Airborne Transmission of the Delta Variant of SARS-CoV-2 in an Auditorium

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Abstract

The Delta variant of SARS-CoV-2 has inflicted heavy burdens on healthcare systems globally, although direct evidence on the quantity of exhaled viral shedding from Delta cases is lacking. Literature remains inconclusive on whether existing public health guidance, formulated based on earlier evidence of COVID-19, should respond differently to more infectious viral strains. This paper describes a study on an outbreak of the Delta variant of COVID-19 in an auditorium, where one person contracted the virus from three asymptomatic index cases sitting in a different row. Field inspections were conducted on the configuration of seating, building and ventilation systems. Numerical simulation was conducted to retrospectively assess the exhaled viral emission, decay, airborne dispersion, with a modified Wells-Riley equation used to calculate the inhalation exposure and disease infection risks at the seat level. Results support the airborne disease transmission. The viral emission rate for Delta cases was estimated at 31 quanta per hour, 30 times higher than those of the original variant. The high quantity of viral plume exhaled by delta cases can create a risky zone nearby, which, for a mixing ventilation system, cannot be easily mitigated by raising mixing rates or introducing fresh air supply. Such risks can be reduced by wearing an N95 respirator, less so for social distancing. A displacement ventilation system, through which the air is supplied at the floor and returned from the ceiling, can reduce risks compared with a mixing system. The study has implications for ventilation guidelines and hygiene practices in light of more infectious viral strains of COVID-19.

Keywords: COVID-19, Delta Variant, Airborne Transmission, Numerical Simulation, Auditorium

1. Introduction

The COVID-19 pandemic is dominated by more infectious viral lineage, such as the Delta or Omicron variant. Both contain diverse mutations in the viral RNA compared with the ancestral lineage, allowing them to evade immune responses (Planas et al., 2021) and infect or even transmit via fully vaccinated persons (Chia et al., 2021). The Delta variant of COVID-19, in particular, has inflicted heavy burdens on health and healthcare systems globally. First discovered in late 2020, it has shorter incubation periods and can generate higher viral loading in respiratory tracts and a longer duration of viral shedding for infected persons (Wang et al., 2021), and for this reason, spreads faster in a susceptible population. A review of available disease transmission data by the World Health Organization (WHO) concluded that Delta is 40-60% more transmissible (WHO, 2021) than earlier strains of COVID-19. Its base reproduction number (R_0), the number of new infections generated by each case, was estimated to be 5.08, much higher than 2.79 of the original strain (Liu and Rocklöv, 2021). Delta can purportedly inflict severe illness for the unvaccinated population (USCDC, 2021), resulting in exceedingly large numbers of global cases and hospitalizations. Its main route of transmission is by inhalation of aerosol containing the virus, which is exhaled by breathing, talking or singing. The risk of inhaling the viral aerosol is greater when an individual is close from an infected person, where the aerosol concentration is higher.

Research gaps remained as more knowledge on COVID-19 emerge. On the one hand, the quantity of exhaled viral emission from Delta cases has not been estimated in scientific literature. On the other hand, literature remained inconclusive on whether public health guidance should respond differently towards more infectious viral variants in global circulation. Prevailing literature suggest that sufficient air ventilation, such as supplying clean outdoor air, or increasing the mixing of indoor air, should be prioritized in order to reduce the risk of disease transmission in an indoor space. In addition, hygiene measures such as mask wearing, social distancing, and body temperature-checking should be practiced in public buildings. These guidance above were largely formulated based on evidence of the ancestral lineages of COVID-19, their protective effects against new viral variants have not be sufficiently studied.

This paper describes an epidemiological investigation on a disease outbreak of the Delta variant of COVID-19 in a mechanically ventilated auditorium in China. An hour-long performance was attended by 2000+ mask-wearing audiences; one person contracted the virus which can be epidemiologically linked to three asymptomatic index cases sitting in a different row. Evidence were collected from field inspection and from local Centers for Disease Control (CDC). Numerical simulations were conducted using a zonal airflow network model and the Wells-Riley (WR) equation. The research was structured to answer three questions: 1) whether the airborne route can explain patterns of disease transmission in the auditorium? 2) If yes, what are the quanta emission rate from index cases required to deliver new infection under the study conditions? 3) And what are implications for building air ventilation and hygiene practices, such as mask-wearing and social distancing, in response to new viral variants that are more contagious?

2. Relevant Works

The airborne transmission COVID-19 and other infectious diseases have been studied by a wealth of research literature. Numerical simulation models were used extensively to assess the disease transmission risks in indoor and outdoor environments, whilst ventilation guidelines and hygiene practices have been established and widely implemented. Knowledge gaps remain on the quantitative estimation of viral shedding rate of Delta and other more infectious viral variants, and their implications on mitigation of disease mitigation.

2.1. Exhaled Viral Emission

SARS-CoV-2 primarily infect the respiratory tract. Virus-laden droplets of saliva or respiratory secretions from an infected person are shed during breathing, vocalization, coughing or sneezing (Beeching et al., 2020). Approaches to quantify viral shedding from patients can be categorized by 1) the numerical viral particle, and 2) the Well-Riley approach.

The first approach aims to directly quantify viral RNA copies exhaled by patients. Using PCR tests on samples collected from the exhaled breath collector, a specialized mechanical device, researchers were able to quantify viral RNA copies from patients' breath samples (Milton et al., 2013; Yan et al., 2018). Exhaled viral emissions for the original lineage of COVID-19, according to Leung et al. (2020), were in the range of 630 and 56,200 viral RNA copies per 30-min sample. Other studies used empirically derived viral loading from respiratory secretion and the quantity and size distributions of exhaled microdroplets to infer viral emissions. For example, Riediker and Tsai (2020) studied exhaled viral emission from a person contracted with the original lineage of COVID-19, which was estimated in the range between 2.5 and 318,500 copies per hour, depending on assumptions on viral load in the sputum. These estimates had a wide range of because, till now, they were derived from relatively small numbers of participants enrolled in laboratory studies. The findings may be inflated, since only a fraction of viral particles can survive the aerosolization, dehydration, and airborne transport, even fewer can settle into alveoli and initiate new infections in real-world outbreaks.

The second approach adopted hypothetical infectious dose unit, without attributing a definitive number of viral copies. An example is the Wells-Riley (WR) equation (Riley et al., 1978), widely used in epidemiological studies of airborne diseases, such as Tuberculosis, influenza, and COVID-19 (Nardell, 2016; Sze To and Chao, 2010). Researchers used "quanta" as a hypothetical infectious dose unit, each quantum is a minimum dose of inhaled airborne viral pathogens necessary to cause infection (Wells, 1955), regardless of the numbers of infectious viral particles involved. For patients contracted with the original strain of COVID-19 (B.1.617), the rates of viral "quanta" were estimated in the range of 4.9 to 31 quanta per hour (q/hr) for patients engaged in light activities while speaking (Buonanno et al., 2020a), 60 q/hr during domestic activities (Huang et al., 2021), or over 100 q/hr for speaking and walking (Buonanno et al., 2020b). Higher estimates, although rare, have been made in the range of 460 and 970 q/hr during super-spreading events of COVID-19 (Miller et al., 2020; Prentiss et al., 2020).

2.2. Modeling Airborne Transmission

The airborne transmission of COVID-19, in which viral pathogens spread through dried residua of respiratory droplets exhaled from infected persons which can suspend in the air for a prolonged period (CDC, 2020), has been studied extensively. Researchers resort to various fluid mechanics models to assess the transport and dispersion of viral particles. An example is the Computational Fluid Dynamics (CFD) method, which has been used to study airborne disease transmission in enclosed environments, including aircraft cabins (Liu et al., 2021), buses (Ou et al., 2022), movie theatre (Liang *et al.*, 2021), and multi-family residential buildings (Niu and Tung, 2008). Alternative models, such as the zonal airflow network model, originally developed to assess heat and moisture content inside buildings (ASHRAE, 2009), have been used to simulate the movement of contaminant and airborne pathogens in enclosed environments. Examples include the zonal model developed by Li et al., (2006) to study the airborne transmission of SARS virus, which is closely related to COVID-19. Another example is the study by Zhu et al. (2020) on the spread of influenza in dormitories, and so on. The zonal models were also used to assess airborne transmission of COVID-19 via the outdoor route by Huang et al (2021).

