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Quantification of Respirable Aerosol Particles from Speech and Language Therapy Exercises

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Summary: Introduction. Voice assessment and treatment involve the manipulation of all the subsystems of voice production, and may lead to production of respirable aerosol particles that pose a greater risk of potential viral transmission via inhalation of respirable pathogens (eg, SARS-CoV-2) than quiet breathing or conversational speech.

Objective. To characterise the production of respirable aerosol particles during a selection of voice assessment therapy tasks.

Methods. We recruited 23 healthy adult participants (12 males, 11 females), 11 of whom were speech-language pathologists specialising in voice disorders. We used an aerodynamic and an optical particle sizer to measure the number concentration and particle size distributions of respirable aerosols generated during a variety of voice assessment and therapy tasks. The measurements were carried out in a laminar flow operating theatre, with a near-zero background aerosol concentration, allowing us to quantify the number concentration and size distributions of respirable aerosol particles produced from assessment/therapy tasks studied.

Results. Aerosol number concentrations generated while performing assessment/therapy tasks were log-normally distributed among individuals with no significant differences between professionals (speech-language pathologists) and non-professionals or between males and females. Activities produced up to 32 times the aerosol number concentration of breathing and 24 times that of speech at 70-80 dBA. In terms of aerosol mass, activities produced up to 163 times the mass concentration of breathing and up to 36 times the mass concentration of speech. Voicing was a significant factor in aerosol production; aerosol number/mass concentrations generated during the voiced activities were 1.1-5 times higher than their unvoiced counterpart activities. Additionally, voiced activities produced bigger respirable aerosol particles than their unvoiced variants except the trills. Humming generated higher aerosol concentrations than sustained /a/, fricatives, speaking (70-80 dBA), and breathing. Oscillatory semi-occluded vocal tract exercises (SOVTEs) generated higher aerosol number/mass concentrations than the activities without oscillation. Water resistance therapy (WRT) generated the most aerosol of all activities, ~10 times higher than speaking at 70-80 dBA and >30 times higher than breathing.

Conclusions. All activities generated more aerosol than breathing, although a sizeable minority were no different to speaking. Larger number concentrations and larger particle sizes appear to be generated by activities with higher suspected airflows, with the greatest involving intraoral pressure oscillation and/or an oscillating oral articulation (WRT or trilling).

Key Words: Respirable aerosols—Speech language pathology—Voice therapy—Respiratory pathogens—SARS-CoV-2.

INTRODUCTION

On 11 March 2020, the World Health Organization (WHO) declared the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which causes coronavirus disease 2019 (COVID-19), to be a global pandemic.[1] In line with local policies, many outpatient and elective hospital services in most countries ceased operating or prioritized only the most clinically urgent cases. Clinicians, including speech-language pathologists, were redeployed to support the needs of the critically ill and assist in the effort to manage the burden on health care systems worldwide.[2]

Aerosol generating procedures (AGPs) have been defined as any medical and patient care procedure that results in the release of aerosol particles capable of carrying infectious pathogens.[3,4] Indeed, a variety of medical procedures undertaken in disciplines as diverse as respiratory care, orthopaedic surgery and dentistry are considered to be AGPs. However, there remains little certainty on any definitive list

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of the healthcare procedures that should be classified as such,[4,5] a fact highlighted by the WHO as far back as 2014.[6] As healthcare services began to reopen in many countries from June 2020, Ear, nose and throat (ENT) and head and neck professional bodies formulated recommendations[7,8] to guide a safe return to face-to-face clinical practice with limited evidence-based knowledge as to which procedures carried out in these clinical areas were aerosol generating.

National speech-language pathology bodies in the UK, US, and Australia[4,9] recommend that both instrumental and clinical dysphagia assessments be considered an AGP owing to the risk of triggering reflexive cough and prolonged contact with oral secretions. These guidelines also reflect the belief that ENT professionals and, by extension, speech-language pathologists, were at increased risk of exposure to COVID-19 due to their extended time in close contact with the nasopharynx of patients where there is an increased viral load.[10] Voice assessment and treatment involve the purposeful modulation of all the components of voice production - phonation, respiration and resonance - often within wider parameters than typical speech and breathing. Therefore, it might be expected that these activities produce more expiratory particles than quiet breathing or conversational speech.[11,12] This expectation is borne out by the available literature, however, the data frequently represent low-level evidence as identified in a recent systematic review.[11] Few current clinical guidelines issued since the pandemic have made particular mention of voice and voice therapy,[9] and those that do[13,14] have been based on expert consensus opinion rather than physical measurements with human participants. Castillo-Allendes et al.[13] for example, recommended that a respirator mask, face shield, gloves, and long-sleeved gown be worn for voice assessment and that contact should be limited to 15 minutes. In the absence of specific data on the risk of continuing with face-to-face treatment, many services rapidly adapted and deployed remote care modalities, or “telehealth” solutions, some seeing rates of remote patient contacts rising from prepandemic levels of less than 1% of total contacts to well over 70% of total contacts.[15] Official professional guidance has been to continue to rely on these remote solutions whenever possible.[2]

To date, there remains little research exploring the aerosol-generating capacity of voice assessment and treatment and the potential risk it poses regarding SARS-CoV-2 transmission via inhalation of respirable pathogens. Timmons Sund et al.[12] found that carrying out voice assessment and therapy tasks in a clinical space resulted in an increased number of particles compared to background ambient aerosol levels (baseline) and reading aloud the “Rainbow Passage” (speech) conditions and that these emitted particles did not accumulate over time. However, results from their study are limited due to their single subject design. Further, data collection was also hampered by significant fluctuations in background aerosol concentration from the closing and the opening of the clinic room door, prohibiting any analysis of respirable particles with sizes below 1 μm. To our knowledge, studies involving statistically meaningful numbers of participants and with robust control of background aerosol have not been published.

Herein, we present a robust measurement and quantification of respiratory aerosol particle emissions during a range of selected speech-language pathology assessment and therapy tasks across 23 healthy adult participants. Measurements were carried out in an ultra-clean laminar flow operating theatre, with a near-zero background aerosol number concentration, allowing direct attribution of the expired aerosol particles produced to the range of the assessment and therapy tasks studied. We report aerosol number and mass concentrations as well as *aerosol* size distributions ($\sim$0.54-20 μm) measured with both an optical particle sizer (OPS) and an aerodynamic particle sizer (APS) from a range of selected assessment and therapy tasks, comparing to baseline breathing and speaking measurements.

METHODS AND STUDY PROTOCOLS

Human subject

The PERFORM study[16−18] was approved by the Public Health England Research Ethics and Governance of Public Health Practice Group (PHE REGG): PERFORM-1 PHE study number NR0221, PERFORM-2 R&D reference 429. All research was performed in accordance with the relevant guidelines and regulations of the Ethical Review Board. As part of the PERFORM-2 project, we recruited 23 healthy adult volunteers (11 male and 12 female, ranging in age from 29 to 63 years (mean ± standard deviation, median: 45.5 ± 10.1, 48)). Of the 23 adult participants, 12 were nonprofessionals and 11 were speech-language pathologists with at least one year of experience treating voice disorders. Informed consent was obtained from all participants at the time of the measurement procedures. Participants were prescreened to ensure they were healthy, which was defined as free from cardiac, metabolic, or respiratory disease, including severe asthma and COVID-19 symptoms. All participants had a negative lateral flow test for COVID-19 before participating in the study. Participants also completed a prescreening questionnaire including questions regarding age, gender, weight, height, singing training history and ethnicity to fulfil inclusion/exclusion criteria.

