Potential for occupational exposures to pathogens during bronchoscopy procedures

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ABSTRACT

Bronchoscopy is classified as an aerosol-generating procedure, but it is unclear what drives the elevated infection risk observed among healthcare personnel performing the procedure. The objective of this study was to characterize pathways through which bronchoscopists may be exposed to infectious agents during bronchoscopy procedures. Aerosol number concentrations (0.2–1 μm aerodynamic diameter) were measured using a P-Trak Ultrafine Particle Counter 8525 and mass concentrations ($<10\mu\text{m}$) were measured using a SidePak Personal Aerosol Monitor AM510 near the head of patients during bronchoscopy procedures. Procedure pathway, number of patient coughs, number of suctioning events, number of contacts with different surfaces by the pulmonologist, and the use and doffing of personal protective equipment were recorded by the investigator on a specially designed form. Any pulmonologist performing a bronchoscopy procedure was eligible to participate. A total of 18 procedures were observed. Mean particle number and mass concentrations were not elevated during procedures relative to those measured before or after the procedure, on average, but the concentrations were highly variable, exhibiting high levels periodically. Patients frequently coughed during procedures (median 65 coughs, range: 0–565 coughs), and suctioning was commonly performed (median 6.5 suctioning events, range: 0–42). In all procedures, pulmonologists contacted the patient (mean 22.3 contacts, range: 1–48), bronchoscope (mean 19.4 contacts, range: 1–46), and at least one environmental surface (mean 31.2 contacts, range: 3–62). In the majority of procedures, the participant contacted his or her body or personal protective equipment (PPE), with a mean of 17.3 contacts (range: 4–48). More often than not, the observed PPE doffing practices differed from those recommended. Bronchoscopy procedures were associated with short-term increased ultrafine or respirable aerosol concentrations, and there were opportunities for contact transmission.

KEYWORDS

Aerosol-generating procedures; bronchoscopy; infection prevention; contact patterns; personal protective equipment

Introduction

Bronchoscopy is one of several respiratory procedures classified as an aerosol-generating procedure (AGP). AGPs are procedures thought to generate respirable aerosols and have been associated with increased risk of occupationally acquired infection among healthcare personnel.^[1,2] During a bronchoscopy procedure, a bronchoscope is inserted through the nose or mouth of a sedated patient to visualize the respiratory tract and diagnose or treat medical problems. The procedure may involve administration of nebulized medication. The procedure can induce coughing, particularly during removal of the bronchoscope.

The elevated infection risk observed among healthcare personnel who perform AGPs is typically attributed to increased concentrations of infectious aerosols, which has led to recommendations for respiratory protection,^[1]

but limited empirical data exist to support this hypothesis to date. The data are limited, at least in part, because of the logistical difficulty of observing AGPs on patients with respiratory infections outside of an epidemic.^[3,4] Thompson et al.,^[5] however, measured H1N1 (2009) pandemic influenza virus during 22 AGPs and found that the size distribution of respirable aerosols containing viral RNA was different during AGPs relative to baseline and that bronchoscopy, but not respiratory suctioning or intubation, was associated with increased median viral RNA concentrations. There may be aspects of AGPs beyond the aerosol source strength, however, that contribute to infection risk among healthcare personnel, including: proximity to the source, duration of patient contact, and the contact transmission route. For example, tracheal suctioning has been observed to aerosolize bacteria detected in aspirate cultures and

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disseminate droplets 25–168 cm from the tracheal tube,^[6] which could contribute to contact transmission if the contaminated surface is touched by health-care personnel.

This study sought to characterize a range of potential determinants of occupational exposure to pathogens to improve the understanding of occupational exposures to pathogens during bronchoscopy procedures. Specifically, ultrafine and respirable aerosols were measured in proximity to the head of patients undergoing bronchoscopy procedures, as a surrogate for infectious aerosols, and the contact patterns of pulmonologists during the procedure, pulmonologists' use of personal protective equipment (PPE) and doffing practices, the number of patient coughs, and the duration of suctioning during the procedure were observed. To our knowledge, this is the only study of bronchoscopy procedures to measure determinants of exposure beyond aerosol concentrations.