2.3. Public Health Guidance

A variety of public health guidance were implemented since the COVID-19 pandemic. Most can be categorized as 1) ventilation guidelines, and 2) hygiene measures. The former consists of operational strategies for building Heating, Ventilation and Air Conditioning (HVAC) systems in order to reduce exposure in indoor environments. The majority of researchers emphasize building engineering controls, such as increasing air ventilation, particle filtration, disinfection, and the avoidance of air recirculation, i.e., the provision of sufficient outdoor air (Morawska et al., 2020). Their views have been corroborated by a flurry of studies on COVID-19 transmission in enclosed space, from restaurants (Li et al., 2021) to exercise facilities (Lendacki et al., 2021); most conclude that inadequate air ventilation was among major factors enabling disease transmission in enclosed spaces. Their evidence has been translated into air ventilation guidelines in the US, China, Japan, and Europe (Guo et al., 2021). For instance, the Epidemic Task Force of the American Society of Heating, Refrigerating and Air Conditioning Engineers (AHSRAE), a professional association, listed the minimum rates for supplying outdoor air in various types of buildings (Bahnfleth and Degraw, 2021). It also promoted the mixing of air in indoor environments, provided that such does not cause strong air currents that increase person-to-person transmissions. There has been no guidance on COVID-19 mitigation regarding the displacement ventilation versus the mixing ventilation, the two widely adopted ventilation strategies in auditoriums. Their impact on occupant thermal comfort, energy savings, or indoor air quality have been extensively studied in literature (Lau and Chen, 2007), while their roles in removing aerosol particles and, in particular, mitigating the transmission of airborne infectious disease, remain disputed in literature (Jurelionis et al., 2015; Lipinski et al., 2020).

The second category consists of hygiene measures, such as face masks, social distancing, and body temperature-screening. The mask-wearing, for example, can reduce the amount of exhaled and inhaled viral particles (Leung et al., 2020) and it is considered essential in suppressing disease transmission for the general public and the medical staff (WHO, 2020). The filtration efficiencies of face masks to remove particles of various sizes have been studied extensively in laboratories. Researchers found considerable discrepancies between the inward and outward protection. The former, i.e., the efficacy of removing inhaled viral particles, measured at 50-60% for cloth masks (van der Sande et al., 2008) and 80%-89% for surgical masks (Makison Booth et al., 2013). The latter, i.e. the efficacy to filter exhaled viral particles for source control, measured at 77% (Li et al., 2020) and 64-96% (Milton et al., 2013) for both types of masks. Maintaining a social distance, either by one or two meters (WHO, 2020), or by six-feet (CDC, 2020), have been practiced widely, although its efficacy remain debated (Bourouiba, 2020). Social distancing in high-occupancy buildings is practiced in the form of reduced seating capacity, such as audience seating in separate rows or in every other seat, to allow more distances between occupants (Liang et al., 2021). Body-temperature checking, a mean to identify and isolate persons with fever, a common symptom of COVID-19, is regarded as a key public health response in the management of public facilities (Cheng et al., 2020)

2.4. Research Gaps

Two important knowledge gaps remained. First, quantitative estimates on viral emission rates from Delta cases are lacking. Existing evidence, such as the higher R0 number derived from epidemiological data (Liu and Rocklöv, 2021) or high viral loading in patient nasal or oral swaps (Li et al., 2022; Wang et al., 2021), are insufficient to inform public health measures. From a practical perspective, none of these can help determine the amount of air ventilation needed or the type of masks occupants should wear. Furthermore, literature remained inconclusive over whether public health guidance should respond differently to Delta or other more infectious variants. Existing air ventilation guidelines and hygiene measures have been formulated based on evidence from earlier strains of COVID-19. It is unknown whether they offer the same protective effect against more contagious viral variants. There is a need for empirical estimates for the viral emission rate from Delta cases in order to inform not only air ventilation guidelines, but also public health practices, such as social distancing and room capacity limit.

3. Methods

An epidemiological investigation was conducted on a disease outbreak of the Delta variant of SARS-CoV-2 in an auditorium in Hunan Province in Central China. The airborne disease transmission inside the auditorium was assessed using the Zonal Aerosol Dispersion and Infection Risks (ZADIR) model, which was based on an earlier study of model development and field evaluation using tracer-smoke experiments and cross-checking with CFD software (Huang et al., 2021). ZADIR was applied retrospectively to analyze disease transmission and to back-calculate the quanta emission rate of the index cases. Sensitivity studies were conducted to identify disease transmission risks under various air ventilation and social distancing practices.

3.1. Epidemiological Evidence

The disease outbreak took place during a performance an auditorium in Hunan Province in Central China. The performance was held between 18:00-19:00 on July 22, 2021, featuring local culture and arts which was a tourist attraction in itself. The name of the venue, the name of the city, and individuals involved have been anonymized in this paper for privacy protection.

The audience was assumed to remain sedentary and silent, without laughing, eating, drinking, nor speaking with each other. The index cases were three tourists who had contracted COVID-19 via a flight connection in an airport on July 17, 2021. They had tested positive for SARS-COV-02 Delta variant in PCR on July 26, and they were designated as “asymptomatic cases” due to the lack of disease symptoms. Therefore, the viral aerosols were supposedly generated via breathing. One secondary infection, a person sitting in the row behind the index cases during the same performance, was diagnosed on July 27, 2021. A review of the viral genome sequencing results by China Center for Disease Control and Prevention concluded that the secondary infection was linked to the Delta variant descended from the viral lineage of the three index cases by (Zhang and Wang, 2021).

The above information was independently verified via multiple channels since the outbreak was highly publicized. Information used in this study was collected from the news media, online discussions, released government documents, and interviews with two CDC officials at the city and the provincial level. Evidence was also obtained from the contract-tracing programme of the local Center for Disease Control and Prevention (CDC) Office. Patients' medical reports, mobile phone-based spatial trajectory, records of close contact within the last 14 days, etc., were compiled in accordance with the national guidelines set forth by China Centre for Disease Control and Prevention (CCDC, 2020). All members of the audience and staff were tested and placed under a two-week quarantine in the aftermath, no additional infections were found.

3.2. Field Inspection

Retrospective field inspections were conducted on Sept.16, 2021. The purpose was to collect information on the configuration of seating, building floor plan, air ventilation parameters, and behavioral details during the disease outbreak. The auditorium is configured as a large column-less space (Fig. 1), measuring 1,700 m^2 in footprint area and 18,050 m^3 in volume. The performance stage was located at the front, while the seats were arranged in tiered rows. The audience were served by four entrance doors in the back wall, which linked with the entrance lobby. There were six emergency exits on the side walls. All entrances were supposedly closed during the performance, while air exfiltration through the gaps of doors were possible. The building floorplan with dimensions, in the format of AutoCAD drawings, was obtained from the facility manager of the auditorium (Fig. S1 in the Supplementary Materials).