Respirable aerosol measurements

Respiratory aerosols were measured using an aerodynamic particle sizer (APS, model 3321, TSI, USA, sampling particles 0.54-20 μm diameter at 1 L min^{-1} with sheath flow 4 L min^{-1}) and an optical particle sizer (OPS model 3330, sampling particles 0.3-10 μm diameter, flow rate 1 L min^{-1}). The experimental configuration and procedures were similar to our previous studies,[16,17,19] except that during these studies, participants performed the series of expiratory speech and language therapy exercises while sitting down on a chair (Figure 1A). Similar to our previous work,[16,17,19] all measurements and tasks were carried out with the participant's face directed into the sampling funnel

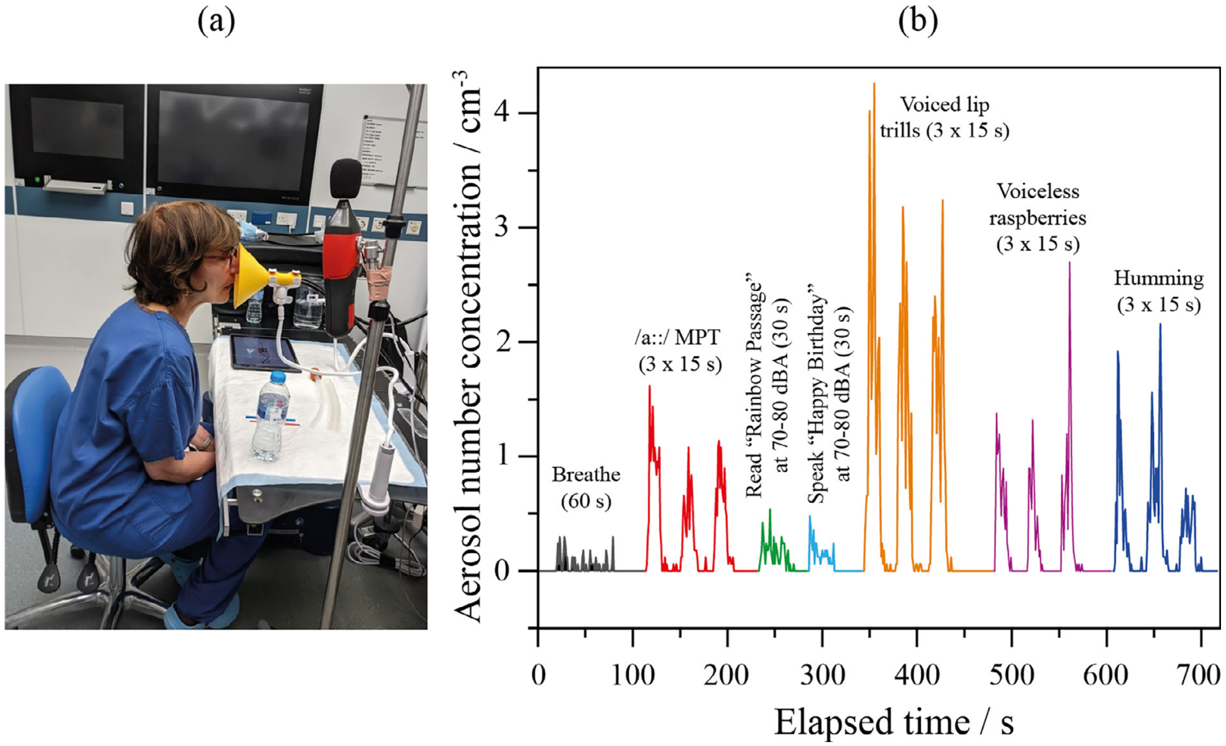

FIGURE 1. (**A**) Experimental configuration of APS measurements and (**B**) representative time series plot of aerosol number concentration for one participant completing a series of selected activities.

at a distance of approximately 10 cm from mouth to funnel apex. Participants were asked to sit back from the sampling funnel for a rest period of 20 s between sampling periods and were reminded regularly to take a sip of water throughout data collection. An APS (0.54-20 μm) and/or OPS (0.3-10 μm) sampled the expired aerosols via a collection funnel and through a 100 cm section of conductive tubing (TSI Inc., inner diameter 0.19 in, outer diameter 0.375 in). Additionally, a datalogger Sound Level Meter with an LCD display screen (RS PRO RS-8852 Sound Level Meter, accuracy: ± 1.4 dB, dynamic range 30-130 dB, resolution 0.1 dB) was also mounted ~30-40 cm from the sampling funnel at an adjustable height, with the display visible to the participant eye level to self-regulate their voice amplitudes. All the measurements were carried out in a laminar flow operating theatre, with a near-zero background aerosol number concentration in the 0.54-20 μm diameter size range, allowing confident attribution and quantification of the relatively small amounts of the expired aerosol particles produced by the different expiratory activities. Temperature and relative humidity were typically 20°C and 45%, respectively. A representative time series recording of APS-measured aerosol number concentration data for a single participant performing a selected series of voice therapy exercises is shown in Figure 1B.

Breathing and speaking experiments

The experimental protocol was based on our previous studies investigating respiratory aerosol generation[16,17,19,20] where participants were instructed to perform specific respiratory tasks into a sampling funnel for a set time. In between activities, participants moved their faces away from the funnel for 20 seconds to enable the measured aerosol concentration to return to background (~0 cm^{-3}, ie, the concentration of aerosol in the room). Breathing and two speaking activities were used as reference measurements. Participants were first invited to breathe into a funnel for 60 seconds, inhaling through the nose and exhaling through the mouth in a non-forced "quiet" fashion. Next, participants were invited to read the "Rainbow Passage"[21] at 70-80 dBA for 30 seconds. Lastly, participants were invited to speak the words of the "Happy Birthday" song to "Susan" at 70-80 dBA for 30 seconds.

Assessment and therapy tasks experiment

The experimental speech and language therapy activities were selected to represent a range of assessment and therapeutic tasks utilized in current clinical practice in the treatment of a variety of voice disorders. In total, 34 activities were investigated. For each activity, participants were cued both verbally by the investigators as well as visually by means of a computer monitor positioned at eye level directly in front of the participant. Table S1 summarizes all the tasked activities, their durations, and the number of repetitions elicited for each exercise. Briefly, participants performed a series of tasks including sustained productions of /a/ (as in a maximum phonation time), sustained /s/ and /z/ (as in an S:Z ratio), sustained /m/ (as in humming/resonant voice therapy), yawn-sigh, and loud elicitations of /heɪ/ (as in projection work). Participants also performed semi-occluded vocal tract exercises (SOVTEs) with flow resistant straws (Ø3 mm / Ø6 mm, 15.5 cm long), two water resistance therapy (WRT) tubes (Ø9 mm/Ø22 mm, 30 cm long) immersed in two water depths (5 cm and 10 cm), lip trills, tongue trills, raspberries and pulsed fricatives. For the water resistance therapy exercises, there was the potential for aerosol and droplet generation due to atomization of the water. To avoid this confounder, respirable aerosol particles were sampled with an OPS and an antiviral Eco BVF Office Spirometer with bite lip filter (Vitalograph Ltd, UK) from the WRT tube (ie, before the air passed into the water) as in Figure S1.

