Evaluation of Ventilation Strategies to Mitigate Airborne Infection Risk in a Dental School: A Three-Dimensional CFD Analysis of Airflow Patterns and Ventilation Efficiency

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ARTICLE INFO	ABSTRACT
	Infection prevention and control is a crucial element in providing a safe environment for dental clinics and reducing airborne infections risks during dental procedures. In response to the prevailing COVID-19 situations, the clinical space in the dental school was operated with ventilation strategies, increasing air exchanges and incorporating supply and return air arrangement based on seating positions. This study evaluated airflow patterns to examine personal exposure to airborne infection risk under these strategies. The three-dimensional computational fluid dynamics technique using computational fluid dynamics (CFD) analysis was performed in 50 multi-units of the dental school of the university in Bangkok, Thailand. The results revealed substantial improvements in indoor ventilation. Improvement of airflow patterns and directions surpassed conventional design of the pre-existing building's system and helped reduce airborne contaminant concentrations. The further discussion of occupant-based design in dental schools is needed to optimize ventilation systems and engineering controls concerning indoor airborne infections.

1. Introduction

Since the first cases of novel coronavirus were reported in December 2019 with the SARS-CoV-2 causing COVID-19 spreading rapidly across the world, this led the World Health Organization (WHO) to declare a Public Health Emergency of International Concern (PHEIC), and to characterize the outbreak as a pandemic by March 2020 [1]. When the new caseloads were on the rise, the healthcare facilities were adapted to manage significant challenges related to their operations, while their staffs

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were first-hand as frontline to handle a crisis for saving lives and providing treatments as new information emerges. Vaccination must be complemented in a long-term [2]. Meanwhile, for addressing near-term needs, a framework for implementations was created to help minimize infection risks in healthcare facilities and settings to assure optimal delivery of health services [3]. The indoor airborne transmission has been reported by the droplets and the aerosols [4, 5] relying on the air distribution and ventilation, where their adequate and effective strategies should be ensured.

While the pandemic has continued to rage around the world, building healthcare facilities that can maintain normal operating is essential. The dental professionals and their staff are at a under the high risk of airborne infections since they come into close contact with the droplets and the aerosols during dental treatment procedures. This increases their chances of inhaling the saliva and respiratory secretions from an infected individual or coming into direct contact with mucous membranes, oral fluids, and contaminated instruments [6]. In terms of the dental school, the pandemic also caused a huge disruption on on-campus activities [7], which have been operated under screening and infection control restrictions while maintaining the safety of students and staff.

The core of dental curriculum requires several studies or assessment methods related to dental practice as clinical training progresses. The pandemic changed how face-to-face learning and clinical activities were delivered with limitations on interpersonal and physical contacts. Meanwhile, the improved air conditioning and mechanical systems is a key to control infection risks to supply clean air and dilute contaminated air [8]. The clinical spaces performed to operate under ventilation strategies, increasing the air change per hour (ACH) and incorporating supply and return air coping with seating positions, focusing on prevention practices to protect the health of dental personnel and patients. Thus, this study aims to evaluate airflow patterns and directions to examine personal exposure to airborne infection risk under these improvement strategies. The three-dimensional computational fluid dynamics technique using computational fluid dynamics (CFD) analysis was performed in 50 multi-unit of the dental school of the university in Bangkok, Thailand. As a few studies in multi-unit clinic have been done, the results from this study can act as an initial step to develop operation strategies to optimally enhance health and wellbeing of the occupants, while the insight gained from this study will help improve engineering controls techniques for future perspectives on designing out these risks.

2. Literature Reviews
2.1 Patterns of Airborne Infection

Ventilation in buildings has been seen significant due to a major scientific effort to identify the person-to-person infection transmission of the SARS-CoV-2 through the respiratory droplets and contact routes, causing the COVID-19 [5]. Transmission routes identified as,

   i.   Fomites
  ii.   ballistic drops (or large droplets)
 iii.   aerosol (or airborne) particles (or droplets)

The small significant role of the fomites effect on the spread of the disease has been widely reported, while large droplets are thought to contain far less viral material than airborne particles [9]. The Aerosol or the airborne, involving particles travelling through air dominated by advection over gravitational effects, is the main vector for the viral transportation and transmission in the adjacent operating field as well as the area beyond the frontier [10]. This is often referred to the

airborne infection route. The main sources of uncertainty from the behavior of ballistic drops and aerosol particles are affected by environmental constraints [11].

Airborne pathogens play important roles in the spread of infection. To protect the healthcare workers, the contaminant concentration should be decreased to reduce the exposure risks through tuberculosis, the lower respiratory infection, and other viral or bacterial diseases as produced by various dental procedures, like Pneumonia. A major purpose of ventilation is to dilute contaminated air in the breathing zone and provide clean air to healthcare workers by achieving high air change rates that help to dilute the contaminant [12].

2.2 Ventilation Strategies to Mitigate Airborne Infection Risk

Mechanical ventilation systems should be regularly and adequately cleaned, tested and maintained in line with control approaches. Some controlled parameters are temperature, filtration, relative humidity, reducing recirculation or increasing the outside air fraction [13]. Past research showed that improving strategies can efficiently reduce contamination in clinical spaces. One of the critical factors in refreshing indoor air and removing pathogens is ACH [14, 15]. The number of ACH used to ventilate the healthcare space directly impacts the transmission. ASHRAE 170 (2017) [13] and the CDC guidelines (2019) [16] suggest a minimum of 12 ACH for hospital insulation rooms. For dentistry, the ACH consider the total air including recirculated and outside air brought into a room. It require a minimum of 10 ACH for newly built dental treatment rooms [17]. The guidance for dental settings during the COVID-19 response mark on 6 ACH [18] while the Dental Association of Thailand recommend [19] minimum 12 ACH for the dental clinic, referring to ASHRAE 62.1 (2019).

Yu *et al.,* [20] and Verma *et al.,* [21] found that the higher ACH minimized infection risk in removing the airborne pathogens in hospitals while maximizing energy efficiency. Chow and Yang [22] found that the particle concentrations in the operating room and at the patient's position increased with decreasing inlet velocity. Moreover, adjusting air velocities corresponding to exhaust location can improve the ventilation performance in removing aerosols, which were quickly removed at the area with high exhaust velocity, closing to the outlets [23, 24]. Although the concept of ACH is generally applied in practice to enhance airborne pathogen dilution and removal, higher ACH could lead to more air mixing and thus increased risk of airborne transmission. Mousavi and Grosskopf [25] and Villafruela *et al.,* [26] said that particle concentrations were found higher due to the enhanced ventilation created by higher ACH. The decrease of ventilation rates could produce less turbulence, and better pathogen containment [27]. As the optimal ventilation rate depends on the location of the infection source, containing and exhausting the airborne microbes within the area of the source may be a better choice. Any new ventilation strategies to cope with unexpected surges of demand like the pandemic would be evaluated.

By replacing air concept, age of air (AOA), as an average time the air has spent in a space accumulating unwanted contaminants, is one of the common metrics used for evaluating contaminant control. It can be used to evaluate the efficiency of the ventilation system in relation to changing the old air to new, the lesser the AOA, the better the indoor air quality. It is also defined as the average time that the particles of supplied air move from the inlet to indoor vantage point [28].

