

# Experimental evaluation of the airborne infection probability in ventilated office room at different supply airflow rates

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**Abstract.** The impact of the supplied airflow rate on the distribution and exposure of exhaled airborne pathogens in a room with mixing ventilation was studied. Experiments were conducted in a field laboratory at three supply airflow rates: 20, 40, 60 L/s. Two breathing thermal manikins were used to resemble infected and susceptible occupants. Nitrous oxide (N<sub>2</sub>O) was dosed into the air exhaled by the infected manikin to simulate the emission of infectious aerosols. N<sub>2</sub>O concentration was measured in the air inhaled by the susceptible manikin. The measured data were used to calculate infection probability by modified Wells-Riley model. The highest infection probability of 4.3-5.1%, obtained in the case of 20 L/s, decreased with increasing the supply airflow rate. The decrease slowed with the increase of the supply flow. The calculated infection probability based on the tracer gas concentration in the inhaled air of the exposed manikin was in all studied cases higher than the infection probability obtained in the occupied zone and the exhaust. The infection probability based on the tracer gas concentration in the inhaled air of the exposed manikin was up to 65% higher than the infection probability calculated by the Wells-Riley method, which assumes complete room air mixing.

## 1 Introduction

Infectious respiratory pathogens, such as SARS-CoV-2, are emitted in aerosol particles produced by disease carriers during coughing, sneezing, talking, and breathing [1,2]. Keeping the distance of 2 meters (6.5 feet) apart between individuals has been recommended to prevent viral transmission through large droplets [3]. However, the exhalation jet contains a wide range of droplets (0.01–1000 µm), and most of them have sizes less than 5 µm [4]. Such airborne particles are strongly dependent on air patterns. Within the first minutes after exhalation, infectious aerosols can travel 3 to 12 meters at typical indoor air speeds depending on the air distribution in the room [5–7].

The dominant view on airborne transmission control in the indoors through ventilation is based on the dilution of viral aerosols by the supply of outdoor and filtered air [8]. Most indoor transmission has been shown to occur in poorly ventilated spaces [7,9]. Therefore, the technical mitigation actions to reduce the transmission of pathogenic microbial aerosols (e.g., influenza, SARS-CoV-2, MERS) should first focus on meeting ventilation standards [10–12]. In general, it is recommended to provide an outdoor airflow of at least 10 L/s per person, which corresponds to the requirements for category I of indoor air quality according to EN 16798 [12–16]. Furthermore, the recommendation is to increase the rate of viral aerosol removal by elevated ventilation rates and/or improved

filtration [15,17,18]. The combined filtration should achieve F7 (MERV 13) or better levels of performance. Centers for Disease Control and Prevention (CDC) currently recommends adjusting HVAC systems to increase total airflow to occupied spaces when possible [19].

Apart from the ventilation rate, enhancing ventilation should also consider other parameters such as control of thermal conditions, airflow distribution, and direction. The aim of the presented work is to study how increasing the supplied airflow rate affects the risk of infection and whether it can be predicted accurately by the Wells-Riley model assuming complete room air mixing.

## 2 Methodology

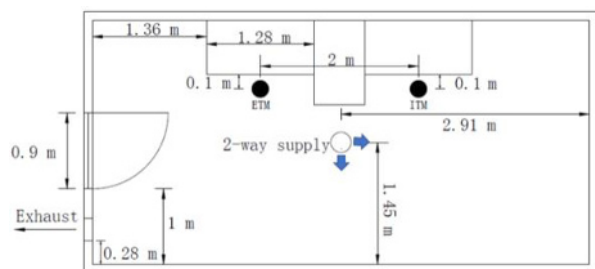
### 2.1 Facilities and measuring equipment

Tracer gas measurements were performed in a field lab (5.9×2.9×3.2 m) with two breathing thermal manikins. The test room was arranged as an office with manikins seated at desks in a straight position and at a distance of 2 m from each other (measured from mouth to mouth), as shown in **Fig. 1**. The manikins were shaped as 1.7 m tall women dressed in a T-shirt, long trousers, underwear, socks and sneakers (the total estimated clothing insulation of 0.47 clo). They were controlled to simulate a dry heat gain from people in a thermally

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comfortable state. **Fig. 2** shows the field laboratory arrangement during the experiments.