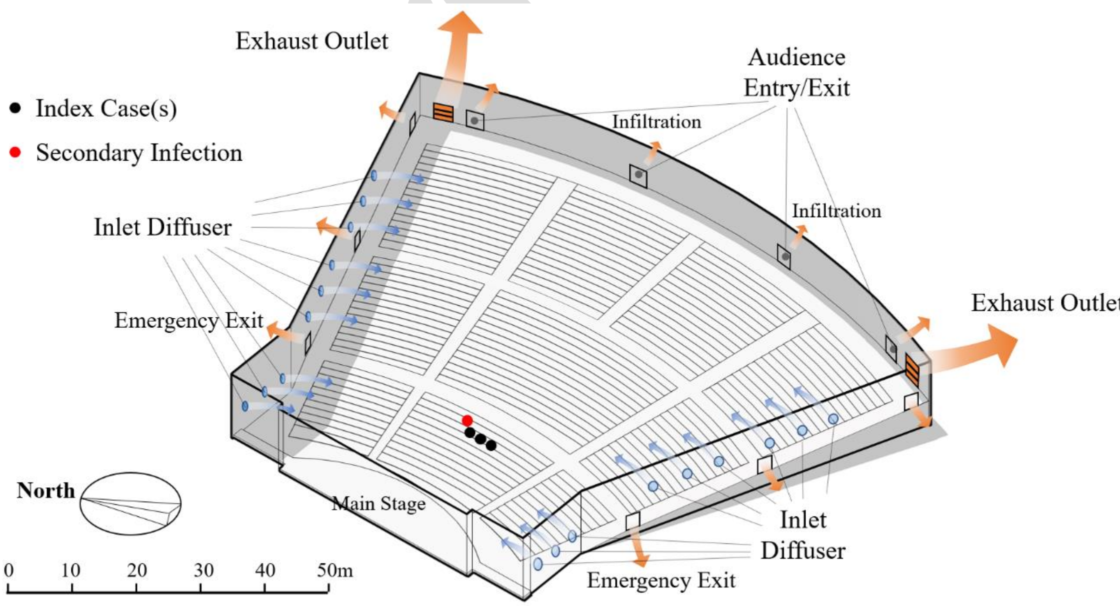

Fig. 1 The layout of the auditorium during the disease outbreak

The seating information of the index and secondary cases was acquired from the local CDC and verified during the field inspections. The three index cases were sitting in Row 8 at the center (seat # R8-28, R8-29, R8-30). The secondary infection case was seating in Row 9 (seat # R9-33), with a distance of 1.5 m in between. The seating information and personal IDs for members of the audience during the outbreak was recorded by the ticketing office, which required registration of personal information upon ticket sales. This information was made available to the contact tracing programme. An indicative map of the seating plan is provided in Fig. S2 in the Supplementary Materials.

The auditorium was mechanically ventilated during the outbreak. The HVAC system used a mixing ventilation design, which diluted the contaminated room air by mixing the outdoor and indoor air to lower the contaminant concentrations (Cao et al., 2014). The air is supplied through 60 jet nozzles on the side walls and recirculated back to the system via the exhaust outlets on the back wall. The system was powered by two large air conditioning units (FG-V-25-CR-10, Gaocun Air Conditioning Equipment Ltd., Shenzhen, China), with the technical parameters summarized in Table S1 of the Supplementary Materials. No filtration devices capable of removing particles smaller than 5 µm were present during the site inspections. The layout of the air ventilation systems, including the location, count, and dimension of the inlet diffuser and exhaust outlet were robustly checked during our site visit, with the photographic evidence included in the Supplementary Materials (Fig. S3 & S4).

Operational parameters of the HVAC system during the disease outbreak were confirmed from an interview conducted with the facility manager (Wang, 2021, personal communication, 16 September). The two air conditioning units were operating with a combined air supply rate of 13.88 m^3/s. The system was operating in recirculation mode without outdoor air supply during the hour-long performance, and the outdoor air was supplied only during the intervals between performances. The external air temperature on July 22 from local weather station was between 34-25 °C with relatively humidity at 94%. Meteorological records between July 18 and 30, 2021 at the local airport were acquired from the China Meteorological Data Service Centre (CMDC, 2021).

Mask-wearing and temperature checking were mandated at the entrance. The audience were purportedly wearing masks and they were assumed to remain silent throughout the performance, according to a CDC official who reviewed footages from surveillance cameras mounted inside the auditorium (Hu, 2021, personal communication, 30 November). The likelihood of index and secondary cases of speaking with each other is low, giving their lack of acquaintance. Available evidence was insufficient to determine whether masks were worn loosely, there is a possibility that people had let their guard down due to no reported COVID-19 cases in Hunan Province for more than a year (HNCDC, 2021)

3.3. Simulation Model

The airborne disease transmission in the auditorium was simulated using the Zonal Aerosol Dispersion and Infection Risk (ZADIR) model, which consists of a zonal airflow network model, a viral aerosol dispersion model, and the WR equation for infection risks. The model can account for viral exhalation from index cases, airborne dispersion, and inhalation exposure from susceptible persons. It adopted a steady-state approach to simulate the air ventilation conditions, while the viral aerosol injection, decay, and build up over time was simulated dynamically. Its schematic depiction is shown in Fig. 2, and the model was applied to assess conditions during the disease outbreak in the auditorium and in sensitivity studies to identify disease infection risks under alternative conditions, such as increased air mixing and outdoor air supply.

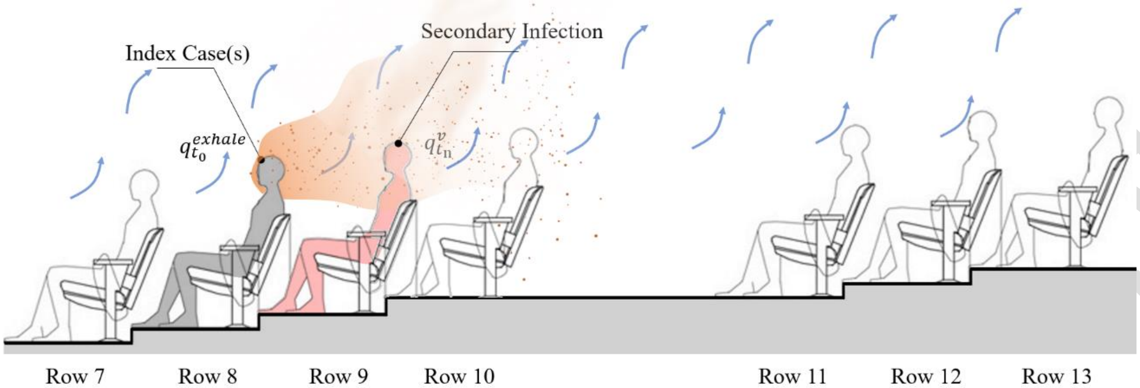

Fig. 2 A schematic depiction of the Zonal Aerosol Dispersion and Infection Risk model.

3.3.1. Zonal Air Flow Network Model

The mechanical and buoyancy-driven air ventilation in the auditorium was modeled using a zonal airflow network model, which has been developed and evaluated in previous studies (Huang et al., 2020, 2015; Liang et al., 2018). The model domain consists of the volume of air in the auditorium, divided into a network of interconnected 'zones'. The air and viral particles within each zone were considered well-mixed, in accordance with the WR approach (see section 3.3.2). The model domain was enclosed by walls, ceiling, and the ground, with the boundary conditions consisted of the inlet diffuser and exhaust outlet, and anthropogenic heat generated from each person. Zonal temperature, pressure, and airflow conditions are solved using mass continuity, energy conservation, and pressure balance equations, and inter-zonal airflow is driven by pressure, temperature, and density differences. A steady-state approach was adopted, assuming that the boundary conditions of air inlet and temperature remain constant.

The volume of air in each zone is assumed to have a uniform temperature (T_i) and density (ρ_i). The zonal air pressure (P_i^e) at any given height (H_e) is expressed as $P_i^e = P_i^c - \rho_i g H_e$ (1), where P_i^c is the air pressure at the geometric center of the zone, and H_e is the vertical distance from the zone centre. Pressure, temperature, and density observe the ideal gas law $\rho_i = P_i / R_{air}\, T_i$ (2), where R_{air} is the gas constant. The airflow rate F_{ij} from zone i to neighboring zone j is a function of pressure and density differences at the border and characteristics of the shared areas between the two.

$$F_{ij} = f[\Delta P_{ij}, \Delta\rho_{ij}, A_{ij}] \tag{3}$$

Mass conservation is observed at each zone $V_i \frac{\partial \rho_i}{\partial t} + \sum_{j=1}^{J} F_{i,j}\, \rho_j = 0$ (4), which can be simplified as $\sum_{j=1}^{J} F_{i,j} = 0$ (5) since mass changes caused by density differences is negligible under the study conditions. The energy conservation equation for the body of air within zone i is expressed in formula (6), which describes heat transfer from airflows to and from neighboring zones, thermal massing, and anthropogenic heat generation.

$$\frac{\partial T_i}{\partial t} C_p \rho_i V_i = \sum_{a=1}^{H} q_a^p + \sum_{j=1}^{J} C_p \left(\rho_j F_{ji} T_j - \rho_i F_{ij} T_i \right) \tag{6}$$

where H is the number of anthropogenic heat sources within zone i, q_a^p is the heating power (W) of each person, assumed to be 100 W per person in this study; F_{ij} and F_{ji} are the airflow rates (m^3/s) between zone i and neighboring zone j; J is the number of neighboring zones; C_P and V_i are the specific heat capacity (J/kg·K) and volume (m^3) of the zonal air. Heat exchanges between zonal air and solid surfaces, i.e., wall, ground, and ceiling surfaces can be negligible, therefore the adiabatic conditions hold.