The positions of the inlet and outlet vents significantly affect the pathogen removal efficiency, and that can be more cost-effective when airflow is taken into consideration [29]. King *et al.,* [30] found that while increasing the ACH had little improvement on the airborne pathogen reduction, the location of the outlet vent with respect to the infectious patient played a decisive role in the process. Ho *et al.,* [31] found that placing the inlet near the center of the wall could give better ventilation

performance, whereas the location of the outlet did not affect the performance much in a hospital operating room. The co-ordination between the inlet and the outlet was highly recommended [32].

Using filtration and decontamination devices can increase ventilation performance. Increasing the ventilation rate is not an energy-efficient strategy without appropriate filtration [33]. The high-efficient filtration, like Minimum Efficiency Reporting Values (MERV), might be a cost-effective strategy compared to similar outdoor air ventilation [34, 35]. High-efficiency MERV filters help decrease contamination spread at a reasonable price based on indoor space functions. Recently, the US-CDC recommended upgrading the central HVAC filter efficiency to a MERV-13. This measure is particularly useful when there are limited options for enhanced outdoor air delivery. Additionally, High-Efficiency Particulate Air (HEPA) are another most common used devices reserved for medical settings. HEPA filter system was tested for different settings and positions. Anghel *et al.,* [36] indicated increasing ACH and using HEPA can remove contaminants in clinical areas. However, it contributes to a pressure drop and hence higher energy use for fanning [37].

Employing barriers like partitions [38, 39], a buffer zone between spaces with higher and lower infection risk and spaces under negative pressure [40], and engineering controls like filtration [41] are suggested as practical strategies to remove contaminations. The impacts of using barriers with different heights on airborne transmission as a low-cost strategy. For dental facilities with an open floor plan, it is recommended to keep at least 6 feet of space between patient chairs and place physical barriers between patient chairs. If fire code compliant, floor-to-ceiling barriers are preferred. It is also recommended to orient operatories parallel to the direction of airflow [18]. In the post-COVID-19 era, more research efforts should be put into investigating ventilation and airborne transmission in the whole-building multi-zone context.

Innovative ventilation strategies, such as Personalized ventilation (PV), could considerably improve occupant's wellbeing in indoor spaces. It is a strategy controlled by an individual to supply clean air directly to breathing zones [42, 43] for reducing airborne transmission and preventing cross-contamination. Yang *et al.,* [44] suggested using a Personalized Exhaust (PE) to reduce the aerosol spread to the breathing zone from a full-scale experiment in a test chamber representing a health consultation room and compared exposure reduction for infected and healthy occupants. Tham and Pantelic [45] investigated PV performance in reducing the infection risks when associated with other ventilation strategies.

Combination of engineering controls, such as decontamination devices and filtration, reduce contamination concentration if these decontamination facilities were selected based on building functionalities and the expected level and size of particles. All ventilation strategies could be efficient for removing contaminations, if the essential design features were optimized. Highlight on the exhaust's number and location, ventilation rates, and airflow pattern are critical elements. Past research recommends a future direction for researching the possibility of shifting the ventilation paradigm from space-based central systems to occupant-based design for infection control in indoor spaces [37].

2.3 CFD-based Simulations Study on Airborne Infection Risk

The airflow in enclosed environments can be described by a set of differential equations [46]. CFD-based simulations can calculate fluid motion using numerical approaches to evaluate the ventilation effectiveness, becoming a tool for the modelling of disease transmission in buildings after the 2003 SARS epidemic [47] to improve healthcare ventilation. It is necessary to carry out multi-phase simulations, where the transport and the trajectories of the pathogen droplets can be described [48].

Various CFD-based simulations can be found with infections of different airflow patterns to understand the effects of different ventilation strategies. They discussed the effects of various ventilation strategies on airborne pathogen dispersion and the pathogens removal efficiency, while looked into the airflow and transmission pathways influenced by healthcare designs. One of the benefits of using computational simulation is that it is completely remote, causing no disturbance to the target, and thus highly favorable for less strictly accessible environments. It can also simulate various scenarios and building configurations that are difficult to achieve in experiments [49, 50].

Combinations of inlet and outlet locations, air velocity, and ACH were investigated using CFD to understand the airflow patterns and identify the best combination. The simulated results can model the airflow pattern and tracer distribution to identify the airborne transmission pathways, and help reconstruct the transmission routes. For example, Yam *et al.,* [51] found that using exhaust air ducts to extract air at the ceiling with desired ACH could restrict the flow of contaminated air. The proposed system could be adopted as a ventilation strategy for makeshift isolation wards in the case of an outbreak. Yang [52] suggested to maintain better air quality by the inlet and outlet arrangements on the airflow in a sickroom, comparing to other types of ventilation. Satheesan *et al.,* [53] found that using of outlets above and at the back of the patient's heads with a high exhaust airflow rate helped remove exhaled pathogens and enhanced the deposition of particles back onto the source patient's body, while the pathogen's concentrations in the air was reduced. Jo *et al.,* [54] analyzed the indoor airflow and tracer dispersion during the MERS-CoV outbreak in South Korea. The results indicated that the outdoor wind dominated the airflow while the mechanical ventilating was not operating, causing a spread of tracer particles to the downstream ward where most reported cases were found.

Although many have discussed various ventilation strategies for reducing the airborne transmission, it is difficult to generalize the best ventilation strategy as both the airflow and the dispersion and deposition of airborne particles depend on several environmental factors including the location of an infectious patient, the positions of obstacles, and human movements and activities. It is often difficult and computationally exhaustive to model all possible combinations of parameters. CFD, therefore, can only provide an insight into the possible airflow patterns in different ventilation scenarios and facilitates the process of identifying and determining the most appropriate design, operation and maintenance for simulated healthcare environments.

3. Methodology
3.1 Case Study Approaches

The air-conditioned clinical space in faculty of dentistry, Chulalongkorn university, built in 2016 in Bangkok, Thailand, was chosen to study on indoor environmental conditions with ventilation strategies. The clinical space is an open-planned layout for 50 multi-dental units, located on 13th floor of the building. Each unit fully equipped, divided with 1.10 m. partition, as shown in Figure 1. Dentists, dental staff, with faculties perform service to patients as they are voluntarily available to be treated by undergraduate dental students for patientcare training skills, such as scaling the teeth, filling the tooth and extract the tooth. As the layout shown in Figure 2(a) and 2(b), the target space volume did not include waiting area, offices, toilets, storages, mechanical rooms, and other non-ventilated controlled space.

