ORIGINAL ARTICLE

Aerosol Generation from the Respiratory Tract with Various Modes of Oxygen Delivery

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Abstract

Rationale: Aerosol generation with modes of oxygen therapy such as high-flow nasal cannula and noninvasive positive-pressure ventilation is a concern for healthcare workers during the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic. The amount of aerosol generation from the respiratory tract with these various oxygen modalities is unknown.

Objectives: To measure the size and number concentration of particles and droplets generated from the respiratory tract of humans exposed to various oxygen delivery modalities.

Methods: Ten healthy participants with no active pulmonary disease were enrolled. Oxygen modalities tested included nonhumidified nasal cannula, face mask, heated and humidified high-flow nasal cannula, and noninvasive positive-pressure ventilation. Aerosol generation was measured with each oxygen mode while participants performed maneuvers of normal breathing, talking, deep breathing, and coughing. Testing was conducted in a negative-pressure room. Particles with a diameter between 0.37 and 20 μm were measured using an aerodynamic particle spectrometer.

Measurements and Main Results: Median particle concentration ranged from 0.041 to 0.168 particles/cm^3. Median diameter ranged from 1.01 to 1.53 μm. Cough significantly increased the number of particles measured. Measured aerosol concentration did not significantly increase with the use of either humidified high-flow nasal cannula or noninvasive positive-pressure ventilation. This was the case during normal breathing, talking, deep breathing, and coughing.

Conclusions: Oxygen delivery modalities of humidified high-flow nasal cannula and noninvasive positive-pressure ventilation do not increase aerosol generation from the respiratory tract in healthy human participants with no active pulmonary disease measured in a negative-pressure room.

Keywords: SARS-CoV-2; droplet; particle

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At a Glance Commentary

Scientific Knowledge on the Subject: Transmission of infectious diseases can occur through exhaled respiratory particles and droplets. During the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic, there has been concern about increased aerosol generation with the use of oxygen delivery systems such as high-flow nasal cannula and noninvasive positive-pressure ventilation, which could lead to nosocomial spread and illness in healthcare workers. No published data are available examining the effects of oxygen systems on aerosol generation.

What This Study Adds to the Field: This study measured particle and droplet generation from the respiratory tract of 10 healthy individuals receiving oxygen with various modes of delivery. There was no observed increase in the concentration of aerosol generated with the use of humidified high-flow nasal cannula or noninvasive positive-pressure ventilation when compared with breathing room air or nonhumidified oxygen modalities.

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus that causes coronavirus disease (COVID-19) pneumonia and associated hypoxemia, is highly contagious, and there is concern of airborne and droplet transmission (1, 2). Defining what medical procedures generate aerosol particles and droplets is important to protect healthcare workers and limit nosocomial spread of virus. The potential to aerosolize respiratory tract secretions with common oxygen delivery methods such as high-flow nasal cannula (HFNC) and noninvasive positive-pressure ventilation (NIPPV) is unknown and debated (3). There are reports of increased transmission of the 2003 SARS-CoV virus to healthcare workers exposed to patients requiring NIPPV (4, 5). In studies using a human patient simulator, NIPPV dispersed exhaled air further than a nasal cannula (NC) or face mask (FM) (6). These findings have called into question the use of NIPPV in SARS-CoV-2 illness. Regarding HFNC, increasing flow rates do slightly increase dispersion of exhaled air with a human patient simulator (7) and may lead to moderate increases in the distance traveled by cough-expelled respiratory secretions (8). Conversely, other experiments show no significant dispersion of water or yeast droplets with HFNC in a mannequin (9), and no increased room contamination of gram-negative bacteria when HFNC is compared with FM in human patients (10). There have not been any described cases of SARS-CoV-2 transmission with HFNC.

Studies examining the generation of respiratory particles via exhalation, speech, and cough have been performed previously (11–14). These studies reveal that sub–3-μm particles and droplets, which can remain suspended in air for extended periods of time, are generated from breathing and speaking actions. The mode particle size is near 1 μm in aerodynamic diameter, and the rate of production increases when speaking at elevated volumes and with certain speech patterns (15). In this study, using similar instrumentation to previous studies (13, 15), we measured the concentration of aerosol particles in the 0.37- to 20-μm size range arising from the respiratory tract of healthy participants during breathing, talking, and coughing while receiving oxygen by various modes of delivery.

Methods

Participants

Recruitment e-mails were sent to the respiratory therapy, pulmonary, and critical care divisions. The inclusion criterion was age ⩾18 years. Exclusion criteria were *1*) active pulmonary symptoms; *2*) symptoms of COVID-19 (fever, cough, myalgias, shortness of breath) in the last 2 weeks; or *3*) diagnosis of COVID-19 at any time. The study protocol was approved by the institutional review board for human subjects and written consent was obtained from the participants.

Procedures

The study was conducted in a negative-pressure room (volume, 29.8 m^3) with 15 air exchanges per hour. A recirculating air scrubber (Airwash Multipro Boss; Amaircare) with a high-efficiency particulate air (HEPA) filter was continuously operated at a flow rate in excess of 10 $m^3 \cdot min^{-1}$ within the room. Additional details regarding the room conditions and experimental methods are available in the online supplement.

