Aerosolization During Common Ventilation Scenarios

Roy Xiao, MD, MS; Alan D. Workman, MD, MTR; Elefteria Puka, BS; Jeremy Juang, MD, PhD; Matthew R. Naunheim, MD, MBA; Phillip C. Song, MD

Massachusetts Eye and Ear, Department of Otolaryngology – Head and Neck Surgery, Boston, MA, USA
Harvard Medical School, Department of Otolaryngology – Head and Neck Surgery, Boston, MA, USA
Massachusetts Eye and Ear, Department of Anesthesiology, Boston, MA, USA
Harvard Medical School, Department of Anesthesiology, Boston, MA, USA

*Corresponding Author:
Roy Xiao, MD, MS
Resident Physician
Department of Otolaryngology
Massachusetts Eye and Ear
Harvard Medical School
Phone: 732.829.5695
Email: roy_xiao@meei.harvard.edu

No funding was received to support this study. The authors have no conflicts of interest to disclose. This study was exempt from IRB (Massachusetts Eye and Ear) approval.

Author Contributions. RX, AW, EP, JJ, MN, and PC contributed to conceptualization, methodology, data curation, and writing – review and editing. RX contributed to formal analysis and writing – original draft, and visualization. MN and PS contributed to supervision and project administration.

Keywords: Aerosol; cough; Covid-19; intubation; tracheostomy; ventilation
Abstract

Otolaryngologists are at increased risk for exposure to suspected aerosol-generating procedures during the ongoing COVID-19 pandemic. In the present study, we sought to quantify differences in aerosol generation during common ventilation scenarios. We performed a series of 30-second ventilation experiments on porcine larynx-trachea-lung specimens. We used an optical particle sizer to quantify the number of 1-10μm particles observed per 30-second period (PP30). No significant aerosols were observed with ventilation of intubated specimens (10.8±2.4 PP30 vs. background 9.5±2.1, \( p=1.0000 \)). Simulated coughing through a tracheostomy produced 53.5±25.2 PP30, significantly more than background (\( p=0.0121 \)) and ventilation of an intubated specimen (\( p=0.0401 \)). These data suggest that undisturbed ventilation, and thus intubation without stimulation or coughing may be safer than believed. Coughing increases aerosol production, particularly via tracheostomy. Otolaryngologists who frequently manage patient airways and perform tracheostomy are at increased risk for aerosol exposure and require appropriate PPE, especially during the ongoing COVID-19 pandemic.
Introduction

The COVID-19 pandemic first reached the U.S. in January 2020. Preliminary research suggests that the responsible virus, SARS-CoV-2, is transmitted through not only large droplets which settle faster, but also small droplets and aerosols, which stay suspended for hours. This is notable for suspected aerosol-generating procedures (AGPs), such as intubation and tracheotomy, which can increase risk of transmission to healthcare workers.

Understanding aerosol generation has significant implications, particularly on personal protective equipment (PPE) usage. This is particularly relevant to otolaryngologists who frequently manage patient airways and perform tracheostomy. We therefore sought to quantify differences in aerosol generation during common ventilation scenarios.

Methods

The present study was undertaken as a Quality Improvement Initiative at Massachusetts Eye and Ear and thus exempt from IRB approval. We used fresh cadaveric porcine specimens in which the larynx, trachea, and lungs were dissected en bloc as our model (Figure 1). We conducted five 30-second ventilation experiments in quadruplicate: (1) background of the surgical laboratory as negative control; (2) manual ventilation of an intubated (7.0 endotracheal tube [ETT]) specimen with Ambu® bag (Bag-Valve Tube [BVT]) at 12 breaths per minute (Figure 1A); (3) BVT manual ventilation with forced lung decompression at peak inspiration to simulate a “cough” every 6 seconds; (4) hyperinflation using the Dri-Scope Aid® 2 as an air compressor followed by forced lung decompression “cough” through an uncovered ETT every 10 seconds; (5) hyperinflation with the Dri-Scope Aid® 2 followed by forced lung decompression “cough” through a Shiley low-pressure cuffed tracheostomy tube (6LPC).
between the second and third tracheal rings every 10 seconds (Figure 1B). Each “cough” was produced by two investigators who performed synchronized manual compression of each lung for rapid deflation and expiratory airflow.

For each experiment, we performed aerosol sampling using an optical particle sizer (OPS 3330, TSI Inc.) to measure particle number, concentration, and size distribution using single particle counting technology up to 10μm across 16 user-adjustable channels. Flow rate through the OPS 3330 is a constant 1.0L/min through a 3mm port. The OPS 3330 sampling port was placed 15cm from the airway’s opening defined as follows: the expiratory valve for experiments (2) and (3); the opening of the ETT for experiment (4); the opening of the 6LPC for experiment (5).

