University of Cincinnati

Date: 7/17/2018

I, Katherine J. Ollier, hereby submit this original work as part of the requirements for the degree of Master of Science in Industrial Hygiene (Environmental Health).

It is entitled:
Inhalation Exposure and Respiratory Protection of Home Healthcare Workers Administering Aerosolized Medications (Simulation Study)

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Inhalation Exposure and Respiratory Protection of Home Healthcare Workers Administering Aerosolized Medications (Simulation Study)

A thesis submitted to the
Graduate School
Of the University of Cincinnati
In partial fulfillment of the
Requirements for the degree of

Master of Science

In the Department of Environmental Health and Industrial Hygiene
Of the College of Medicine

July 2018

By

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May 2016

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Abstract

There is little information regarding the aerosol exposure produced by a medical nebulizer and the factors that affect the exposure, especially when the treatment is performed in a patient home environment. Home healthcare workers (HHWs) is a rapidly growing work population often exposed to significant aerosol hazards. In this study, we designed a simulated environment to measure the inhalation aerosol exposure of a HHW under different conditions. We also determined the relative contributions of different factors on the aerosol reduction in the exposure chamber simulating a patient’s bedroom. Those conditions included room air exchange rate, proximity to the patient, and the patient breathing rate. Additionally, the performance of different respiratory protective devices typically worn by a HHW, a surgical mask and N95 filtering facepiece respirator (FFR), was evaluated. NaCl was used as a surrogate for nebulizer-aerosolized medication. The particle concentration in the breathing zone of an unprotected worker ranged from 7,118 to 284,600 cm$^{-3}$. For unprotected HHWs, ventilation was the most effective mean to reduce the occupational exposure to medical aerosols produced during nebulizer-based treatment. An increase in air exchange rate from 0 (calm air) to 5 h$^{-1}$ significantly reduced the exposure; however, further increase from 5 to 17 h$^{-1}$ provided only a minor decrease in the particle concentration. Consequently, there is no evidence that patient homes should need an extremely efficient ventilation in order to mitigate the HHW’s exposure to the nebulizer-produced medications. In homes with no ventilation, a HHW standing at least 24 inches from the particle source could have significantly lower exposure risk. Increase in patient breathing flow rate was found to reduce the inhalation aerosol exposure. However, this factor cannot be controlled, which makes this effect of no practical implication for controlling the HHW’s exposure. Wearing respiratory protection devices was found to be the most efficient way
to reduce aerosol exposure. As expected, an N95 FFR with a proper seal was about 20 times more efficient than a surgical mask.
Acknowledgments

I would like to thank all of those who have worked alongside me on this project, for without their help I would have never completed this master’s thesis. Special acknowledgement goes to Maija Leppänen and Bingbing Wu—thank you for so many countless hours over winter break. I would also like to thank all of the professors and mentors who have worked tirelessly in the College of Environmental Health and Industrial Hygiene to provide such a wonderful Industrial Hygiene program. My education and research could not have been completed without the funding assistance of the National Institute for Occupational Safety and Health through the Targeted Research Training Program of the University of Cincinnati Education and Research Center. Lastly, I would like to thank all of the individuals who have given me so much support while obtaining my master’s degree and who never gave up on me.
Table of Contents

Abstract ................................................................................................................................. ii-iii

Acknowledgments ................................................................................................................ v

Introduction .......................................................................................................................... 9-10

Materials and Methods ....................................................................................................... 11-14

Results and Discussion ....................................................................................................... 14-20

Conclusions .......................................................................................................................... 20

Funding .................................................................................................................................. 21

Bibliography ......................................................................................................................... 22-24

Appendices

Appendix A ......................................................................................................................... 25

Appendix B .......................................................................................................................... 26
List of Tables

Table 1. A layout of the variables examined in this study ..............................................12
Table 2: Statistical results of the Mixed Effect Model ......................................................15
List of Figures

Figure 1. Effect of distance and AER on particle concentration………………………………...15
Figure 2. Effect of AER on particle concentration………………………………………………16
Figure 3. SWPFs of surgical mask and N95 FFR………………………………………………..19