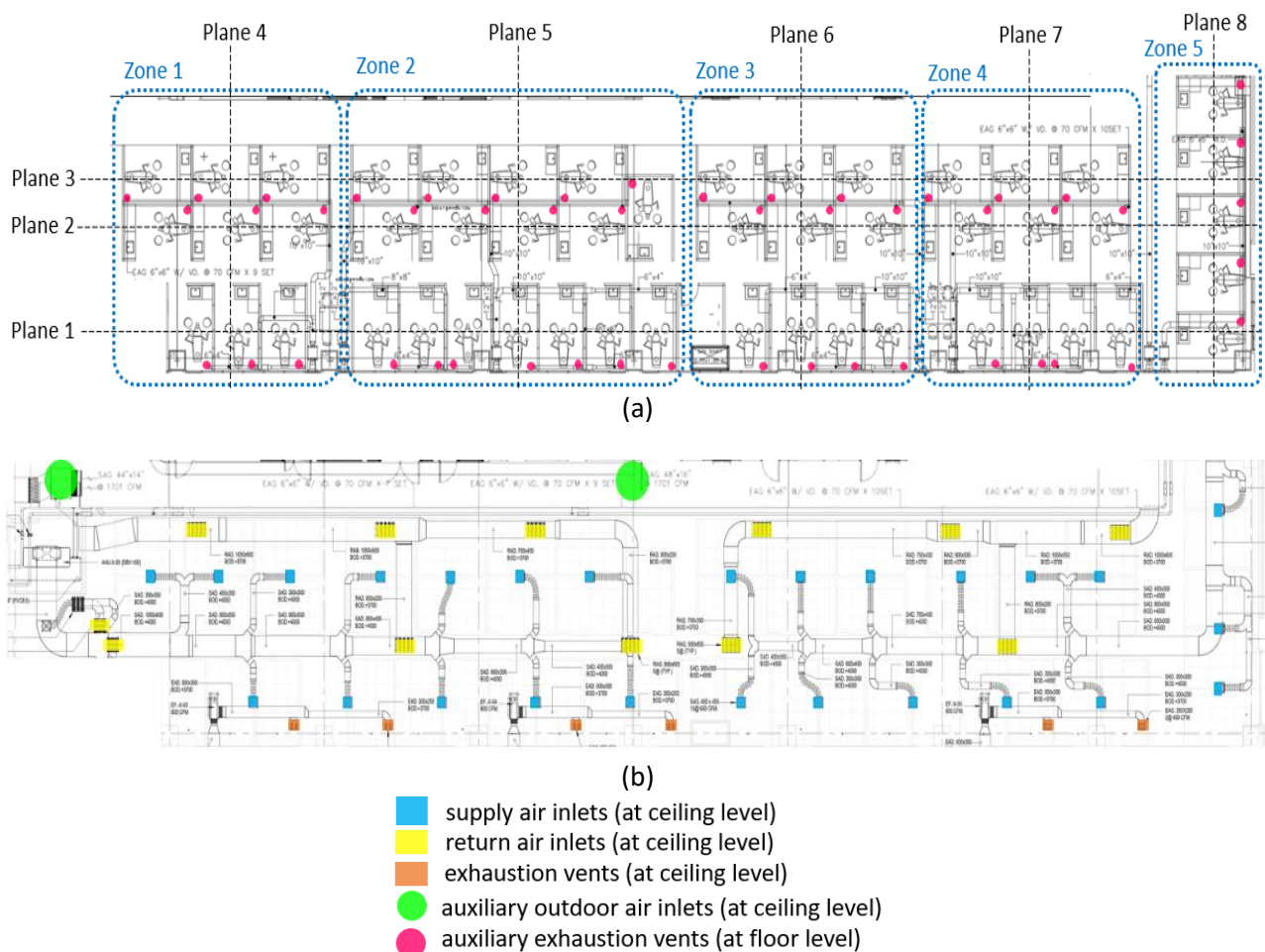**Fig. 1.** Photo of air-conditioned clinical space of 50 multi-unit dental school in this study

(a)

(b)

- 🟦 supply air inlets (at ceiling level)
- 🟨 return air inlets (at ceiling level)
- 🟧 exhaustion vents (at ceiling level)
- 🟢 auxiliary outdoor air inlets (at ceiling level)
- 🔴 auxiliary exhaustion vents (at floor level)

Fig. 2. The layout of multi-unit dental school (a) a room layout with exhaustion vents at the floor level, alongside cross-section planes and zonings, (b) air-conditioned and ventilation diagram with supply air inlets, return air inlets, exhaustion vents, and auxiliary outdoor air inlets at the ceiling level

The clinic is operated with central air conditioners through a system of supply and return ducts. After the COVID-19 outbreak in December 2019, the school employed temporarily closure for practicing social distancing, then improve on ventilations to reopen for basic dentalcare services during mid-2020. As Figure 2(a) and 2(b) illustrated, the ventilation strategies involved installing two

auxiliary outdoor air units at the ceiling level to increase ACH, while auxiliary exhaustion vents were also installed at the floor level under each patient's seating position. These were done to drew outside air in and injected it into the space, with a purpose to improve the impact of supply and return locations on the airflow patterns by removing aerosols or droplets in a mixture of air from clean (at the ceiling level) to less clean area (at the floor level) within the room.

3.2 Computational Domain

This study aimed to investigate indoor air ventilation through the utilization of the computational fluid dynamics technique. Specifically, the research was carried out within a three-dimensional indoor space comprising 50 multi-units located within the dental school of a university in Bangkok, Thailand. To accurately define the flow domain, a three-dimensional representation of the area was generated using CAD software, Autodesk Revit and ANSYS Spaceclaim. Unnecessary objects were then eliminated from the floorplan, resulting in the inclusion of only the walls and wall partitions of the dental units.

Figure 2(a) and 2(b) illustrates the constructed flow domain that will be utilized in this study, with the improved system. The airflow inlets (supply) are primarily positioned on the ceiling, with an inlet size of 350x350 mm. These inlets are strategically designed to distribute the airflow throughout the area, thereby maximizing the flow area. Additionally, the outlet (return) vents are positioned on the ceiling, with dimensions of 120 x 600 mm. The improvements incorporate outside air supply at the ceiling level and exhaust vents at the floor level, based on the configurations of the dental units and seating positions. Overall dimensions of the target clinic are 66.45 x 30.22 x 3.10 m. The geometry was then divided into a computational mesh using ANSYS Fluent Mesher 2023R2, resulting in 25 million cells with an optimal aspect ratio. The grid independence test was also conducted to ensure that the mesh is sufficient for capturing the airflow characteristics and also provide the accuracy of computational resources.

3.3 Mathematical Model

To solve the flow governing equation and determine the AOA, Ansys CFX was employed. The 3D steady-state Reynolds averaged Navier-Stokes equations with standard k-epsilon turbulence model were used in this study. The k-epsilon model is known for its robustness and computational efficiency, making it a popular choice for a wide range of turbulent flow simulations with great accuracy [55-58], utilized to model the airflow within the study area as follows:

$$\frac{\partial}{\partial x_j}(\rho U_j) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho U_i U_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\tau_{ij} - \rho \overline{u_i u_j}\right) + S_M \tag{2}$$

where u_i is the fluctuating velocity, S_M is the sum of the body forces, and τ_{ij} is the viscous stress tensor. The standard k-epsilon model was expressed as:

$$\frac{\partial}{\partial x_j}(\rho U_j k) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \rho \varepsilon + P_{kb} \tag{3}$$

$$\frac{\partial}{\partial x_j}(\rho U_j \varepsilon) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}(C_{\varepsilon 1}P_k - C_{\varepsilon 2}\rho\varepsilon + C_{\varepsilon 1}P_{\varepsilon b}) \tag{4}$$

$$P_k = \mu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_i}{\partial x_j} - \frac{2}{3} \frac{\partial U_k}{\partial x_k} \left(3\mu_t \frac{\partial U_k}{\partial x_k} + \rho k \right)$$

where C_μ = 0.09, $C_{\varepsilon 1}$= 1.44, $C_{\varepsilon 2}$= 1.92, σ_k = 1.0, σ_ε = 1.3.

The air flow velocity is denoted as U. It is assumed that the air properties, including density, ρ and viscosity μ remain constant as 1.185 kg m^{-3} and 1.831 x 10^{-5} Pa s, respectively. A commercial solver, ANSYS CFX, was employed. The meshing and computation processes were conducted on a workstation equipped with a 24-core AMD Threadripper x64 processor and 128GB of RAM.

