the Omicron variant [Figures 4 (5) (6)].

The required ventilation rate changed little with or without an air purifier, with a $CADR$ of 351 m^3 h^{-1} [Figures 2–4 (7) (8)]. However, for cases where an air purifier was used and both the infector and susceptible person worn N95 masks in the confined space, the infection probability was less than 1% with less than 3 h of exposure for the Alpha variant, even without any additional mechanical ventilation [Figures 2 (11) (12)]. For the Delta variant, the

Table 1 Details about three circulating SARS-CoV-2 variants of concern (VOCs)

WHO label	Pango lineage	Earliest documented samples	Date of designation	R_0	q (h^{-1})
Alpha	B.1.1.7	United Kingdom, Sep-2020	VOC: 18-Dec-2020 Previous VOC: 09-Mar-2022	3.2–4.0 (Burki 2021)	89–165
Delta	B.1.617.2	India, Oct-2020	VOI: 4-Apr-2021 VOC: 11-May-2021 Previous VOC: 7-Jun-2022	5.1–8.0 (Liu and Rocklöv 2021; WHO 2022c)	312–935
Omicron	B.1.1.529	Multiple countries, Nov-2021	VUM: 24-Nov-2021 VOC: 26-Nov-2021	7.2–12 (Liu and Rocklöv 2022)	725–2,345

WHO: World Health Organization; VOI: variant of interest; VOC: variant of concern; VUM: variant under monitoring