**Introduction**

Healthcare professionals working in hospitals can come into close contact with numerous types of occupational hazards such as exposure to reproductive hazards,\(^1\) as well as infectious agents and blood borne pathogens.\(^2, 3\) Exposure of healthcare workers to medications, especially when performing treatments involving aerosolized drugs is likely associated with substantial health risks. Home healthcare workers (HHWs) providing their services in patients’ homes do not have the benefit of working in a controlled environment such as a hospital setting. Hospital rooms typically have a high air exchange rate (AER), sometimes in excess of 20 air exchanges per hour and are frequently cleaned. In contrast, residential settings typically have relatively low exchange rate or no ventilation at all. In addition to the healthcare related exposures, HHWs can also be exposed to household hazards including, but not limited to secondhand smoke and lead.\(^4\)

One exposure source of the HHWs is the medication they are administering using medical nebulizers, which aerosolize medication intended for patient inhalation, e.g., for asthma and COPD treatment.\(^5\) Some of the most common medications dispersed by a medical nebulizer are Ipratopium Bromide, Budesonide,\(^6\) and Albuterol Sulfate.\(^6, 7\) A previous study showed that NaCl aerosol could be used as a surrogate for these medications for characterizing the particle transport and HHW’s exposure.\(^6\)

Since nebulizers are not built to provide a particularly tight fit to a patient under treatment (i.e., the facial mask connected to a nebulizer does not have a perfect seal on the patient’s face), a HHW can receive secondhand exposure while administering medication with a nebulizer. This in turn can lead to an increased risk of asthma and lung infection.\(^8\) Although home healthcare is
one of the fastest growing healthcare fields in the United States, very few agencies adequately address occupational aerosol exposure of HHWs and provide respiratory protection training and fit testing to minimize the inhalation exposure of their employees in patient homes. It is not uncommon for HHWs to enter a home with no respiratory protection at all.

There is insufficient information regarding the aerosol produced by a medical nebulizer. Even less is known about the factors affecting the aerosol particle concentration when the treatment is performed in a patient home environment. In a pilot laboratory study conducted with a jet-nebulizer, inhalation exposures to the above-listed medications were evaluated. The quoted pilot study was performed in a small chamber simulating a two-dimensional configuration and utilizing two manikins mimicking a patient and a HHW. The study determined that the total aerosol mass concentration in the breathing zone of a HHW could vary from 0.229 to 1.02 g/m³. As the referred investigation was performed under a specific set of condition, it could not generate a fully relevant evidence about environmental conditions affecting the HHW’s exposure. Another pilot investigation focused on the evaluation of respiratory protective devices used in a home health care environment was carried out under actual field conditions and involved multiple tasks; however, this effort was not specifically focused on the nebulizer treatments and did not consider variables such as AER.

The present follow-up study built on the foundation created by our recent pilot laboratory testing aims at developing the next level simulation setting to measure the aerosol exposure of a HHW affected by different environmental factors, and to determine the relative contributions of these factors on the aerosol exposure reduction in a room-size chamber. The performance of different respiratory protective devices typically worn by a HHW was also evaluated.
MATERIALS AND METHODS

Experimental Design

This simulation study was performed in an exposure chamber (24.3 m³) with a close-loop ventilation and air filtration system under three different AERs: 0 (calm air), 5 h⁻¹, and 17 h⁻¹. The calm air represents a home with turned off or non-functioning ventilation, which serves as the most conservative case from the exposure standpoint. Air exchange rate of 5 h⁻¹ represents a normal to highly efficient residential home ventilation, and 17 h⁻¹ represents a hospital setting AER, which typically ranges from 15 to 20 h⁻¹. The highest AER was used to compare aerosol exposure levels for an HHW administering nebulized medication in a patient’s home and in a hospital room.

A breathing manikin simulating a patient was placed in the center of the test chamber with a nebulizer mask positioned on the manikin’s face. A breathing simulator (BRSS, Koken Ltd., Tokyo, Japan) was connected to the manikin via plastic tubing. A HEPA filter was placed between the manikin and breathing simulator. The filter prevented particles from exiting the manikin breathing zone during exhalation. The tests were conducted at two breathing conditions of a patient represented by the mean inspiratory flow (MIF) rates of 15 and 30 L min⁻¹.

The test variables are presented in Table 1 below. In addition to the AER and MIF, we varied the proximity of a HHW to the aerosol source (nebulizer), and the level of respiratory protection.