3.4 Boundary Conditions

The walls of the building were treated as no-slip boundary conditions. The air only enters the building through the designated air inlets, which are divided into five zones as Figure 1(a). Zone 1 to 3 consists of 12 inlets, each with a volumetric flow rate of 650 CFM. Zone 4 and 5 consists of 14 inlets, with each inlet also having a volumetric flow rate of 650 CFM. The outlets were defined as pressure outlets given gauge pressure of 0 pascal. In the improved case, two additional auxiliary outdoor air inlets were incorporated, as depicted in Figure 1B. Furthermore, additional outlets were installed on the floor level of each dental unit. Each auxiliary air inlet has a volumetric flow rate of 1701 CFM. For the initial conditions, the pressure is set as atmospheric pressure. The boundary conditions assigned to the system were summarized in Table 1. The x, y, and z-component of the air velocity are set to zero.

Table 1
Boundary conditions

Boundaries	Value	Unit
Zone 1/2/3 Air Supply (Velocity Inlet)	2.329	m/s
Zone 4/5 Air Supply (Velocity Inlet)	2.329	m/s
Air Return (Pressure Outlet)	0	Pa
Auxiliary Air Supply 1 (Velocity Inlet)	0.248	m/s
Auxiliary Air Supply 2 (Velocity Inlet)	0.403	m/s
Auxiliary Air Return (Pressure Outlet)	0	Pa
Wall Shear Condition	No-slip	-

4. Results and Discussions

The clinical spaces of 50 multi-units of the dental school have been replicated in detail as a computational model for CFD simulations. The airflow and the indoor environmental conditions were simulated to evaluate airflow streamlines, patterns, velocity as ideal strategies. A grid independence test was carried out to ensure the reliability of the simulation results, specifically regarding the air velocity and the AOA within the dental clinical space. The objective of this test is to determine the point at which further refinement of the mesh does not significantly affect the simulation outcome, indicating that the numerical solution can be considered independent of the mesh size. Four different mesh densities were analysed, with element counts of 15, 20, 25, and 30 million. For each mesh density, the simulations were run under the same boundary and initial conditions. The results are shown in Figure 3.The average air velocity and AOA values stabilize between the 25 and 30 million element meshes with a variation of approximately 2.10% and 0.65%, respectively. The mesh with 25

million elements was used for the rest of the study for simulation in two case, case A: the existing space and case B: the space with improved ventilation strategies, with consideration to evaluate air distribution throughout the space.
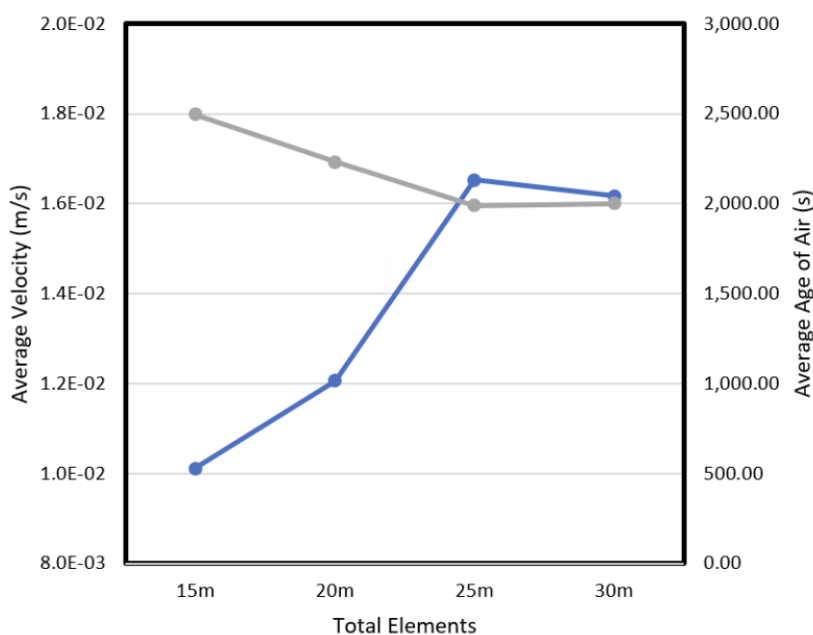

Fig. 3. Grid Independence test showcases the variation of average air velocity and the average age of air (AOA) at height of 1.10 meter across four mesh densities ranging from 15 to 30 million elements

Figure 1(a) illustrates the cross-section plane and the seated zonings to visualize simulation results. Locations of three vertical planes are as plane 1 to 3 in the axis of dental units spanning the entire length of the space. Meanwhile, planes 5 to 8 span the entire width of the space, as representatives of the seated zones from zone 1 to 5, respectively. For evaluating at inhalation level, each plane was simulated in two different spandrel heights, namely 0.70 m. and 1.10 m., to present the results as common dental practices in the dental breathing zones of a patient at lying position to their dentist and a dentist at sitting position, respectively.

In response to the prevailing COVID-19 situations, the clinical space was operated with ventilation strategies for 3.55 ACH by installing auxiliary outdoor air units and exhaustion vents, while the existing system performed 2.26 ACH before the improvements, using the calculation method from the volumetric flow rate and the space volume. It can be seen that the infection prevention and control methods in indoor space can be improved, since allowing more air to enter the space will dilute airborne contaminant concentrations and reduce the transmission risk of airborne infection. This is comparable to the recommendation for air exchange from the Dental Association of Thailand as 3 ACH [19]. However, it is worth noting that improvements for increasing to 6-12 ACH should be discussed in the faculties and staff for getting adequate ventilation strategies on several dental practices [17, 18].

By examining the AOA, it becomes possible to assess the effectiveness in terms of air exchange. This information is valuable for evaluating indoor air quality and creating healthier, more comfortable environments. For the existing condition as case A, Figure 4(a) and 4(b) display the existing contour plot of the AOA at 0.70 m. and 1.10 m., with the average of 2,178.21 and 2,168.17 seconds, respectively. Figure 5(a) and 5(b) display the existing contour plot of the air velocity at 0.70 m. and 1.10 m., with the average of 0.02 and 0.02 m/s, respectively. Although the distributions were

generally consistent, there was a slight difference in some units depending on the layout of the partition and corridor. Interestingly, it is envisaged that many infections control precaution of physical distancing practicing suggested the use of partitions or screens as an engineering method [18, 59]. Additionally, it is observed that the areas lacking sufficient air supply and air return are in the corners of the hallway with higher values of the AOA. It is also evident that there are some variations in the plot, where certain areas exhibit lower AOA values compared to others. This discrepancy arises because these specific dental units are positioned directly beneath the air supply units, continuously receiving fresh air into the system.
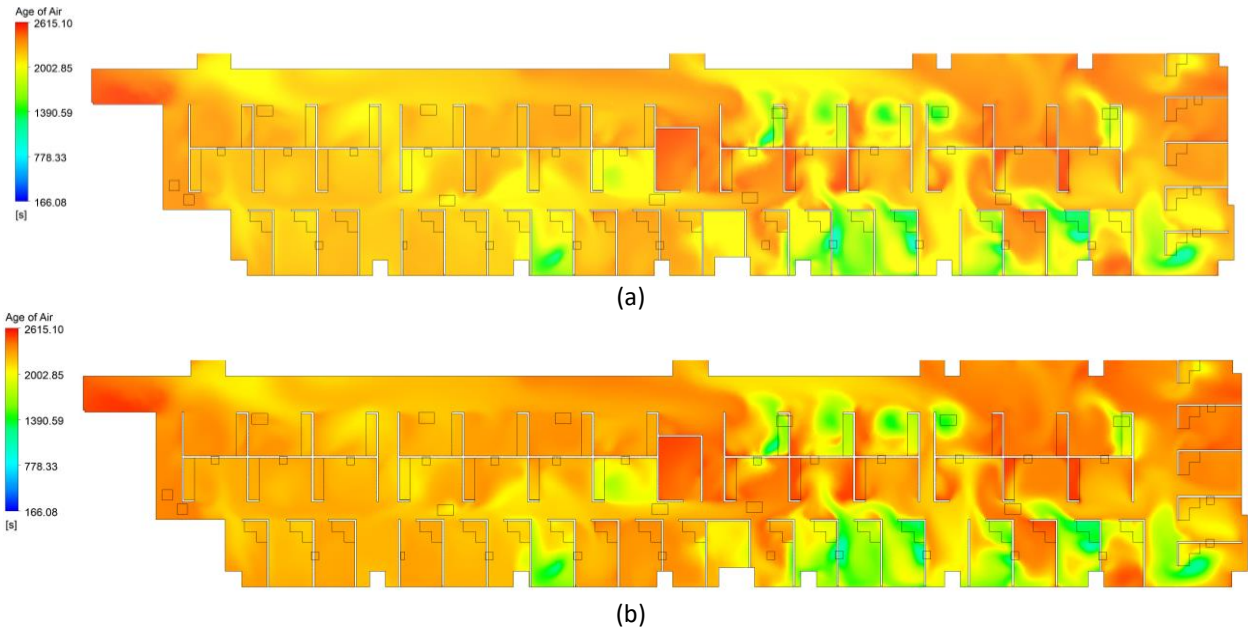