Fig. 2 Infection probability of the Alpha variant with different ventilation rates for different scenarios (the green scale for *y*-axis conveys very low infection probabilities)
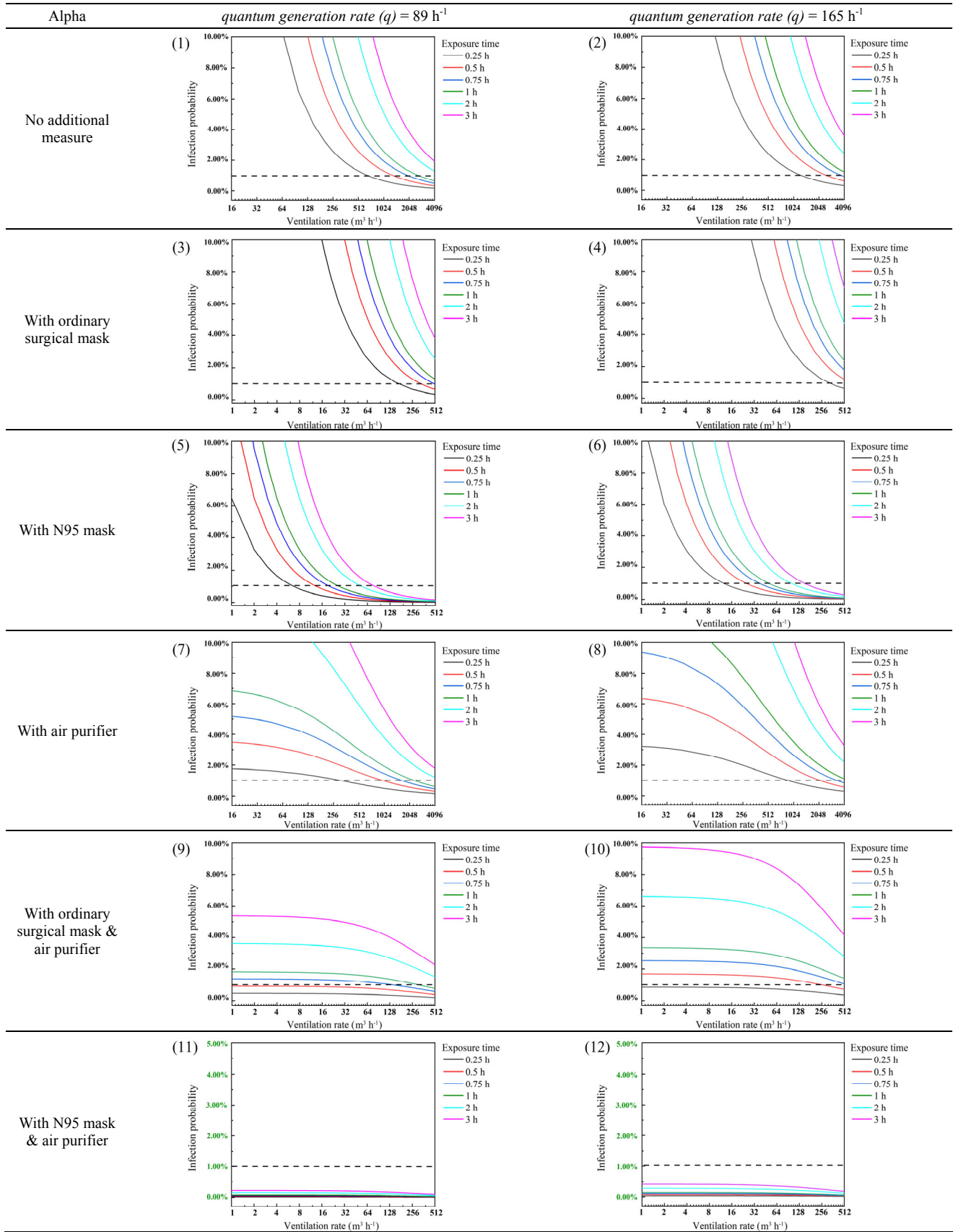
Fig. 3 Infection probability of the Delta variant with different ventilation rates for different scenarios (the green scale for *y*-axis conveys very low infection probabilities)
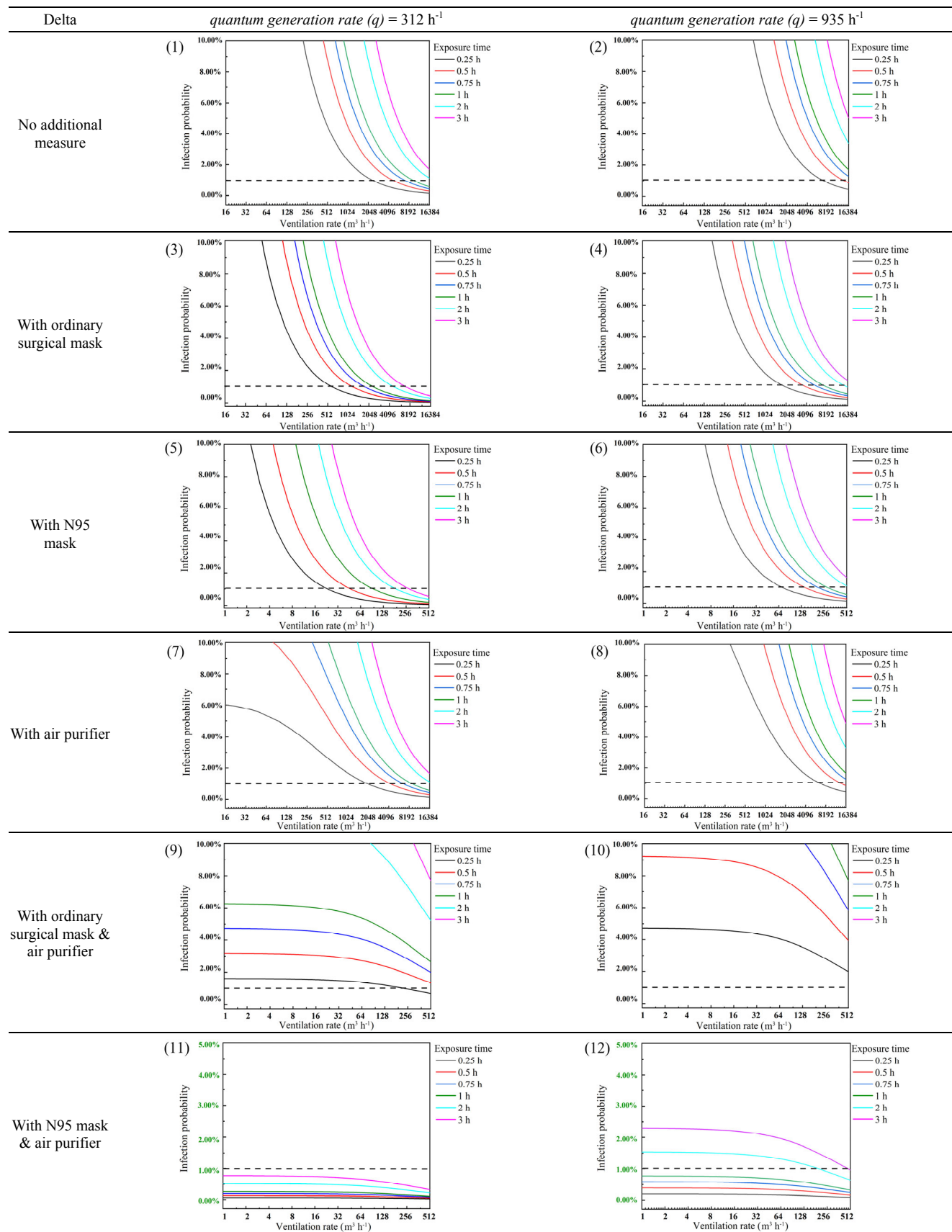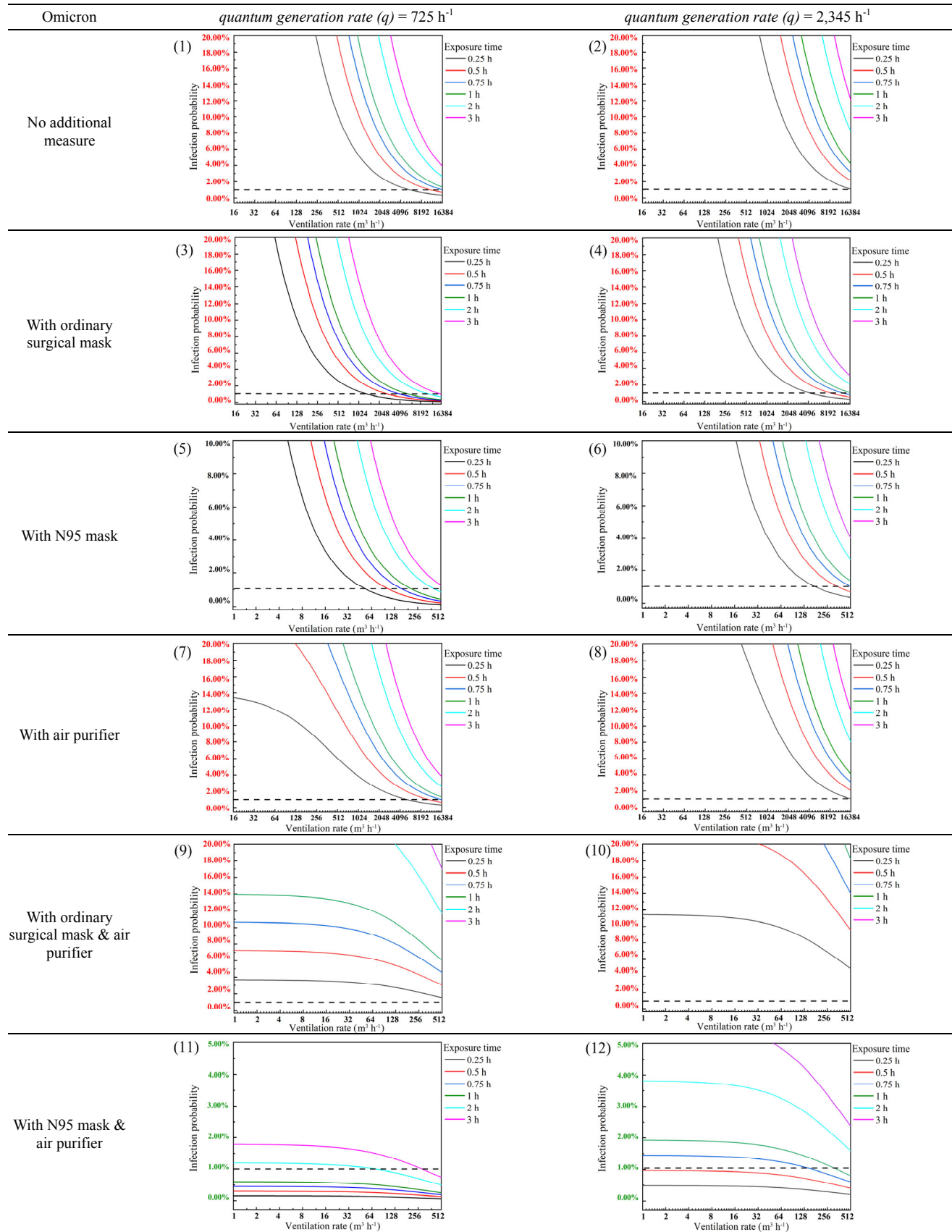