Methods

Bronchoscopy procedures were observed in a pulmonary procedure room at an acute care hospital. Pulmonologists performing bronchoscopies were eligible to participate, and were recruited at the procedure room. Participants provided written informed consent. This study was reviewed and approved by the Institutional Review Board, protocol #2015-0880.

Aerosol concentrations were measured using a P-Trak Ultrafine Particle Counter 8525 (TSI Inc., Shoreview, MN) and a SidePak Personal Aerosol Monitor AM510 (TSI Inc., Shoreview, MN). The P-Trak measures the number concentration of particles ($\#/cm^3$) with aerodynamic diameters 0.2–1 μm , while the SidePak measures the mass concentration of particles (mg/m^3) with aerodynamic diameters $\leq 10 \mu m$. The same instruments (one P-Trak and one SidePak) were used for all observations. Before and after the procedure, the instruments were placed at a stationary location near the patient's head, or near where the patient's head would be during the procedure. The strategy attempted to measure aerosols for at least 20 min prior to the procedure, but the start time of the procedure could not always be anticipated. Aerosols were measured for at least 20 min after the procedure. During the procedure, the P-Trak inlet was held by the investigator, who stood next to the pulmonologist, at torso height, and the SidePak was worn by the pulmonologist on a belt. Pulmonologists declined to wear a sampling tube for the SidePak inlet at their lapel to sample air from the breathing zone,

so the SidePak was positioned at the side or front of the pulmonologist's waist. Measurements were collected every sec and were classified as occurring before, during, or after the procedure.

A standardized paper observation form to record observations was used by the investigator, who stood next to the pulmonologist performing the procedure. Touches by the pulmonologist's hand were recorded on the following surfaces: him/herself, the patient, vital signs machine, bronchoscope, suctioning tube, ultrasound machine, X-ray machine, bronchoscopy equipment, computer station, bed, cabinet and bench, room door, sink, wall cabinet with supplies, the I.V. pole, and other surfaces. Patient coughs and number of times suctioning was performed were tabulated. The pieces of PPE worn by the pulmonologist were recorded. The PPE doffing sequence and practices were recorded and compared to guidelines from the Centers for Disease Control and Prevention.^[7]

Data from the aerosol sampling devices were downloaded using TrakPro Analysis Software (TSI Inc., Shoreview, MN), and then exported into Excel (Microsoft, Redmond, WA) and cleaned of extraneous information, such as the instrument serial number and date of sampling, for analysis. Data were truncated to include no more than the 20 min of measurements immediately preceding and 20 min of measurements subsequent to the procedure. Data from the observation form were entered using double data entry into an Access 2016 database (Microsoft, Redmond, WA).

Summary statistics of the aerosol concentrations were tabulated for the three periods of each observation (pre-procedure, during procedure, and post-procedure) and sampling device. Peak aerosol emission was defined as mean plus one or two standard deviations of the measured concentration. Paired t-tests were used to test whether mean aerosol concentrations were greater during the procedure than before or after the procedure. Spearman's correlation was used to compare 30-sec-averaged aerosol concentrations measured with the two sampling devices. The time averaging was done only for this statistical test with the intent of minimizing the influence of mismatching and high variability on a second-to-second basis. Wilcoxon rank sum tests were used to compare distributions of values between two groups, while Kruskal-Wallis tests were used to compare distributions of values among ≥ 3 groups. All tests had statistical significance fixed at $\alpha = 0.05$. Data analysis was performed using the R Project for Statistical Computing (R Foundation, Vienna, Austria).

Table 1. Characteristics of observed bronchoscopy procedures.