The room was ventilated with mixing air distribution. The air diffuser (Lindab LCA125, Lindab AB, Sweden) was installed in the middle of the ceiling at a height of 2.8 m. The diffuser was adjusted to 2-way air discharge to optimize its performance at the reference airflow rate of 20 L/s. The exhaust grill was installed on the wall directly below the ceiling.



**Fig. 1.** Plan view of the field laboratory arranged as a two-person office (ETM – Exposed Thermal Manikin, ITM – Infected Thermal Manikin)



**Fig. 2.** Photographs of the test room during the experiments

Respiratory-generated airborne pathogens were simulated by nitrous oxide (N<sub>2</sub>O) dosed into the exhaled air of one of the manikins acting as an infected person [20] at a constant rate of 0.334 L/min. The pulmonary ventilation rate for both manikins was 6 L/min. The typical breathing frequency for a person in light activity (1.2 met) was simulated (2.5 s – inhalation, 2.5 s – exhalation, 1 s – break) [21,22]. The breathing mode was set to exhalation through the nose and inhalation through the mouth. The mouths of both manikins were at a height of 1.15 m above the floor.

The tracer gas concentration was measured with a set of multipoint sampler and a gas analyzer based on the photoacoustic principle with an accuracy of 2% of the reading (GASERA ONE, Gasera Ltd., Finland). The N<sub>2</sub>O concentration was measured in the inhaled air of the second manikin (simulating susceptible person), the ventilation exhaust, and the vicinity of the room. All measurement instruments met the accuracy requirements according to EN ISO 7726 [5]. Air temperature (accuracy of ±0.2 °C) and relative humidity (accuracy of ±2% in the range 10-90% RH) were monitored by Sensirion sensors (Sensirion AG, Switzerland).

## 2.2 Study conditions

The impact of supply airflow rate on airborne pathogen distribution and exposure at three supply airflow rates: 20 L/s (1.3 ACH), 40 L/s (2.6 ACH) and 60 L/s (4 ACH). The supply rate of 20 L/s was selected as the reference rate based on the ventilation standards [12] and current coronavirus pandemic guidelines [14]. The supply flow fluctuated within a range of ±1.5 L/s. The supply air was 100% outdoor air. Exhaust airflow was controlled to maintain a 0.1 Pa overpressure in the room. Room layout simulated office with two workstations. All other indoor environmental parameters were kept unchanged throughout the sessions. The room air temperature was kept at 22.6±0.4°C. The only heat loads in the room were manikins that simulated dry heat gains from people in the thermally comfortable state (average whole-body heat flux of 64 W/m<sup>2</sup>) and 6 ceiling lamps (38 W each). Table 1 summarizes the studied conditions.

**Table 1.** Experimental conditions (mean ± standard deviation)

Supply airflow rate	Supply air temperature	Air temperature	Relative humidity
20 L/s	18.0±0.9°C	22.7±0.1°C	32.5±1.3%
40 L/s	18.2±0.8°C	22.9±0.0°C	49.5±0.4%
60 L/s	18.5±1.6°C	22.1±0.0°C	38.2±0.4%

## 2.3 Infection probability calculations

The Wells-Riley model was used to calculate the reference infection probability:

$$P = 1 - e^{-I p q t / Q} \quad (1)$$

where  $P$  is the infection probability,  $I$  is the number of infected persons in the room;  $p$  is the pulmonary ventilation rate (m<sup>3</sup>/h);  $q$  is the quantum generated rate (quanta/h);  $t$  is the exposure time (h); and  $Q$  is the supply flow rate (m<sup>3</sup>/h).

For our calculation, we assumed that  $q$  is equal to 2 quanta/h (corresponding to the quanta emission rate for SARS-CoV-2 of a sitting and non-speaking person [2]). The exposure time,  $t$ , was considered to be 6 hours.

Obtained in such a way, infection probability values are based on the complete room air mixing assumption. In practice, this is rarely the case; therefore, we used the dilution ratio ( $DR$ ) to analyze the obtained tracer gas measurements [23]:

$$DR = \frac{E_0}{E} \quad (2)$$

where  $E_0$  was the N<sub>2</sub>O concentration in the exhaled air of the infected person (N<sub>2</sub>O<sub>exhaled air</sub> = 22669 ppm) and  $E$  was the average N<sub>2</sub>O concentration (ppm) measured in analyzed point (inhaled air of the exposed person or one of room points).

