Chula Med J Vol. 68 No. 2 April - June 2024; 125 - 131 DOI : 10.56808/2673-060X.5386

Original article

Effectiveness of the novel ventilation system for airborne particle reduction in ambulance

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Abstract

Background: During the coronavirus disease 2019 pandemic, emergency medical service (EMS) workers are exposed to infectious particles in closed spaces such as in the ambulances. Few studies have demonstrated the effectiveness of ambulance ventilation systems in reducing airborne particles.
Objectives: To evaluate the efficacy of a proposed ventilation system for use in ambulances in decreasing the volume concentration of airborne particulates and the return-to-background time.
Methods: Aerosol particles of varying sizes were administered into the cabin by saline nebulization for 1 min. The aerosol volume concentrations of particles at 0.5 - 1.0, 1 - 2.5, and 2.5 - 5.0 microns were measured with three ventilation settings (switched-off, medium, and maximum) at three seat positions (front, side, and rear).
Results: The return-to-background time was significantly different among the three ventilation settings ($P < 0.001$). Regardless of the particle size, the return-to-background times were 815 (IQR790 - 840), 830 (IQR790 - 840), and 790 seconds (IQR760 - 810) seconds for the switched-off ventilation setting at the front, side, and rear seats, respectively. At all three seat positions, the return-to-background time for the medium ventilation setting was 360 (IQR360 - 360) seconds. For the maximum ventilation setting, the return-to-background time were 285 (IQR280 - 290), 295 (IQR290 - 300), and 300 (IQR290 - 300) seconds at the front, side, and rear positions, respectively.
Conclusion: Clearance of airborne particles is increased at higher ventilation settings Installation of this system in the ambulance cabin may provide better control of aerosol particle suspension and will minimize the risk of airborne transmission among ambulance workers.

Keywords: Aerosol particles, airborne transmission, ambulance, pandemic, ventilation system.

The prevention of infectious respiratory diseases is essential for emergency medical service (EMS) providers who work in ambulances, particularly during the coronavirus disease 2019 (COVID-19) outbreak, in which the virus can be transmitted via droplets and airborne particles. [1, 2] EMS workers are at higher risk of infection when performing aerosol-generating procedures (AGPs) [3, 4] such as intubation, noninvasive ventilation, and cardiopulmonary resuscitation. Furthermore, the ambulance cabin is considered a confined area with poor ventilation. [5 - 8] Thus, the rear doors of ambulances should be opened, and the heating ventilation air condition system must be activated during AGPs.[9, 10] However, opening the rear door may cause delays in the transportation of patients with critical conditions.[11]

The transmission of airborne infections depends on the particle size and environment at a certain time. Droplets are defined as particles measuring > 5 microns that usually spread through coughing or sneezing and are likely to float in the air and drop to the ground within 6 feet of their source.[12] Particles measuring < 5 microns can spread > 6 feet away from their source. [13 - 15] This type of aerosol will suspend and accumulate longer, increasing the increased risk of disease transmission.

A study suggested that aerosol-generating medical procedures should be performed in a negative pressure cabin with at least 12 times of air change per hour (ACH) to reduce the risk of contracting airborne infections.[16] However, very few studies have focused on the ventilation system in the close-space cabin of ambulances. Although some studies have shown that an increase in the ventilation rate could reduce the aerosol particles in the ambulance, most ambulances do not install or use a proper ventilation

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Received: September 26, 2023
Revised: February 22, 2024
Accepted: March 24, 2024

system. In Thailand, a ventilation system that uses a medium-type filter in the ambulance is recommended.[17] Therefore, the ambulances of our EMS service were installed with a novel ventilation system. Accordingly, this study aimed to determine the effectiveness of this equipment in reducing the aerosol particles in the ambulance.

Materials and methods

This study was conducted in the EMS service unit of the King Chulalongkorn Memorial Hospital, Thai Red Cross Society and Department of Emergency Medicine, Faculty of Medicine, Chulalongkorn University. The EMS service has 10 rotating advance ambulances available for regular EMS service. The study was performed during the period from August 2020 to October 2020.

Advance ambulance

This study used a passenger van-type ambulance (Toyota Ventury®) as the test vehicle. The ambulance was parked outdoors during the test. The patient cabin size is 1.5 m in width, 2.7 m in length, and 1.4 m in height, and contains three seat positions relative to the patient's cot: front, side, and rear seats.