The study protocol was designed so that any exposure to potentially hazardous aerosolized drugs would be avoided. A sodium chloride (NaCl) aerosol was used as a surrogate of nebulized medications commonly administered by HHWs based on the findings reported in
our earlier study.[6] Particles were aerosolized by a PARI LC Sprint reusable nebulizer (Model 023F35, PARI Respiratory Equipment Inc., Midlothian, VA, USA) charged with a 0.9% NaCl solution. The nebulizer was connected to an adult PARI mask. A Vios PRO compressor ran at 10 L min\(^{-1}\) for a minimum of 10-12 minutes to reach concentration plateau in the chamber before data collection started for the tests conducted at AER = 5 and 17 h\(^{-1}\). When testing at no air exchange, it took longer, 15-20 minutes to reach the intended plateau. Typically, nebulizer treatment sessions last between 5 and 10 minutes, but some may take up to 20 minutes.

A study subject representing a HHW administered the nebulizer treatment to the manikin while standing at different distances from the latter (measured from nose to nose). The four levels of proximity (Table 1) were chosen to represent a working range, including close interaction (6 inches), a typical operational proximity (90\(^\circ\)-bent elbow) (12 inches), manipulation of the nebulizer with a stretched-out arm (24 inches), and no manipulation with the nebulizer (the HHW standing 48 inches away).

Table 1. A layout of the variables examined in this study.\(^A\)

| Variable                   | Levels            |
|----------------------------|-------------------|
| AER                        | 0, 5, 17 h\(^{-1}\) |
| Distance                   | 6, 12, 24, 48 inches |
| MIF                        | 15, 30 L min\(^{-1}\) |
| Protection Condition\(^B\) | Unprotected, Surgical Mask, N95 FFR |

\(^A\) The number of replicates varied if the HHW subject was unprotected (6 replicates) vs. protected (3 for surgical mask and 3 for N95 FFR).

\(^B\) The tests involving respiratory protective devices were operated only at a MIF = 15 L min\(^{-1}\).
The three respiratory protection conditions for the subject included wearing no mask/respirator (HHWs often operate in patient homes unprotected), wearing a surgical mask (Surgine II, model 4260 Ethicon, Inc., Arlington TX, USA), and wearing an N95 facepiece filtering respirator (FFR) (3M, model 1860S, Maplewood, MN, USA). Two P-Trak condensation particle counters (Model 8525 TSI Inc., Shoreview, MN, USA) were operated in parallel to measure the particle concentration inside \( C_{\text{in}} \) and outside \( C_{\text{out}} \) the mask/respirator when worn. Each trial ran for five minutes with three replicates for each study condition. For both types of protection devices, the measured \( C_{\text{out}} \) represented the exposure of an unprotected worker. As \( C_{\text{out}} \) was measured – simultaneously with \( C_{\text{in}} \) – for both respiratory protection devices (three times for each), the total number of replicates for the unprotected HHW was six.

The study protocol was approved by the University of Cincinnati Institutional Review Board (IRB). The informed consent was signed prior to study. After passing a questionnaire-based medical examination, the human subject was cleared to wear an N95 FFR.

**Data Analysis**

The time-weighted average (TWA) values of the particle concentration measured in the HHW’s breathing zone (with and without mask/respirator) were calculated for each condition over a 5-min run time. The arithmetic mean and standard deviation were calculated for all replicates. The Simulated Workplace Protection Factor (SWPF) for both the surgical mask and N95 FFR was determined as a ratio of time-weighted averages of \( C_{\text{out}} \) and \( C_{\text{in}} \).

\[
SWPF_{TWA} = \frac{\int_0^t C_{\text{out}}(t)\,dt}{\int_0^t C_{\text{in}}(t)\,dt}
\]  

(1)
A mixed effect model was fit to the data obtained for exposure level (represented by the aerosol concentration) and for the SWPF. Accordingly, the effects of the studied factors, such as AER, distance, and MIF were examined. If any factor was found statistically significant, a multiple comparison method (Tukey Contrast Test) was performed to look for the differences among multi-levels of each factor and identify the trend in reduction. A p-value of <0.05 was considered to be statistically significant. Statistical analysis was performed in R-Studio (1.1.447, The R Foundation, New Zealand).