Procedure No.	Participant	Pathway	No. Patient Coughs	No. Airway Suctioning Events
1	A	Mouth	135	22
2	B	Nose	20	1
3	B	Mouth	565	42
4	B	<i>Not Recorded</i>	182	17
5	B	Tracheal Opening	76	8
6	C	Nose	39	5
7	D	Mouth	329	38
8	C	<i>Not Recorded</i>	79	10
9	D	Nose and Mouth	345	17
10	B	Mouth	18	3
11	B	Mouth	102	20
12	C	Nose and Mouth	242	17
13	D	Mouth	0	1
14	E	Mouth	21	0
15	F	Nose	54	1
16	B	Mouth	16	5
17	B	Nose and Mouth	24	3
18	G	Mouth	25	1
	Mean		126	11.7
	Median		65	6.5

Results

Procedures observed

A total of 18 bronchoscopy procedures performed by 7 pulmonologists were observed between March and June 2018 (Table 1). Healthcare personnel present during the procedure typically included: two pulmonologists (fellow and attending physician), a technician, a nurse, and a cytologist. The infection status of patients was unknown because patient medical records were not reviewed, but it is unlikely that patients had respiratory infections as the procedures had been scheduled in advance. The observed procedures used three pathways to access the respiratory tract. Airway suctioning occurred in 17 of the 18 procedures. All but one patient coughed during the procedure. The number of coughs was highly variable and did not differ among procedures involving the access through mouth (mouth only or mouth and nose) and those involving other pathways (e.g., nose only, tracheotomy; Wilcoxon $p = 0.96$).

Aerosol measurements

Mean aerosol concentrations measured by both sampling devices are shown in Table 2 before, during, and after each observed procedure. For most procedures, the mean aerosol concentration measured during the procedure was lower than the mean concentration measured before the procedure, and were similar to those measured after the procedure (Figure 1). Paired t-tests found that the mean aerosol concentrations were lower during the procedure than before the procedure, with an average difference of -1608 #/cm^3

(95%CI $-2822, -394$) and -0.056 mg/m^3 (95%CI $-0.092, -0.019$). Paired t-tests found that the mean aerosol concentrations were not statistically significantly different during the procedure than after the procedure (average difference 55.5 #/cm^3 [95%CI $-55.3, 166$] and 0.004 mg/m^3 [95%CI $-0.0002, 0.008$]). To explore the relatively high aerosol concentrations measured before the procedure, the analysis was repeated using only the aerosol concentrations measured over the 4 min prior to the procedure (rather than 20 min), and while this approach led to slightly lower particle number and mass concentrations before the procedure, the inference was the same.

Figure 2 displays the change in aerosol number and mass concentration over time for five randomly selected bronchoscopy procedures, with the procedure start times aligned. Periodic peaks are clearly visible in the aerosol number concentration (Figure 2a), and also occur in the aerosol mass concentration (Figure 2b). Note that the high pre-procedure aerosol concentrations present for some procedures (e.g., procedures number 7 and 8) decreased rapidly with the start of the procedure, suggesting that perhaps the ventilation was increased in the procedure room at the time the procedure started or background activity ceased. Patient coughs and suctioning events were too numerous for the procedures shown (Table 1) to explain the large peaks visible in Figure 2.

Table 3 describes characteristics of peak aerosol concentrations measured by both aerosol sampling devices during the procedure. In the absence of an occupational exposure limit or other health-related threshold, two criteria were used to define peaks: (1) the event that the concentration exceeds the mean

Figure 1. Ratio of aerosol concentration measured during the procedure to that measured before or after the procedure by the P-Trak (shaded) and SidePak. Ratios greater than 1 indicate the aerosol concentration during the procedure was greater than that before or after the procedure. The dashed horizontal line demarcates the ratio equal to 1.

plus one standard deviation of the concentration measured during a procedure; and (2) the mean plus two standard deviations of the concentration measured during a procedure. On average, the aerosol concentrations exceeded the latter threshold for approximately 2% of the procedure duration, or less than 1 min. Maximum concentrations ranged from 308–8,930 $\#/\text{cm}^3$ (mean 4,738 $\#/\text{cm}^3$) and 0.051–3.22 mg/m^3 (mean 0.545 mg/m^3).

