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Efficacy of Various Mitigation Devices in Reducing Fugitive Emissions from Nebulizers

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Competing interests

Dr. Li received research funding from Fisher & Paykel Healthcare Ltd, Aerogen Ltd, and Rice Foundation, lecture honorarium from AARC, Aerogen Ltd, Heyer, and Fisher & Paykel Healthcare Ltd. Dr. Fink is Chief Science Officer for Aerogen Pharma Corp. Dr. Dhand reports remuneration from GSK Pharmaceuticals, Boehringer-Ingelheim, Mylan, Teva, and Astra-Zeneca Pharmaceuticals outside the submitted work. Other authors have no conflicts to disclose.

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Authors' contributions

JL conceived and designed the study, implemented the study, analyzed the data, drafted and revised the manuscript. LH implemented the study, interpreted the data, drafted and revised the manuscript. AA implemented the study and revised the manuscript. GJ analyzed and visualized the data, revised the manuscript. JBF conceived the concept, interpreted the data and revised the manuscript. RD interpreted the data and revised the manuscript. All authors reviewed and approved the final version. JL is the guarantor of the paper, taking responsibility for the integrity of the work as a whole from inception to published article.

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Abstract

Introduction: Fugitive aerosol concentrations generated by different nebulizers and interfaces *in vivo*, and mitigation of aerosol dispersion into the environment with various commercially available devices are not known.

Methods: Nine healthy volunteers were given 3 mL saline with a small volume nebulizer (SVN) or vibrating mesh nebulizer (VMN) with a mouthpiece, a mouthpiece with an exhalation filter, an aerosol mask with open ports for SVN and a valved facemask for VMN, and a facemask with a scavenger (Exhalo) in random order. Five of the participants received treatments using a face tent scavenger (Vapotherm) and a mask with exhalation filter with SVN and VMN in a random order. Treatments were performed in an ICU room, with 2 particle counters positioned 1 and 3 feet from participants measuring aerosol concentrations at sizes of 0.3-10 μm at baseline, before, during and after each treatment. The Ethics Committee at Rush University approved this study.

Results: Fugitive aerosol concentrations were higher with SVN than VMN and higher with a facemask than a mouthpiece. Adding an exhalation filter to a mouthpiece reduced aerosol concentrations of 0.3-1.0 μm in size for VMN and 0.3-3.0 μm for SVN (all $p<0.05$). An Exhalo scavenger over the mask reduced 0.5-3.0 μm sized particle concentrations for SVN (all $p<0.05$) but not VMN. Vapotherm scavenger and filter facemask reduced fugitive aerosol concentrations regardless of the nebulizer type.

Conclusion: SVN produced higher fugitive aerosol concentrations than VMN, while facemasks generated higher aerosol concentrations than mouthpieces. Adding an exhalation filter to the mouthpiece or a scavenger to the facemask reduced aerosol concentrations for both SVN and VMN. Vapotherm scavenger and filter facemask reduced fugitive aerosol as effectively as a

mouthpiece with an exhalation filter. This study provides guidance for reducing fugitive aerosol emissions from nebulizers in clinical practice.

Key words: nebulization; fugitive aerosol; aerosol generation procedure; aerosol transmission

Introduction

Prior to the COVID-19 pandemic, aerosol particle concentrations in room air were reported to be higher with nebulization than with other treatments such as noninvasive ventilation[1] and bronchoscopy,[2] or with other patient care activities, including bathing, pouring, flushing or changing linens.[2] While using smoke to simulate aerosol dispersion, the exhaled air dispersion distance was found to be greater with nebulization than with a simple oxygen mask and noninvasive ventilation.[3] As such, nebulization was considered an aerosol generating procedure (AGP).[4,5] Due to concerns that aerosol generated by the nebulizer might carry virus to the surrounding environment, especially with reports of SARS-CoV-2 being viable in aerosols for up to 3 hours.[6] In the recent systematic review and meta-analysis, nebulization was found to significantly increase the odds of health care workers contracting SARS-CoV-1 or SARS-CoV-2 virus.[7] Thus, several clinical societies made recommendations against the use of nebulizers during the COVID-19 pandemic.[8,9] Switching from nebulizers to other aerosol devices such as metered-dose inhalers (MDIs) or dry powder inhalers (DPIs) caused a shortage of those devices[10] and inefficient drug delivery for some patients who were unable to correctly use MDIs or DPIs. More importantly, some inhaled medications such as antimicrobials, mucolytics and prostaglandins are only available in the solution form, so that avoiding the use of nebulizers limited the potential for patients to benefit from those treatments.[11]

Clinically, there are different types of nebulizers and interfaces (facemask or mouthpiece) available for aerosol therapy. Fugitive emissions consist of aerosol that has been exhaled from the patient (bio-aerosol) and/or aerosol that escaped from the nebulizer system prior to inhalation. The latter are medical aerosols and do not carry infectious particles unless the nebulizer is contaminated by patients' secretions. An *in-vitro* study reported lower fugitive

aerosol concentrations with use of vibrating mesh nebulizers (VMNs) than small volume nebulizers (SVNs),[12] especially when a mouthpiece was utilized; and that adding expiratory filters reduced fugitive aerosol concentrations.[12] However, no *in-vivo* data is available on the fugitive aerosol particle concentrations using different nebulizers with common interfaces.