RESULTS AND DISCUSSION

Unprotected HHW

The overall particle concentration measured in the breathing zone of an unprotected subject ranged from 7,118 cm$^{-3}$ to 284,600 cm$^{-3}$. The concentrations found in this investigation were generally in excess of those measured in the field$^{[11]}$ (the upper limit was about 5-fold greater) suggesting that this simulation study represents a conservative case. Figure 1 presents the measurement results. Increase in each of the factors (AER, distance, and MIF) led to the decrease in aerosol exposure. As expected, the aerosol concentration was highest at AER=0 and when the HHW was in the closest proximity from the nebulizer outlet. The concentration decrease was less pronounced (with respect to distance) when the AER was 5 or 17 h$^{-1}$, compared to AER=0. The highest level of data variation was found for the 6-inch distance because the particle dispersion via the manikin exhalation introduced variability that was much more evident within closer proximity.
Figure 1. The effect of the HHW proximity to the patient-manikin (distance) and AER on the aerosol particle concentration in the HHW breathing zone at manikin’s MIF of 15 L min\(^{-1}\) (A) and 30 L min\(^{-1}\) (B). Each data point represents an arithmetic mean and standard deviation of six measurements.

The effect of AER, distance, and MIF on the inhalation aerosol exposure of an HHW was found significant (p<0.001), as shown in Table 2.

Table 2. Statistical results of the Mixed Effect Model.

| Environmental Factors | Estimated Effect Value | Std. Error | Degrees of Freedom | t-value | p-value |
|-----------------------|------------------------|------------|--------------------|---------|---------|
| Intercept             | 12.786709              | 0.06811332 | 8675               | 187.72701 | 0.0000  |
| AER                   | -0.208143              | 0.01371614 | 8675               | -15.17502 | 0.0000  |
| DISTANCE              | -0.037332              | 0.00134901 | 8675               | -27.67400 | 0.0000  |
| MIF                   | -0.052838              | 0.00133073 | 8675               | -39.70609 | 0.0000  |
| AER:DISTANCE          | 0.000983               | 0.00062669 | 8675               | 1.56883  | 0.1167  |
| AER:MIF               | 0.000032               | 0.00069705 | 8675               | 0.04645  | 0.9630  |
| DISTANCE:MIF          | 0.000918               | 0.00006275 | 8675               | 14.62228 | 0.0000  |
| AER:DISTANCE:MIF      | 0.000005               | 0.00002895 | 8675               | 0.17399  | 0.8619  |

A Mixed Effect Model was used to compare the variables in this study. This model allowed for the variables to have fixed effects within the same parameters, granting the ability to compare AER, distance, and MIF with their different units. This model revealed that the AER in the chamber was the most significant factor reducing the particle concentration. AER was 5-fold
more effective than the proximity, and 4-fold more effective than MIF. In fact, with the introduction of fixed AER, such as 5 or 17 h\(^{-1}\), the distance and MIF were no longer significant (p>0.05). In addition, an increase of AER from 5 to 17 h\(^{-1}\) did not provide the same substantial reduction as seen when AER increased from 0 to 5 h\(^{-1}\). This suggests that an introduction of air exchange as little as 5 h\(^{-1}\) could significantly reduce the aerosol exposure of a HHW in a home environment, and it may not be necessary to establish an AER as high as the one used in hospital settings (17 h\(^{-1}\)) to effectively decrease the inhalation exposure risk. Figure 2 demonstrates the concentration reduction as AER is increased.

Figure 2. The effect of AER on the aerosol particle concentration while the subject stood at 12 inches and manikin’s MIF was 15 L min\(^{-1}\). The increase of the AER from 0 to 5 h\(^{-1}\) decreased the particle concentration most significantly.
Based on the Tukey Contrast Test, proximity to the source had the most substantial effect on the particle concentration in the HHW’s breathing zone only when there was no air exchange. The particle concentration decrease with the distance was significant ($p<0.001$) but appeared less pronounced as the distance increased beyond 24 inches. This suggests that the benefit of staying far away from the source of the nebulizer-aerosolized medication diminishes because of the air dilution factor. When the chamber was ventilated ($AER = 5$ and $17\ h^{-1}$), the overall concentration in the environment was approximately 10 times lower than when there was no ventilation, and the distance did not appear to affect the concentration as much (Figure 1). However, according to the Tukey Contrast Test, the concentration decreased significantly whenever the distance increased with two exceptions: (1) between 6 and 12 inches ($AER = 5\ h^{-1}, \ MIF= 15\ L\ min^{-1}$); and (2) between 12 and 24 inches ($AER = 17\ h^{-1}, \ MIF= 30\ L\ min^{-1}$). Testing for linear hypothesis revealed that the estimated effect of distance on particle concentration in a ventilated environment was much lower than that with no ventilation. This indicates that in a well-ventilated room, increasing the distance to the patient may not necessarily affect the exposure level.