Oxygen modalities studied. Room air, 4 L/min nonhumidified NC, 15 L/min nonhumidified FM, HFNC at 10 L/min, HFNC at 30 L/min, HFNC at 50 L/min, NIPPV with an inspiratory positive airway pressure/expiratory positive airway pressure of 12/5 and 20/10 cm H_2O. The FM was an OxyMask. The HFNC system was heated and humidified (MR850; Fisher and Paykel) with an $F_{I_{O_2}}$ of 30% (3600 air/gas blender; Sechrist). NIPPV was administered with a Philips Respironics V60 at 30% $F_{I_{O_2}}$ with a vented oral–nasal mask (AF541; Respironics). A nonhumidified NIPPV circuit was used (BiPap Vision; Respironics).

Measurements. For each oxygen modality, five separate measurements were obtained: *1*) background particle measurement of the room, with the funnel sampler directed away from the participant; *2*) normal breathing; *3*) talking, in which literature was provided to read at a normal volume; *4*) deep breathing, in which the participant was instructed to "take deep breaths at a fast rate that does not cause lightheadedness"; and *5*) five deep coughs. Measurements (*2*–*5*) were done with the funnel sampler directed toward the participant's mouth. Respiratory rate was recorded during deep breathing. The order of oxygen modality was changed randomly. Between oxygen modes, the participant took a sip of water to keep the oral cavity hydrated.

Determination of number and size of respiratory particles. An aerodynamic particle spectrometer (APS) (TSI model 3321) was used (16). It is able to measure the aerodynamic diameter of particles ranging from 0.52 to 20 μm and detect the presence of particles as small as 0.37 μm. The participant sat in an upright position, with a funnel sampler approximately 5 cm away from his or her mouth (Figure E1 in the online supplement). The funnel was connected to the APS inlet, drawing air at a flow of 5 L/min, with 1 L/min directed to the measurement zone and 4 L/min filtered and used as sheath flow in the instrument. Using APS data, particle concentration and geometric mean diameter (the exponential of the logarithm mean) were calculated.

The APS collected 1-second spectra repeatedly for 100 seconds (100 samples) in each measurement for measurements 1–4. Measurement 5 was for 20 seconds (20 samples) because of the difficulty of voluntarily coughing for longer durations of time. The background room measurement was used for reporting purposes and not subtracted from measurements during oxygen delivery.

Statistical analysis. Particle concentration and geometric mean diameter of the background air in the room were calculated by averaging data of individual 1-second samples collected during background room measurements from all participants. During normal breathing, talking, and deep breathing, 100 one-second samples were averaged to determine the particle concentration and geometric mean diameter. For coughing, they were averaged over 20 seconds. These average values for each measured condition (breathing maneuver and oxygen mode) were used for the statistical analysis. The Wilcoxon matched-pairs signed rank test was used to make pairwise comparisons between groups. *P* values were adjusted for multiple comparisons using the Holm method. Analyses were conducted using R version 4.0.1.

Results

Ten healthy participants were enrolled in the study. The median (interquartile range) age of the group was 35 (34–39) years. Four of the 10 participants were female. There was no history of chronic lung disease.

Table 1 describes the respiratory rate during deep breathing for all the oxygen modalities studied. Minute ventilation during NIPPV is listed. The median respiratory rate with deep breathing using various oxygen therapies was between 24 and 28 breaths/min.

With the use of a HEPA-filtered air scrubber continuously running during the study, the average background particle concentration (diameter between 0.37 and 20 μm) in the room was 0.060 particles/cm^3. The median particle concentration exhaled from the respiratory tract ranged from 0.041 to 0.168 particles/cm^3, and the median of the geometric mean diameter of particles ranged from 1.01 to 1.53 μm (Table 2). With the exception of room air, participants inhaled particle-free (immeasurably low concentration) oxygen gas; hence, the measured particles presumably originated from participants' respiratory tracts (Table E1).

After adjustment for multiple comparisons, the number and size of particles measured from the respiratory tract did not significantly change with the oxygen modalities tested. This was the case during normal breathing, talking, deep breathing, and coughing (Table 2). Unadjusted analyses did demonstrate comparisons that reached significance ($P < 0.05$). In the setting of deep breathing, the use of HFNC with flow ⩾30 L/min or NIPPV significantly decreased particle concentration when compared with breathing room air. Of note, in the unadjusted comparisons, no oxygen modality significantly increased particle concentration above breathing only room air.

As expected, coughing produced a higher number of particles than the other maneuvers tested and was the only maneuver to significantly increase measured particle number above the background room concentration (Table E2). Figure 1 demonstrates the number concentration of particles for each test condition in relation to the average background particle concentration of the room. Figure 2 displays the geometric mean diameter of measured particles. Residual background particles were significantly larger than those sampled from participants, demonstrating that we were collecting particles unique to the individual as opposed to just the background air (Table E2). Respiratory maneuvers did appear to have an impact on number and size of particles. When stratified by over or under 1 μm, deep breathing and coughing appear to generate more small-sized particles than talking or normal breathing (Figure 3). Table 3, comparing deep breathing, cough, and normal breathing, demonstrates this contrast further. There were some conditions in which cough and deep breathing produced significantly smaller particles than normal breathing, even after adjustment for multiple comparisons. This difference was lost with higher flows of HFNC and NIPPV.

There were noticeable interindividual differences in the generation of particles. Figure 4 demonstrates three representative participants and the particle number concentration over the time of testing. Charts for all 10 participants are located in Figure E2. Aerosol generation varies from similar measurements to the background room concentration in participant 5 to more dramatic changes with deep breathing and coughing in participant 7.