Adding an expiratory filter to a mouthpiece during nebulization has been recommended for treatment of COVID-19 patients.[13,14] Unfortunately not all patients are able to effectively use a mouthpiece; for example, patients with cognitive or neurological defects who cannot hold the mouthpiece in their mouth and form a tight seal with their lips. Consequently, reducing the concentrations of fugitive aerosols generated during the use of a facemask could promote the safe and efficient use of facemasks with nebulizers. Filter facemasks and two designs of scavengers are commercially available. The filter facemask incorporates filters at the exhalation holes on the aerosol mask while the scavenger device continuously suctions the aerosol particles during AGPs. However, the effectiveness of those devices in reducing fugitive aerosol concentrations *in-vivo* is still unknown. Thus, we aimed to investigate the concentrations of fugitive aerosols generated by VMN and SVN with the use of an interface (facemask and mouthpiece) with and without a mitigation device (filter or scavenger) among healthy volunteers. Another aim was to determine the most effective mitigation device(s) to reduce fugitive aerosol concentrations during nebulization.

Methods

This prospective, randomized cross-over trial was registered in clinicaltrials.gov (NCT04681599) and was approved by the Rush University Ethics Committee (approval No. 20121804-IRB01). Healthy adults, aged 18-65 years, with no history of respiratory disease were

included. Subjects were excluded if they met any of the following criteria: had chronic lung disease such as asthma or chronic obstructive pulmonary disease, upper airway anatomical abnormalities, uncontrolled diabetes, hypertension, or untreated thyroid disease; were pregnant; had a positive COVID-19 test or any COVID-19 related symptoms (including sore throat, cough, body aches or shortness of breath for unknown reasons, loss of taste or smell, and fever with temperature ≥ 100 °F) within 21 days of enrollment.

Written consent was obtained from each participant prior to starting the study. The study was conducted in an intensive care unit patient room (3.65×3.65×2.8 m^3 with air exchange frequency of 6 times/hour). The door remained closed throughout the study and talking or moving around was discouraged. Participants were seated in an upright position and two particle counters (Model 3889, Kanomax, Andover, NJ) were placed at 1 and 3 feet from participants at the mouth level, with continuous monitoring of aerosol particle concentrations from 0.3 to 10µm in size (Figure 1). A single investigator wearing an N95 mask stayed in the room with the participant throughout the study, while the participant wore an N95 mask before and between the use of different devices/interfaces. The interval between device use was 15 minutes and devices/interfaces were used in a pre-determined random order. A nominal dose of 3mL of normal saline was administered and nebulization ended when no aerosol was visible.

Comparisons of VMN vs SVN with mouthpiece and facemask

A SVN (AirLife 002446, CareFusion, Yorba Linda, CA) was compared with a VMN (Aerogen Ultra, Aerogen Ltd., Galway, Ireland) with a mouthpiece. Per manufacturer's instructions, an open facemask (Vyaire Medical, Mettawa, IL) for SVN and a valved facemask (Salter Labs, El Paso, Texas) for VMN(Figure 2). Per manufacturer's instructions, 8 L/min

compressed air was used to drive the SVN, while 2 L/min air was connected to the VMN chamber.

Comparisons of different mitigation devices to reduce fugitive aerosols generated by nebulizer and interfaces

Nine subjects used SVN and VMN with a mouthpiece with an expiratory filter and a facemask with a scavenger (Exhalo, McArthur Medical, Ontario, Canada) consisting of a collection scoop designed to attach to an aerosol mask and continuous draw suction set to -100 mmHg. Five subjects received 4 additional nebulizations, using SVN and VMN with a facemask fitted with exhalation filters (Respan Products, Ontario, Canada) and a different scavenger (Vapotherm, Exeter, New Hampshire) consisting of a face tent attached to a vacuum pressure of -100 mmHg, placed over the open facemask for SVN and the valved facemask for VMN (Figure 2).

Sample size

This study was designed as a superiority study based on our previous clinical study that showed reduced aerosol particle concentrations when wearing a surgical mask,[15] particularly in close proximity to the source. With a filter or scavenger, the aerosol particle concentrations would be expected to decrease even more. Thus we expected that various methods to mitigate the release of aerosols into the environment would have a medium to large treatment effect. Using G power software[16] to calculate the sample size in repeated ANOVA measures, with confidence level (1-α) of 95%, power (1-ß) of 80%, the number of patients that needed to be enrolled was 9.

Data collection

Aerosol particle concentration data was extracted as the mean aerosol concentration for each particle size range during the initial baseline and with each device. The mean concentration was the average of the concentrations taken from the beginning to the end of the nebulization. Additionally, participants self-evaluated their comfort while breathing with each device, using a five-point Likert scale ranging between 1 (very uncomfortable) and 5 (very comfortable).

Statistical analysis

Continuous variables at each particle size with each device were expressed as mean ± standard deviation (SD) or median (Inter-Quartile Range [IQR]) based on the distribution of variables, which was analyzed by Kolmogorov-Smirnov test. Paired t test or Wilcoxon test was used to compare the differences of aerosol concentrations between two devices, while independent t test or Mann Whitney test was used to compare aerosol concentrations at 1 and 3 feet from participants. A p-value of <0.05 was statistically significant. Data analysis was conducted with SPSS statistical software (SPSS 26.0; SPSS; Chicago, IL). To minimize bias, the statistician who analyzed the data was blinded to the names of each device.