The two aerosol sampling devices measure particles with different aerodynamic diameters to allow for an examination of how well these measures correlated, which might inform the nature of aerosols generated. The distributions of Spearman's correlation coefficients between 30-sec average aerosol concentrations measured by the P-Trak and SidePak devices vary with observation period (Kruskal-Wallis $\chi^2 = 16.1$, $p < 0.001$), tending to decline over the duration of observation (Figure 3).

The number of patient coughs and suctioning events were thought to influence aerosol concentrations. The number of patient coughs was not statistically significantly correlated with the mean aerosol number concentration ($\rho = -0.23$, $p = 0.36$), maximum aerosol number concentration ($\rho = 0.23$, $p = 0.34$), or with duration of peak aerosol concentration (mean + 1SD, $\rho = -0.33$, $p = 0.18$). The number of patient coughs was not statistically significantly correlated with the mean aerosol mass concentration ($\rho = -0.01$, $p = 0.97$), maximum aerosol mass concentration ($\rho = 0.16$, $p = 0.52$), or with the duration of peak aerosol concentration (mean + 1 SD, $\rho = 0.11$, $p = 0.66$). Similarly, the

number of suctioning events was not statistically significantly correlated with mean or maximum aerosol mass or number concentration or with the duration of peak aerosol concentration (results not shown). The patient in Procedure 1 received supplemental oxygen and the patient in Procedure 3 received nebulized medication, but there was no indication that the aerosol concentrations during these procedures differed from those in other procedures (Table 2): the sample size was too small to justify statistical analysis.

Pulmonologists' behaviors

The contacts made by pulmonologists with surfaces in the procedure room are summarized in Table 4. The pulmonologist touched the patient and the bronchoscope in every procedure observed, as expected. The likelihood that pulmonologists contacted other surfaces varied, likely in part due to the need to use specific pieces of medical equipment during some procedures (e.g., the x-ray machine or cytology station). Pulmonologists were not observed to contact the I.V. pole, procedure room door, or ultrasound machine (not used). Pulmonologists contacted their own torso more often than other parts of their own body.

All pulmonologists wore gloves and a reusable textile gown during the procedure. Three pulmonologists wore N95 respirators during four procedures and one participant wore a surgical mask during one procedure; otherwise participants wore a surgical mask with integrated visor. No participants wore goggles or other pieces of PPE. One pulmonologist, who was observed in six procedures, wore the facemask in such a way

Figure 2. Time series plot of aerosol mass and number concentrations (30-sec average) during five randomly selected bronchoscopy procedures. All procedures started at time $t = 0$, denoted by the vertical line, and the procedures stopped at the times indicated by the dots.

that it did not cover the mouth or nose. Observed doffing practices—both the sequence and technique—frequently deviated from those recommended by the CDC (Table 5). Pulmonologists wore reusable fabric gowns, so the recommended doffing sequence is: (1) gloves, (2) gown, and (3) facemask or respirator.^[7]

Discussion

The aerosol concentrations measured before the bronchoscopy procedures were high relative to the concentrations measured during and after the procedure (Figure 1 and Table 2), which was contrary to the

expectation that aerosol concentrations present before the procedure would be similar to, or lower than those, present after the procedure. The reason for the high concentrations before the procedure is unclear, but Figure 2 shows that when the pre-procedure aerosol concentration was high, it decreased during the first minutes of the procedure and the downward trend ceased. Human activity (movement of healthcare personnel into and out of the room, arrival of the patient, or preparation of equipment and supplies) could elevate the particle concentrations before the procedure, and given the pattern observed in Figure 2, was judged the more likely driver of the phenomenon

Table 2. Mean particle number and mass concentrations and coefficient of variation (CV) measured using the P-Trak and SidePak instruments, respectively, before, during and after bronchoscopy procedures. Duration of measurements truncated to no more than 20 min before and after the procedure.