Table 1. Respiratory Data during Deep Breathing

Oxygen Delivery	Median Respiratory Rate (IQR)	Median Minute Ventilation (IQR)
Room air	28 (20–40)	—
4 L/min nasal cannula	27 (22–36)	—
15 L/min face mask	25 (22–40)	—
HFNC 10 L/min	24 (20–36)	—
HFNC 30 L/min	28 (24–44)	—
HFNC 50 L/min	26 (26–44)	—
NIPPV 12/5	24 (22–28)	48.0 (40.2–70.0)
NIPPV 20/10	26 (22–30)	51.4 (42.3–87.8)

Definition of abbreviations: HFNC = heated and humidified high-flow nasal cannula; IQR = interquartile range; NIPPV = noninvasive positive-pressure ventilation.
Approximately 20 seconds into deep breathing, the respiratory rate was calculated over 30 seconds. While on NIPPV, respiratory rate and minute ventilation were recorded from the display screen at 20 seconds. Respiratory rate measured in breaths/min. Minute ventilation measured in L/min.

Discussion

In this study, we examined the generation of aerosol from the respiratory tract of healthy human volunteers using various oxygen delivery modalities. The key finding is that in healthy individuals, NIPPV or HFNC did not produce higher-concentration aerosol from the respiratory tract than room air or nonhumidified oxygen conditions. In fact, in some instances HFNC and NIPPV might

Table 2. Exhaled Particle Concentration and Size with Various Oxygen Modalities

	RA	4 L/min NC	15 L/min FM	HFNC 10 L/min	HFNC 30 L/min	HFNC 50 L/min	NIPPV 12/5	NIPPV 20/10	Adjusted *P* Value*
Particle number concentration, particles/cm^3									
Normal breathing	0.068 (0.046–0.091)	0.060 (0.044–0.065)†	0.059 (0.055–0.074)‡	0.050 (0.036–0.076)	0.046 (0.035–0.073)†	0.041 (0.025–0.056)†	0.056 (0.036–0.079)	0.057 (0.037–0.090)	N.S.
Talking	0.071 (0.056–0.104)	0.064 (0.049–0.080)§	0.063 (0.050–0.074)	0.074 (0.054–0.088)‡ §	0.058 (0.051–0.072)§	0.055 (0.037–0.069)	0.049 (0.030–0.070)†	0.046 (0.038–0.064)†	N.S.
Deep breathing	0.105 (0.080–0.115)	0.087 (0.061–0.107)	0.068 (0.047–0.080)† §	0.074 (0.052–0.110)§	0.067 (0.053–0.074)†	0.058 (0.046–0.090)†	0.050 (0.037–0.091)†	0.044 (0.038–0.068)†	N.S.
Cough	0.138 (0.098–0.191)	0.168 (0.122–0.195)	0.126 (0.095–0.313)‖	0.141 (0.133–0.188)‖	0.099 (0.078–0.176)	0.141 (0.095–0.180)	0.089 (0.055–0.098)	0.063 (0.047–0.125)	N.S.
Particle geometric mean diameter, μm									
Normal breathing	1.48 (1.22–1.54)	1.58 (1.43–1.61)	1.46 (1.24–1.86)	1.42 (1.28–1.51)	1.30 (1.12–1.50)	1.19 (1.01–1.56)	1.45 (1.32–1.83)	1.43 (1.21–1.95)	N.S.
Talking	1.28 (1.14–1.43)	1.46 (1.20–1.50)	1.33 (1.12–1.64)	1.26 (1.23–1.32)	1.51 (1.32–1.53)†	1.29 (1.14–1.50)	1.44 (1.24–1.56)	1.36 (1.20–1.84)	N.S.
Deep breathing	1.00 (0.98–1.14)	1.16 (1.02–1.31)	1.12 (1.00–1.36)§	1.14 (1.00–1.33)§ ‖	1.19 (0.99–1.33)§	1.25 (0.92–1.42)	1.38 (1.09–1.50)†	1.53 (1.09–1.70)†	N.S.
Cough	1.03 (0.94–1.46)	1.01 (0.93–1.20)	1.35 (0.95–1.45)	1.09 (1.01–1.27)	1.04 (0.93–1.17)	0.93 (0.86–1.09)‖	1.18 (1.02–1.38)	1.20 (0.88–1.95)	N.S.

Definition of abbreviations: FM = face mask; HFNC = heated and humidified high-flow nasal cannula; NC = nasal cannula, NIPPV = noninvasive positive-pressure ventilation; N.S. = nonsignificant; RA = room air.

All data are median (interquartile range). For each breathing maneuver, multiple pairwise comparisons of oxygen modalities were made with the Wilcoxon matched-pairs signed rank test. There were no significant differences between oxygen modalities after adjustment for multiple comparisons.

*P values were adjusted for multiple comparisons with the Holm method and considered significant if $P < 0.05$.

†Unadjusted $P < 0.05$ versus RA.

‡Unadjusted $P < 0.05$ versus HFNC 50 L/min.

§Unadjusted $P < 0.05$ versus NIPPV 20/10.

‖Unadjusted $P < 0.05$ versus NIPPV 12/5.