Fig. 4 Infection probability of the Omicron variant with different ventilation rates for different scenarios (the red scale for *y*-axis conveys higher infection probabilities; the green scale conveys lower infection probabilities)
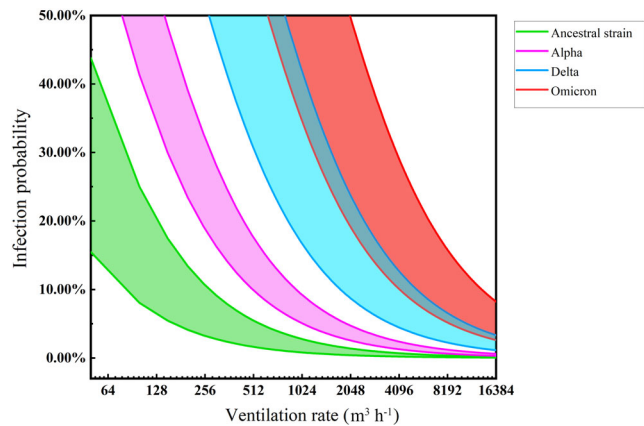
Fig. 5 Comparison of the infection probability of the ancestral strain and SARS-CoV-2 variants with different ventilation rates (using 2 h of exposure as an example). The different colored strips represent the range of the infection probability with the maximum and minimum value of q for the different variants