No.	Before Procedure				During Procedure				After Procedure			
	P-Trak		SidePak		P-Trak		SidePak		P-Trak		SidePak	
	Conc. (#/cm ³)	CV (%)	Conc. (mg/m ³)	CV (%)	Conc. (#/cm ³)	CV (%)	Conc. (mg/m ³)	CV (%)	Conc. (#/cm ³)	CV (%)	Conc. (mg/m ³)	CV (%)
1	2164	34	0.049	107	609	43	0.003	287	421	6.0	0.002	195
2	1222	25	0.044	77	553	13	0.003	580	567	15	0.000	420
3	1948	30	0.075	72	586	50	0.002	491	599	70	0.002	174
4	955	40	0.014	161	561	9.6	0.003	149	603	13	0.004	191
5	210	5.5	0.000	769	199	19	0.000	2387	262	20	0.000	2279
6	1268	36	0.045	113	255	188	0.004	239	238	227	0.004	226
7	8825	66	0.291	68	395	114	0.007	716	341	108	0.004	67
8	9388	33	0.193	64	1684	40	0.021	219	1060	41	0.004	81
9	1706	23	0.012	132	1641	19	0.003	83	1387	26	0.004	91
10	1184	48	0.039	139	671	6.6	0.004	209	832	7.0	0.003	86
11	3486	24	^A	^A	886	17	^A	^A	830	7.0	^A	^A
12	2048	28	0.067	95	953	41	0.005	268	850	3.4	0.004	105
13	1822	27	0.003	102	1756	31	0.002	120	2077	22	0.005	1503
14	819	23	0.005	878	805	53	0.003	634	899	47	0.003	140
15	2591	17	0.070	56	1332	28	0.028	77	1241	43	0.007	287
16	1930	22	0.044	71	1114	27	0.006	90	1213	43	0.005	236
17	1901	25	0.060	62	1200	41	0.029	78	724	28	0.007	463
18	2364	33	0.065	100	1683	12	0.006	203	1740	3	0.005	138
Mean	2546		0.065		938		0.008		882		0.004	
Median	1915		0.047		846		0.004		831		0.004	

^AThere was an error with the SidePak instrument operation and data were not collected during the majority of the observation period, thus these data have been excluded.

Table 3. Characteristics of peak particle number and mass concentrations measured using the P-Trak and SidePak instruments, during bronchoscopy procedures, including the concentration at the mean value plus one or two standard deviations, the duration of at which concentrations exceed these thresholds in minutes and percent of the procedure duration, and maximum concentrations.