Fig. 4. Age of air (AOA) distribution in the clinical space at hight level 0.70 m (a) and 1.10 m (b) for case A
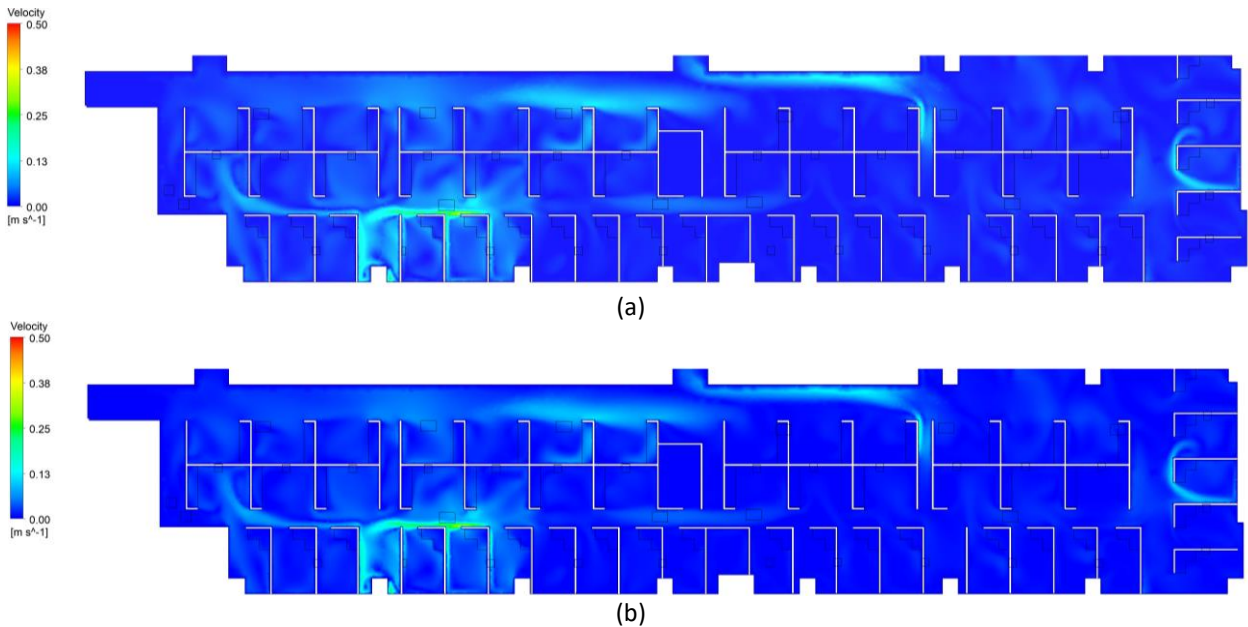

Fig. 5. Air velocity distribution in the clinical space at hight level 0.70 m. (a) and 1.10 m. (b) for case A

Time required for airborne-contaminant removal in this study is on target to reach at 8,280-12,420 seconds [16], with slightly high air velocity from the supply air. However, considering on the existing ACH, the new supply air within 60 minutes should be less than 1,592.92 seconds to

adequately dilute the concentration of contaminants in the air without an impact on health. Practical ways to improve ventilation strategies can be found as case B: the space with improved ventilation strategies. Figure 6(a) and 6(b) display the contour plot of the AOA at 0.70 m. and 1.10 m., with the average of 222.03 and 220.53 seconds, respectively. Figure 7(a) and 7(b) display the contour plot of the air velocity at 0.70 m. and 1.10 m., with the average of 0.06 and 0.07 m/s, respectively. The AOA exhibits higher values, indicating that the improved ventilation design performs effectively. The results show substantial improvements on airflow and ventilations. The AOA significantly reached the target by supplying new air less than 1,014.08 seconds within 60 minutes. However, the ventilated improvements indicated that the auxiliary outdoor air unit resulted in a higher air velocity which can possibly increase the deviation between thermal neutral and comfort [60]. Any improvements should be cautiously discussed with all forms of human factors considerations for better health and wellbeing in the long run.
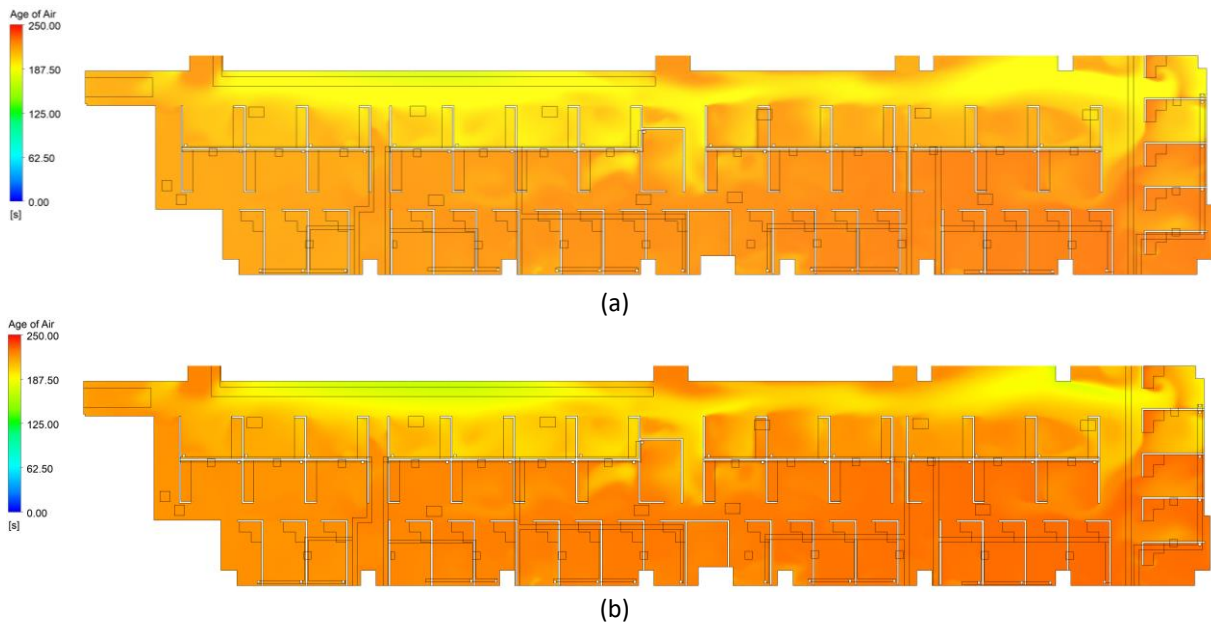