Ventilation system

In this study, the effectiveness of the Camfil® air purifier system, (Model CC410, with pre-filter; UVC; and HEPA filter H14, Germany) was assessed. Three different ventilation settings were assessed by adjusting the fan speed of the equipment. The intake fan was set up the top of the patient compartment, and an exhaust blower was placed on the right side of the ambulance next to the patient's cot. The performance of three ventilation settings was also compared according to the exhaust blower vacuum fan speed setting to level 0 (switched-off setting), level 3 (medium ventilation), and level 6 (maximum ventilation). The exhaust blower in the switched-off ventilation setting represents native ambulance ventilation. The medium and maximum ventilation settings yielded an ACH of approximately 40 and 80, respectively, based on the equipment's specification sheet and cabin volume.

Aerosol particle simulator

Normal saline was used to create aerosol particles. The particles were generated via a portable ventilator (Oxylog 3000 plus) connected to a nebulizer. A portable ventilator rhythmically supplies airflow to the nebulizer, by replicating the normal human breathing cycle.[18] The ventilator was set to the volume-controlled (VCV) mode with a tidal volume of 500 mL, inspiration-to-expiration ratio (I:E) ratio of 1 : 2, and respiratory rate of 12 breaths per minute.

Optical particle counter

To measure the amounts of particles at three different seat positions, three particle counters (PMS5003, Plantower, Jiangxi, China) were used. The devices were calibrated with the standard calibrator: Handheld 3016 particle counter, (Light House, USA). The volume concentration of the particles was measured over time at different seat locations with three different ventilation speeds as the study. Although the amount of a transmission carrier did not only depend on the number of particles bus also on the volume of particles. [19] The particle volume concentration was calculated and reported according to the formulation shown below.

Because PMS 5003 measured the amounts of aerosol particulates per cubic feet of air in each particle size bin, the data are transformed into volume concentration (μL/m^3):

$\sigma = 4.7\times10^{-8} N \pi r^3$ where

σ = volume concentration ($\mu L/m^3$)

N = number of particles ($1/ft^3$)

r = mean radius in each size bin (μm)

The return-to-background time is defined as the time spent from when the particle concentration rises after the activation of a particle simulator until it declines ot the background state.

Experimental procedure

Environmental preconditioning

The air conditioner was set at 25° C and the ventilation system was turn on with the exhaust blower at the maximum ventilation setting for 15 min to eliminate the remaining particles in the cabin and allow it to return to the background state. The airflow in the cabin was stabilized with the blower at the switched-off ventilation setting for 5 min.

Performing the test in a different ventilation speed

After airflow stabilization, The particle counter was then activated for data collection. After 3 min, the aerosol particles were generated into the cabin for 1 min by activating the particle simulator. Then, the amount of particles measuring > 0.5 microns was measured for 15 min at medium and maximum ventilation settings, and the same was performed for 26 min at the switched-off ventilation setting. To increase the measurement accuracy, repetitive experiments were conducted for a total of six times for each ventilation setting. At each ventilation setting test, measurements at all three different seat positions were performed simultaneously. Environmental preconditioning and compartment stabilization were completed before each round of experiments.

Statistical analysis

The particle volume concentration at different ventilation rates and seat positions were recorded. STATA version 15 for Windows (TX, USA) was used for all statistical tests**,** and data were expressed as median (interquartile range, IQR). Normality testing in continuous variables was performed using the Q-Q plot with Kolmogorov-Smirnov test. Normally distributed data were analyzed using the two-independent *t* - test and the Mann-Whitney U test for nonnormally-distributed data. A $P < 0.05$ was considered statistical significance.

Results

Return-to-background time

The median return-to-background times at the maximum ventilation setting were 285 (IQR280 - 290), 295 (IQR290 - 300) and 300 (IQR290 - 300) seconds at front, side, and rear seat positions, respectively. The median return-to-background time at medium ventilation was 360 (IQR360-360) seconds at all seat positions. The median return-to-background times at the switched-off ventilation setting were 815 (IQR790 - 840), 830 (IQR790 - 840), and 790 (IQR760 - 810) seconds at front, side, and rear seats, respectively. The return-to-background times were significantly different at all seat positions between maximum and medium, maximum and switched-off, and medium and switched-off ventilation setting ($P < 0.001$).