Data processing and statistical analysis

The raw data of aerosol counts from the APS instrument were collected with the Aerosol Instrument Manager software (TSI, USA) and postprocessed with custom-written software in LabVIEW. The postprocessed files were then analyzed in Origin (OriginLab). For the statistical analysis, we adopted a similar approach to our previous work.[16−19] Variables were aggregated to the individual level due to different sampling regimes across studies. Data were inspected and log transforms were used when the data were skewed. For pairwise comparisons between professionals (speech-language pathologists) and non-professionals and between males and females, independent sample *t*-tests were used whereas for comparisons of different activities within individuals, paired *t*-tests were used.

RESULTS

This work investigated aerosol number and mass concentrations as well as particle size distributions generated by a cohort of 23 adult participants performing a range of respiratory activities, including breathing, speaking, and voice therapy techniques. The activities included a range of unvoiced and voiced tasks, which provide insight about the role of phonation, as well as place and manner of articulation in respiratory aerosol generation.

Baseline aerosol measurements for breathing and speaking

Figure 2 shows the aerosol number concentration (Figure 2A) and mass concentration (Figure 2B) generated during breathing and speaking at 70-80 dBA across this cohort compared with adult participants from our previous studies (n = 95, aggregate cohort across PERFORM and AERATOR studies).[16,17,19,22] The data in Figure 2 are also summarized in Table S2. Aerosol number concentrations describe the number of aerosol particles released per unit volume of exhaled air within the 0.54-20 μm aerodynamic particle size range. The mass concentrations are estimated from size-resolved measurements of particle number concentration, assuming the aerosol particles have the density of water (1 g cm^{-3}). Breathing by this cohort generated aerosol number (P = 0.999) and mass (P = 0.059) concentrations consistent with adult participants from our previous studies.[16−19,22] The median aerosol number concentration (0.072 cm^3, IQR 0.047-0.116) and median mass concentration (0.041 cm^3, IQR 0.021-0.079) are within the range of similar results reported by us (median number (0.049 cm^3, IQR 0.024-0.226), mass (0.060 cm^3, IQR 0.017-0.224)) across the PERFORM and AERATOR studies.[16−19,22]

A comparison of two different speaking activities ("Happy Birthday" and the "Rainbow Passage") performed at the same loudness level (70-80 dBA) demonstrates that they generate comparable aerosol number (P = 0.980) and mass (P = 0.148) concentrations. Moreover, respiratory aerosol generated by speaking "Happy Birthday" (P = 0.374) and the "Rainbow Passage" (P = 0.372) was consistent with previous measurements of adults speaking "Happy Birthday" at 70-80 dBA (n = 95)[16−20,22] with respect to emitted aerosol number concentrations. Hence, the "Rainbow Passage" will serve as the reference when comparing other activities to speaking.

Aerosol number and mass concentrations from voice therapy tasks

Results across all the studied tasks are presented in Table 1 and Table 2. The data are presented in a ranked order comparing the relative median value ratios of the average aerosol number (Table 1) and mass (Table 2) concentrations to breathing and speaking the "Rainbow Passage" at 70-80 dBA across the cohort. Corresponding P-values from paired *t*-tests showing the relative statistical significance of all the tasks compared to breathing and speaking are also reported in Tables 1 and 2. In terms of number concentrations (Table 1), all the therapy tasks, except /s/ pulses, generated more respirable aerosol particles than breathing, with significant relative median number concentration ratios ranking lowest for the voiceless narrow (Ø3 mm) straw task (a factor of 1.9, P = 0.001) to the highest (a factor of 33, P < 0.001) for the voiced water resistance therapy (WRT) (Ø9 mm in 10 cm water) task. For median mass concentration ratios (Table 2), all but three tasks (sustained /s/, voiceless Ø3 mm straw, /s/ pulse) generated significantly more particle mass when compared to breathing, sustained /z/ (a factor of 2.3, P = 0.007) ranked lowest through to the highest for voiced WRT (Ø9 mm in 10 cm water) (a factor of 163, P < 0.001).

A similar pattern is observed when the therapy tasks are compared to speaking, in that most therapy task activities generated more aerosol than during speaking the "Rainbow Passage" at 70-80 dBA in terms of both aerosol number and mass concentrations. However, one-third of the tasks generated either significantly less or comparable aerosol number and/or mass concentrations to speaking. For the median number concentrations (Table 1), pulsed /s/ produced half the aerosol of speaking (a factor of 0.53, P = 0.006), while significantly greater median number concentration ratios were found ranging from yawn-sigh (a factor of 1.9, P <