(a)

(b)

Fig. 6. Age of air (AOA) distribution in the clinical space at hight level 0.70 m. (a) and 1.10 m. (b) for case B
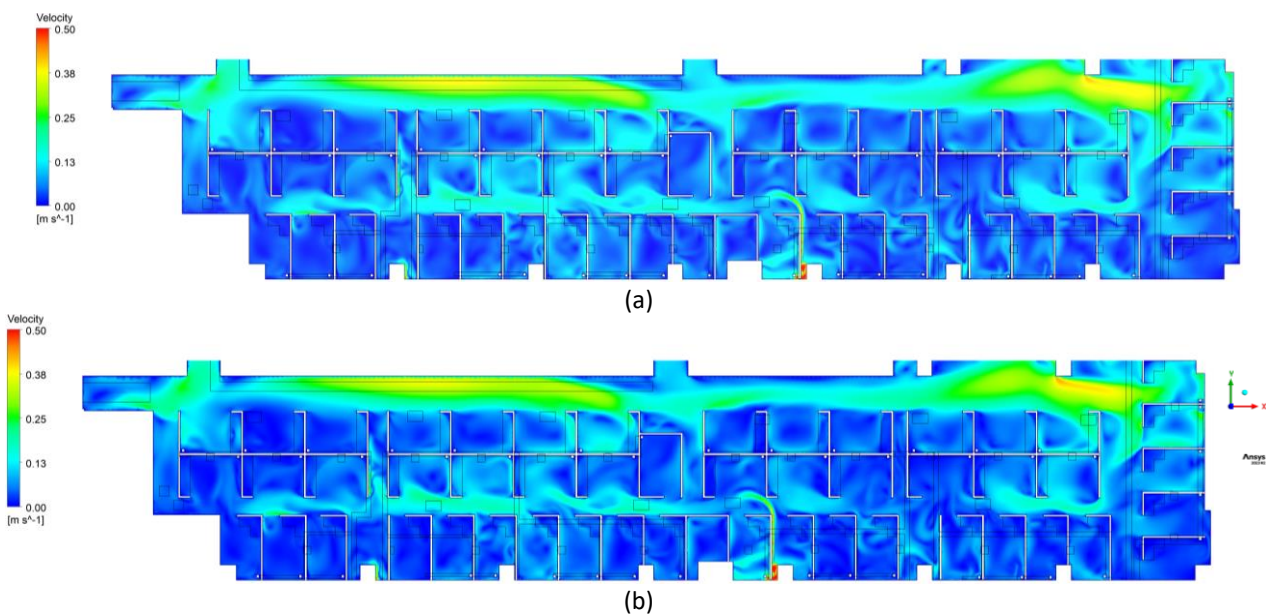

(a)

(b)

Fig. 7. Air velocity distribution in the clinical space at hight level 0.70 m (a) and 1.10 m (b) for case B

By considering airflow directions, Figure 8 and 9 display the spatial distribution of the AOA and air velocity distribution with airflow direction in the clinical space at vertical plane 1 to 8. Overall, ventilations strategies performed effectively to maintain air quality. The averages AOA of plane 1 to 8 are as 220.90, 221.62, 211.88, 218.97, 215.77, 224.77, 223.67, and 214.80 seconds, respectively, while the averages air velocity of plane 1 to 8 are as 0.11, 0.10, 0.08, 0.05, 0.09, 0.05, 0.08, and 0.10 m/s, respectively. It can be observed that installing auxiliary outdoor air units at the ceiling level and exhaustion vents at the floor level under each patient's seating position can significantly improve vertical streamline to circulate from the designed direction as the clean (at the ceiling level) to the less clean area (at the floor level) within the spaces. Thus, this directional airflow as a protective ventilation concept should be controlled properly for the clinical spaces, as it substantially reduces the risk for healthcare associated airborne infections by leading to dilution of airborne pathogens.

Planes 1 to 3 exhibit similar patterns of the AOA. As the air is introduced from the ceiling, it is evident that the green spots represent areas with the lowest AOA. As the air descends towards the floor, the age of air gradually increases. This confirms that the ventilation system effectively delivers fresh air from the top, ensuring a downward flow of air throughout space. The vector plot illustrates the direction of the airflow. It is observed that the airflow moves from the top to the floor, aligning with the expected head-to-toe direction as the clean to the less clean area. Additionally, some recirculation occurs within each dental unit due to the wall-like structures that disrupt the flow, causing it to move in circular patterns. However, this recirculation is not a cause for concern, as it still maintains the desired airflow direction.

Planes 4 to 8 represent cross-sections along the width of the building, showcasing the different effects of airflow when it is further away from the air supply area. Similar to planes 1 to 3, these cross-sections exhibit the same patterns. For plane 8, located at the end of the hallway near the building wall, demonstrates significant movement of the air. The presence of the wall perpendicular to the airflow disrupts the jet of air coming from the auxiliary air supply, causing it to break apart from the mainstream. As a result, high-velocity airflow and strong circulation are observed within each dental unit in plane 8. However, despite the presence of these circulation patterns, they do not significantly impact the overall ventilation efficiency of the building. The improved system, with the auxiliary air supply and strategically placed return air outlets, still maintains a successful airflow direction from the ceiling to the floor. The circulation within individual units does not hinder the overall fresh air delivery and removal of older air.
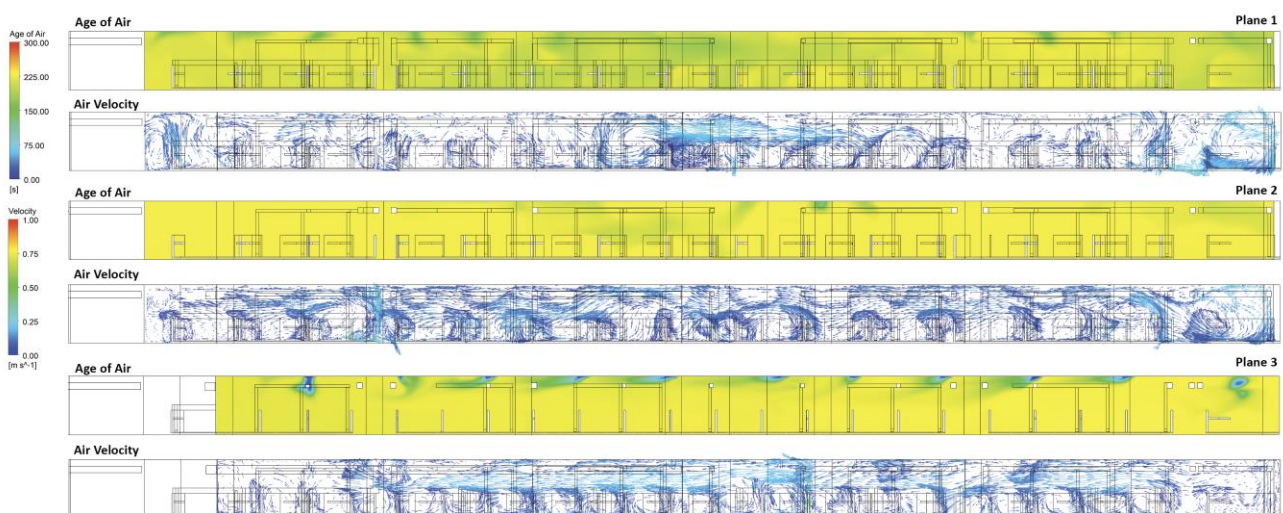