infection probability was below 1% in most cases, but a ventilation rate of 450 m³ h⁻¹ was required for 3 h of exposure when the q reached the maximum value [Figures 3 (11) (12)]. For the Omicron variant, natural ventilation or normal mechanical ventilation also provided a sufficient ventilation rate to ensure that the infection probability was less than 5% for most cases [Figures 4 (11) (12)]. It should be noted that the effect of ordinary medical surgical masks was far less than that of N95 masks, and the infection probability at common ventilation rates was about 10% for the Alpha and Delta variants, and even as high as 20% for the Omicron variant [Figures 2–4 (9) (10)].

3.2.2 Typical scenarios

Tables 2–4 lists the estimated ventilation rates with different infection probabilities and the corresponding air change rates (ACHs) for typical confined space scenarios. These tables listed results for some realistic scenarios in order to meet different application needs. The results may serve as a basic data set for checking or determining required ventilation rates for confined spaces in actual engineering. The ACH is a measurement of how much fresh/clean air replaces the indoor air in one hour (Sherman and Wilson 1986), and is widely used in engineering to determine if ventilation and air conditioning systems can provide a sufficient ventilation rate.

If people were wearing N95 masks, natural ventilation or normal mechanical ventilation provided a sufficient ventilation rate to ensure that the infection probability was less than 1% for most scenarios. However, not wearing N95 masks resulted in a relatively higher infection risk in all cases for all three SARS-CoV-2 variants, especially the Omicron variant.

4 Discussion

The continuous rapid spread of SARS-CoV-2 in the COVID-19 epidemic highlights the much higher transmissibility of the SARS-CoV-2 variants than the ancestral strain. The q values of the SARS-CoV-2 variants increased dramatically, resulting in changes to the corresponding association between the infection probability and ventilation rate. A large

Table 2 Air change rate (ACH) versus the infection probability of the Alpha variant (N: no additional measure; M: N95 masks worn; P: air purifiers used; M&P: N95 masks and air purifiers used, one infector inside)

Scenario		Bus				Classroom				Aircraft cabin				Office			
Volume (m³)		75				348				100				150			
Exposure time (h)		0.5				2.0				4.0				8.0			
Alpha variant		ACH (h⁻¹)															
Infection probability		N	M	P	M&P	N	M	P	M&P	N	M	P	M&P	N	M	P	M&P
2.0%		8.6	0.09	4.0	\	7.5	0.07	6.3	\	51.0	0.51	49.0	\	27.3	0.27	25.3	\
1.5%		11.7	0.12	6.9	\	10.0	0.10	9.0	\	70.5	0.71	67.0	\	94.7	0.95	91.3	\
1.0%	$q = 89\ \mathrm{h^{-1}}$	17.3	0.17	13.0	\	14.4	0.14	13.8	\	100	1.0	96.0	\	140	1.40	137	\
0.5%		36.0	0.36	30.7	\	30.2	0.30	28.7	\	210	2.1	206	\	280	2.80	277	0.4
0.1%		173.3	1.73	167	\	144	1.44	141	0.43	1,000	10.0	980	6.5	1,340	1.34	1,334	11.3
2.0%		16.0	0.16	11.3	\	14.1	0.14	13.0	\	98.0	0.98	94.0	\	127.3	1.27	123	\
1.5%		21.6	0.22	17.0	\	18.7	0.19	17.8	\	131	1.31	128	\	174.7	1.75	172	\
1.0%	$q = 165\ \mathrm{h^{-1}}$	32.0	0.32	26.7	\	28.2	0.28	27.3	\	195	1.95	190	\	265.3	2.65	260	0.2
0.5%		65.3	0.65	60.0	\	56.0	0.56	54.9	\	390	3.90	385	0.5	520	5.20	517	2.8
0.1%		320	3.2	307	\	282	2.82	274	1.72	1,980	1.98	1,960	15.0	2,540	25.4	2,533	23