The boundary condition consists of the inflow, enclosure, and boundary zones from the east, south, west, and north. Zones where inlet diffusers were located were assumed to have a constant inflow (F_{inlet}) at a rate estimated in accordance with the operational parameters (See Section 3.3.3). The zonal air was expected to find its way out through exhaust outlets and exfiltration through gaps around doors. The exhaust outlet was connected to the outside boundary zones of standard atmospheric pressure. The dimension of the exhaust outlet (A_{outlet}) has been measured from architectural drawings. The effective leakage areas of closed doors were modeled in accordance with an empirically derived dataset (Orme et al., 1998)

3.3.2. Viral Aerosol Dispersion and Infection Risks

The exhaled viral aerosol emission, concentration, decay, and inhalation by susceptible persons in the auditorium was simulated using the ZADIR model. The time-varying viral concentration at each time step was predicted, under the above steady-state airflow condition.

The rate of exhaled viral emission from an index case ($q_{t_0}^{index}$) was not known a priori. It was instead predicted back from the pattern of disease infection based on the values needed to initiate secondary infections. In case that masks were wore, the viral emission rates becomes $q_{t_0}^{index} * (1 - OPE)$, where OPE is the Outward Protection Efficiency of the mask, which quantifies its capacity to filter out particles from outward breath to the surrounding air for source control. The backcalculated $q_{t_0}^{index}$ was then checked against the literature. Additional sources of viral aerosols may enter the auditorium through air recirculation, the mode in which the air ventilation system was operating during the outbreak. The rate of recirculated viral mission ($q_{t_n}^{recir}$) at the time step *n* was estimated in Formula (*7*)

$$q_{t_n}^{recir} = F^{inlet} * C_{i_n}^{inlet} = F^{inlet} * (1 - \eta_{hvac}) * C_{i_n}^{outlet} \tag{7}$$

where F^{inlet} is the airflow rate (m^3/s) from all air inlets; η_{hvac} is the filtration efficiency of the HVAC filter; $C_{i_n}^{inlet}$ and $C_{i_n}^{outlet}$ are the mean viral concentration at the inlet diffusers and exhaust outlets.

The viral concentration for zone i at a time step n ($C_{i_n}^{v}$) can be solved using a mass conservation equation shown in Formula (8), in which the increment of viral aerosol quantities equals the gains of which from sources and incoming airflow, minus the losses from outgoing airflow and viral decays since the previous time step

$$\frac{(C^v_{i_n} - C^v_{i_{n-1}})V_i}{\Delta t} = q^{index}_{t_n} + q^{recir}_{t_n} + \sum_{k=1}^{K} C^v_{k_{n-1}}F_{k,i} - \sum_{j=1}^{J} C^v_{i_{n-1}}F_{i,j} - \frac{C^v_{i_{n-1}}V_i * 10^{k_d\,\Delta t}}{\Delta t} \qquad (8)$$

where $q^{index}_{t_n}$ and $q^{recir}_{t_n}$ are the rate of viral aerosols added to zone i by index case(s) and the recirculating air; V_i and ρ_i are the volume and density of air in zone i; J is the number of zones to its downwind, and K to its upwind. $C^v_{i_{n-1}}$ and $C^v_{k_{n-1}}$ are the concentration of infectious viral copies for zone i and the neighboring zone k at the previous time step $n-1$; Δt is a small time lag between time step n and n-1; $F_{i,j}$ is the outgoing airflow from zone i to j (m^3/s); $F_{k,i}$ is the incoming airflow from zone i to j (m^3/s); ρ_k is the density of air at zone k. k_d is the empirically estimated airborne viral survival rate for SARS-CoV-2 at -0.25 ($quanta/m^3.hr$) according to van Doremalen et al.(2020). The calculations of $F_{i,j}$, $F_{k,i}$, ρ_i, ρ_k are specified in the air and energy flow equations above.

The inhalation exposure of viral aerosols and the resulting disease infection risk was assessed using the modified WR equation by Gammaitoni and Nucci (1997), which accounts for the time-varying exposure under transient conditions. The disease infection risk P is a probability function of time-weighted average inhaled infectious viral quanta (q^v_e), which is dependent on the time-dependent quanta concentration in the ambient air, the length of exposure, and the pulmonary ventilation rate of individuals (Formula (9))

$$P = 1 - \exp(-q^v_e) = 1 - \exp\left(-(1 - IPE)\int_1^N \frac{C^v_{i_n} \times V_T}{T_b}\partial t\right) \qquad (9)$$

where q^v_e is the inhaled infectious viral quanta; IPE is the Inward Protection Efficiency of masks, which is the fraction of viral particle filtered in protection of the wearers. IPE equals 0% when no mask is worn; $C^v_{i_n}$ is the airborne viral load concentration at a specific time step n; T_b the duration of breath under normal respiration rate, estimated at one breath in every 4 seconds; V_T is the tidal volume, estimated at 500 cc (5×10^{-4} m^3) per breath in reference to the EPA exposure factors handbook (2011). N is the total number of time steps during the length of exposure. ∂t is a sufficiently small time period, during which the viral concentration can be regarded as stable. The air and viral particles inside the zone i of a susceptible person was assumed to be well-mixed, following the basic assumption of the WR approach. The same WR equation was also used to reversely calculate the source emission rate and the quanta concentration, if the disease infection patterns, length of exposure, and the pulmonary ventilation rate of individuals were known.

3.3.3. Model Setup, Evaluation and Sensitivity Studies

A schematic depiction of the ZADIR model setup is provided in Fig. 3. The model domain consists of the auditorium, which was divided into 2,951 interconnected zones. Each is shaped in a quadrilateral to match the dimension of an audience seating (a chair with a sitting person), which is 0.6*1.0m in width and length approximately. This allows for simulation of inter-zonal dispersion of viral aerosols and the person-to-person transmission risks. The peripheral spaces further away from the index cases were modelled in larger zones, in order to reduce the computational load. Similarly, the second floor and skyboxes, having played no role in disease transmission, were excluded in the model setup.

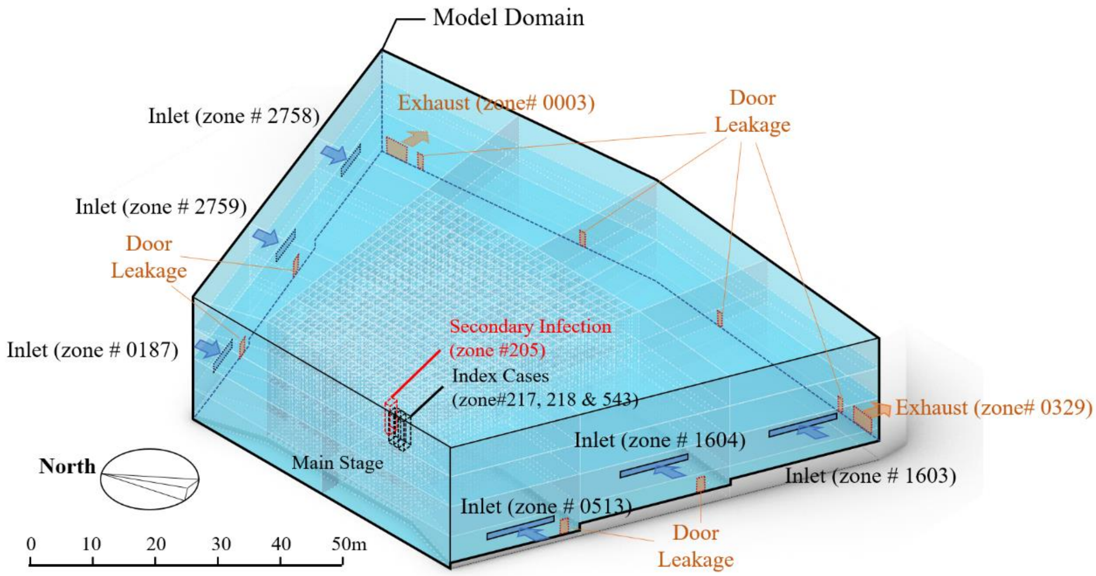

Fig. 3 The setup of ZADIR model to assess disease transmission in the auditorium outbreak.