Fig. 8. Age of air (AOA) and air velocity distribution with airflow direction in the clinical space at vertical plane 1 to 3, for case B
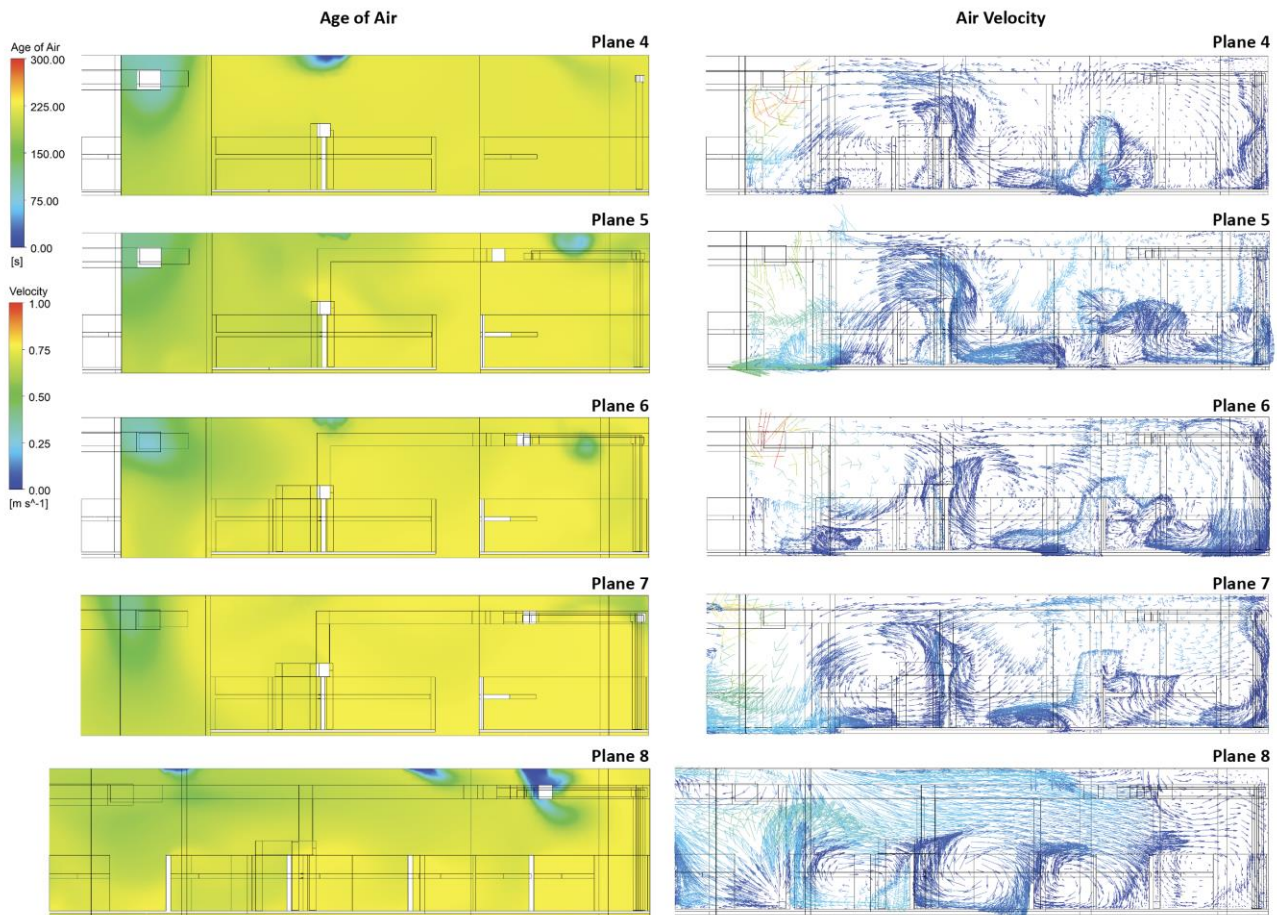
Fig. 9. Age of air (AOA) and air velocity distribution with airflow direction in the clinical space at vertical plane 4 to 8, for case B

Figure 10 and 11 show the comparison of case A and B at 0.70 m. and 1.10 m. for the AOA and the air velocity, respectively. The results indicate that the improvements by incorporating supply and return air significantly change airflow patterns. The AOA enhanced by 88.95-90.50% at 0.70 m., and 88.80-90.45% at 1.10 m., while the air velocity enhanced by 18.17-82.00% at 0.70 m., and 56.84-81.03% at 1.10 m. It is worth noting that higher level of improvements can be found in the area close to the auxiliary supply air units, such as plane 2 and 3 as Figure 1(a) and 1(b) shown, since the positions of the inlets and outlets greatly influence removal efficiency [30, 31]. Moreover, the importance of their number, together with the balance and distance between airflow rate, as well as the exhaust distance to the infection source, must be carefully considered to remove airborne contaminants [37].

Generally, the results reveal that improving ventilation strategies are commonly accounted as efficient by diluting or eliminating pathogens from droplets and aerosols, and therefore to reduce the infection risks. It can be observed that the AOA significantly reaches low in the main hallway. This significant reduction is attributed to the installation of auxiliary supply air, which helps propel the air longitudinally across the floor. As a result, the dental units positioned along the hallway also benefit from this setup, as fresh air can enter the units and displace the older air. In contrast to the existing conditions, where the air supply was primarily located on the ceiling, the improvements demonstrate a more uniform distribution of air in the other rows of dental units. This is due to the substantial volume of air provided by the auxiliary supply air. Moreover, each dental unit is equipped with a return air outlet positioned near the patient's feet, which aids in extracting air and reducing stagnant

air that may otherwise accumulate within the rooms. The combination of additional supply air and strategically placed return air outlets contributes to improving air circulation and minimizing areas with stagnant air. This ensures a more efficient flow of fresh air into each dental unit and facilitates the removal of older air, resulting in higher air exchange rate throughout the space.
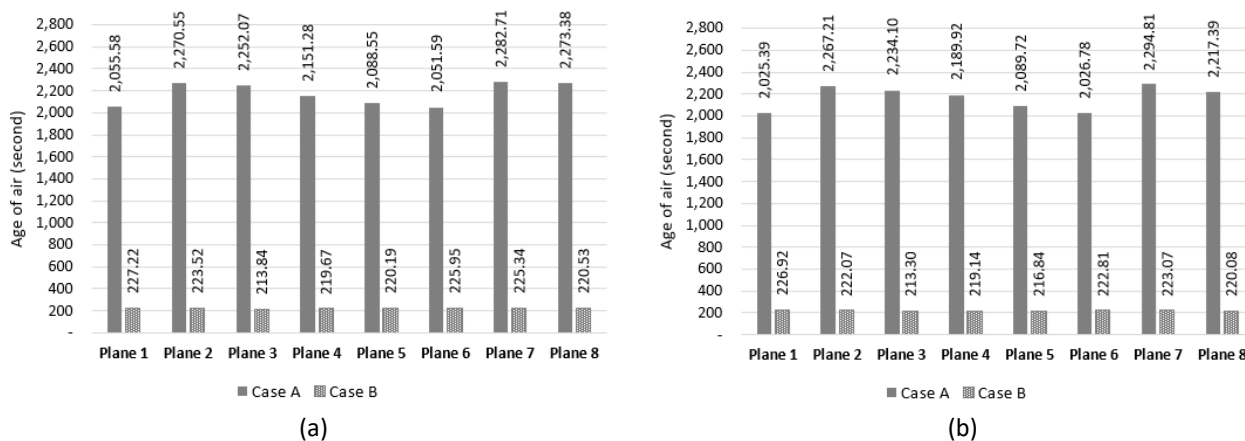