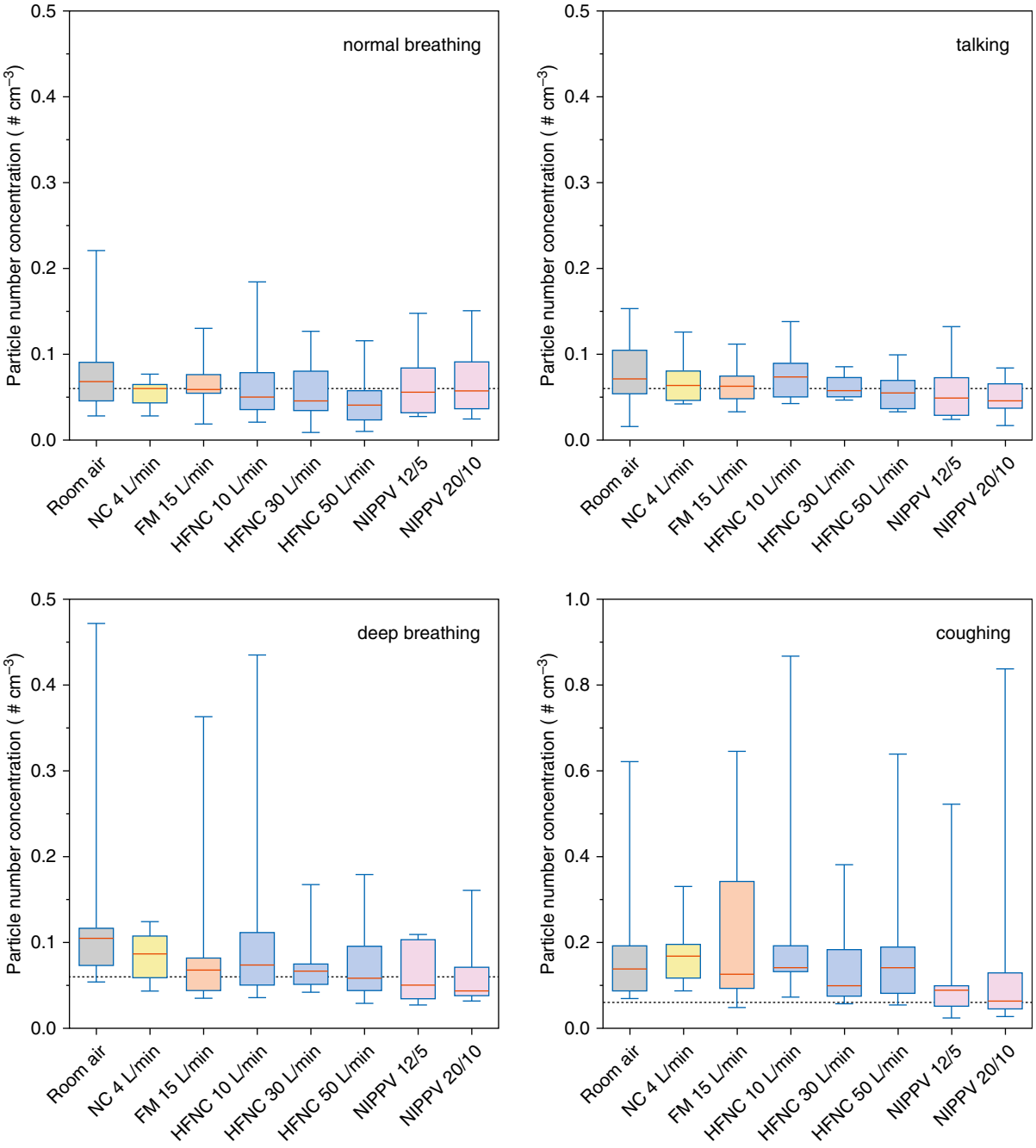

Figure 1. Particle number concentration with various modes of oxygen delivery. Box-and-whisker plots demonstrate the median and interquartile ranges. Note the change in scale of the *y*-axis in coughing. The horizontal dashed line represents the average baseline particle number concentration of the room (0.060 particles/cm^3). FM = face mask; HFNC = heated and humidified high-flow nasal cannula; NC = nasal cannula; NIPPV = noninvasive positive-pressure ventilation.

decrease aerosol. We remark that different respiratory patterns and characteristics of the individual have more of an impact on aerosol generation than the mode of oxygen therapy applied. For example, when participants were asked to take deep breaths, in some instances the average diameter of particles were smaller when compared with breathing normally. A similar finding was seen with coughing, in which particle number was also noted to increase. Finally, some participants produce substantially more particles than others during normal breathing, deep breathing, talking, and coughing. This suggests that risk of aerosol-based respiratory infection transmission is affected more by individual respiratory system motion and interindividual variability in particle generation than specific oxygen therapies applied.