The boundary conditions consisted of the air inlet, exhaust outlet, gaps of doors, and the domain was bounded by the structure enclosure of the walls, ceiling, and floor (Fig. 3). The inlet boundary consists of a volumetric inflow of 13.88 m^3/s from the air handling unit, distributed evenly via jet nozzles installed in six zones, each was assumed to have the inlet airflow rate of F^{inlet}= 2.31 m^3/s. The supply air temperature was assumed to have a constant value of 19 °C. The volume of air in the model domain, in the absence of a mechanical fan exhaust, was assumed to be forced to find its way out to the external boundary, which was set to equal the standard atmospheric pressure at 101,325 Pa. The dimension of the outlet openings was sized in accordance with the return grille (see Fig. S1 of the Supplementary Materials) and the gaps of entrance / auxiliary doors sized using the effective leakage area (ELA), estimated to be 1.8% of the door area by empirical literature (Orme et al., 1998). The initial condition of the model domain was assumed to be at standard atmospheric pressure at 101,325 Pa.

The Air Handling Unit was equipped with a Prefilter Section (labelled filter efficiency ⩾65%) and a Medium Efficiency Filter (labelled filter efficiency ⩾90%) according to evidence obtained from field studies. The total HVAC filtration efficiency η_{hvac} was therefore assumed to be 96.5%. The reduction of viral particle through deposition inside HVAC duct was considered negligible according to an empirical study conducted by Zhao et al., (2006).

The audiences in the auditorium were modeled both as heat sources (100W per person) and sensors, in which the viral concentration was computed and used to calculate inhalation exposure and infection risks. The masks worn by the audiences were assumed to be disposable surgical masks, the popular choice for the Chinese population according to a recent survey by Tan et al. (2021). Its inward and outward filtration efficiencies (IPE_S & OPE_S) were assumed to be 45%

and 75% for particles of 2 μm in size, which is considered the most likely to deposit in the respiratory tract when wearing a mask (Pan et al., 2021). The inward and outward filtration efficiencies for N95 respirator (IPE_N & OPE_N) were both assumed to be 99%.

The ZADIR model by components and as a whole has been evaluated using mock-up site experiment (Liang et al., 2018), wind tunnel (Huang et al., 2015), measurement in an urban neighborhood (Huang et al., 2020), and smoke tracer experiments (Huang et al., 2021), with reasonably good agreements between predicted and measure temperature, airflow, and tracer concentration (Fig. 4). The model can predict the trend and distribution of temperature, flow field, humidity, PM concentration, in reasonably good agreement with measurement data and CFD simulation (Liang et al., 2018).

On-site tracer gas experiment was considered impractical for many reasons. First, SF_6 can hardly reach a steady concentration in such as large space due to the dilution effect. Also, it is also difficult to simultaneously measure the tracer gas concentration at various locations inside the auditorium. The current multi-channel sampling equipment in possession by the research team (Innova 1409 and 1412i LumaSense Technologies, Ballerup, Denmark) would encounter large uncertainties in the temporal dimension given the time lags induced by sampling tubes reaching over long distances. Nor is it feasible to retrospectively duplicate the precise environment setting during the disease outbreak, i.e., temperature, anthropogenic heat sources, and external weather conditions.

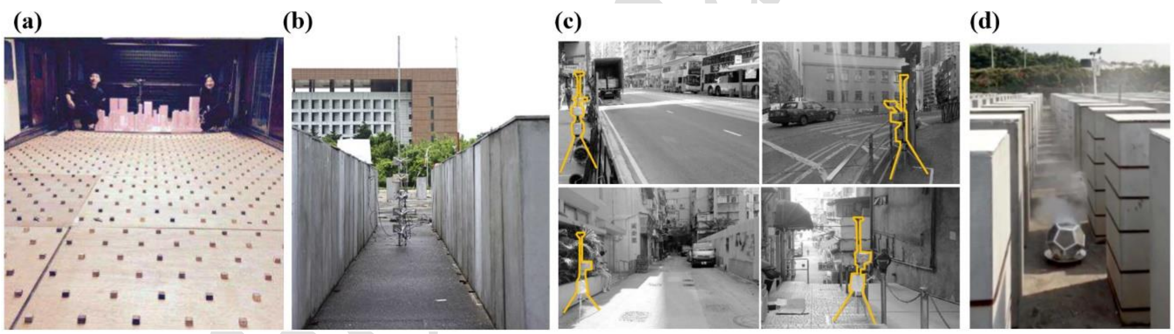

Fig. 4 Evaluation studies for components of (a) wind tunnel (Huang et al., 2015), *(b) mock-up street canyon* (Liang et al., 2018), *(c) urban neighborhood measurement* (Huang et al., 2020), *(d) smoke tracer experiments on mock-up site* (Huang et al., 2021).

Sensitivity studies were conducted to assess the infection risks in the auditorium under various scenarios (S1-S6), such as increased air mixing, outdoor air supply, displacement ventilation, social distancing, mask upgrade to N95 respirator with 99% inward and outward protection, and mask downgrade to thin cotton cloth with inward and outward protection of 40% and 50% (Table 1). The aim was to assess the protective effect for various ventilation and hygiene measures. Modeling parameters, such as the supply of recirculated or outdoor air, ventilation mode, seating capacity and mask filtration rates were allowed to change. Disease infection risks under each were compared with those of the S1, the status quo during the disease outbreak.

Table 1 A summary of simulation scenarios in sensitivity study

Scenario #		Air Supply Rate	Outdoor Air Supply	Ventilation Mode	Seating Capacity	Mask Type (Inward & Outward Filtration Efficiencies)
Status Quo	S0 Status Quo	13.88 m^3/s	0%	Mixing	100%	Surgical (45%, 75%)
Ventilation	S1 Increased Air Mixing	27.76 m^3/s	0%	Mixing	100%	Surgical (45%, 75%)
	S2 Outdoor Air Supply	13.88 m^3/s	100%	Mixing	100%	Surgical (45%, 75%)
	S3 Displacement Ventilation	13.88 m^3/s	100%	Displacement	100%	Surgical (45%, 75%)
Hygiene	S4 Social Distancing	13.88 m^3/s	0%	Mixing	50%	Surgical (45%, 75%)
	S5 Mask Upgrade (N95)	13.88 m^3/s	0%	Mixing	100%	N95 (99%)
	S6 Mask Downgrade (Cloth)	13.88 m^3/s	0%	Mixing	100%	Thin Cotton Cloth (40%, 50%)

4. Results and Discussion

The ZADIR model was used to investigate the disease infection risks in the auditorium. The results are presented as follows: 1) predicted infection risks in comparison with disease infection pattern, 2) back-calculation of quanta emission rate from index cases, and 3) predicted infection risks under alternative HVAC operational conditions and hygiene practices. Implications for public health practices in light of more contagious viral variants of COVID-19 are discussed.

4.1. Airborne Route and Patterns of Disease Infection

Simulated evidence of viral concentration supported the airborne transmission route. The transient viral concentration near the index cases is visualized in Fig. 5. The viral plume emanating from index cases spreads backwards, carried by the indoor airflow pattern from the stage towards the rear, driven by the location of the exhaust outlets on the back wall. The plume also spread sidewards, creating a high-risk zone in the row immediately behind the index cases, covering the location of the secondary case. A cross-sectional view of the viral concentration is shown in Fig. 7 (a). The viral plume travelled primarily upwards and backwards, driven by buoyancy and mechanical airflow.

The airborne transmission route is supported by statistical evidence. Table 2 shows the logistic regression of disease infection on predicted viral exposure. The results are statistically significant at the 99.9% confidence level. The odds ratio for viral exposure in 8950 (95% CI: 55, 1,456,422), suggesting a positive relationship between predicted viral inhalation exposure and disease infection (p=0.000). The odds ratio for the intercept is low at 0.00018, suggesting a low risk factor when viral exposure is low.