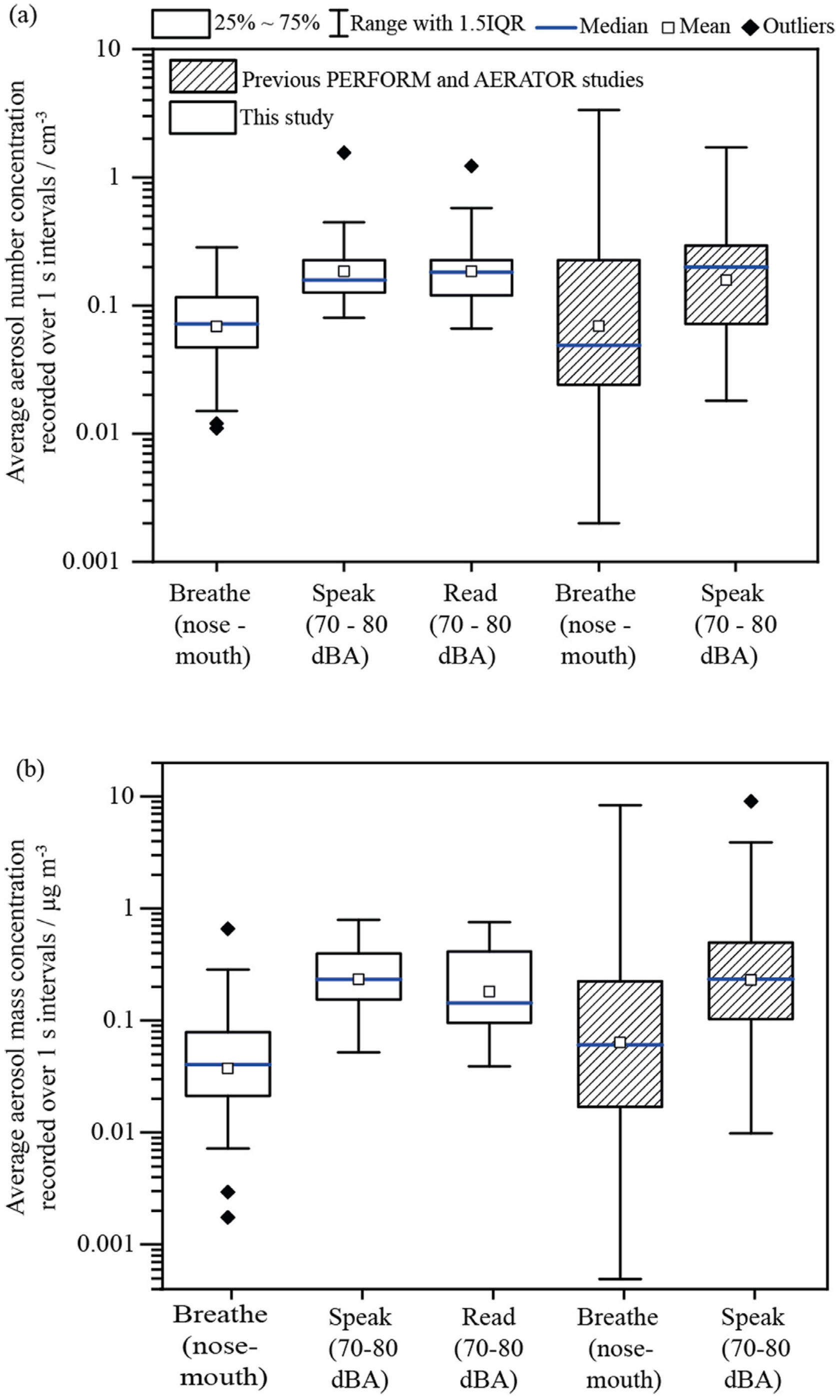

FIGURE 2. (**A**) Number and (**B**) mass concentrations of respirable aerosol particles generated from breathing, speaking "Happy Birthday" and reading aloud the "Rainbow Passage" at 70-80 dBA compared with adult participants from our previous studies (n = 95, aggregate cohort across PERFORM and AERATOR studies). Blue lines indicate medians, while bottom and top of black boxes indicate the 25th and 75th percentiles respectively; sample size in this study is n = 23. Sample size across aggregate of PERFORM and AERATOR studies, n = 95.

0.001) to voiced WRT (Ø9 mm in 10 cm water) (a factor of 14, $P < 0.001$). For median mass concentrations (Table 2), tasks which generated significantly less aerosol than speaking ranged from sustained /s/ (factor of 0.37, $P < 0.001$) to sustained /z/ (factor of 0.89, $P = 0.002$), whilst tasks which generated significantly more aerosol than speaking ranged from yawn-sigh (factor of 2.2, $P = 0.001$) to voiced WRT (Ø9 mm in 10 cm water) (factor of 36, $P < 0.001$).

Figures S2-S4 present box and whisker plots for mean aerosol number (S2a-S4a) and mass (S2b-S4b) concentrations for the tasks investigated in this study. Corresponding summary data are also included in Tables S3-S7 and include the statistical parameters visualized by the box and whisker plots. The parameters were calculated on the logarithmically transformed data and the number of participants for each activity is given by *n*. For the WRT exercise, the

TABLE 1.
Ranks in Terms of Median Aerosol Number Concentration Ratio Comparison to Breathing and Speaking the “Rainbow Passage” at 70-80 dBA Across the 23 Adult Participants

Voice Therapy Task	Median aerosol *number concentration* compared to Breathing		Voice Therapy Task	Median aerosol *number concentration* compared to speaking the Rainbow Passage at 70-80 dBA	
	Ratio	*P-value*		*Ratio*	*P-value*
/s/ pulse	1.3	-	/s/ pulse	0.53	†
Ø3 mm straw [-V]	1.9	†	Ø3 mm straw [-V]	0.73	-
/s::/ (S:Z)	1.9	†	/s::/ (S:Z)	0.75	-
/ʃ/ pulse	2.0	‡	/ʃ/ pulse	0.80	-
/z/ pulse	2.1	*	/z/ pulse	0.85	-
/f/ pulse	2.3	‡	/f/ pulse	0.91	-
/v/ pulse	2.6	‡	/v/ pulse	1.0	-
Ø3 mm straw [+V]	2.8	‡	Ø3 mm straw [+V]	1.1	-
/z::/ (S:Z)	2.9	‡	/z::/ (S:Z)	1.1	-
/ʒ/ pulse	3.2	‡	/ʒ/ pulse	1.3	-
Hey	3.8	‡	Hey	1.5	-
Yawn-sigh	4.8	‡	Yawn-sigh	1.9	†
/a::/ (MPT)	6.2	‡	/a::/ (MPT)	2.5	‡
Ø6 mm straw [-V]	7.3	‡	Ø6 mm straw [-V]	2.9	†
Tongue trills [-V]	7.6	‡	Tongue trills [-V]	3.0	‡
Lip trills [-V]	8.7	‡	Lip trills [-V]	3.5	‡
/m::/	10.3	‡	/m::/	4.1	‡
Ø6 mm straw [+V]	10.5	‡	Ø6 mm straw [+V]	4.2	‡
Lip trills [+V]	10.6	‡	Lip trills [+V]	4.2	‡
Tongue trills [+V]	13.4	‡	Tongue trills [+V]	5.3	‡
Raspberries [-V]	16.4	‡	Raspberries [-V]	6.5	‡
Ø9 mm WRT (5 cm) [-V]	17.3	‡	Ø9 mm WRT (5 cm) [-V]	7.6	‡
Ø22 mm WRT (5 cm) [-V]	20.2	‡	Raspberries [+V]	8.4	‡
Raspberries [+V]	21.2	‡	Ø22 mm WRT (5 cm) [-V]	8.8	‡
Ø22 mm WRT (10 cm) [+V]	22.8	‡	Ø22 mm WRT (10 cm) [+V]	9.9	‡
Ø9 mm WRT (5 cm) [+V]	23.5	‡	Ø9 mm WRT (5 cm) [+V]	10.3	‡
Ø22 mm WRT (5 cm) [+V]	26.7	‡	Ø22 mm WRT (5 cm) [+V]	11.6	‡
Ø22 mm WRT (10 cm) [+V]	27.6	‡	Ø22 mm WRT (10 cm) [+V]	12.0	‡
Ø9 mm WRT (10 cm) [-V]	29.0	‡	Ø9 mm WRT (10 cm) [-V]	12.7	‡
Ø9 mm WRT (10 cm) [+V]	32.5	‡	Ø9 mm WRT (10 cm) [+V]	14.2	‡

* indicates $0.05 > P >= 0.01$.
† indicates $0.01 > P >= 0.001$.
‡ indicates $P < 0.001$,and (-) not significant.
Corresponding P-values are from paired t-tests showing the relative statistical significance between all the tasks compared to breathing and speaking. [±V] indicates presence of voicing.

comparison was to breathing and speaking data from the OPS measurements (see Figure S3 and Table S4).

Comparing aerosol number and mass concentrations from voice therapy tasks across gender and professional status

In our previous studies, we demonstrated that no significant difference exists between respirable aerosol generation by male and female participants for the same activity and loudness level.[16–19] For the cohort of 23 adult participants in this study, no differences in generated aerosol number (Figure 3A) and mass (Figure 3B) concentration are apparent when the cohort is separated by gender (female vs male) or by professional experience (ie, voice specialist speech-language pathologists vs non-speech-language pathologists) for a subset of the investigated activities (breathing, speaking, sustained /m:/, sustained /a:/, voiced lip trills, voiceless raspberries and voiceless WRT (Ø9 mm, 10 cm water)). Males and speech-language pathologists generated modestly more aerosol than females and non-speech-language pathologists, respectively, but the differences were not statistically significant across all the activities. The observation about gender differences is consistent with a previous study that found that differences in aerosol generation by male and female participants could be explained by differences in the vocal loudness and exhaled CO_2 levels.[23]

Comparing respirable aerosol mean size distributions from voiced and voiceless tasks

The aerosol size distribution provides insight into the sources and mechanisms of respiratory aerosol generation and determines the aerosol mass concentration.[16,24,25] Figure 4 presents measured aerosol size distributions generated by a voiced activity relative to an unvoiced variant for selected therapy task activities based on: (a) no difference in aerosol number concentrations, (b) modest difference in number concentration and (c) significant differences in number concentrations. The size distributions were fitted to multimodal log-normal distributions[26] ($R^2 > 0.90$) with full fitting parameters provided in Table S8. Aerosol size distributions for a subset of additional exercises (breathing, speaking and reading at 70-80 dBA, S:Z ratios, /a::/ (MPT), humming, yawn-sigh and hej!) are also reported in Figure S5.