The above findings are generally consistent with the pilot study\textsuperscript{[6]} that utilized a simplistic approach for assessing the aerosol particle concentrations during a nebulizer use at distances of 6, 12, and 21 inches from the source involving two manikins and no air exchange factor. It was reported that the distance had a significant effect ($p<0.05$) on the total mass concentrations of specific aerosolized medications.

Similar to distance, the patient’s MIF significantly reduced particle concentration ($p<0.001$) as was shown by the comparison of the data obtained at 15 and 30 L min$^{-1}$, but only had a substantial effect when there was no ventilation present. However, this finding can be at least
partially attributed to the experimental design, and not necessarily to the effect of MIF per se. As a HEPA filter was placed between the breathing simulator and the manikin’s breathing line, more particles were naturally drawn onto the filter at 30 L min$^{-1}$ compared to 15 L min$^{-1}$, thus decreasing the overall aerosol concentration in the environment. An increase in MIF during a fixed ventilation rate was significant, but according to the Tukey Contrast Test, the estimated effect was much less compared to the effect of ventilation.

**Protected HHW**

When the subject was wearing the surgical mask, the particle concentration measured inside the mask ranged from 58 to 128,400 cm$^{-3}$, and the SWPF varied from 3 to 7 (TWA values, Figure 3). Thus, the surgical mask provided low respiratory protection, which is consistent with findings of numerous studies. There was no consistent significant trend in which the AER and distance affected the SWPF of the surgical mask.

The particle concentration inside the N95 FFR ranged from 32 to 7,324 cm$^{-3}$, and the SWPF varied from 52 to 305 (TWA values, Figure 3). No significant effect of either distance or AER was identified (p>0.05). A HHW wearing an N95 FFR will be significantly (p<0.001) better protected than an individual wearing a surgical mask (Figure 3). The respiratory protection improvement was on average around 20-fold.
Figure 3. SWPFs of the surgical mask and the N95 FFR determined at different HHW’s proximities to the aerosol source and different air exchange conditions. The patient-manikin’s MIF was 15 L min⁻¹. Each data point represents an arithmetic mean and standard deviation of three measurements.

In a study conducted in a real home healthcare environment with different working tasks including a nebulizer treatment,¹¹ the workplace protection factors of surgical masks were comparable to the SWPFs found in this simulation effort while the testing with the N95 FFR produced somewhat higher SWPF values compared to the field study.¹¹ The difference may be attributed to the fact that the subject in our study was less active than the actual workers performing multiple tasks in a home; consequently, less intense body movement helped maintain the respirator fit resulting in higher measured SWPF.
Among all factors affecting the aerosol exposure of a HHW tested in this investigation, wearing an N95 FFR was the most effective mean for the exposure reduction.

**Conclusions**

This simulation study suggests that, for an unprotected HHW administering nebulizer-aerosolized medications, the most effective way of reducing aerosol exposure is to have some form of ventilation (air exchange) present. This ventilation does not have to be as effective as in a hospital room; five air changes per hour could be sufficient to significantly reduce the exposure risk. The proximity to the aerosol source matters, but the distance effect diminishes when the distance increases beyond 24 inches.

The SWPF offered by a surgical mask was significantly lower than that of the N95 FFR. Among all factors affecting the aerosol exposure of an HHW tested in this investigation, wearing an N95 was the most effective way for the exposure reduction. It is recommended for an HHW to wear an N95 FFR during a home visit.

It is acknowledged that while this follow-up effort allowed for a considerable expansion of our earlier investigation,\textsuperscript{[6]} it is still a simulation study and as such has various limitations. Future investigations should be initiated in homes to enhance the assessment of exposure of HHWs to aerosolized medication and other aerosol hazards to better understand the role and potential of respiratory protective devices in the exposure control.
FUNDING

This research study was supported by the National Institute for Occupational Safety and Health through the Targeted Research Training Program of the University of Cincinnati Education and Research Center Grant #T42OH008432.
1. Lawson, C.C., C.M. Rocheleau, E.A. Whelan, E.N.L. Hibert, B. Grajewski, D. Spiegelman and J.W. Rich-Edwards: Occupational exposures among nurses and risk of spontaneous abortion. *Am. J. Obstet. Gynecol.* 206(4): 1-16 (2012).

2. Vecchio, D., A.J. Sasco, and C.I. Cann: Occupational risk in health care and research. *Am. J. Ind. Med.* 43(4): 369-397 (2003).