Results

Comparisons of VMN vs SVN with mouthpiece and facemask

Nine participants (8 females) were enrolled in the first section of the study. The baseline particle concentrations in the room were stable, except for the sole male participant, whose baseline concentrations were higher than the female participants. Fifteen minutes after the use of each interface, the aerosol particle concentrations in the room air returned to each individual's baseline level. No participants coughed during nebulization.

SVN generated higher fugitive aerosol concentrations than VMN with mask at particle sizes of 1.0-5μm (Figure 3A) and with mouthpiece at particle sizes of 1.0-3μm (Figure 3B) (all $p<0.05$). When VMN was utilized, mouthpiece generated lower fugitive aerosol concentrations than aerosol mask with particle sizes of 0.5-3μm (Figure 3D) (all $p<0.05$) while no differences were observed for SVN (Figure 3C). Fugitive aerosol concentrations were lower at 3 feet than 1 foot from participants when VMN was utilized with a facemask at particle sizes of 0.3μm ($p=0.012$), and SVN with a facemask at particle sizes of 3μm ($p=0.024$). (Figure 4)

Comparisons of different mitigation devices to reduce fugitive aerosols generated by nebulizer and mask

Fugitive aerosol concentrations were lower when mouthpiece was used with a filter than that without a filter at particle sizes of 0.3-3μm with SVN (Figure 5A) (all $p<0.05$) and at particle sizes of 0.3-1μm with VMN (Figure 5B) (all $p<0.05$).When SVN was utilized with a mask, fugitive aerosol concentrations were lower with the Exhalo scavenger at particle sizes of 0.5-3μm (Figure 5C) (all $p<0.05$). While for VMN, no significant differences of fugitive aerosol concentrations were found with vs without the use of the Exhalo scavenger (Figure 5D).

Five participants continued to complete the second part of the study. Compared to the aerosol facemask alone, using a facemask with exhalation filters significantly reduced fugitive aerosol concentrations at particle sizes of 0.3-3μm for both VMN and SVN (all $p<0.05$). (Figure 6) Similarly, using the Vapotherm scavenger significantly reduced aerosol concentrations at particle sizes of 0.3-3μm (all $p<0.05$) for VMN while at particle size of 3μm for SVN ($p=0.043$). When SVN was used, both filter mask and Vapotherm scavenger had lower fugitive aerosol concentrations than Exhalo scavenger at particle sizes of 0.3-3μm (all $p<0.05$). Compared to the

mouthpiece, both filter mask and Vapotherm scavenger had similar fugitive aerosol concentrations at all particle sizes (Figure 6). Among the four mitigation devices with SVN and VMN, use of VMN with mouthpiece and an expiratory filter, a facemask with Vapotherm scavenger, and the filter facemask were the most efficient in reducing fugitive aerosols.

Participants' comfort on different interfaces

When SVN was utilized, participants' self-evaluated comfort while breathing was similar among different interfaces (Figure 7). In contrast, when VMN was utilized, there was considerable variation in the comfort while breathing; participants ranked the facemask with the exhalation filters and mouthpiece with filter as being the most comfortable interfaces, and mask with and without scavengers the least comfortable, with the complaint of the asphyxia feeling when breathing via the valved facemask. During the use of VMN, the comfort was higher with the mouthpiece and a filter than the valved facemask with Exhalo scavenger ($p=0.047$). No significant differences regarding comfort were noted while breathing with VMN or SVN.

Discussion

In this first *in-vivo* study, we found that the concentrations of fugitive aerosols at particle sizes in the inhalable range (0.5-3µm) were higher with a SVN than a VMN, and with a facemask than a mouthpiece for SVN at a distance of 3 feet from participants and for VMN at a distance of 1 foot. Adding a filter to the end of the mouthpiece further reduced fugitive aerosol concentrations in both SVN and VMN. The facemask with exhalation filters and the Vapotherm face tent scavenger were both as effective in reducing fugitive aerosol concentrations as the mouthpiece with an expiratory filter. Large particles (5-10µm) settle by gravity close to the source, while particle of 0.5-5µm are suspended in air and have a high likelihood of depositing in

the airway after inhalation. Thus, reducing their concentrations in the patients' vicinity is clinically meaningful.

Similar to the *in-vitro* findings by McGrath and colleagues,[12] a SVN generated higher fugitive aerosol concentrations than a VMN. This might be explained by the higher driving flow used by SVN (8 L/min) than VMN (2 L/min), which dispersed aerosols to a further distance. Indeed, we found that the differences in fugitive aerosol concentrations between SVN and VMN were greater at 3 feet from participants than at 1 foot away. Therefore, regarding the reduction of fugitive aerosols during nebulizer use, a mouthpiece would be preferred over a facemask, provided that the subject can form a tight seal around the mouthpiece with their lips.