Measured aerosol size distributions for the post-alveolar /ʃ/-/ʒ/ fricative pairs and voiced/voiceless lip trills are presented in Figure 4A. The insert shows normalised size distributions with respect to the mean concentration of the first 3 smaller size bins. The aerosol size distributions for the post-alveolar /ʃ/-/ʒ/ fricative are similar in shape, all well-described by a unimodal log-normal distribution (R^2 >0.92), as few particles >2 μm were detected (thus concentrations in this size range are very uncertain and limited by Poisson arrival statistics)[20] and with maximum number concentrations at 0.50 (SE ± 0.02) μm, and 0.53 (SE ± 0.01) μm diameter for /ʃ/ and /ʒ/ respectively. However, the average size distribution generated by the lip trills (voiced and unvoiced) were best fit by a bimodal log-normal distribution ($R^2 > 0.99$). The first mode (similar within the aerodynamic size range of the post-alveolar /ʃ/-/ʒ/ pair fricatives) for the unvoiced and voiced lip trills had maximum number concentrations at 0.58 (SE ± 0.02) μm and 0.59 (SE ± 0.01) μm, whereas the second mode had maxima at 1.97 ((SE ± 0.14) μm and 1.99 (SE ± 0.01) μm, respectively. The two overlapping modes are consistent with those associated with respirable aerosol particles generated during processes occurring deep in the lower respiratory tract (bronchiolar mode 0.3-1 μm) and in the region of the larynx (laryngeal mode 1-2 μm).[16,17,26,27] However, the lip trills (similar to tongue trills and raspberries) are fundamentally different from other activities in that both voiced and unvoiced trills produced similar size distributions over a wide aerodynamic size range. Thus, the modes associated with the trills could also be attributed to the extensive oral articulation which generates a large amount of aerosol compared to those produced by breathing and speaking.

Figure 4B shows /s/ and /z/ alveolar fricative pairs, which are well described by a unimodal lognormal distribution (R^2 > 0.82) with the mode centred at 0.49 (SE ± 0.01) μm, and 0.55 (SE ± 0.02) μm diameter, respectively. Respirable aerosol generated during the unvoiced and voiced Ø6 mm straw exercise (also shown in Figure 4B) are best fit by a bimodal lognormal distribution ($R^2 > 0.97$) with a mode diameter of 0.58 (SE ± 0.01) μm and 0.62 (SE ± 0.01) μm for the bronchial mode, and a mode diameter of 1.02 (SE ± 0.001) μm and 1.4 (SE ± 0.05) μm, respectively, for the laryngeal mode. Modest differences between the size distribution for voiced (~3 μm for the /z/ pulse) and unvoiced (<2 μm for the /s/ pulse) activities are apparent in the normalized plot, a consequence of voiced activities generating larger respirable particles (due to the enhancement of the laryngeal mode).

The role of voicing is most striking in Figure 4C, which compares the WRT activities (Ø9 mm and Ø22 mm in 5 cm and 10 cm of water, respectively), which have voiced-to-unvoiced mass concentration ratios spanning 4.1-5.2 (see Figure 5). The voiced WRT activities are best described by a trimodal lognormal distribution ($R^2 > 0.94$) compared to a bimodal fit for the unvoiced WRT activities. The first two modes of the unvoiced and voiced WRT activities had similar mode diameters at ~0.41 (SE ± 0.001) μm and ~1.80 (SE ± 0.08) μm and are representative of aerosol production from the bronchioles and the larynx. However, voiced WRT activities exhibit a third mode, potentially arising from laryngeal and oral articulation particle generation, and were best fit by a tri-modal lognormal distribution that showed a third peak (σ of 1.20 and 1.23 respectively) with similar mean D_p values of 5.1 μm.

DISCUSSION

This work presents the most comprehensive measurement and analysis of respirable aerosol generation in a wide selection of voice therapy techniques employed in common

TABLE 2.

Ranks in terms of median aerosol mass concentration ratio comparison to breathing and speaking the "Rainbow passage" at 70-80 dBA across the 23 adult participant

Voice Therapy Task	Median aerosol mass concentration compared to Breathing		Voice Therapy Task	Median aerosol mass concentration compared to speaking the *Rainbow Passage* at 70-80 dBA	
	Ratio	*P*-value		Ratio	*P*-value
/sː:/ (S:Z)	1.3	-	/sː:/ (S:Z)	0.37	‡
Ø3 mm straw [-V]	1.3	-	Ø3 mm straw [-V]	0.37	*
/s/ pulse	1.6	-	/s/ pulse	0.45	†
/z::/ (S:Z)	2.3	†	/z::/ (S:Z)	0.66	†
/ʃ/ pulse	2.8	†	/ʃ/ pulse	0.80	-
Ø3 mm straw [+V]	3.1	‡	Ø3 mm straw [+V]	0.88	-
/z/ pulse	3.2	*	/z/ pulse	0.89	-
/f/ pulse	4.2	‡	/f/ pulse	1.2	-
/ʒ/ pulse	4.3	‡	/ʒ/ pulse	1.2	-
/v/ pulse	5.9	‡	/v/ pulse	1.7	-
Ø6 mm straw [-V]	7.3	‡	Ø6 mm straw [-V]	2.1	-
Yawn-sigh	8.0	‡	Yawn-sigh	2.2	†
/a::/ (MPT)	13.6	‡	/a::/ (MPT)	3.8	‡
Hey	14.1	‡	Hey	4.0	‡
Tongue trills [-V]	16.1	‡	Tongue trills [-V]	4.5	‡
Ø6 mm straw [+V]	18.3	‡	Ø6 mm straw [+V]	5.2	‡
Tongue trills [+V]	20.7	‡	Tongue trills [+V]	5.8	‡
/m::/	24.4	‡	/m::/	6.8	‡
Ø22 mm WRT (5 cm) [-V]	34.7	‡	Ø22 mm WRT (5 cm) [-V]	7.7	‡
Ø9 mm WRT (5 cm) [-V]	34.8	‡	Ø9 mm WRT (5 cm) [-V]	7.7	‡
Ø22 mm WRT (10 cm) [-V]	36.0	‡	Ø22 mm WRT (10 cm) [-V]	8.0	‡
Lip trills [-V]	41.0	‡	Ø9 mm WRT (10 cm) [-V]	9.9	‡
Lip trills [+V]	44.0	‡	Lip trills [-V]	11.6	‡
Ø9 mm WRT (10 cm) [-V]	44.6	‡	Lip trills [+V]	12.4	‡
Raspberries [-V]	60.9	‡	Raspberries [-V]	17	‡
Raspberries [+V]	73.0	‡	Raspberries [+V]	20.6	‡
Ø22 mm WRT (5 cm) [+V]	124	‡	Ø22 mm WRT (5 cm) [+V]	27.4	‡
Ø22 mm WRT (10 cm) [+V]	138	‡	Ø22 mm WRT (10 cm) [+V]	30.6	‡
Ø9 mm WRT (5 cm) [+V]	161	‡	Ø9 mm WRT (5 cm) [+V]	35.7	‡
Ø9 mm WRT (10 cm) [+V]	163	‡	Ø9 mm WRT (10 cm) [+V]	36.1	‡

* indicates 0.05> P >=0.01,

† indicates 0.01> P >=0.001,

‡ indicates $P < 0.001$,and (-) not significant.