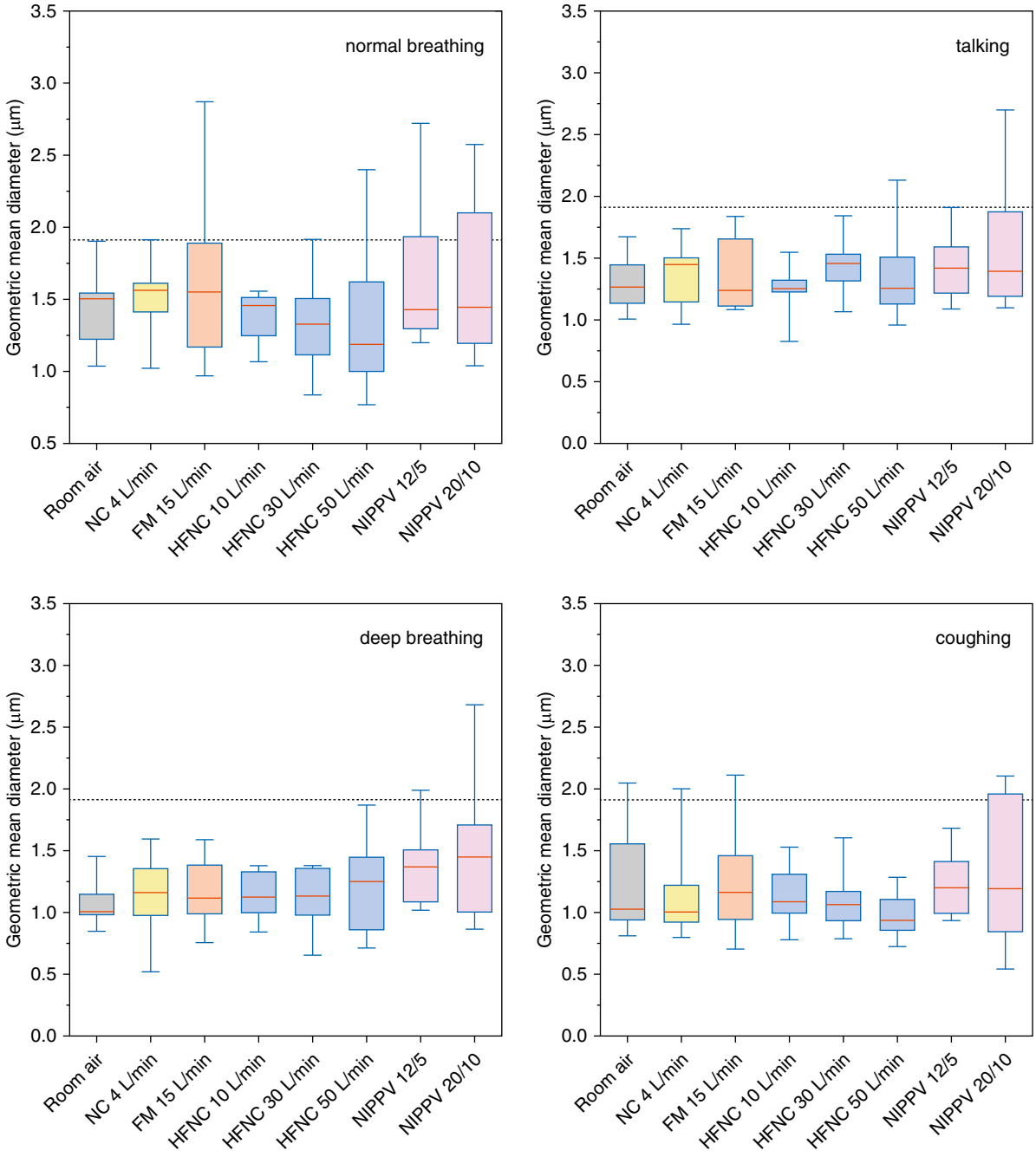

Figure 2. Geometric mean diameter of particles with different modes of oxygen delivery. Box-and-whisker plots demonstrate the median and interquartile ranges. The horizontal dashed line represents the average geometric mean diameter of the particles in the baseline measurements of the room (1.80 μm). For definition of abbreviations, *see* Figure 1.

Overall aerosol production was very low and did not rise above background room concentrations in most test conditions. However, we do believe we captured exhaled particles. The geometric mean diameter of most every test condition was significantly lower than the background room air, indicative of a separate lung-generated collection of aerosol. Additionally, cough served as a positive control for the number concentration of aerosol.

Our findings are consistent with previous work done on exhaled aerosols. This includes the magnitude of size and concentration of the exhaled particles (11, 17), the change in particle characteristics with deep breathing or coughing (12, 14, 18), and the variability between individuals (13, 19).

It is worth mentioning that previous experiments by Hui and colleagues measuring dispersion of air in human patient simulators with various oxygen delivery methods are not in conflict with our