To our knowledge, this is the first study to investigate the efficacy of commercially available scavengers and filter facemask in reducing fugitive aerosol concentrations. The two scavengers and the filter facemask reduced fugitive aerosol concentrations when compared to a traditional aerosol facemask with nebulizer. The Vapotherm scavenger had a similar effectiveness as the properly fitted filter facemask, both of which were more effective in reducing fugitive aerosol concentrations than the Exhalo scavenger. This is probably due to the larger vacuum space surrounding the nebulizer and facemask with the Vapotherm face tent scavenger (Figure 2). Particularly, when the aerosol mask does not perfectly fit the subject's face, some aerosols could leak from the gap between the mask and subject's face without being suctioned by the Exhalo scavenger. Likewise, some aerosols could leak from a filter facemask when it does not form a tight fit with the subject's face. Moreover, the scavenger might suction the aerosol from the aerosol facemask, or the filter mask may capture the aerosol, but the impact of the scavenger or filter mask on aerosol delivery is unknown. Adding a filter to the end of a mouthpiece is recommended by groups of researchers and scientific committees,[9,13,14] and our

study is the first *in-vivo* trial to prove its effectiveness in reducing fugitive aerosol emissions. It should be noted that with the use of the mouthpiece and an exhalation filter, aerosol could still leak or be exhaled via the subject's nose, despite achieving a tight mouth seal.

Our results provide valuable clinical implications that should be considered when choosing the appropriate nebulizer and interface for patients with respiratory diseases that are spread by the airborne route, such as COVID-19, influenza, or tuberculosis. Especially at the current phase, there are emerging reports of using aerosol treatment for COVID-19 patients, including inhaled glucocorticoid[17] or heparin,[18] aerosolized vaccine,[19] etc. Moreover, our findings are meaningful to help clinicians avoid second-hand inhalation of medical aerosols when providing nebulizer treatment for patients. Clinicians should consider not only fugitive aerosol concentrations, but also the possibilities of contaminating the nebulizers and interfaces.[13] Lower chances of contamination would reduce the risk of generating and dispersing bio-aerosol to the surrounding environment. The possibility of contaminating the nebulizer depends on the structure and the use of the nebulizer. As the nebulizer cup is directly open to a facemask or a mouthpiece via a T-piece, a SVN has a higher possibility of contamination by patient's secretions.[14] Additionally, SVN can be easily soiled in the process of cleaning, air drying or storage after use.[20] In contrast, in VMN the cup is isolated from the nebulizer reservoir, the cup is usually sealed with a cap and only opened for filling medication. There is little to no possibility that patient secretions contact with the mesh plate to generate contaminated aerosol.[14] As such, use of VMN may be preferred over SVN for COVID-19 patients.[9,13,14]

If SVN is the only choice, adding a filter to the mouthpiece is recommended if patients can breathe via the mouth with a tight seal around the mouthpiece. During nebulization, removing the mouthpiece from the mouth is discouraged. If patients need to cough or talk, the

SVN should be turned off. Otherwise, using a filter mask or adding a face tent scavenger with the aerosol mask is required. Furthermore, if possible, clinicians should stand at a minimum of 3 feet from patients as fugitive aerosol concentrations decrease with increasing distance from the source.[21] Regardless, clinicians should always wear appropriate personal protection equipment (PPE) when providing nebulization for patients, to avoid inhaling the second-hand medical aerosol and protect clinicians from bio-aerosols generated by patients during coughing or talking, or contaminated aerosols during nebulization. Previous studies showed that coughing generated even more aerosols than the fugitive aerosols generated during nebulization[22] and coughing generated bio-aerosol that contains microorganisms.[23] Thus, wearing PPE during the care for any COVID-19 patient is essential as patients might cough at any time or cough may be provoked by nebulization. As a further precautionary measure, the number of people inside the patient room should be minimized during nebulization. It should be noted that fugitive aerosol suspended in the room requires time to clear to baseline after nebulization (15 minutes in our ICU room), depending on the space volume, air exchange frequency and the use of negative pressure in the room.[23,24]

There are several limitations to our study. Due to the lengthy process, only five participants volunteered to continue the additional tests with the filtered facemask and Vapotherm scavenger. Future studies with larger sample size are needed to confirm our findings with both devices, especially the cost-effectiveness in avoiding/reducing transmission is warranted. Additionally, only limited number of mitigation devices were evaluated, future studies are needed to compare a broader range of commercial devices. Secondly, healthy volunteers may have different breathing patterns than patients, and cough, especially productive cough, could influence the results in patients compared to healthy volunteers. Thus studies on

patients with varying respiratory patterns should be performed to validate our findings. Thirdly, all the measurements were made in one ICU room at our hospital, results may vary in different hospital rooms depending on environmental factors, such as temperature and humidity in the room, and the number of air exchanges/hour.[23] Fourthly, we only had two particle counters placed in two positions, especially the particle counter at 1 foot was placed at slightly behind the participant (convenient for stabilizing the particle counter), the aerosol concentrations especially the large particles might vary at different position, future studies with more particle counter placements are needed. Fifthly, similar to other studies that used aerosol particle concentrations to indirectly reflect the aerosol transmission risk,[25] our study did not investigate the virus load nor its infectivity. Sixthly, we found that our participants had large variance in comfort with breathing when different interfaces were employed with VMN, in contrast to similar comfort with breathing when different interfaces were employed with SVN. The asphyxia feeling with VMN and valved facemask might be due to the low oxygen flow setting (2 L/min). Whether the comfort noted by healthy volunteers would differ from patients with respiratory diseases also needs further investigation. Lastly, the particle concentrations in the room at baseline varied under various experimental settings. Ideally, such experiments should be conducted in a particle-free environment.