Corresponding *P*-values are from paired *t*-tests showing the relative statistical significance between all the tasks compared to breathing and speaking. [±V] indicates presence of voicing.

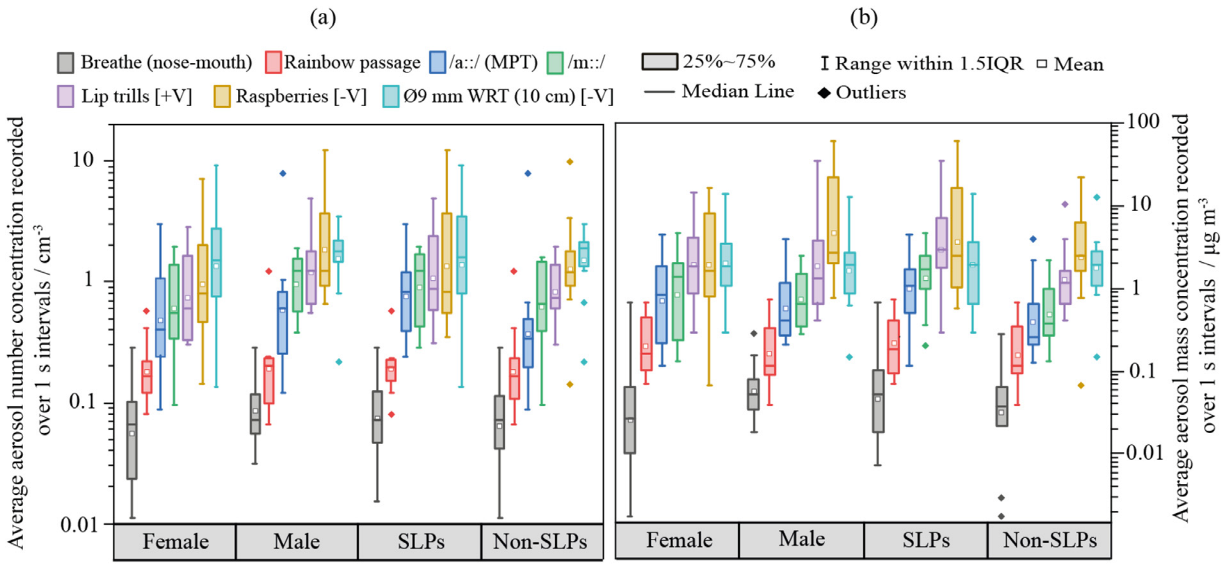

FIGURE 3. Comparing respirable aerosol production during breathing, speaking, maximum phonation time (/a/), humming (/m::/), voiced lip trills [+V], voiceless raspberries [-V] and voiceless WRT[-V] exercises with the narrow tube immersed in 10 cm depth of water across sex, professional and non-speech & language pathologist. Box and whisker plots showing (**A**) number concentration of respirable particles for females (n = 12) vs males (n = 11) and SLPs (n = 11) vs non-SLPs (n = 12) and (**B**) mass concentration of respirable particles for females vs males and SLPs vs non-SLPs. Middle lines indicate medians, while bottom and top of boxes indicate the 25th and 75th percentiles respectively; sample size in this study is n = 23. [±V] indicates presence of voicing.

clinical practice in the treatment of voice disorders. Owing to the range of tasks studied, these measurements allow comparisons of relative aerosol generation along broad phonological and physiological lines, namely the presence/absence of voicing, the place and the manner of articulation, and the presence of a secondary source of vibration in the vocal tract.

Table 1 confirms that all voiceless tasks investigated, with the exception of /s/ pulses, generated significantly more aerosol than breathing, but the differences vary from modest (around 2×more) for fricatives and narrow straw exercises, to more significant (from 7×-30×more) for wide straws, trills and WRT tasks. Asadi et al.[21] observed that plosives were associated with larger particle emission rates than fricatives and it was suggested that this was due to the higher egressive airflow of the former resulting in an increased capacity to carry aerosols away from the respiratory tract. Our data allow some tentative explanations along similar lines. Trills are known to have narrower allowable pressure and flow conditions than fricatives, requiring more pressure to initiate and more airflow to sustain than fricatives.[28] Indeed, our data demonstrate systematically higher aerosol production for all the trilled activities than for fricatives.

A similar effect is seen in the differences observed in the straw exercise tasks. Fluid dynamics dictate that the airflow or volume of air moving past a given point per unit of time in Ls^{-1} (ie, U) is determined by the difference in pressure, ΔP(in cm H_2O) between two cavities separated by an aperture of area, A (in cm^2), such that $U = A(\Delta P)^a c$ (where c is a constant and the exponent, a, relates to the type of flow, laminar to turbulent).[28] A 6 mm diameter straw has a cross-sectional area roughly four times that of a 3 mm diameter straw, and given an identical length and pressure gradient, it will produce four times the airflow. Table 1 confirms that the wider straw exercise produced around five times the aerosol of the narrow straw.

Available airflow data support some of the differences in our experimental findings regarding place of articulation in the fricative and trilled tasks. The literature indicates that post-alveolar fricatives require 25%-50% more airflow than alveolar fricatives,[29] and our data do indeed show more aerosol for /ʃ/ than for /s/. Although the airflow required to initiate and sustain oscillation in trilled exercises will depend on the positioning, stiffness, and mass of the articulator in question,[30] the intraoral pressures identified in the production of tongue trills, lip trills and raspberries by Maxfield et al.[31] (that raspberries generate the highest pressures and tongue trills the lowest) predict the tasks' relative order in Table 1. In this case, the higher intraoral pressures seem to result in higher respirable aerosol production and this is due perhaps to a higher airflow resulting from the progressively greater pressure gradients of the trills at these different places of articulation (alveolar, labial, linguolabial).