3. Arif, A.A., G.L. Delclos, and C. Serra: Occupational exposures and asthma among nursing professionals. *Occup. Environ. Med.* 66(4): 274-278 (2009).

4. Sherman, M.F., R.R. Gershon, S.M. Samar, J.M. Pearson, A.N. Canton, and M.R. Damsky: Safety factors predictive of job satisfaction and job retention among home healthcare aides. *J. Occup. Environ. Med.* 50(12): 1430-1441 (2008).

5. Campbell, S.: For COPD a combination of ipratropium bromide and albuterol sulfate is more effective than albuterol base. *Arch. Intern. Med.* 159(2): 156-160 (1999).

6. Elmashae Y., M. Yermakov, E. Frank, B. Michael, A. Maier, N. Newman, T. Reponen, S.A. Grinshpun: Exposure of home-Attending healthcare workers to aerosolized medications (Simulation study). *J. Aerosol Sci.* [Submitted].

7. Kerwin, E.M., H. Taveras, H. Iverson, D. Wayne, T. Shah, M.S. Lepore, and D.S. Miller: Pharmacokinetics, pharmacodynamics, efficacy, and safety of albuterol (salbuterol) multi-dose dry-powder inhaler and ProAir® hydrofluoroalkane for the treatment of persistent asthma: Results of two randomized double-blind studies. *Clin. Drug Investig.* 36(1): 55-65 (2016).
8. **Ari, A., J.B. Fink, and S.P. Pilbeam:** Secondhand aerosol exposure during mechanical ventilation with and without expiratory filters: An in-vitro study. *Indian J. Respir. Care.* 5(1): 677-82 (2016).

9. **Gershon, R.R., M. Pogorzelska, K.A. Qureshi, P.W. Stone, A.N. Canton, A.M. Samar, L.J. Westra, M.R. Damsky, and M. Sherman:** Home health care patients and safety hazards in the home: Preliminary findings. *Advances in Patient Safety: New Directions and Alternative Approaches*, 1 (2008).

10. **Gershon, R.R., L.A. Magda, A.N. Canton, H.E. Riley, F. Wiggins, W. Young, and M.F. Sherman:** Pandemic-related ability and willingness in home healthcare workers. *Am. J. Disaster Med.* 5(1): 15-26 (2010).

11. **Elmashae, Y., S.A. Grinshpun, T. Reponen, M. Yermakov, and R. Riddle:** Performance of two respiratory protective devices used by home-attending health-care workers (A pilot study). *J. Occup. Environ. Hyg.* 14(9): 145-149 (2017).

12. **Booth, C.M., M. Clayton, B. Crook, J.M. Gawn:** Effectiveness of surgical masks against influenza bioaerosols. *J. Hosp. Infect.* 82(1): 22–26 (2013).

13. **Chen, C.C., and K. Willeke:** Aerosol penetration through surgical masks. *Am. J. of Infect. Control.* 20(4): 177-184 (1992).

14. **He, X., T. Reponen, R.T. McKay, and S.A. Grinshpun:** Effect of particle size on the performance of an N95 filtering facepiece respirator and a surgical mask at various breathing conditions. *Aerosol Sci. Tech.* 47(11): 1180-1187 (2013).

15. **Gao, S., R.H. Koehler, M. Yermakov, and S.A. Grinshpun:** Performance of facepiece respirators and surgical masks against surgical smoke: workplace protection factor study. *Ann. Occup. Hyg.* 60(5): 608-618 (2016).
16. Grinshpun, S.A., H. Haruta, R. Eninger, T. Reponen, R. McKay, and S.A. Lee: Performance of an N95 filtering facepiece particulate respirator and a surgical mask during human breathing: two pathways for particle penetration. *J. Occup. Environ. Hyg.* 6(10): 593-603 (2009).

17. Grinshpun, S.A., S. Gao, M. Yermakov, Y. Elmashae, T. Reponen, and R. Koehler: “Surgical Smoke Aerosol: Exposure Assessment and Respiratory Protection.” Presented at the Abstracts of the European Aerosol Conference, Tours, France, September 4-9, 2016.

18. Rengasamy, A., Z. Zhuang, and R. Berryann: Respiratory protection against bioaerosols: literature review and research needs. *Am. J. Infect. Control* 32(6): 345-354 (2004).
Appendix A – Equipment and Chamber Setup Photos

-Nebulizer placed on the manikin breathing zone

-HHW subject wearing an N95 FFR attached to two P-Traks
Appendix B – Raw Data

See corresponding electronic data.