No.	P-Trak							SidePak						
	Mean + 1SD			Mean + 2SD			Max Conc. (#/cm ³)	Mean + 1SD			Mean + 2SD			Max Conc. (mg/m ³)
	Conc. (#/cm)	Duration		Conc. (#/cm ³)	Duration			Conc. (mg/m ³)	Duration		Conc. (mg/m ³).	Duration		
		min	%		min	%			min	%		min	%	
1	872	4.65	6.5	1136	2.88	4.0	3360	0.011	4.77	6.2	0.019	2.43	3.4	0.169
2	622	2.17	22	692	0.07	0.67	724	0.018	0.13	1.3	0.034	0.02	0.17	0.368
3	878	0.95	1.6	1169	0.18	0.32	5890	0.012	0.97	1.7	0.022	0.43	0.75	0.532
4	615	5.95	14	669	0.75	1.8	1280	0.008	2.85	6.8	0.013	1.32	3.1	0.106
5	236	7.82	15	273	1.83	3.6	308	0.009	0.27	0.52	0.018	0.10	0.20	0.462
6	734	0.17	0.58	1214	0.17	0.58	8930	0.014	0.43	1.5	0.023	0.13	0.46	0.329
7	846	2.02	3.10	1297	0.37	0.56	8180	0.060	0.57	0.87	0.112	0.37	0.56	3.22
8	2389	4.43	16	3034	1.82	6.5	4070	0.065	2.05	7.3	0.110	0.38	1.4	1.52
9	1945	3.80	6.0	2250	0.55	0.87	7270	0.006	4.35	6.9	0.009	1.80	2.9	0.051
10	714	4.07	18	759	0.47	2.0	817	0.011	0.60	2.6	0.019	0.25	1.1	0.214
11	1040	4.50	12	1194	2.62	7.1	1580	—	—	—	—	—	—	—
12	1342	0.18	0.51	1732	0.12	0.32	8660	0.020	0.65	1.8	0.035	0.35	0.97	0.403
13	2294	9.92	15	2832	0.32	0.50	7030	0.005	2.67	4.2	0.008	1.33	2.1	0.080
14	1228	0.38	0.77	1651	0.38	0.77	8620	0.020	0.23	0.47	0.037	0.07	0.13	0.932
15	1698	2.02	20	2065	0.58	5.8	2210	0.050	1.22	12	0.072	0.52	5.2	0.198
16	1418	0.23	0.93	1722	0.13	0.53	6540	0.113	1.60	6.4	0.017	0.65	2.6	0.125
17	1691	0.48	6.7	2183	0.10	1.38	5100	0.051	1.02	14	0.074	0.30	4.1	0.190
18	1892	3.60	13	2101	0	0	2020	0.019	0.85	3.1	0.032	0.40	1.5	0.374
Mean	1246	3.19	9.6	1554	0.74	2.1	4739	0.023	1.48	4.6	0.038	0.64	1.8	0.545
Median	1134	2.88	9.4	1474	0.38	0.82	4585	0.014	0.97	3.1	0.023	0.38	1.4	0.329

than increased ventilation at the time of the procedure.

Both the number and mass concentration of aerosols were variable during bronchoscopy procedures, exhibiting high concentrations over short durations (Figure 2, Table 3). In this study, cough and suctioning occurred too frequently to explain each peak (Table 1). Cough generates polydisperse aerosols,^[8] many of which are larger than can be captured by the instruments used in this study. As a result, while our instrumentation was able to detect rapid changes in concentrations of respirable particles, the equipment was unable to detect changes in the concentration of larger “droplet” particles that may project onto the facial mucous membranes of healthcare personnel or be inhaled. Peak aerosol concentrations are important for the occupational health of healthcare workers during bronchoscopy procedures as the infectious dose of many respiratory pathogens is very low.

The finding that bronchoscopy was not associated with elevated mean ultrafine and respirable aerosol concentrations (Table 2), is consistent with O’Neil et al.,^[3] who used these same instruments (and others), and observed aerosol number and mass concentrations to be elevated only during bronchoscopies with nebulized medication administration. However, Lavoie et al.,^[4] who used a Ultraviolet Aerodynamic Particle Sizer (UV-APS) to measure particles 0.5–15 µm diameter, found that the number

concentrations of fluorescent particles (containing biological materials) and non-fluorescent particles were 3-times and 124-times greater during bronchoscopy procedures than at the beginning or end of the day (occupancy at these times was not described), respectively. The finding of Lavoie et al.^[4] may be explained by the larger particle size range captured by the UV-APS than the P-Trak and SidePak used in this study.

Limitations of this study with respect to the interpretation of the aerosol measurements are that only generic aerosol particles were measured and that sampler inlets were not in the breathing zone of the pulmonologists. With respect to the former limitation, interpretation of these data for infection risk among healthcare workers requires an assumption about the concentration of pathogens in respiratory secretions and aerosols. The UV-APS instruments, such as have been used by others,^[3,4] are able to identify bioaerosols, but are not able to distinguish between pathogens, commensal microorganisms, and other particles of biological origin, such as human epithelial cells including human skin cells. Future work should capitalize on epidemics and pandemics, such as Thompson et al.,^[5] to characterize pathogen emission, transport, and fate during bronchoscopy procedures. With respect to the latter limitation, the actual aerosol concentrations breathed in by pulmonologists or other healthcare personnel present during bronchoscopy procedures may be higher or lower than what was

Table 4. The number and rate of contacts per hour made by the pulmonologist with the patient, themselves, and environmental surfaces in the procedure room.