Conclusion

SVN produced higher fugitive aerosol concentrations than VMN, while facemasks generated higher fugitive aerosol concentrations than mouthpieces. Adding an exhalation filter to the mouthpiece or a scavenger to the facemask reduced fugitive aerosol concentrations for both SVN and VMN. Vapotherm scavenger and filtered facemask had similar effectiveness in reducing fugitive aerosol concentrations as mouthpiece and an exhalation filter.

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Quick look

Current Knowledge

Nebulization is considered an aerosol generating procedure (AGP). Due to the concerns that aerosol generated by the nebulizer might carry virus to the surrounding environment, several clinical societies made recommendations against the use of nebulizers during the COVID-19 pandemic. However, no *in-vivo* data is available on the fugitive aerosol particle concentrations using different nebulizers with common interfaces.

What This Paper Contributes To Our Knowledge

Small volume nebulizer produced higher fugitive aerosol concentrations than vibrating mesh nebulizer, while facemasks generated higher fugitive aerosol concentrations than mouthpieces. Adding an exhalation filter to the mouthpiece or a scavenger to the facemask reduced fugitive aerosol concentrations for both nebulizers. Vapotherm scavenger and filtered facemask had similar effectiveness in reducing fugitive aerosol concentrations as mouthpiece and an exhalation filter.

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Figure legends

Figure 1. Study set up.

The study participant was seated on a sofa chair, with particle counters positioned at 1 and 3 feet from the participant at mouth level. The study investigator stayed in the room with the participant, with N95 mask worn throughout the study. Permission was acquired from the subjects to use the figure.

Figure 2. Different devices to reduce fugitive aerosol concentrations.

A mouthpiece with an expiratory filter: VMN (a) and SVN (e);

A facemask with exhalation filters: VMN (b) and SVN (f);

Exhalo scavenger with an aerosol facemask: VMN (c) and SVN (g);

Vapotherm scavenger with an aerosol facemask: VMN (d) and SVN (h).

VMN, vibrating mesh nebulizer; SVN, small volume nebulizer. Permission was acquired from the subject to use the figure.

Figure 3. Mean fugitive aerosol concentrations of VMN vs SVN with mouthpiece and facemask at 1 foot from participants

X-axis presents different sizes of aerosol particles, Y-axis presents the concentrations of aerosol particles (/m^3).

Top row: SVN had higher fugitive aerosol concentrations than VMN with particle sizes of 1.0-5.0 μm for mask (A) and 1.0-3.0 μm for mouthpiece (B).

Bottom row: Mask had higher fugitive aerosol concentrations than mouthpiece with particle sizes of 0.5-3.0 μm for VMN (D) while no differences for SVN (C).

VMN, vibrating mesh nebulizer; SVN, small volume nebulizer.

* $p < 0.05$

Figure 4. Comparison of fugitive aerosol concentrations at 1 and 3 feet from participants

X-axis presents different sizes of aerosol particles, Y-axis presents the concentrations of aerosol particles (/m^3).

When an aerosol facemask was utilized with nebulizers, fugitive aerosol concentrations were higher at 1 foot from participants than at 3 feet with VMN at particle sizes of 0.3 μm ($p=0.012$), and SVN at particle sizes of 3.0 μm

Figure 5. Mean fugitive aerosol concentrations of a mouthpiece with an expiratory filter and a facemask with Exhalo scavenger at 1 foot from participants.

Top row: Compared to using mouthpiece alone, adding an expiratory filter to a mouthpiece significantly reduced fugitive aerosol concentrations with particle sizes of 0.3-3.0 μm for SVN (E) and 0.3-1.0 μm for VMN (F).

Bottom row: Compared to using aerosol mask alone, using the Exhalo scavenger with the aerosol mask significantly reduced fugitive aerosol concentrations with particle sizes of 0.5-3.0 μm for SVN (G) while no differences were observed for VMN (H).

Figure 6. Comparisons of Vapotherm scavenger and filter facemask to reduce fugitive aerosols generated by nebulizer and facemask at 1 foot from participants

X-axis presents different sizes of aerosol particles, Y-axis presents the concentrations of aerosol particles (/m^3).

Top figure shows the fugitive aerosol concentrations with particle sizes of 0.3-10.0 μm with the use of SVN, while bottom figure shows the fugitive aerosol concentrations with particle sizes of 0.3-10.0 μm with the use of VMN.

When SVN with an aerosol mask was utilized, fugitive aerosol concentrations with particle sizes of 0.3-3.0 μm were lower with Vapotherm scavenger, filter mask and mouthpiece with a filter, which had similar effectiveness to reduce fugitive aerosol concentrations and higher effectiveness than Exhalo scavenger.

When VMN with an aerosol mask was utilized, fugitive aerosol concentrations with particle sizes of 0.3-1.0 μm were lower with Vapotherm scavenger, filter mask and mouthpiece with a filter, which had similar effectiveness to reduce fugitive aerosol concentrations. While slightly lower fugitive aerosol concentration with mouthpiece and filter than Exhalo scavenger was only found at particle size of 3.0 μm.