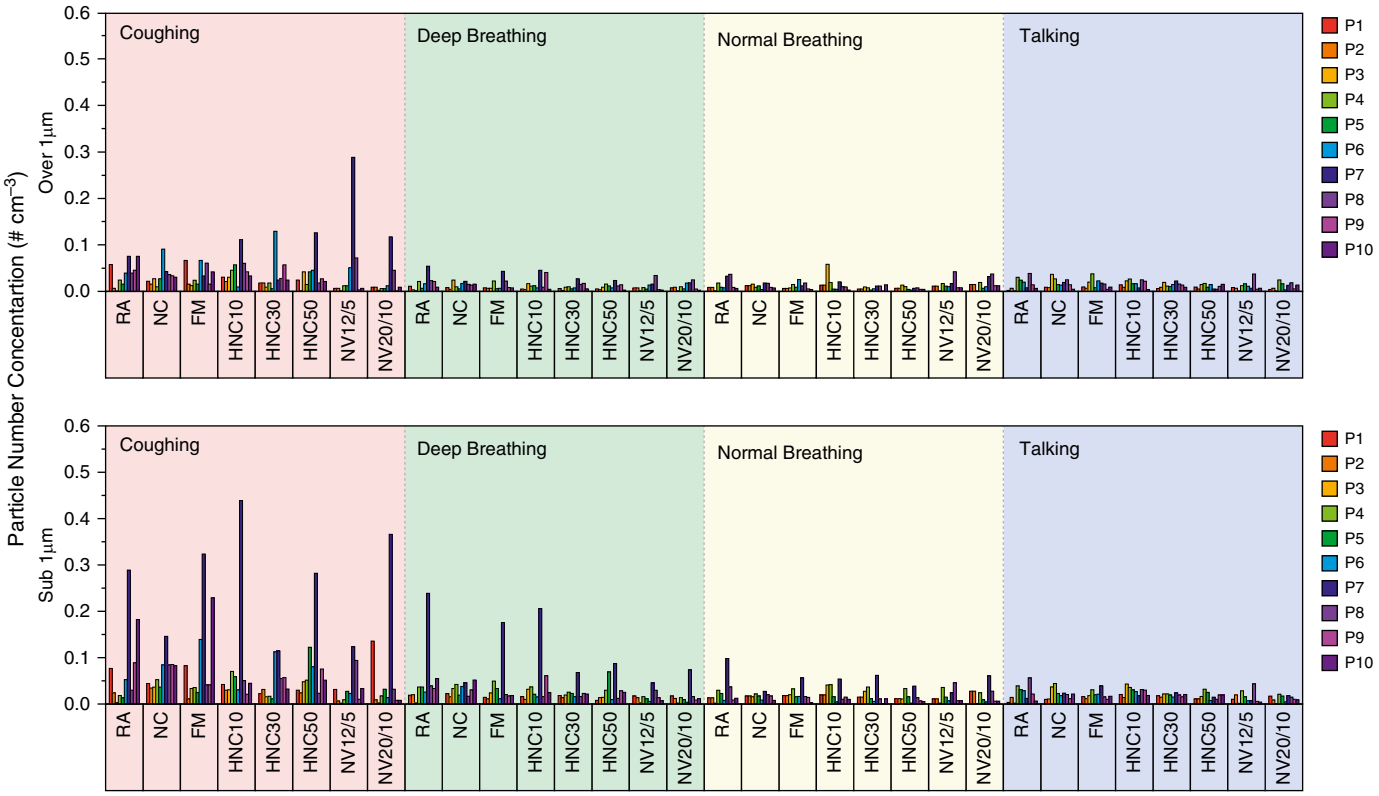

Figure 3. Particle concentration (aerodynamic diameter 0.52–20 μm) exhaled from the respiratory tract during coughing, deep breathing, normal breathing, and talking and divided into particles with an aerodynamic diameter greater than 1 μm (top chart) and less than 1 μm (bottom chart). There appears to be a difference in the number and diameter of particles with different respiratory maneuvers, when stratified by particle size. Coughing and deep breathing appear to generate a larger number of particles less than 1 μm than normal breathing or talking. FM = 15 L/min face mask; HNC 10 = humidified high-flow nasal cannula 10 L/min; HNC 30 = humidified high-flow nasal cannula 30 L/min; HNC 50 = humidified high-flow nasal cannula 50 L/min; NC = 4 L/min nasal cannula; NV 12/5 = noninvasive positive-pressure ventilation 12/5; NV 20/10 = noninvasive positive pressure ventilation 20/10; P1–P10 = participants 1–10; RA = room air.

study. In the previous studies, an aerosol (smoke) was placed inside the lungs of the human patient simulator and the trajectory and distance of smoke emanating from the human patient simulator were evaluated (6, 7). Not surprisingly, the extra pressure generated from NIPPV would cause the smoke to escape through mask leaks or the small NIPPV exhaust port with a higher velocity and thus farther distance than NCs, FMs, or HFNC. Our study evaluated the *de novo* generation of droplets and particles from the respiratory tract with oxygen therapies, but it does not discuss the distance traveled by respiratory droplets

Table 3. Comparison of Geometric Mean Diameter with Various Breathing Maneuvers

Oxygen Delivery	Geometric Mean Diameter (μm) [*Median (IQR)*]			Adjusted *P* Value		
	Normal Breathing	Deep Breathing	Cough	Normal Breathing vs. Deep Breathing	Normal Breathing vs. Cough	Deep Breathing vs. Cough
RA	1.48 (1.22–1.54)	1.00 (0.98–1.14)	1.03 (0.94–1.46)	0.11	0.39	0.56
4 L/min NC	1.58 (1.43–1.61)	1.16 (1.02–1.31)	1.01 (0.93–1.20)	0.0060	0.012	0.49
15 L/min FM	1.46 (1.24–1.86)	1.12 (1.00–1.36)	1.35 (0.95–1.45)	0.059	0.13	0.63
10 L/min HFNC	1.42 (1.28–1.51)	1.14 (1.00–1.33)	1.09 (1.01–1.27)	0.029	0.055	0.77
30 L/min HFNC	1.30 (1.12–1.50)	1.19 (0.99–1.33)	1.04 (0.93–1.17)	0.65	0.25	0.77
50 L/min HFNC	1.19 (1.01–1.56)	1.25 (0.92–1.42)	0.93 (0.86–1.09)	0.77	0.11	0.11
NIPPV 12/5	1.45 (1.32–1.83)	1.38 (1.09–1.50)	1.18 (1.02–1.38)	0.55	0.11	0.55
NIPPV 20/10	1.43 (1.21–1.95)	1.53 (1.09–1.70)	1.20 (0.88–1.95)	0.85	0.70	0.70

Definition of abbreviations: FM = face mask; HFNC = heated and humidified high-flow nasal cannula; IQR = interquartile range; NC = nasal cannula; NIPPV = noninvasive positive-pressure ventilation; RA = room air.
Talking was not included in this analysis in order to limit the amount of multiple comparisons. Pairwise group comparisons made with the Wilcoxon matched-pairs signed rank test. *P* values were adjusted for multiple comparisons with the Holm method.