Turning now to the comparison of voiced activities to speaking the "Rainbow Passage" at 70-80 dBA, the same overall pattern holds as identified in voiceless tasks. Namely, voiced fricatives and voiced narrow straws produced similar amounts of aerosol to speaking, whilst the other voiced tasks generated significantly more. This difference was modest with yawn sigh and sustained /a/ (around 2 ×), more with sustained /m/, voiced wide straws, voiced lip and tongue trills (around 4-5 ×), and greatest with voiced raspberries and WRT (around 8-14 ×). These comparisons

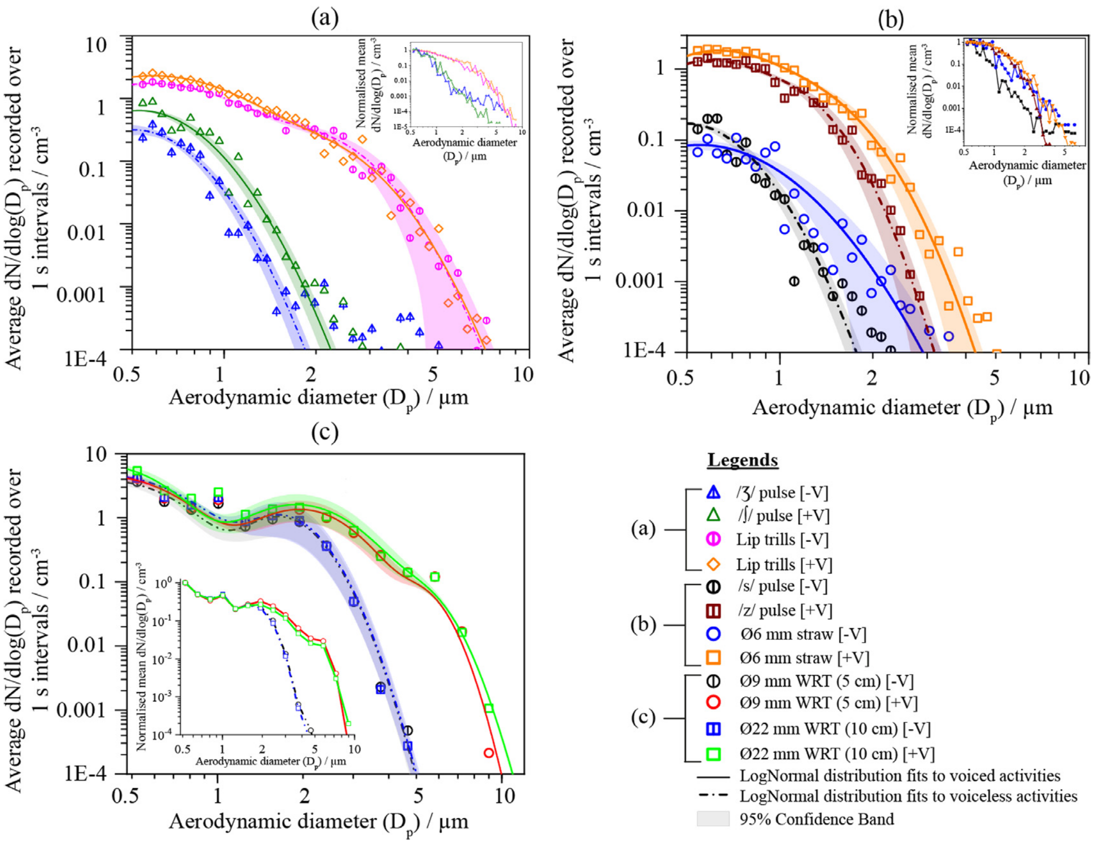

FIGURE 4. Comparison of mean aerosol size distributions generated during: (**A**) the post-alveolar [ʃ]-[ʒ] fricative pairs and lip trills with no significant differences in mean aerosol mass concentrations.;(**B**) alveolar [s]-[z] fricative pairs and flow resistant straws (6 mm diameter, 15.5 cm long) with modest mean aerosol mass concentrations differences between voiced and unvoiced variants.; (**C**) voiced and voiceless pair WRT (Ø9 mm and Ø22 mm) with large mean mass concentration differences.. Curves of the corresponding color indicate log-normal fit of each dataset. Shaded colors indicate 95% confidence band of the fit and [±V] indicates presence of voicing. The insert shows normalized size distributions with respect to the mean concentration of the first 3 smaller size bins.

appear to confirm that airflow remains a factor in the relative ranking of tasks, with the same general order holding from the voiceless tasks to the voiced tasks.

Some of the differences, however, do not appear to be attributable solely to airflow. A somewhat unexpected finding was the greater aerosol production for sustained /m/ as compared to sustained /a/, at roughly twice the rate. The literature supports that humming, or at least the phoneme /m/ , has a comparable airflow to /a/, and that vowels and vowel-like sonorants have the lowest airflow values of all the phonemes.[29,32] In articulatory terms, a hum differs from a sustained /a/ only in channel of airflow (nasal vs oral) and therefore implicates this factor in the greater amount of aerosol observed in this task. Studies[33,34] have shown that an oscillating nasal airflow, such as that produced in humming, dramatically increases the exchange of air between the paranasal sinuses and the nasal cavity (96% air exchange for humming vs 4% for quiet nasal breathing).[35] It has also been found that an oscillating airflow introduced via the nose increases the deposition of an aerosolised solution *into* the sinuses, and that this was most effective when the humming frequency was close to the resonance of a sinus model (approximately 130 Hz for *in vivo* data).[33,34] Although the specific resonances of an individual's paranasal sinuses will be dictated by their shape and size, it does appear that these resonances are within the fundamental frequencies generated by the normal habitual phonation. It is therefore possible that the comparatively large amount of aerosol generated by humming may be due to the contribution of the sinuses during the phonation.

Table S7 presents mean aerosol number and mass concentration comparisons (in terms of median values) for paired voiced/voiceless tasks across the cohort with corresponding *P*-values from paired *t*-tests**.** Overall, and as expected, voiced tasks produced more respirable aerosol than corresponding unvoiced tasks, confirming similar findings by Asadi et al.[21] This comparison was less pronounced in terms of differences in number concentration (only a factor of 1.1-1.8 ×) than for differences in mass concentrations (a factor of 1.1-4.6 ×), suggesting that voiced variants were perhaps more likely to produce larger (and thus more massive) particles than they were to produce a greater number of particles. For particle diameters >2 μm, as observed in Figure 4**B** and more pronounced in Figure 4C, the mean