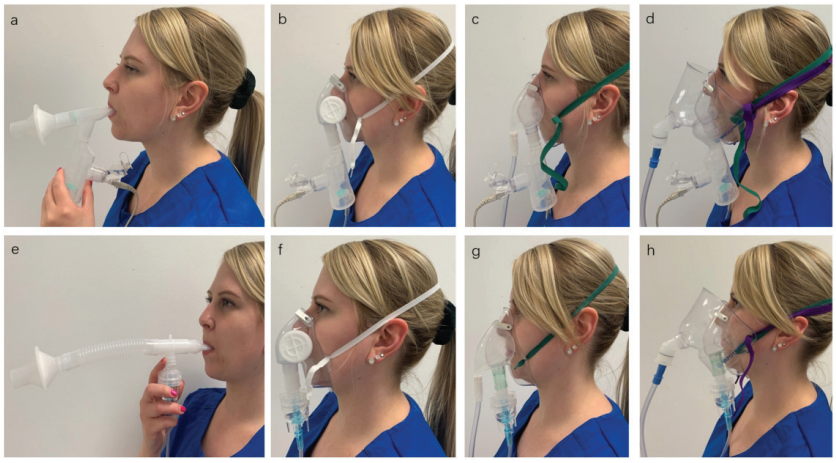
VMN, vibrating mesh nebulizer; SVN, small volume nebulizer.

* $p < 0.05$

Figure 7. Participant self-evaluated comfort while breathing with different devices

The devices with the highest comfort scores are: VMN with a filter mask, VMN with a mouthpiece and a filter, and SVN with a filter mask. While the two devices with mean comfort score below 3.0 are VMN with an aerosol mask and VMN with an aerosol mask and Exhalo scavenger. During the use of VMN, the comfort was higher with the mouthpiece and a filter than the valved facemask with Exhalo scavenger ($p=0.047$).

VMN, vibrating mesh nebulizer; SVN, small volume nebulizer.



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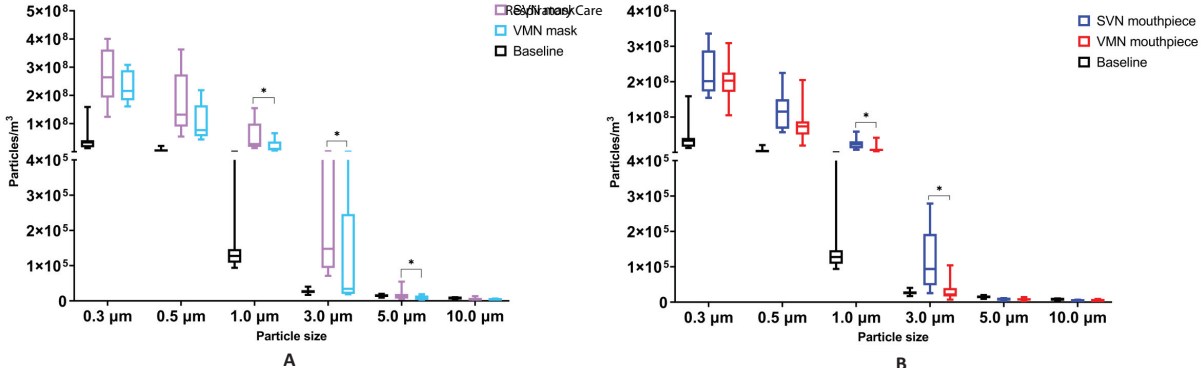
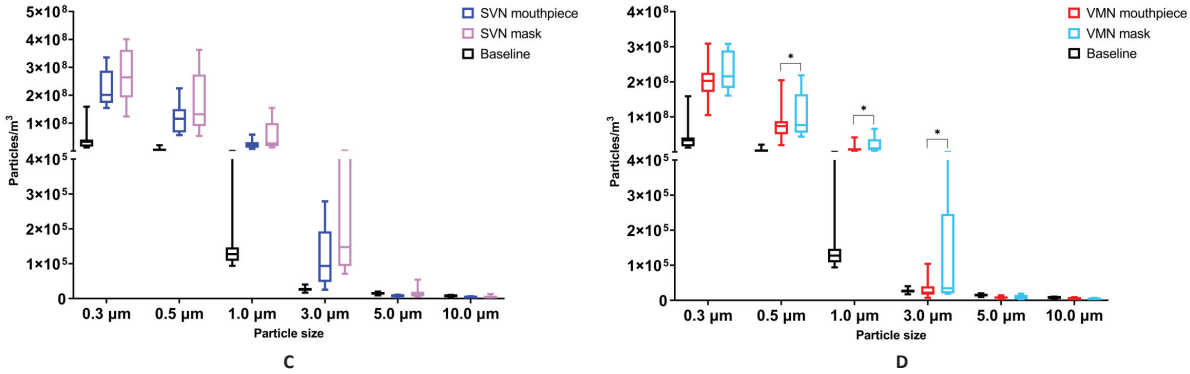
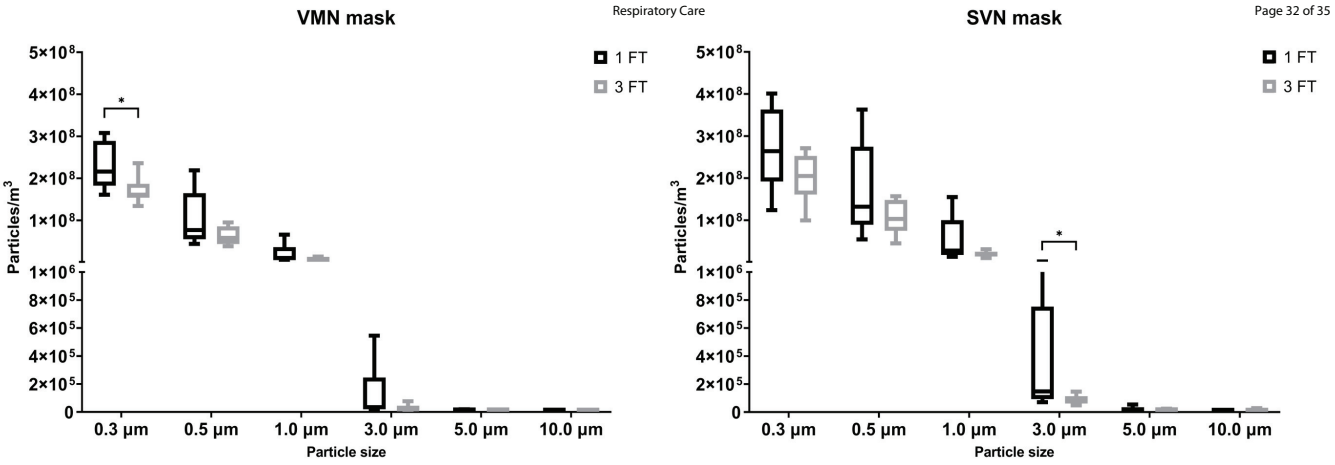
SVN vs VMN