The return-to-background time significantly decreased at the maximum ventilation setting compared with those at the switched-off, and medium ventilation settings at all seat positions.

Peak concentration of the particles

The overall peak concentration of the particle significantly decreased at the maximum ventilation sitting compared with those at the switched-off and medium ventilation setting at all seat positions. The peak concentrations of 0.5 - 1.0 micron aerosol particles at the maximum, medium and switched-off ventilation setting at the front, side, and rear position microliter per cubic meter (% CV) are shown in **Figure 1A.** The peak aerosol concentrations at the maximum ventilation setting were 0.036 (3.9%), 0.044 (4.9%), and 0.041 (3.5%) at the front, side and rear positions, respectively. The peak aerosol concentra tions at medium ventilation were 0.038 (10.3%), 0.048 (4.4%), and 0.031 (4.7%) at the front, side, and rear positions, respectively. The peak aerosol concentra-tions at the switched-off ventilation setting were 0.049 (3.4%), 0.55 (4.1%), and 0.043 (5.1%) at the front, side and rear positions, respectively. In summary, the peak aerosol concentration significantly decreased at medium and maximal ventilation settings compared with that at the switched-off ventilation setting ($P < 0.001$).

The peak concentrations of 1.0 - 2.5 micron aerosol particles at the maximum, medium, and switched-off ventilation settings at front, side, and rear position microliter per cubic meter (% CV) is shown in **Figure 1B.** The peak concentrations of the overall aerosol significantly decreased at medium and maximum ventilation settings compared with that when the machine was switched-off ($P < 0.001$).

The peak concentration of 2.5 - 5.0 micron aerosol particles at maximum, medium, and switched off ventilation settings at front, side, and rear position microliter per cubic meter (% CV) are shown in **Figure 1C**.

Initially, the ventilation rates were considered independent variables. Adjusting the ventilation settings from medium to maximum in each position caused the maximum aerosol volume concentration to significantly decrease in every volume size ($P < 0.05$). For the rear position, the switched-off ventilation setting compared with the medium ventilation setting had a lower aerosol volume concentration, similar to other positions; however, at the maximum ventilation setting, the maximum aerosol volume concentration increased, particularly in 1.0 - 2.5 and 2.5 - 5.0 microns aerosol. However, no statistical significance was found when compared with the minimum ventilation setting as shown in **Figure 1.**