As a result, the original Wells- Riley model was revised to:

$$P = 1 - e^{-q t / DR} \quad (3)$$

The standard uncertainty of the infection probabilities was calculated using Equation (4):

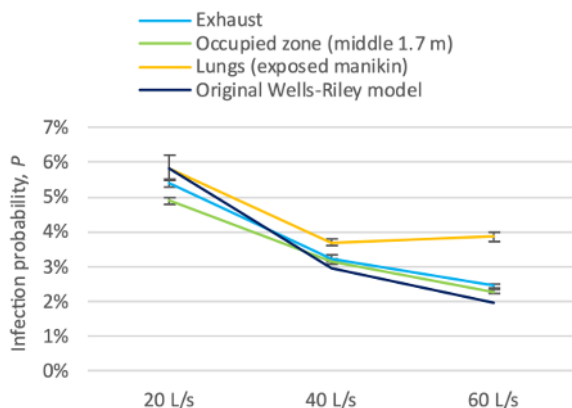
$$U_P = \sqrt{\left(\frac{\partial P}{\partial C_{N_2O,emission}} \cdot U_{C_{N_2O,emission}}\right)^2 + \left(\frac{\partial P}{\partial C_{N_2O,meas}} \cdot U_{C_{N_2O,meas}}\right)^2} \quad (4)$$

where  $P$  was the infection probability calculated using Equation (3),  $C_{N_2O,emission}$  was the  $N_2O$  concentration (ppm) in the exhaled air of the infected person,  $C_{N_2O,meas}$  was the average  $N_2O$  concentration measured in analyzed point.  $U_{C_{N_2O,emission}}$  was the standard uncertainty due to the accuracy of the flow rate measurements of the tracer gas emission rate, and  $U_{C_{N_2O,meas}}$  was the total uncertainty of the  $N_2O$  measurements [24]. The expanded combined uncertainties of the infection probabilities are reported at a 95.45% confidence interval with a coverage factor of 2.

### 3 Results and Discussion

The impact of airflow rate on infection probability is shown in Fig. 3. The highest infection probability of 4.9-5.8% was obtained in the case of 20 L/s, depending on the measurement point. The probability of infection based on the  $N_2O$  concentration measured in the air inhaled by the susceptible manikin decreased with increasing airflow from 20 L/s to 40 L/s. Further increase of the supplied flow rate to 60 L/s leads to a slight increase in infection probability. Similar phenomena have previously been observed [25,26]. The infection probability calculated based on the measurements in the exhaust and the occupied zone decreased with the increase of the supplied flow rate.

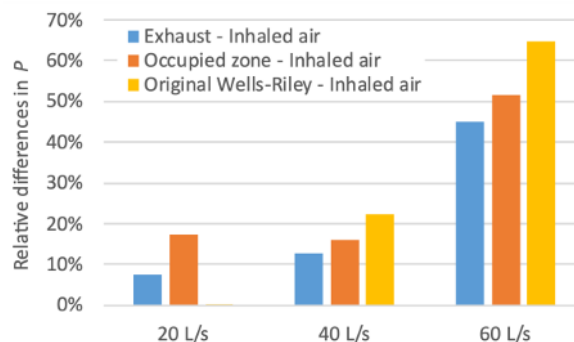
The infection probability based on the tracer gas concentration in the inhaled air of the exposed manikin was different and, in all studied cases, higher than the infection probability obtained in the occupied zone and the exhaust.



**Fig. 3.** Infection probability depending on the airflow rate and sampling point

The relative differences in infection probability calculated for the inhaled air and the remaining points

(exhaust and occupied zone) increased with increasing airflow rate, as shown in Fig. 4. At the supply flow rate of 60 L/s, the difference in the infection probability based on inhaled air calculations and calculations for the other measured locations was up to 51%. The measured probability of infection in inhaled air at 60 L/s was also 65% higher than the value obtained with the original Wells-Riley model (Equation 1), assuming perfect room air mixing.



**Fig. 4.** Infection probability - relative differences between points for each experimental case depending on airflow rate

### 4 Conclusions

The results presented in this paper indicate that control cross-infection in the spaces solely through an increase in the ventilation supply rate can be misleading. An increase in dilution of the airborne pathogens by increasing the supplied flow rate may create an unfavourable directional flow current. As observed in this study, such local air currents could support the spread of infectious airborne pathogens in the space and increase aerosol inhalation instead of simply diluting them.

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