Surface	No. Procedures with Contact ^A	No. of Contacts ^B		Contacts per Hour ^B	
		Mean	Range	Mean	Range
Patient	18	22.3	1–48	32.2	6.0–57
<i>Participant's Body and Personal Protective Equipment</i>					
Facemask	11	1.6	1–5	2.4	0.8–8.3
Hands	11	3.6	1–15	4.6	1.2–13
Head	11	2.1	1–6	3.2	1.5–10
Lower Body	9	2.2	1–9	2.7	1.2–8.4
Torso	13	13.5	1–71	20.8	1.8–59
All Sites	16	17.3	4–88	25.5	3.8–73
<i>Procedure Room Furnishings and Equipment</i>					
Bed	15	5.3	1–15	8.6	1.2–24
Bronchoscope	18	19.4	1–46	28.0	6.0–57
Bronchoscopy Station	9	5.3	1–13	6.6	1.2–22
Cabinet	4	2.0	1–3	2.2	0.8–3.2
Computer Station	1	1	–	1.2	–
Cytology Station	6	2.2	1–4	3.2	1.2–4.9
Suction Tube	7	4.6	1–13	6.1	1.0–11
Supplies on Wall	4	1.5	1–2	1.9	1.4–2.4
Vital Signs Machine	2	1.5	1–2	2.0	0.8–3.2
X-Ray Machine	4	1.25	1–2	1.5	0.9–2.1
All Sites	18	31.2	3–62	47.7	18–84

^AA total of 18 procedures were observed.^BOnly for procedures in which a contact was made.**Table 5.** Personal protective equipment (PPE) doffing practices observed.

Piece of PPE	Type of Error	No. of Observed per No. Observations
Mask ^A or N95 respirator	Remove from the front	12/16
	Not careful ^B	10/16
Gown	Not careful ^B	4/18
	Remove from the front	8/18
Gloves	Not inside-out	5/18
	Wore outside procedure room	3/18
	Not careful ^B	9/18
Hand hygiene	Not inside-out	4/18
	Wore outside procedure room	4/18
	Not performed before leaving procedure room	12/15
All	Doffing sequence	12/18

^AMask with or without visor.^BNot careful means that the item was removed with flourish or inattention, increasing the chance of aerosol generation or contact with other objects.

measured. The position of the SidePak at the pulmonologists' waist may have damped the short-term peaks, which were small compared to those measured by the P-Trak, which was held at chest height by the investigator.

The change in correlation between aerosol mass and number concentrations over the course of the measurement period (Figure 3) suggests that the particle size distribution of the aerosol may change as a result of the procedure, or simply over time of occupancy of the procedure room. Given the presence of cough and suctioning, it is plausible that the aerosol size distribution generated by the procedure differs from that observed through human occupancy. However, Lavoie et al.,^[4] who did not observe a change in the median number aerodynamic diameter of fluorescent or non-fluorescent aerosols during bronchoscopies relative to that measured before and

after the procedure, suggesting little or no change in the particle size distribution. In contrast, Thompson et al.^[5] found that the size distribution of particles containing influenza viral RNA differed, with a greater proportion of RNA in smaller particles (0.86–7.3 µm vs. > 7.3 µm diameter), during bronchoscopies and other AGPs relative to baseline, although this difference may not translate into a change in the mass or number concentration of particles, just the particle sizes containing viral RNA. Alternatively, an effect of infection could be a change in the aerosol size distribution.

A second limitation with respect to the aerosol measurements, was that the instruments used did not capture the full range of particles sizes expected to be generated during bronchoscopy procedures. The instruments utilized measured particles in the ultrafine and respirable ranges, and thus are relevant to the

Figure 3. The distributions of Spearman's correlation coefficients between aerosol concentrations (30-sec averages) measured by the P-Trak and SidePak devices by observation period (before, during and after the bronchoscopy) and overall.

risk for occupationally-acquired infections with pathogens that can initiate infection via inhalation into the respiratory tract, including *Mycobacterium tuberculosis*, Severe Acute Respiratory Syndrome coronavirus, and influenza.^[9] However, this study does not contribute to our understanding of the potential exposures to larger particles (e.g., droplets), which may be inhaled or project onto the facial mucous membranes of healthcare personnel during bronchoscopy.