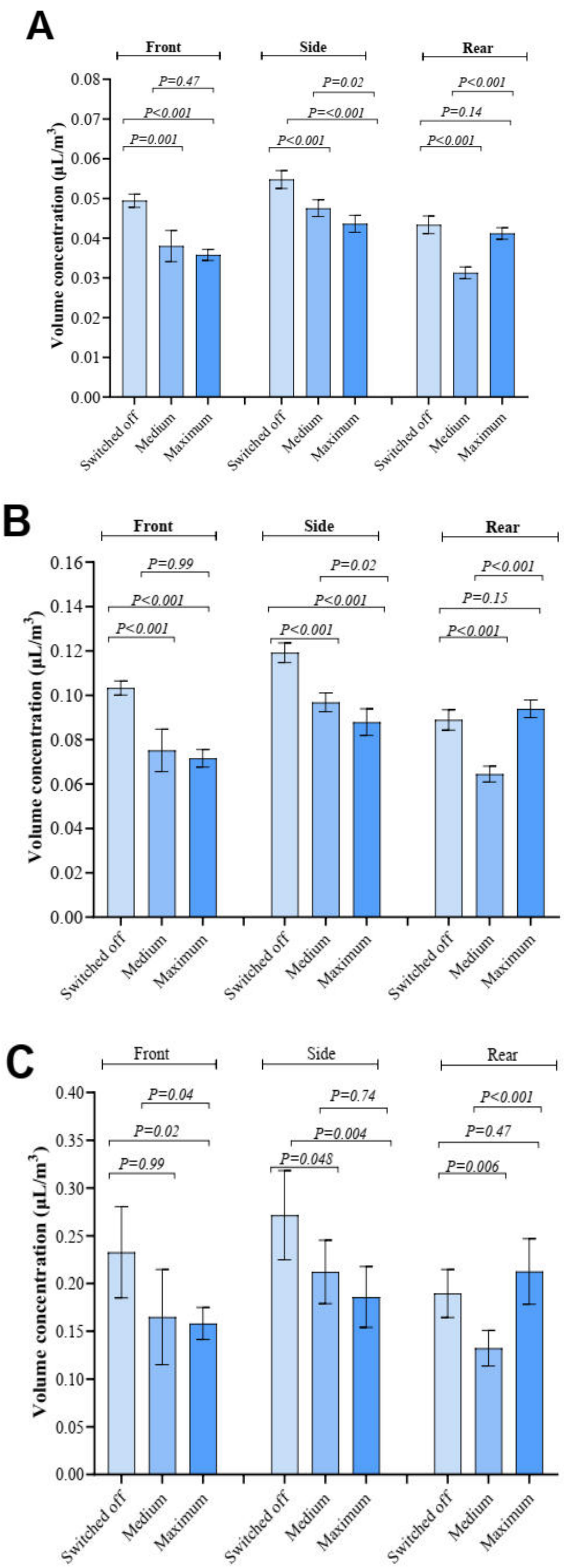

Figure 1. Comparison of maximum aerosol volume concentration among switched off, medium and maximum group in size range between **(A)** 0.5 and 1.0 micron, **(B)** 1.0 and 2.5 micron, and **(C)** 2.5 and 5.0 micron.

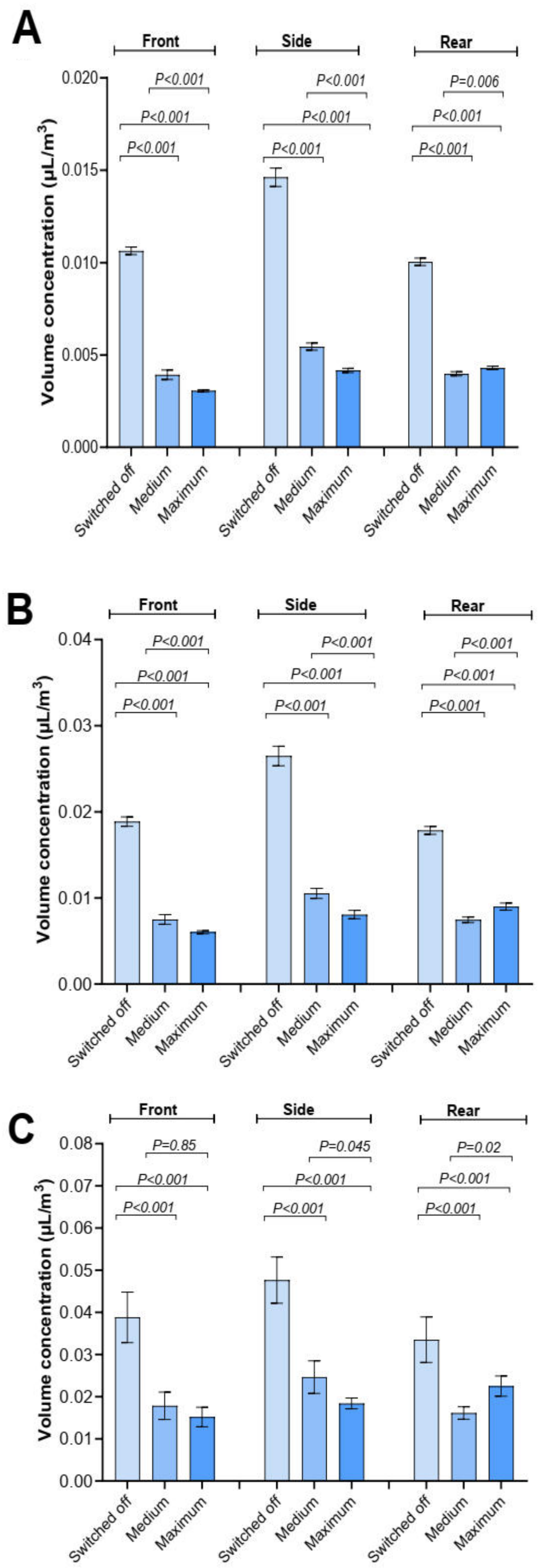

Figure 2. Mean aerosol volume concentration at three different seats position of particle size **(A)** 0.5 - 1.0 micron, **(B)** 1.0 - 2.5 micron, and **(C)** 2.5 - 5.0 micron.