For our outcome, we report mean ± standard deviation number of particles larger than 1μm observed per 30-second period (PP30). We performed a Kruskal-Wallis one-way ANOVA test with multiple comparisons to compare experiments with α=0.05 as our significance threshold. We analyzed and visualized data using GraphPad Prism 7.0e.

Results

At baseline, we observed 9.5±2.1 background PP30 (Figure 2). No significant increase in aerosols was observed with BVT ventilation of an intubated specimen (10.8±2.4 PP30, p=1.0000). Simulated coughing did not significantly increase aerosol production with 30.3±24.9 PP30 produced in the setting of BVT ventilation (p=0.4792 vs. background) and 23.0±8.1 PP30 in the setting of hyperinflation (p=0.2656 vs. background). Simulated coughing in the setting of hyperinflation through a tracheostomy produced 53.5±25.2 PP30, significantly more than background (p=0.0121) and BVT ventilation of an intubated specimen (p=0.0401). No
statistically significant differences in PP30 were observed between our three coughing scenarios. Of note, by direct visualization, we observed expectoration of water droplets during coughing scenarios too large to be detected by the OPS 3330.

Discussion

Our findings demonstrated that undisturbed ventilation did not show significant aerosol generation beyond background in our model; thus, intubation more generally without excessive stimulation and coughing may be safer than believed. These data also showed that coughing via tracheostomy does produce significant aerosols, much more than coughing through the ETT. As human aerosols are understood to be produced within the alveoli, these data suggest that the upper aerodigestive tract is effective in filtering the smallest particles despite visual evidence of larger droplet expectoration. Moreover, the significantly greater distance between the lungs and the opening of the ETT offers greater opportunity for physical filtration of aerosolized particles. Accordingly, during the ongoing COVID-19 pandemic, tracheotomy and care for patients with tracheostomy represent significant risks for healthcare workers and demand sufficient PPE. Thus, otolaryngologists who frequently manage patient airways and, in particular, tracheostomies should be especially vigilant in using appropriate PPE.

The present study is limited by the use of a porcine model which can only approximate human anatomy. Our coughing data were moderately variable, as manual “coughs” introduced human error; furthermore, this model may underestimate true aerosolization, as our “coughs” cannot reach the full force of a true coordinated thoracic cough, and aerosol particle size is inversely related to air speed across the mucosal surface. Finally, our experiments focused on short 30-second exposure periods for consistent data comparable to background, rather than
assess variable or extended periods of exposure. While BVT and hyperinflated coughs were not found to produce significantly more aerosols compared to background after 30 seconds, longer exposure periods could reveal a statistically significant effect size.

Conclusion

Undisturbed ventilation through an endotracheal tube using Ambu® bag does not generate significant aerosols. Coughing appears to increase aerosol production, with coughing via tracheostomy producing the most aerosols. Otolaryngologists who frequently manage patient airways and perform tracheostomy are at increased risk for aerosol exposure and require appropriate PPE, especially during the ongoing COVID-19 pandemic.
Author Contributions

Roy Xiao had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Concept and design: All authors.
Acquisition, analysis, or interpretation of data: All authors.
Drafting of the manuscript: Xiao
Critical revision of the manuscript for important intellectual content: Workman, Puka, Juang, Naunheim, Song
Statistical analysis: Xiao
Administrative, technical, or material support: Naunheim, Song
Supervision: Naunheim, Song

Acknowledgments

The authors are grateful to Dr. Benjamin S. Bleier for graciously sharing his TSI Inc. optical particle sizer (OPS 3330) with our group.


Figure Legends

Figure 1. Experimental Setups

(A) Bag-valve tube manual ventilation of cadaveric porcine larynx-trachea-lung specimen. (B) Tracheostomy performed on cadaveric porcine trachea specimen.

Figure 2. Production of Aerosol Particles During Ventilation and Cough Scenarios

Columns and error bars indicate means and standard errors. Baseline: 9.5±2.1 background PP30. Bag-valve tube (BVT) ventilation: 10.8±2.4 (p=1.0000). Cough with BVT ventilation: 30.3±24.9 (p=0.4792). Cough with hyperinflation: 23.0±8.1 (p=0.2656). Cough via tracheostomy: 53.5±25.2 (p=0.0121).
This manuscript has been accepted for publication in Otolaryngology-Head and Neck Surgery.
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![Bar chart showing aerosol particle production during different scenarios.](Figure 2.pdf)