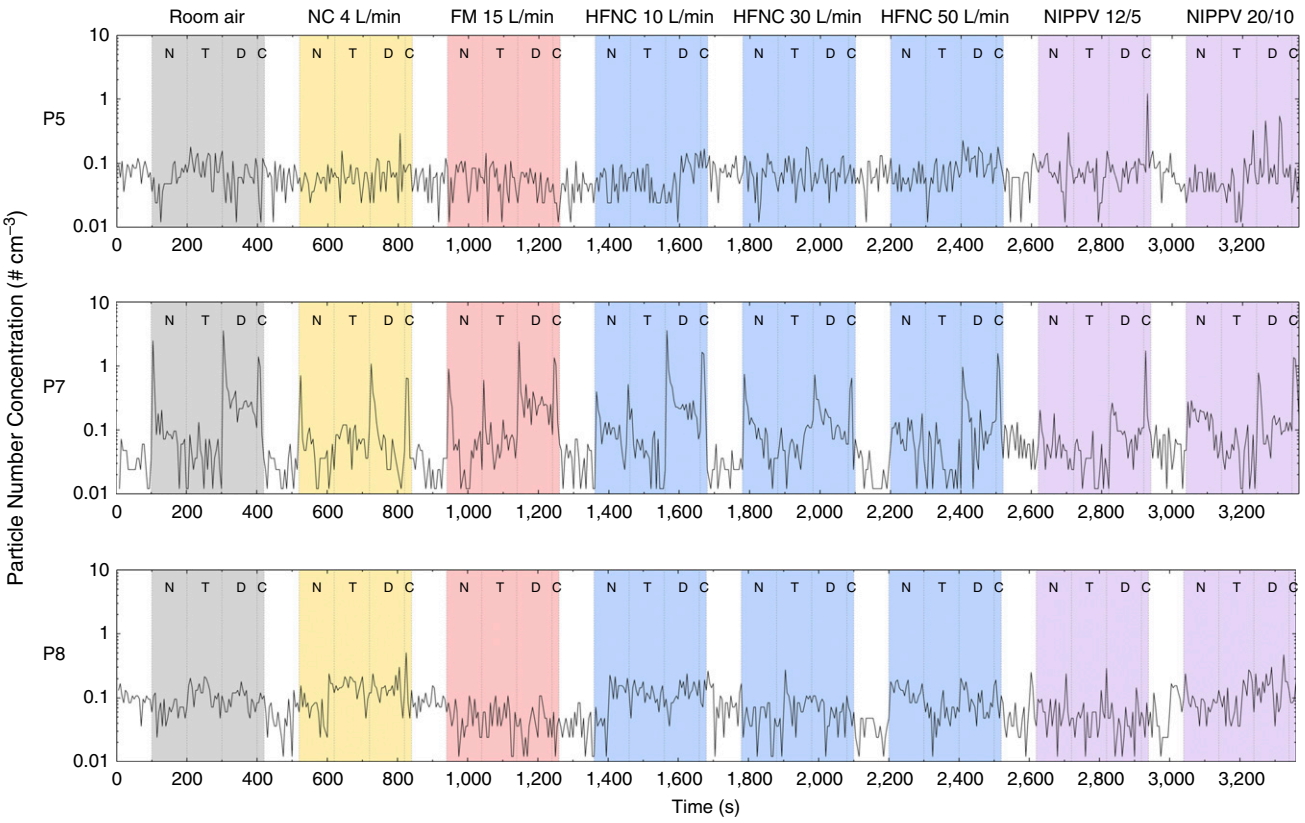

Figure 4. Representative samples of three participants (P5, P7, and P8). Particle number concentration exhaled over time on a logarithmic scale with the various oxygen modalities and respiratory maneuvers are shown. White colored rectangles denote background room measurements. C = coughing; D = deep breathing; FM = face mask; HFNC = heated and humidified high-flow nasal cannula; N = normal breathing; NC = nasal cannula; NIPPV = noninvasive positive-pressure ventilation; T = talking.

and particles. Distance traveled is not only affected by expiratory flow and applied pressure from any respiratory therapy but also influenced by relative humidity (evaporation) and local ventilation in the room (20). All of these factors need to be considered in mitigating aerosol-based nosocomial disease transmission. This concept is echoed in a recent review article published in this journal in which HFNC and NIPPV are described as instruments that disperse bioaerosols rather than generate them (21). Our data suggest that modes of oxygen delivery do not increase particle concentrations greater than breathing room air during breathing, talking, and coughing and hence could only be considered "aerosol-generating" if they cause more coughing or lead to deeper breathing.

To be clear, a detailed understanding of aerosol generation in the respiratory tract is still in development. In one analysis, the size and number of particles generated depends on the anatomic location and the action of the person. Breathing produces the smallest-sized particles. When air passes vibrating vocal cords, slightly larger particles are added to each exhaled breath. Finally, the movement of the tongue and lips to speak adds a third distinct group of particles, which are by far the largest in size but smaller in number. The act of coughing appears to increase the number of particles emanating from the larynx and oral cavity, which broadens the size distribution of detected particles and droplets (12). Our data showing cough has a smaller average particle size than other maneuvers challenges this framework, but the difference could be due to difference in measurement techniques and the sensitive nature of measuring aerosol.