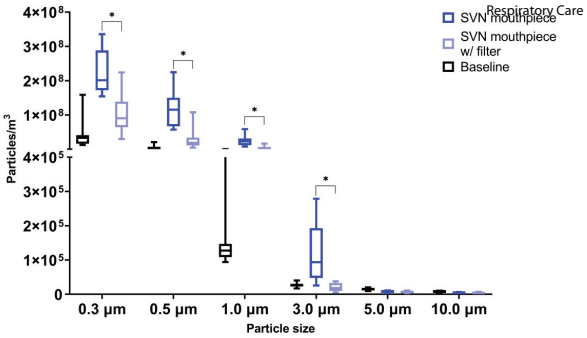


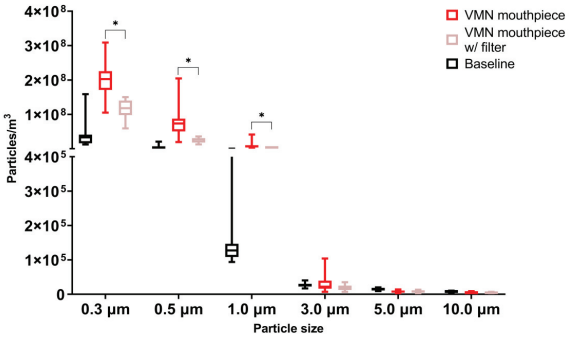
Mouthpiece vs facemask



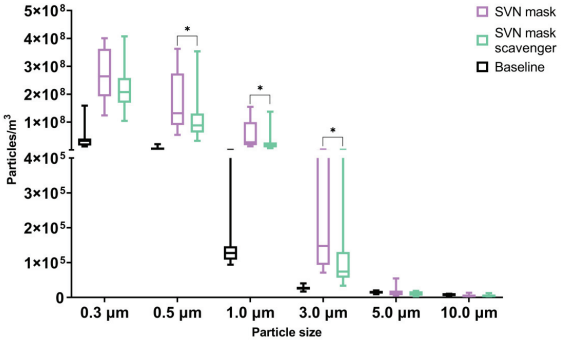


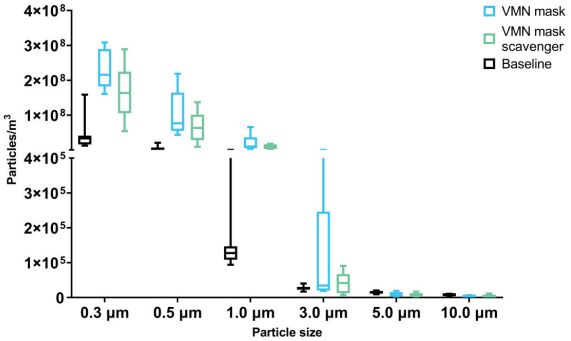
Mouthpiece with vs without an exhalation filter