(a)   (b)

Fig. 10. Comparing of age of air (AOA) at hight level 0.70 m (a) and 1.10 m (b) between case A and B

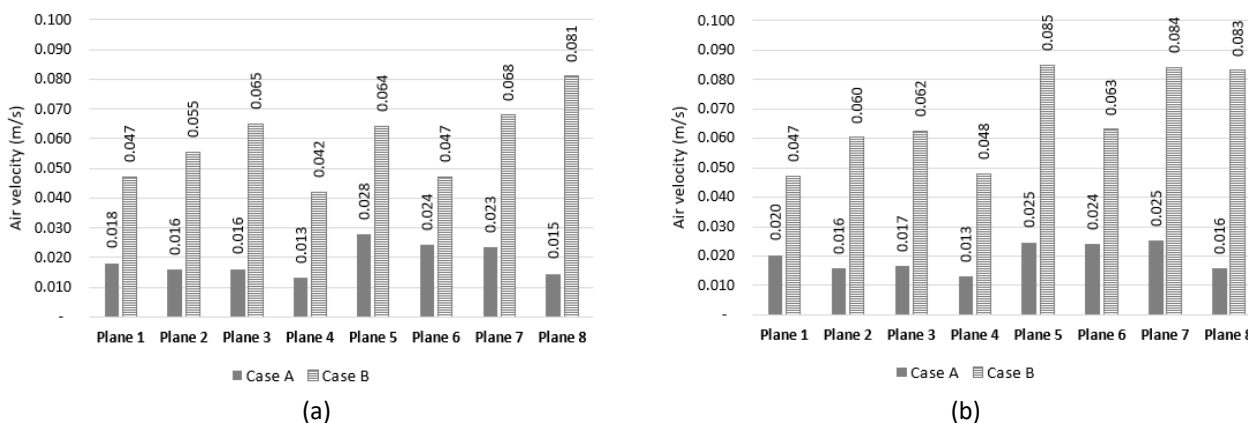(a)   (b)

Fig. 11. Comparing of air velocity at hight level 0.70 m (a) and 1.10 m (b) between case A and B

At this point, it can be seen that incorporating supply and return air arrangement can significantly improve airflow streamlines, patterns, and velocity, which can be developed as ideal ventilation strategies for reducing airborne infection risks. To practically be applied in dental clinics, details on designing and installation techniques required further discussed to serve at the highest potential of infection prevention and control, such as, size and direction of terminal devices, occupant's seating position, distance to occupants, and height level of breathing zone [37]. Implementing new technologies with these considerations like PV are also recommended [42, 43]. Comprehensive study can develop concrete evidence to establish a link between health-related issues and spectrum of interventions that are intended to reduce the risk of infection in healthcare settings.

5. Suggestions for the Implementation in the Dental School

Since the COVID-19 is primarily spread through droplets and aerosols, it could reasonably be assumed that dentistry might be among the professions with the highest risk due to close contact between the patients and dentists and nature of dental procedures. The activities of dental schools have been resumed by imposing some restrictions on operating hours and number of occupants. Transmission-based precautions are encouraged as additional measures that must always be used

with the standard precautions in dental clinic. Some interventions are necessary to be implemented for operating and reopening the schools with support services, such as patient screening, infection control (environmental disinfection, equipment and tools, and unit isolation), behavioural measures (use of personal protective equipment and handwashing), and treatment measures (performing essential and emergency treatments, using rubber dam placement, reducing aerosol production during examination) [2, 16].

Improvement on ventilation strategies should adopted as a preventative measure [61], since infection prevention and control is a crucial element for reducing airborne infections risks during dental procedures. Besides the supply and return air settings, a combination of strategies and engineering controls, such as air filtration, air sanitizing, and multi-compartment [37], should be incorporated into the air-conditioning or ventilation systems to perform higher potential in reducing contamination concentration than ordinary systems. Moreover, particle size with its transmission routes must be carefully considered according to particularities of each dental treatment [62].

Additionally, the combination of pre-pandemic and alternative assessments implemented during the pandemic that reinforced student learning and clinical competencies will likely be the future of the dental curriculum [63]. Assessment changes implemented during the pandemic included a significant shift towards computer-based and remote-proctored assessments across the curriculum to reduce the personal contact. However, in Dentistry, laboratory activities and clinical practices are at the core of training student's skills for patientcare [64]. It is also essential to consider that, to return to clinical activities, it will be necessary for students to receive reinforcement in training regarding updates to airborne infection control measures, with considerations on the improvements of clinic infrastructure and reducing the number of student classes per term. [65, 66]. Prioritizing the theoretical content to improve student's knowledge before clinical activities return is also recommend [66, 67]. The arguments regarding the perception experienced for professors and students with the combination of pre-pandemic and alternative assessments require further investigation to make this teaching format more efficient for developing the dental curriculum.

6. Conclusions

The dental clinic was managed to operate by incorporating auxiliary air supply and exhaustion vents since the recent COVID-19 pandemic has brought ongoing attentions to airborne transmission in dentistry due to a great variety of exposed to infection risk. The three-dimensional computational fluid dynamics technique using CFD analysis was performed in this study to evaluate ventilation efficiencies of the multi-unit dental school in Bangkok, Thailand, where this study is one of the few studies to serve research-based evidence in large space rather than in a typical room or a small unit. The results revealed that strategies to increase air exchange substantially improve airflow patterns and directions, surpassing conventional design of the pre-existing building's system to dilute airborne contaminants. The insight gained from this study can provide guidance on designing ventilation and air distribution approaches with similar settings to assess the infection risk of respiratory diseases from the airborne route.

The CFD-based tools provided full control over the access boundary conditions for the modelled environment to analyse computationally conditions, especially for scenarios of examining airborne infection controls under limitations of the complex full-scale study in healthcare environments. It is practically used to investigate airflow pattern, direction, and velocity for enhancing appropriate design, operation techniques, and maintenance of ventilation systems. It is important to note that healthcare environments are sensitive to any changes. More focuses on field surveys can be

conducted to collect on-site data, such as tracer gas test and human movement detection techniques, to supplement with the CFD simulation for developing a comprehensive model.

Since new paradigm to develop occupant-based ventilation strategies is generally discussed in healthcare environments, this study suggested controlling the airborne at source using increasing air exchange and directional airflow. In this regard, future study is recommended that combination strategies, such as filtration and decontamination devices, should be taken into account. Additionally, as improving on ventilation modes must be carefully consider on a balance between energy conservation and occupant's health. Future study may discuss ideal strategies or engineering controls to help ensure energy efficiency while maintain healthy and comfortable environments to push onward efforts in developing a manual ventilation protocol during the post-pandemic scenarios, including any risk of future outbreak events.

Acknowledgement

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