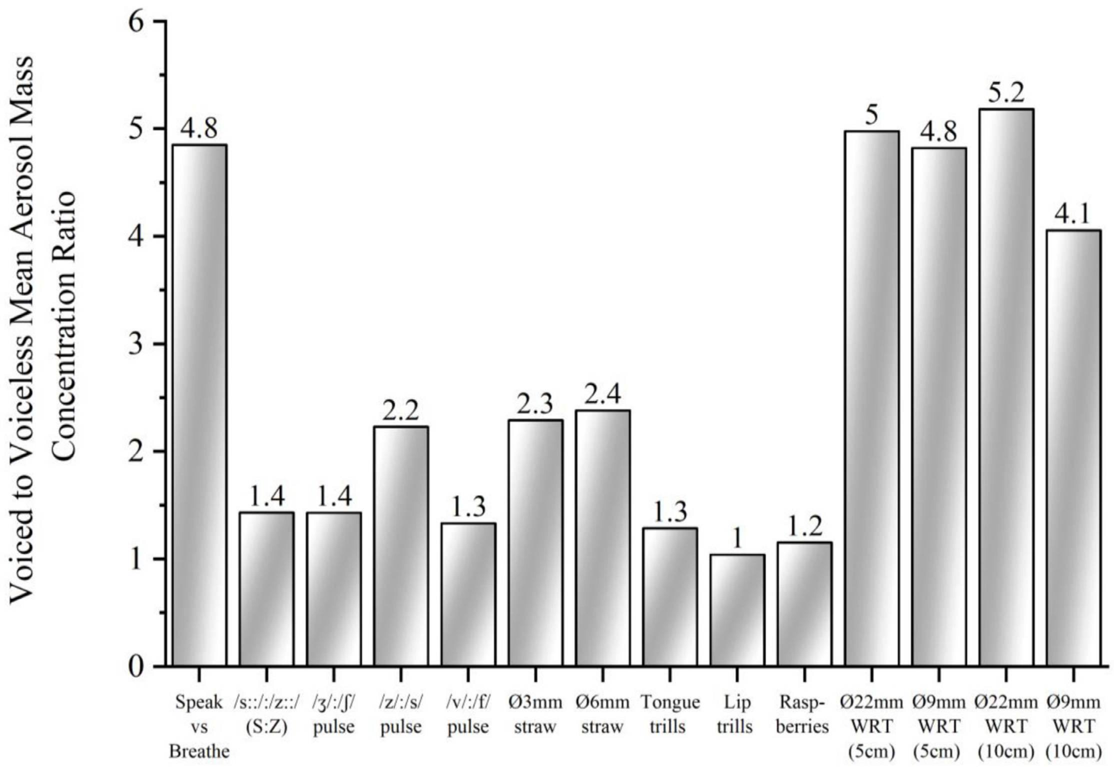

FIGURE 5. Bar chart showing voiced to voiceless pair mean aerosol mass concentration ratios of respirable particles generated across all 23 adult participants.

aerosol particle concentrations generated by unvoiced activities decrease more sharply than for voiced pairs resulting in substantial differences in the lognormal fitting parameters (see Table S8). A comparison of the mean mass concentrations generated by a voiced activity relative to an unvoiced activity is presented in Figure 5. Voiced and unvoiced pair activities such as the trills (lip, tongue and raspberries) as well as some fricative pairs generated comparable mean mass concentration ratios (<1.5) with the particle size distributions presented in Figure 4A showing similar shapes. Activities that resulted in higher mean mass concentration ratios (> 2) between the voiced and unvoiced pair activities also lead to a shift in the aerodynamic particle size range measured (see Figure 4A and 4C). Indeed, the fits for all the voiced activities gave higher mean diameters and variance (see Table S8, SI) for the second "laryngeal" modes than their paired unvoiced activities, except the lip trills where there is enhanced oral articulation and more aerosol particle generation.

The presence of the "laryngeal mode" in the size distribution data clearly support increased vocal fold oscillation in the larynx and increased aerosol generation than that generated in the lower airways, giving rise to the differences seen in the voiced versus the corresponding unvoiced paired task. The differences were not significant for the paired fricatives, which together with the narrow straw produced the least aerosol of all the studied tasks. Significant differences in number and/or mass concentrations were found, however, amongst the remaining pairs, although this varied amongst the tasks. For example, significantly higher number and mass concentrations were found for the voiced variants of both straw exercises compared to the unvoiced variants, suggesting that voicing in this case contributed to a comparable increase in both number and size of aerosol particles. Voiced WRT exercises, on the other hand, produced much higher mass concentrations (3.6-4.6 ×) than their unvoiced pairs ($P < 0.001$) but only borderline/moderately significantly higher number concentrations ($P = 0.027\text{-}0.070$), indicating that the presence of voicing in these tasks contributed significantly to aerosol mass. Voiced trilled tasks, on the other hand, produced only moderately higher number concentrations than unvoiced trills (significant for lip trills, $P = 0.017$, and tongue trills, $P < 0.001$), but no significant increases in the aerosol mass. This would seem to indicate that for trills there is already a large source of aerosol mass, likely arising from an oscillating oral articulation, so the addition of a laryngeal source of aerosol is comparatively small in relative terms. This preponderance of an oral source in the aerosol generation of trilling tasks has been referred to by some as their inherently "high spit factor."[36]

Both trills and WRT are classed as oscillatory SOVTEs, or those which induce a secondary source of vibration into the vocal tract. However, the WRT tasks accomplish this via water bubbling rather than the oscillation of articulators. Interestingly, these exercises uniformly generated the highest number and mass concentrations of all the examined tasks. WRT has been shown in several experimental studies[37−41] to affect both the oral pressure oscillation and the vocal fold vibration, the former being thought to induce a therapeutic "massage-like sensation" of the vocal tract tissues. The oral pressure modulation for a tube submerged in 10 cm water has been shown in modelling[42] and *in vivo*[37] studies to result more than a two- to four-fold increase in peak-to-peak pressure variation than that of the vowel /u:/. This effect may well be intensified by both a lowering of the first acoustic resonance toward the fundamental frequency and a convergence of the mechanico-acoustic resonance of the vocal tract and the frequency of bubbling, identified both in modelling[43] and *in vivo*[44] experiments, leading to potentially increased mechanical forces on the tissues of the vocal tract. Furthermore, several studies of vocal fold contact quotient in electroglottography[45] or closed quotient from highspeed imaging of glottal area[46] have also shown increased vocal fold contact and closure with increasing depths of water, although other work has shown less clear trends. Finally, tube diameter is known to impact bubbling frequency, with narrower tubes producing a faster rate of bubbling and therefore pressure oscillation.[47−49] Table 1 confirms that the 9 mm diameter WRT tube produced systematically more aerosol than the 22 mm diameter tube, possibly as a consequence of this difference in oscillation frequency. However, no statistical differences were observed in the number concentration of particles generated during voicing and as a result of the tube diameters (P = 0.18 and P = 0.87, both in 5 cm and 10 cm H_2O respectively). All these factors may well explain both the pattern of higher rates of aerosol emission and the larger particles identified in size distributions for the WRT tasks in this study, but clearly further investigation into the exact mechanism is warranted.

CONCLUSIONS

This study demonstrates that the risk assessment associated with the inhalation transmission of SARS-CoV-2 during voice assessment and treatment should consider the number and the mass concentrations as well as the sizes of particles generated by these activities and should lead to the production of evidence-based guidelines for clinicians and their services. Our data confirm that the majority of the tasks investigated in this study generate more respirable aerosol than conversational speech, some quite significantly so, with increases of over 30 times the aerosol mass of speaking. Significant factors affecting the aerosol number and the mass concentrations appear to be the presence of phonation, the higher airflow tasks and tasks which introduce a second source of vibration into the vocal tract. These tasks, therefore, should be carried out with requisite care and with adequate mitigations in place. Future studies should seek to evaluate a variety of mitigation strategies so that guidelines can be informed by experimental findings of their effectiveness.

DATA AVAILABILITY

Data underlying the figures and the raw data used in the analysis have been made publicly available in the BioStudies database, https://www.ebi.ac.uk/biostudies/ under accession number S-BSST871

AUTHORS' CONTRIBUTIONS

PLS, DC, JPR, BRB and RE led the study design and secured funding. BSK, JA, HES, JH, JPR, BRB and RE collected the data. NAW, CMO and PLS secured ethical approval. BSK, NAW, CMO, DC and RE managed the registration and coordination of participant volunteers and secured access to the operating theatres. BSK and JA analysed the data. WJB and JA performed the statistical analysis. JC, DC, JPR and BRB provided technical guidance and advice. BSK, JA, HES, NAW, CMO, WJB, JH, PLS, DC, JPR, BRB and RE drafted the manuscript. All authors read and approved the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

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SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at doi:10.1016/j.jvoice.2022.07.006.

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