Naturally, the mechanism by which particles form will depend on where they are generated. Some authors have suggested that aerosol forms from shear stress along the airway wall during turbulent flow, as well as vibration of the vocal cords (12, 17). A separate theory, the bronchiole fluid film burst model, describes the generation of aerosol from the opening of closed bronchioles in the lung, which creates the smallest-sized particles. In this model, increasing the diameter of bronchioles during inhalation stretches out a film of fluid, causing it to burst and create aerosol that travels to the alveoli before being exhaled. In one study, larger and faster inhalation maneuvers produced higher-concentration aerosol, and the rate of exhalation did not substantially affect aerosol generation (18). In another experiment that assessed pulmonary function tests and exhaled particles, increasing V_T created far higher concentration aerosol than increasing inspiratory or expiratory flow (22). These experiments suggest that surface tension properties in the small airways during inhalation have a bigger impact on aerosol formation than turbulent flow through the airways during peak exhalation.

With these theories in mind, the lack of a clear increase in particles with HFNC or NIPPV could be for a few reasons. First, the flow used in these oxygen systems may not be high enough to promote aerosolization. The shear force needed to generate aerosol

from a mucus-lined airway is not known, but flows from oxygen systems are lower in rate than what a person can generate. High-flow settings in HFNC are around 50 L/min, and in NIPPV it can be around 90 L/min inspiratory flow. These are much lower flows than what a healthy 50-year old male can generate at peak inspiration (440 L/min) or expiration (590 L/min) (23, 24). If turbulent flow over the mucus lining of the respiratory tract is indeed aerosol generating, flows created by HFNC and NIPPV may not be fast enough to increase aerosol generation rates. In our unadjusted analysis of exhaled particle concentration (Table 2), several comparisons actually demonstrated a decrease in measured particle concentration with NIPPV. The magnitude of difference appeared to be the greatest with deep breathing. The interior surface of NIPPV masks may collect, via inertial impaction, droplets or particles that are created during NIPPV, which would decrease the measured count. If the bronchiole fluid film burst theory fully explains how aerosol is made in the lungs, HFNC and NIPPV actually may decrease aerosol production by increasing positive end-expiratory pressure and preventing closure of small bronchioles. Finally, we observed that the first several seconds of a participant engaging in breathing, talking, or deep breathing were a likely time for particle emission to occur; this is evident in participant 7 in Figure 3 as distinct spikes in number concentration, which quickly dissipate. These did not seem to change with oxygen mode applied. These spikes may represent some other novel mechanism for aerosol generation to be determined, but unrelated to oxygen flows.

Previous studies using an APS to measure particle and droplet numbers from normal breathing demonstrate low concentrations ranging from 0.085 to ~0.2 particles/cm^3 (11, 12, 18). The number concentration in an emergency department and inpatient ward are higher and have been measured at 12 and 1.4 particles/cm^3, respectively (25). With the use of a recirculating air scrubber with HEPA filter in a negative-pressure room (15 air exchanges per hour), we were able to decrease the background particle concentration of the room to 0.060 particles/cm^3. Although these room conditions are different than a typical hospital room, it was necessary to decrease background noise to achieve more accurate measurements. Because the participant was very close to the funnel and APS, we do not believe the air currents in the room substantially altered measurements. Relative humidity of the room could be affected by the continuous exchange of air. The humidity of the room was not controlled, and we did not account for the possibility of evaporation of droplets during measurements (26).

There are other limitations to our study. Although the average background particle concentration in the room was substantially lower than characteristic indoor air, it was not as low as that in clean room or HEPA-filtered laminar flow hood studies, in which concentrations of 0.0015 particles/cm^3 have been achieved (11–13, 27). The APS we used has a detection range of 0.37- to 20-μm-diameter particles, and based on our experimental methods of breathing 5 cm away from a collection funnel, we were likely only reliably measuring particles less than 10 μm in diameter. Larger particles may have inertially collided with the funnel and not been counted. Although our data have a similar mean diameter as previous experiments using an APS (12, 13), other studies using different measurement tools have detected a significant amount of particles with a diameter less than 0.37 μm with breathing and coughing (22, 28). These particles are below our limit of detection, and therefore, we likely underestimated total particle counts. Our methods did not permit isokinetic sampling owing to the diversity of procedures, but we believe inertial particle loss to be minimal in the sub–3-μm range. The study was small and included healthy participants without active pulmonary disease, which may limit its applicability to the current pandemic of SARS-CoV-2. The small study may also have limited the power to detect true differences between groups with the multiple comparisons that were made. In viral pneumonias, patients have increased cough and mucus production in addition to a change in the diameter of the airways, surfactant production, and lung compliance. These changes in the lung could impact the amount of aerosol generated (27, 28).

Conclusions

In a population of healthy adults, there was no observed increase in aerosol generation with HFNC or NIPPV when measured in a negative-pressure room. Aerosol generation is influenced more by breathing pattern and coughing than the mode of oxygen therapy applied. Our results make no determination about the distance that respiratory aerosols are emitted. Further work examining aerosol generation with HFNC and NIPPV in active pulmonary disease is warranted. ■

Author disclosures are available with the text of this article at www.atsjournals.org.

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