Table 2 Logistic regression of the diagnosed COVID-19 infection vs. predicted viral exposure at individual level

		N	*2,595*
		LR Chi^2 (1)	*7.060*
		Pseudo R^2	*0.398*
		Log likelihood	*-5.331*
Disease Infection	*Odds Ratio (p-value)*	*[95% Confidence Interval]*	
Inhaled Viral Exposure (quanta)	*8950 (0.000)**	*55*	*1,456,422*
Intercept	*0.00018 (0.000)**	*0.00001*	*0.00312*

** 99.9% confidence level*

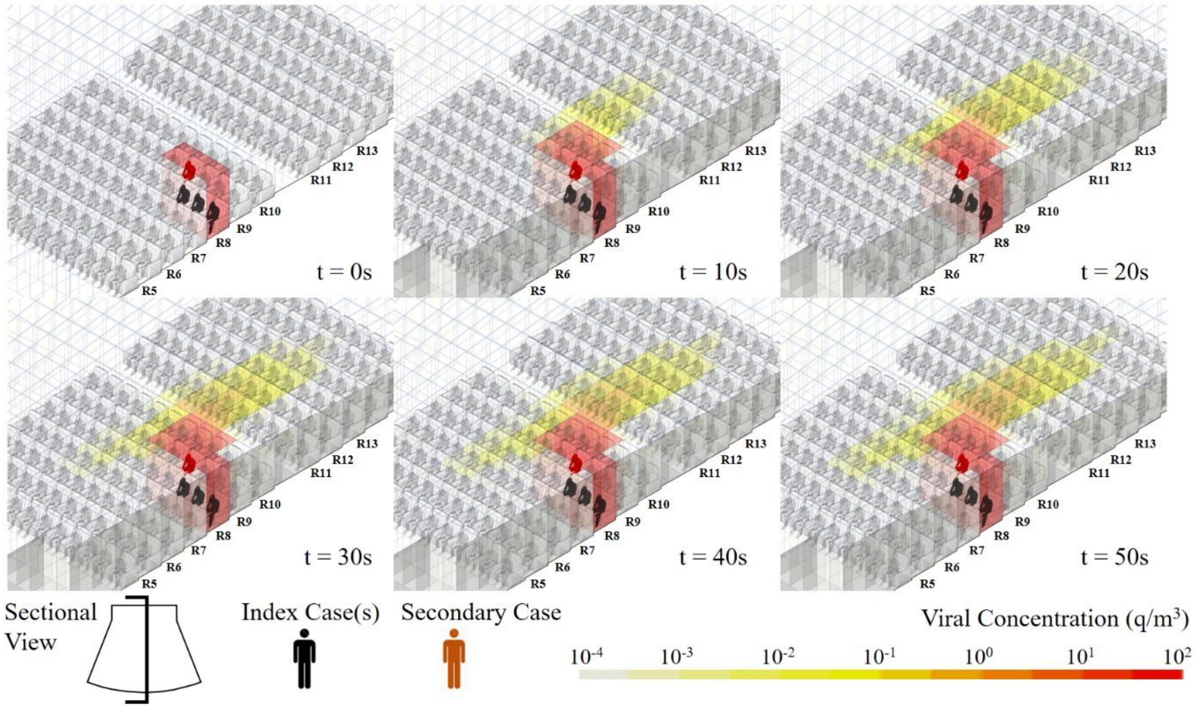

Fig. 5 Predicted transient viral concentration at the seat level.

4.2. Estimation of Source Quanta Emission

The source quanta emission rate $q_{t_0}^{index}$ was back-calculated based on patterns of disease diagnosis. The probabilities of disease infection, a dose-response function of the viral inhalation exposure, was predicted using the logistic regression model shown in Table 2. The source quanta emission rate can therefore be reversely calculated in the order of $q_{t_0}^{index}$ = 31 q/hr per person. The 95% Confidence Interval (CI) can be computed as between 19.1 and 40.0 q/hr based on the probabilities of the linear predictors of the logistic regression, using a method developed by Mark Inlow of the StataCorp (2017). Considering the only secondary infection during the disease outbreak, the above source quanta emission rates should be interpreted with caution.

The estimated $q_{t_0}^{v}$ for Delta cases was compatible with estimates from research literature on the original lineage of COVID-19, measuring between 4.9 and 31 q/hr during speaking (Buonanno et al., 2020a) or 60 q/hr during domestic activities (Huang et al., 2021). The estimate is considered high, however, given the viral aerosols were generated from normal breathing from cases who had supposedly remained silent and sedentary throughout the performance. In reference to the estimates <1 q/hr made by Buonanno et al. (2020a) for the original variant under resting conditions, the quanta emission rate of the Delta variant is at least 30 times higher than the original viral lineage. Since the three index cases in this study were all asymptomatic, who might have lower viral loading (and lower $q_{t_0}^{v}$). The quanta emission rate from symptomatic Delta cases could be higher still. The above calculation is based on the assumption that mask-wearing was uniform, although in reality masks might have been worn loosely by either the index cases or the rest of the audiences without effective protection. In these cases, the quanta emission rates were recalculated and listed in Table 2. $q_{t_0}^{v}$ required to inflict new infections can be 8 or 17 q/hr if either the index cases or the rest wore masks ineffectively. It can be as low as 4 when neither. Mask effectiveness therefore has a major impact on disease transmission.

Table 3 Estimation of quanta emission rate from index cases per mask-wearing scenario

Estimated source quanta emission rate		Index Cases	
		Mask Effective (Outward Protection 75%)	*Mask Ineffective (Outward Protection 0%)*
Secondary Case	*Mask Effective (Inward Protection 45%)*	*31 q/hr (95% CI: 19-40)*	*8 q/hr (95% CI: 5-10)*
	Mask Ineffective (Inward Protection 0%)	*17 q/hr (95% CI: 10-22)*	*4 q/hr (95% CI: 3-6)*

4.3. Infection Risks by Scenario

The disease infection risks inside the auditorium under each sensitivity scenario (and corresponding public health guidance) were plotted in Fig. 6. Each dot represents one of the 2,600 seats other than the three index cases. For scenarios under various HVAC operational conditions (S1-3), the time-weighted mean viral concentrations are illustrated in Fig. 7. The efficacy of each measure in disease mitigation was compared and discussed below.

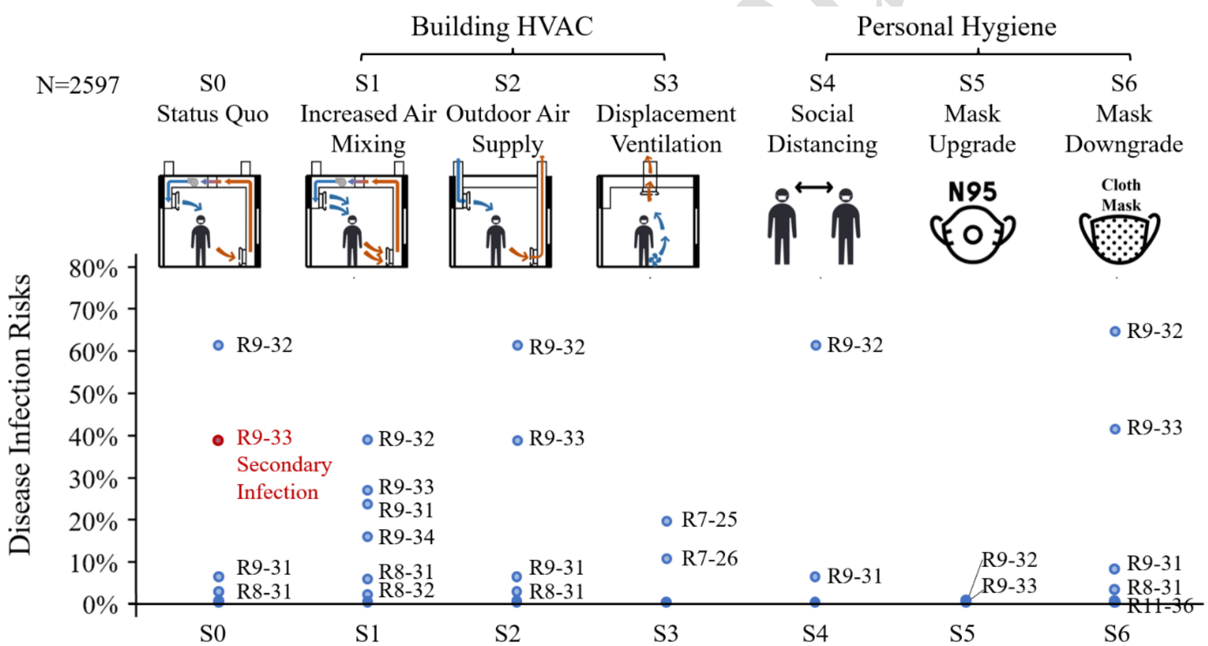

Fig. 6 Predicted infection risks for each scenario in the sensitivity study; each dot represents one of the 2,597 seats (bar the three index cases). The numbers after R stand for the row number and seating number (Row#-seat#)