Note: The ACHs in red indicate that the ventilation rate could be achieved with a normal ventilation system or natural ventilation for the corresponding scenario.

"\": The scenario can ensure the required infection probability without any additional mechanical ventilation rate.

Table 3 Air change rate (ACH) versus the infection probability of the Delta variant (N: no additional measure; M: N95 masks worn; P: air purifiers used; M&P: N95 masks and air purifiers used, one infector inside)

Scenario		Bus				Classroom				Aircraft cabin				Office			
Volume (m³)		75				348				100				150			
Exposure time (h)		0.5				2.0				4.0				8.0			
Delta variant									ACH (h⁻¹)								
Infection probability		N	M	P	M&P	N	M	P	M&P	N	M	P	M&P	N	M	P	M&P
2.0%		30.7	0.31	26.0	\	26	0.26	24.4	\	180	1.80	175	\	246.7	2.47	243	\
1.5%		41.2	0.41	36.0	\	37	0.37	35.9	\	247	2.47	243	\	330	3.30	327	0.89
1.0%	$q = 312\ h^{-1}$	60.0	0.60	57.3	\	54	0.54	53.2	\	360	3.60	350	\	493	4.93	490	2.4
0.5%		126	1.26	120	\	106	1.06	103.5	\	740	7.40	735	4.0	987	9.87	980	7.5
0.1%		576	5.76	573	1.2	517	0.52	502	4.0	3,700	37.0	3,650	32.0	4,933	49.33	4900	46
2.0%		92	0.92	86.7	\	79	0.79	77.6	\	558	5.58	550	1.8	733	7.33	720	4.8
1.5%		123	1.23	120	\	106	1.06	104	\	740	7.40	730	3.8	987	9.87	933	7.5
1.0%	$q = 935\ h^{-1}$	187	1.87	180	\	160	1.60	158	0.5	1,020	10.2	1,010	7.5	1,467	14.67	1,400	12.0
0.5%		373	3.73	367	\	316	3.16	313	2.0	2,040	20.4	2,030	20	2,933	29.33	2,900	27.3
0.1%		1,800	18	1,786	12.4	1,580	15.8	1,566	14.0	10,200	102	10,150	100	14,667	146.7	14,400	144

Note: The ACHs in red indicate that the ventilation rate could be achieved with a normal ventilation system or natural ventilation for the corresponding scenario.
"\": The scenario can ensure the required infection probability without any additional mechanical ventilation rate.

Table 4 Air change rate (ACH) versus the infection probability of the Omicron variant (N: no additional measure; M: N95 masks worn; P: air purifiers used; M&P: N95 masks and air purifiers used, one infector inside)

Scenario		Bus				Classroom				Aircraft cabin				Office			
Volume (m³)		75				348				100				150			
Exposure time (h)		0.5				2.0				4.0				8.0			
Omicron variant									ACH (h⁻¹)								
Infection probability		N	M	P	M&P	N	M	P	M&P	N	M	P	M&P	N	M	P	M&P
2.0%		72.0	0.72	66.7	\	61.8	0.62	58.9	\	430	4.30	420	0.65	567	5.67	560	3.3
1.5%		96.0	0.96	90.7	\	81.9	0.82	80.5	\	575	5.75	570	2.20	767	7.67	760	5.3
1.0%	$q = 725\ h^{-1}$	144	1.44	133	\	124	1.24	118	\	860	8.60	840	4.50	1,133	11.33	1,120	8.7
0.5%		288	2.88	267	\	247	2.47	236	1.4	1,720	17.2	1,680	16.8	2,267	22.67	2,240	20.7
0.1%		1,440	14.4	1,333	9.3	1,235	12.4	1,178	11.0	8,600	86	8,400	84.00	11,333	113.3	11,200	112
2.0%		227	2.27	223	\	200	2.00	198	0.9	1,380	13.8	1,350	10.0	1,800	18.00	1,767	16.0
1.5%		309	3.09	307	\	267	2.67	264	1.6	1,850	18.5	1,820	15.0	2,467	24.67	2,453	22.3
1.0%	$q = 2345\ h^{-1}$	453	4.53	447	\	400	4.00	398	2.8	2,760	27.6	2,700	24.0	3,600	36.00	3,567	34.7
0.5%		907	9.07	900	4.5	800	8.00	796	6.9	5,520	55	5,400	52	7,200	72.00	7,133	73.3
0.1%		4,533	45	4,427	40.0	4,000	40.0	3,979	38.8	27,600	276	27,000	270	36,000	360	35,667	353