Second, the seating positions were also considered independent variables. At minimum and medium ventilation settings, the side position had the maximum aerosol volume concentration in every volume size. At the maximum ventilation setting, the side position had the maximum aerosol volume concentration of 0.5 - 1.0 micron particles, and in 1.0 - 2.5 and 2.5 - 5.0 micron particles, the rear position had the maximum aerosol volume concentration; however, compared with the side position, no statistical significance was noted.

Seat positions

The peak concentrations of 0.5 - 1.0 micron aerosol particles at the maximum, medium, and switched-off ventilation settings at the front, side, and rear positions in microliter per cubic meter (% CV) are shown in **Figure 2A**.

The peak concentrations of 1.0 - 2.5 micron aerosol particles at the maximum, medium, and switched-off ventilation settings at front, side, and rear positions in microliter per cubic meter (% CV) are shown in **Figure 2B.**

The peak concentrations of 2.5 - 5.0 micron aerosol particles at the maximum, medium, and switched off ventilation settings at the front, side, and rear positions in microliter per cubic meter (% CV) are shown in **Figure 2C.**

The comparison of the seating positions using the minimum and medium ventilation settings revealed that the side position had the highest mean aerosol volume concentration in most volume sizes. For the rear position at the maximum ventilation setting, the mean aerosol volume concentration was the highest in every volume size, compared with other positions, showing statistical significance ($P < 0.001$) as presented in **Figure 2.**

The particle concentration measured at the medium ventilation setting was significantly lower in every seat position than those at the switched-off ventilation setting. However, the measurement at the rear seat was slightly higher than those of other positions at the maximum ventilation setting.

Discussion

Reducing the risk of COVID-19 transmission through aerosols among healthcare workers is imperative. The US national institute for Occupational Safety and Health suggests the strict use of personal protective equipment, such as N95 masks as the prevention standard.[20 - 22] In addition, an effective ventilation system in the working environment helps reduce the risk of aerosol transmission. [23] This study provided the information on the effectiveness of a novel ventilation equipment installed in ambulances for particle elimination in the cabin.

The results revealed that the particle concentration peaked rapidly and gradually decreased to the background state after aerosol emission into the cabin. When the equipment was switched off or in the native ambient ventilation, the particle concentration was highest on the side seat at all times. However, when turned on, the peak concentration and return-to-background time decreased significantly in all three seats, particularly in those with the highest ventilation setting. The results indicate that the activation of the novel ventilation equipment significantly accelerates particle clearance in the ambulance cabin. The findings are consistent with those of a previous study.[7]

Interestingly, our results revealed that particle concentration at the rear seat was higher than that of the side position at the maximum ventilation setting because the high ventilation flow in the cabin may create air turbulence that could accumulate at the rear seat position and result in higher particle concentrations. However, all workers should always protect themselves to further minimize the risk of exposure to aerosol particles while working in the ambulance cabin at all times, such as wearing N95 masks with a secure mask fit and personal protective garment.

This study has several limitations. First, 0.9% sodium chloride was used as the simulated aerosol, which is different from the real pathogenic particles according to the biological safety of the research. Second, the outcomes could have been affected by different environmental settings such as the different models of ambulances with various cabin sizes, ambient temperature, humidity, air conditioner fan speed, or particle generation from real human patients with forceful respiratory activities. Therefore, the effectiveness of a specific system or device must be evaluated before its deployment in clinical practice with actual patients. Finally, the benefit of this novel ambulance ventilation system on minimizing aerosol transmission into the human body in addition to the deployment of strict personal protective devices requires further research.

The utilization of a novel ambulance ventilation system accelerated the overall clearance of aerosol particles in the ambulance cabin. Therefore, this equipment may help minimize the risk of airborne transmission among ambulance workers during the pandemic.

Acknowledgements

The researchers would like to thank all engineers for their contribution. We greatly appreciate everyone who has helped guide us. Furthermore, the researchers do not have any financial disclosures or conflicts.

Conflict of interest statement

Each author has completed and submitted an International Committee of Medical Journal Editors Uniform Disclosure Form for potential conflicts of interest. None of the authors has any potential or actual conflict of interest to disclose in relation this article.

Data sharing statement

All data generated or analyzed during this study are included in this published article and cited here. Further details, opinions, and interpretations are available from the corresponding author upon reasonable request.

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