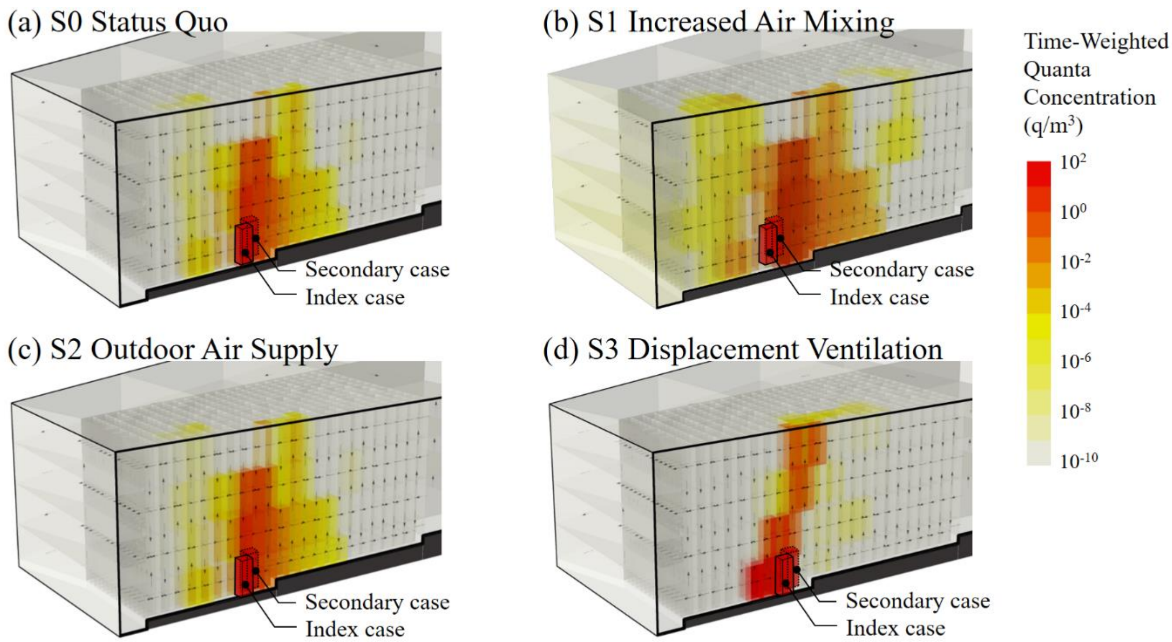

Fig. 7 Predicted time-weighted average viral concentration for (a) S0, (b) S1, (c) S2 and (d) S3

Increased air mixing offers limited protection, as the results in Fig 7 show from S0 to S1. Predicted infection risk for the worst case, the seat in the row immediately behind the index cases (seating ID R9-32), was reduced from above 60% in S0 to some 40% in S1, yet such effect was offset by increased risks of five others in the range of 5-30%. The simulated viral plume under S1 appears to have spread out further away from the index cases (Fig. 7 (b)) compared with those of S0 (Fig. 7 (a)). The result contradicts with the recommendation from ASHRAE Epidemic Task Force on the increase of air mixing in response to COVID-19, which states that "… promote mixing of space air without causing strong air currents that increase direct transmission from person-to-person" (Bahnfleth and Degraw, 2021). The increased air mixing can dilute and spread the viral plumes simultaneously into occupied zones, with or without strong air currents. The choice of air mixing rates, per suggestion from simulated results, is a trade-off between having a few high-risk seats and more medium-risk ones.

The efficacy of providing 100% fresh outdoor air supply seems negligible, as predicted risks in S2 is similar to those in S0. Few viral particles could re-enter the auditorium through recirculation due to the filters installed in the air handling units. From disease mitigation perspectives, the findings do not support ASHRAE's minimum requirement on outdoor airflow supply, which is set at 5.0 L/s per person for theatres (ASHRAE, 2009) or the 7.5 L/s per person based on body-odor control (Janssen, 1989). The protective effect from COVID-19 for doing so, at least in a large auditorium space, may be marginal.

The results support the displacement ventilation strategy. Predicted risk levels between S3 and S0 are visibly difference in Fig. 6. A Mann-Whitney U test (Mann and Whitney, 1947) was conducted on infection risks at the seat level to determine if displacement ventilation lead to a difference in mitigation (N=2597). Results showed that the mean risk differ significantly between the two scenarios ($z = 5.987$, $p=0.000$), rejecting the null hypothesis. This was further explained by simulated viral concentration shown in Fig. 7. With the air inlets at the ground level and exhaust outlets on the ceiling, the viral plume appears to be rising upwards towards the ceiling (Fig. 7 (d)), while the extent of viral horizontal spread has been reduced compared with S0 (Fig. 7 (a)). Our results agrees with a recent study that the mixing ventilation strategy tend to increase the range of infectious particles, while a displacement system can move contaminated air directly to the exhaust (Lipinski et al., 2020).

The protective effect for social distancing, in which audience occupy every other seat (S4), is lower than expected. By reducing the seating capacity to 50%, a commonly adopted guideline in theatres and auditorium, the predicted disease infection risks have been slightly reduced, yet the highest risk case (some 40%) remains. The visualization for S4 was not shown separately in Fig. 7, since it will overlap with those of S0.

Upgrading masking practice from the medical mask to N95 offers the most protection among all scenarios. The risk for the riskiest seat was reduced from 61% in S0 to 2% in S5. Compared with the costs associated with HVAC system retrofitting or the loss of revenues in S4, the mask upgrade is perhaps the most cost-effective as well, provided that the public is willing to comply. Meanwhile, downgrading mask from surgical mask (45%, 75% inward and outward protection) to the thin cotton cloth masks (40%, 50% inward and outward protection) is associated with a moderate rise in disease transmission risk.

4.4. Discussion

Results from this study have confirmed the hypothesis that the airborne transmission route can explain patterns of disease infection during the auditorium outbreak. Disease transmission for Delta cases may occur for susceptible persons in the wake of the exhaled viral plume. Alternative routes, such as close contact or fomite, were unsupported by the available evidence. The risk of transmission due to large ballistic droplets during close proximity situations would seem to be low in this event, considering that the secondary case, without acquaintance from the index cases, was sitting in a different row with a distance of 1.5 m in between. Neither was fomite transmission from index cases via chairs or surfaces likely, since nobody sitting next to the index patients on the same row was infected, while the sole secondary infection occurred in an adjacent row. The possibility that the transmission might have taken place elsewhere (Table S1 of the Supplementary Materials) has even less empirical support, since the only overlap between the index and secondary case, suggested by contract-tracing evidence based on mobile phone-based trajectories, was at the auditorium in the evening of July 22, 2021.

This study contributes new evidence to the viral emission rates of the Delta variant of SARS-CoV-2. The high viral emission rate of Delta cases can explain the airborne disease transmission in a relatively well-ventilated auditorium, despite that all members of audiences are wearing masks without speaking or singing. Our estimate is consistent with findings from existing literature that the Delta variant is more contagious than earlier lineages.

However, the findings from the simulation studies contradict HVAC guidelines which state that sufficient air ventilation can mitigate disease transmission risks (Morawska et al., 2020). Increasing air mixing, although diluting the viral plume, appears to spread it further into the occupied zone, while increasing outdoor fresh air supply had a negligible effect in the large indoor space. With Delta and more infectious viral variants such as the Omicron or its sub-lineage BA.2, the infection risk lies primarily in the high-risk zone near the index cases. Therefore, for a mixing ventilation system, the disease transmission risk cannot be significantly mitigated by raising mixing rates or introducing fresh air supply.