Note: The ACHs in red indicate that the ventilation rate could be achieved with a normal ventilation system or natural ventilation for the corresponding scenario.
"\": The scenario can ensure the required infection probability without any additional mechanical ventilation rate.

increase in the ventilation rate is required for the three SARS-CoV-2 variants to ensure the same low infection probability compared with the ancestral strain. Such update is critical and timely given the SARS-CoV-2 variants are evolving so rapidly.

Previous studies have proven that wearing an ordinary surgical mask can ensure a relatively low risk of infection in most scenarios for the ancestral strain; however, it is less effective for the SARS-CoV-2 variants, making it necessary to replace ordinary surgical masks with N95 masks to reduce the infection probability to approximately 1% in most scenarios.

Our findings also suggest that common air purifiers have little effect on reducing the risk of infection, while their effect can be amplified if N95 masks are worn. Therefore, wearing N95 masks is a very cost-effective prevention

measure for daily use, which also means higher prevention costs for the SARS-CoV-2 variants than the ancestral strain. Furthermore, preventing prolonged exposure times in confined public spaces remains critical for suppressing the spread of the SARS-CoV-2 variants via airborne transmission.

It is acknowledged that the Wells–Riley equation follows the assumption that the infection risk is uniform within the space. Besides, the R_0 may vary in infectious periods and different outbreaking regions. We should have to make sure that the range of each parameter is as reliable as possible so that the estimated results (the range of q and the dataset of ventilation rates) here can be indicative in engineering practice.

Available evidence on the impacts of SARS-CoV-2 variants is continuously reported in editions of the COVID-19 Weekly Epidemiological Update of the WHO (WHO 2022c). Since the last update on the 27th of July 2022, the Omicron variant continues to evolve and the overall global risk related to SARS-CoV-2 variants remains very high. Several studies have tried determining the q value to estimate the infection risk of airborne infection of COVID-19 in confined spaces, but there is no study determining the q value of SARS-CoV-2 variants to date. It's perhaps because another widely adopted digital model to determine q is on the basis of the viral load in the mouth (e.g. viral RNA copies) or the activity levels (e.g. breathing, speaking, whispering) of both the infector and susceptible people (Buonanno et al. 2020). Therefore, to update values of q for different variants with this approach is challenging as it needs more specific exposure scenarios and adequate medical pathological parameters. However, the method presented in this study can be employed to estimate the q value of SARS-CoV-2 variants only according to their R_0, and then to estimate the relationship between ventilation rate and the infection probability in confined spaces with the Wells-Riley equation. Such method may be further expected to guide common ventilation strategies for engineering epidemic prevention and control.

5 Conclusions

With a reproductive number-based fitted approach, we updated the q values of three variants of concern (VOCs) to estimate the association of infection probability of SARS-CoV-2 variants with ventilation rates in confined spaces. The main conclusions are as follows:
(1) The quantum generation rate of the SARS-CoV-2 variants was estimated to be 89–165 h^{-1} for the Alpha variant, 312–935 h^{-1} for the Delta variant, and 725–2,345 h^{-1} for the Omicron variant.