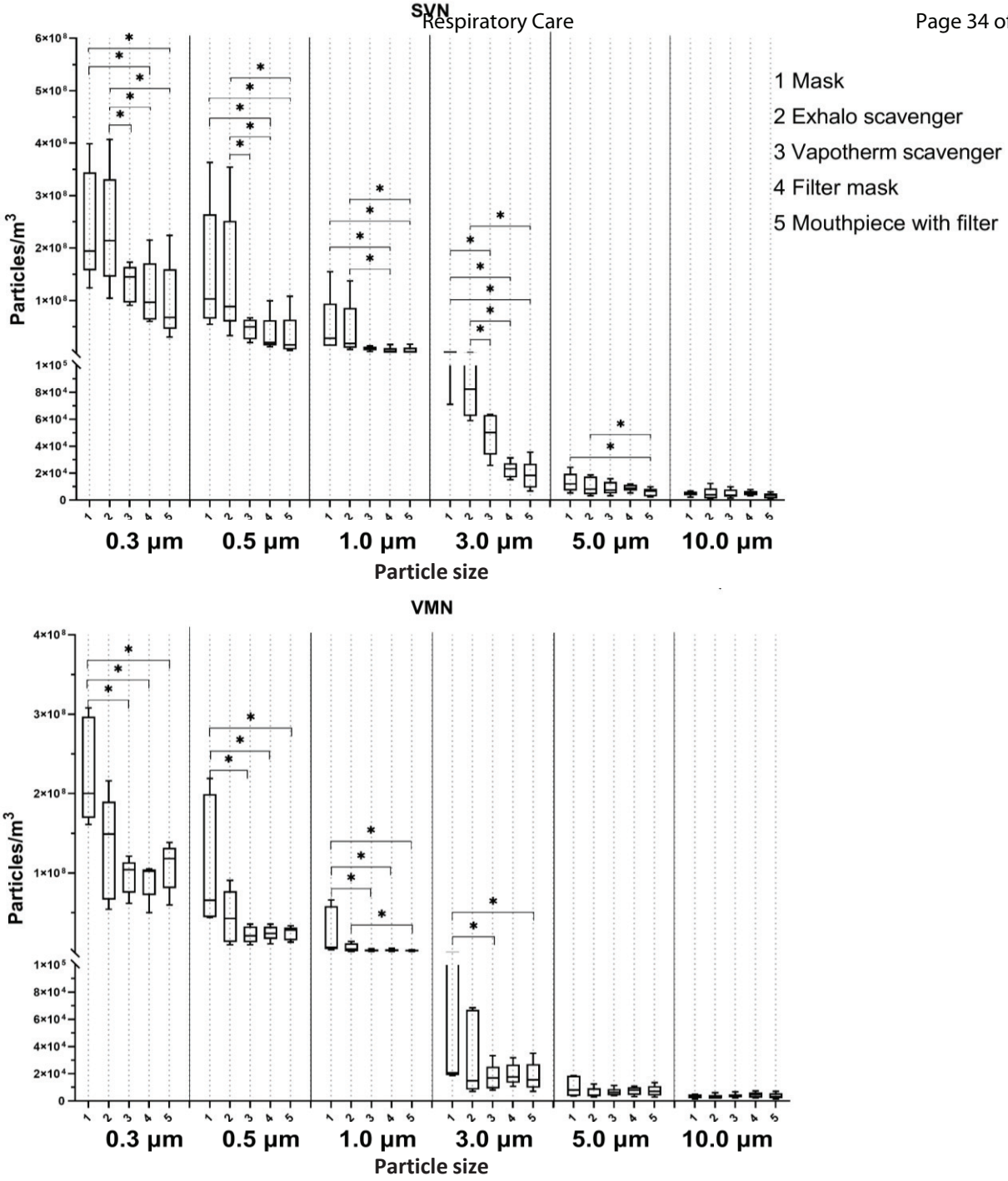


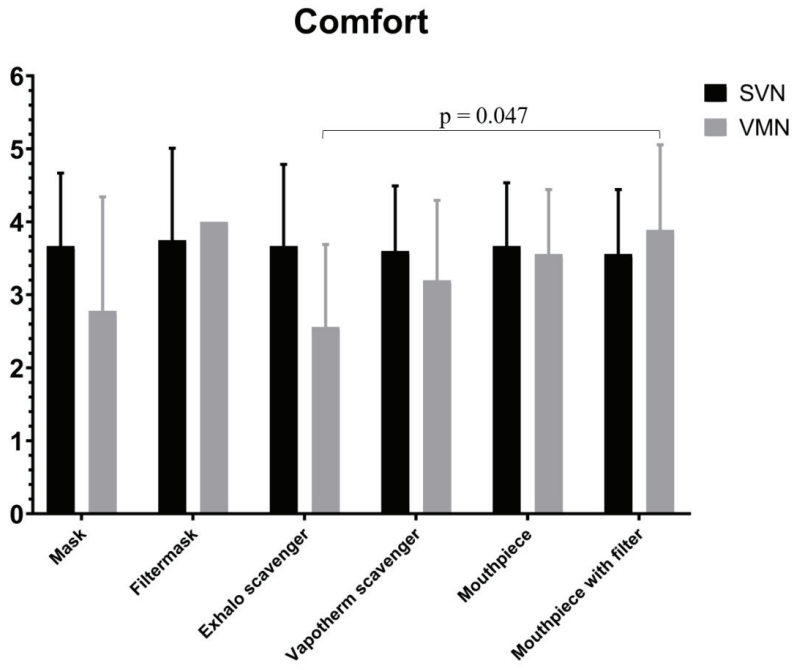


Facemask with vs without Exhalo scavenger









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