The results support the displacement ventilation mode over the mixing ventilation.
The former can reduce the person-to-person transmission by introducing air at the floor level and exhausting it at the ceiling, and this type of system should be promoted in new facilities when possible. The practical implication for this finding, however, may be limited to new buildings in the near term. Retrofitting a building's HVAC system can be costly and time-consuming, and the bulk of mixing ventilation systems in operation can only be phased out eventually, if at all.

Lessons can also be drawn for hygienic measures in public buildings. Maintaining social distance, such as 50% seating capacity, may not be sufficient to protect the person seating in the wake of the viral plume from index cases. Upgrading masks to N95 is highly effective against Delta, while downgrading to cloth masks can greatly elevate disease transmission risks. Body temperature-checking, which is widely adopted in practice, is largely ineffective since the index cases may be asymptomatic.

The study is limited in many aspects. It was unable to conduct the tracer gas experiment in the auditorium: it was practically challenging to reliably measure tracer gas flux in such a large space, given the length of the sampling tube required and possible lag time from gas concentration analyzer. Determining precise behavioral details, such as whether masks were worn properly by members of the audiences throughout the performance, remained a difficult task. The ZADIR model does not include a turbulence model, which might limit its capacity in simulating the diffusion of viral particles. Also, no account was taken of the interactions between viral particles and possible deposition on surfaces. Due to the single case of secondary infection reported in the auditorium outbreak, the estimated source quanta emission rates need to be interpreted with caution.

5. Conclusion

This paper has described a study using epidemiological evidence and numerical simulation on a COVID-19 outbreak in an auditorium involving the Delta variant. Based on a conditional assumption that transmission during this outbreak was dominated by inhalation of respiratory aerosol generated by three asymptomatic index cases, we used the best available evidence to infer the viral emission of the Delta variant of SARS-CoV-2. Exhaled quanta emission rate can be as high as 31 q/hr (95% CI: 19-40) from asymptomatic persons under sedentary activities, which is at least 30 times higher than estimates made for the original lineage of COVID-19. Exhaled viral aerosol can concentrate in the wake of the viral plume, even in a relatively well-ventilated space, creating a high risk zone in the vicinity of index cases. Such risk cannot be effectively mitigated by increasing air ventilation nor by supplying outdoor air. Social distancing also has limited protective effects. The displacement ventilation systems can effectively reduce the horizontal spread of viral plume and disease transmission risks. Lessons can be drawn to the operation, retrofitting and design of HVAC systems in public buildings. The public health message is that air mixing ventilation may not be universally sufficient, and displacement systems provide reduced risk of disease transmission. Mask upgrades to N95 is highly effective against Delta, especially those masks with high filtration rates (>99%) for fine particles. Knowledge on the possible exhaled viral from asymptomatic cases can assist researchers in understanding the characteristics of the Delta variant and more contagious variants of COVID-19 such as Omicron and its sub-lineage BA.2.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary Materials

Table S1 Technical parameters of the air conditioning unit

Item	Parameter
Model	FG-V-25-GR-10
Cooling Power	202.0 kW
Heating Power	343.4 kW
Airflow Rate	25,000 m^3/h
Power	7.5 kW/360 V/3φ 50 Hz
Current	15.6 A
Prefilter Section (3LG65 Bag Filter)	Efficiency ≥65%
Medium Efficiency Filter (3LG90 Bag Filter)	Efficiency ≥90%

Information on the HVAC system layout together with building floorplan were acquired from the operator of the auditorium (Fig. S1). The location of the 60 inlet diffusers and 2 exhaust outlets relative to the auditorium floor plan is shown in Fig. S1. Each diffuser has a circular diameter of 0.4m, and each exhaust outlet measured 1.4m (width) ×2.5m (height) in dimension.

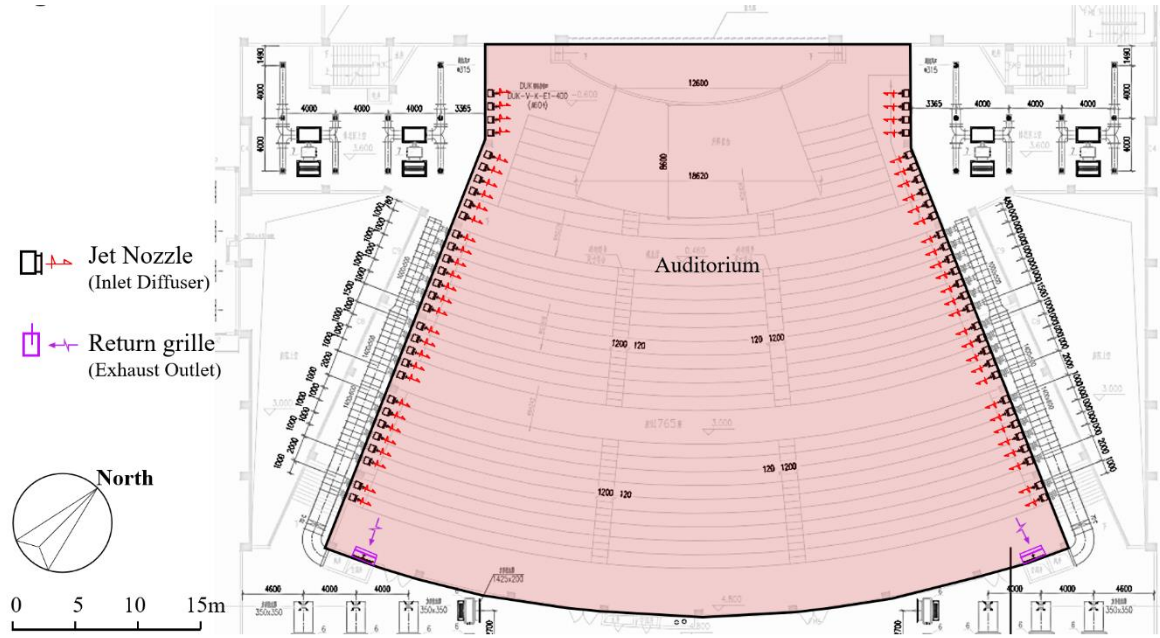

Fig. S1 Building floorplan of the auditorium and the air ventilation systems.

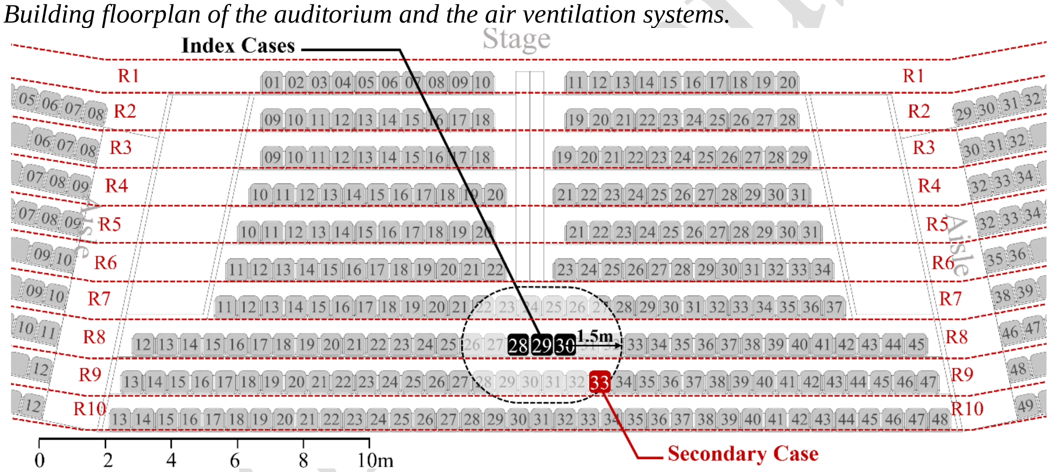

Fig. S2 Seating layout plan with the index and secondary cases during the disease outbreak

(a) (b)

Fig. S3 (a) A close-up photo of the air handling unit of the HVAC system operated by the auditorium; (b) the jet nozzle of the inlet diffuser on the side wall. (Both photos were taken on Sept.16, 2021)

Fig. S4 Panoramic view of the auditorium space (photo taken Sept. 16, 2021)

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