(2) An infection probability of less than 1% in confined spaces for the variants required ventilation rates larger than that required for the ancestral strain; these are not acceptable for actual engineering.
(3) Wearing N95 masks was effective and can reduce the infection probability to less than 1% at ventilation rates common in most scenarios (10–140 m^3 h^{-1} for the Alpha variant, 50–800 m^3 h^{-1} for the Delta variant, and 100–2,500 m^3 h^{-1} for the Omicron variant).
(4) Air purifiers were not effective at reducing the risk of airborne transmission for highly contagious SARS-CoV-2 variants when used in scenarios where N95 masks were not worn.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

Hui Dai: methodology, validation, formal analysis, writing—original draft, writing—review & editing, visualization. Bin Zhao: conceptualization, methodology, formal analysis, writing—review & editing, supervision, funding acquisition.

References

Buonanno G, Stabile L, Morawska L (2020). Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. *Environment International*, 141: 105794.

Burki TK (2021). Lifting of COVID-19 restrictions in the UK and the Delta variant. *The Lancet Respiratory Medicine*, 9: e85.

Dai H, Zhao B (2020). Association of the infection probability of COVID-19 with ventilation rates in confined spaces. *Building Simulation*, 13: 1321–1327.

Dai H, Zhao B (2022). Reducing airborne infection risk of COVID-19 by locating air cleaners at proper positions indoor: Analysis with a simple model. *Building and Environment*, 213: 108864.

Davies A, Thompson KA, Giri K, et al. (2013). Testing the efficacy of homemade masks: would they protect in an influenza pandemic? *Disaster Medicine and Public Health Preparedness*, 7: 413–418.

Duan X, Zhao X, Wang B, et al. (2013). Exposure Factors Handbook of Chinese Population (Adults). Beijing: China Environmental Science Press. (in Chinese)

Duncan S, Bodurtha P, Naqvi S (2021). The protective performance of reusable cloth face masks, disposable procedure masks, KN95 masks and N95 respirators: Filtration and total inward leakage. *PLoS One*, 16: e0258191.

Leung NHL, Chu DKW, Shiu EYC, et al. (2020). Respiratory virus shedding in exhaled breath and efficacy of face masks. *Nature Medicine*, 26: 676–680.

Liu Y, Rocklöv J (2021). The reproductive number of the Delta variant of SARS-CoV-2 is far higher compared to the ancestral SARS-CoV-2 virus. *Journal of Travel Medicine*, 28(7): taab124.

Liu Y, Rocklöv J (2022). The effective reproductive number of the Omicron variant of SARS-CoV-2 is several times relative to Delta. *Journal of Travel Medicine*, 29(3): taac037.

Liu Y, Zhao B (2021). Size-dependent filtration efficiencies of face masks and respirators for removing SARS-CoV-2–laden aerosols. *Infection Control & Hospital Epidemiology*, 42: 906–907.

Lu J, Gu J, Li K, et al. (2020). COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020. *Emerging Infectious Diseases*, 26: 1628–1631.

Morawska L, Buonanno G (2021). The physics of particle formation and deposition during breathing. *Nature Reviews Physics*, 3: 300–301.

Riley EC, Murphy G, Riley RL (1978). Airborne spread of measles in a suburban elementary school. *American Journal of Epidemiology*, 107: 421–432.

Sherman MH, Wilson DJ (1986). Relating actual and effective ventilation in determining indoor air quality. *Building and Environment*, 21: 135–144.

Volz E, Mishra S, Chand M, et al. (2021). Assessing transmissibility of SARS-CoV-2 lineage B.1.1.7 in England. *Nature*, 593: 266–269.

WHO (2021). Coronavirus disease (COVID-19): How is it transmitted? https://www.who.int/news-room/q-a-detail/coronavirus-disease-covid-19-how-is-it-transmitted. Accessed 23 Dec 2022.

WHO (2022a). Advice for the public: Coronavirus disease (COVID-19). https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public. Accessed 10 May 10 2022.

WHO (2022b). COVID-19 advice for the public: Getting vaccinated. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/covid-19-vaccines/advice. Accessed Apr 13, 2022.

WHO (2022c). COVID-19 weekly COVID-19 weekly epidemiological update, edition 102, 27 July 2022.

WHO (2022d). Tracking SARS-CoV-2 variants. https://www.who.int/en/activities/tracking-SARS-CoV-2-variants/. Accessed 29 Jul 2022.

Zhao B, Liu Y, Chen (2020). Air purifiers: A supplementary measure to remove airborne SARS-CoV-2. *Building and Environment*, 177: 106918.

Zhao B, An N, Chen (2021). Using an air purifier as a supplementary protective measure in dental clinics during the coronavirus disease 2019 (COVID-19) pandemic. *Infection Control & Hospital Epidemiology*, 42: 493.