This is the first study, to our knowledge, to describe the contact patterns of pulmonologists during bronchoscopies, or any other AGP. Many respiratory pathogens recognized as posing a risk to occupational health during AGPs, including influenza, are transmitted through multiple routes, including the contact route.^[1] Thus, infectious respiratory aerosols generated during bronchoscopy that deposit onto surfaces in the procedure room may contribute to the risk of occupationally-acquired infection through the contact route. It is appropriate, therefore, to consider disease transmission through multiple mechanisms when measuring or modeling occupational exposures during AGPs, and contact pattern data collected in this study can inform the design of such studies.

Participants were observed to wear a surgical mask (with visor) more often than N95 respirators (14 vs. 4 procedures). Recommendations for use of respiratory protection during AGPs is disease dependent,^[1,2] which requires healthcare personnel to make judgments about the likelihood of a patient's infection status in the absence of comprehensive diagnostic

testing. The uncertainty about patient infection status has led some healthcare facilities to recommend or require the use of respirators for all bronchoscopy procedures. Since the relative contributions of exposure to infectious aerosols through inhalation, droplet spray and contact remain unknown in the context of bronchoscopies (and other AGPs), and likely varies with disease, use of respirators during bronchoscopies remains an appropriate precaution for prevention of occupationally acquired infections.

As in other studies,^[10,11] doffing practices observed in this study were inconsistent with the practices recommended by the CDC,^[7] and suggests the value of additional training in the use and doffing of PPE. The frequency of hand hygiene before leaving the procedure room was very low, but participants may have washed their hands outside the room where they were not observed.

Pulmonologists were the focus of this research because their role brings them in closest proximity to the patient's head—the aerosol source—but other healthcare personnel should be considered in future work. Although the sample size in this study involved observing only 18 bronchoscopy procedures, this sample size is large relative to other studies.^[3,5] Repeated participation of some pulmonologists may have reduced the variance observed if they behaved similarly on multiple occasions. This is more likely a problem for the observed use and doffing of PPE than other variables measured because the individual determines how to use PPE, whereas the patient, procedure, and pulmonologist influence aerosol generation and contact patterns.

Epidemiologic studies have clearly demonstrated these procedures pose a high-risk to healthcare personnel, but many aspects of the exposure pathways remain unknown.^[1,2] It is highly likely that multiple transmission routes—inhalation, droplet spray, and contact—contribute to the risk of occupationally acquired infections of respiratory viruses like influenza, and the AGP likely creates opportunities for atypical routes of transmission for other pathogens, such as Ebola Virus Disease.^[9] This research has shown that healthcare personnel are exposed to high concentrations of respirable and ultrafine aerosols for short-durations during bronchoscopy procedures, and that opportunities for contact transmission exist. Important knowledge gaps remain with respect to the potential for exposure to larger aerosols and the distribution of infectious agents among aerosols of different sizes, and these gaps should be addressed through further field research. Mathematical modeling and

quantitative microbial risk assessment can aid with assessing the contributions of different routes of exposures to the risk for occupationally-acquired infections.

Conclusions

Bronchoscopy procedures were not found to increase the mean number or the mass concentration of respirable particles, but short-duration peak exposures during the procedure were observed. Given the low infectious dose of many respiratory pathogens, respiratory protection is recommended for use by healthcare personnel during bronchoscopies to protect against these peak concentrations. Pulmonologists frequently contact environmental surfaces, which may result in exposures to pathogens through the contact transmission route. Practices for doffing personal protective equipment were frequently inconsistent with those recommended by the CDC, and education and training are recommended to improve effective utilization.

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