Emission of respiratory particles

Inhaling and exhaling air — breathing — is one of the basic physiological functions of the human being.

Breathing is essential to sustain the body with oxygen and eliminate the waste generated in the process: carbon dioxide.

Because it is a physiological function, it is normally considered in the domain of medical sciences, not physics.

During inhalation, air enters the respiratory tract and flows down through the upper and lower parts of the tract, finally reaching the alveolar region.

During exhalation, when the passages contract, air flows in the opposite direction and is ultimately exhaled.

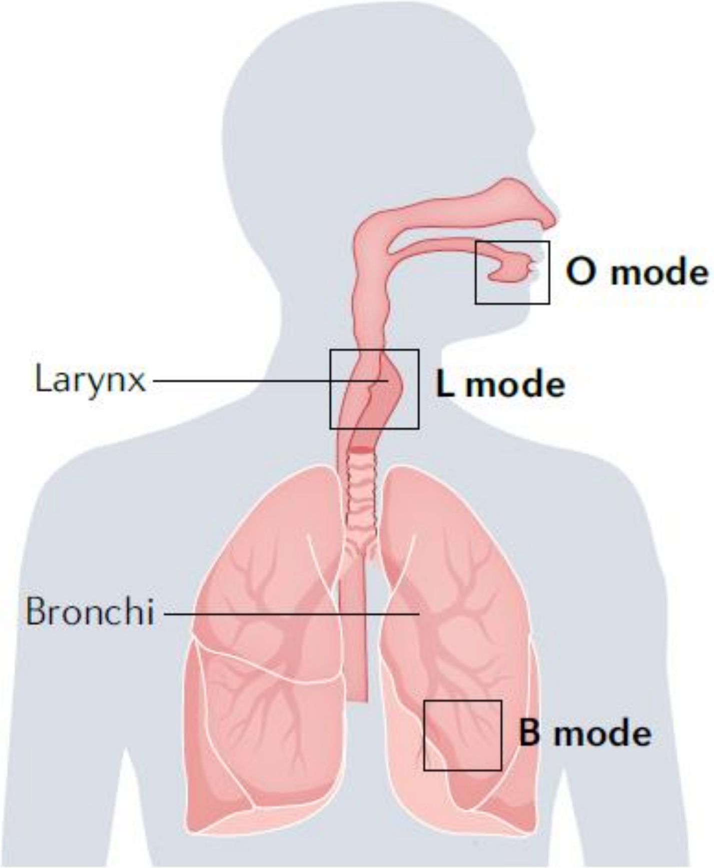
The exhaled stream of air passes at high speed over the surface of the water-based liquid lining the respiratory tract, and aerosolizes the liquid.

The particles that are generated contain, in addition to water, many other constituents, including salts, proteins, mucus, and pathogens such as bacteria or viruses.

The process of particle generation during human respiratory activities — which in addition to breathing include speaking, singing or coughing — is, however, more complex than aerosolization from the surface.

During exhalation, fluid blockages form in respiratory bronchioles, which burst during subsequent inhalation to produce particles; during vocalization, fluid bathing the larynx is aerosolized owing to vocal cord vibration; and during speech articulation, saliva in the mouth is aerosolized owing to interaction of the tongue, teeth, palate and lips.

After the particles are generated, some are deposited in the respiratory tract, and those that eventually leave the respiratory tract with the airflow are subjected to numerous physical processes, including hygroscopic growth and deposition; both processes change the initial particle size distribution.

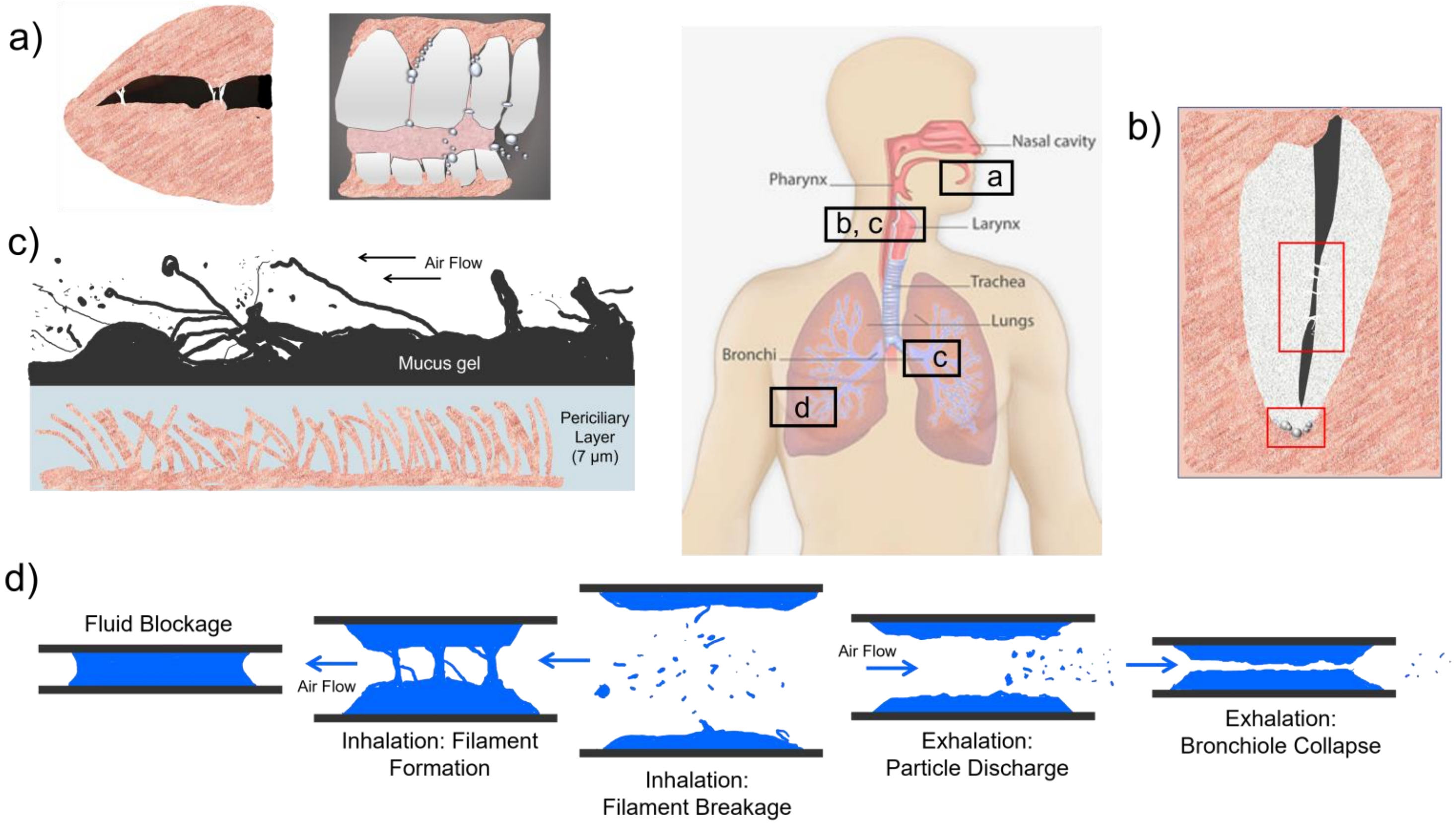


Particle generation

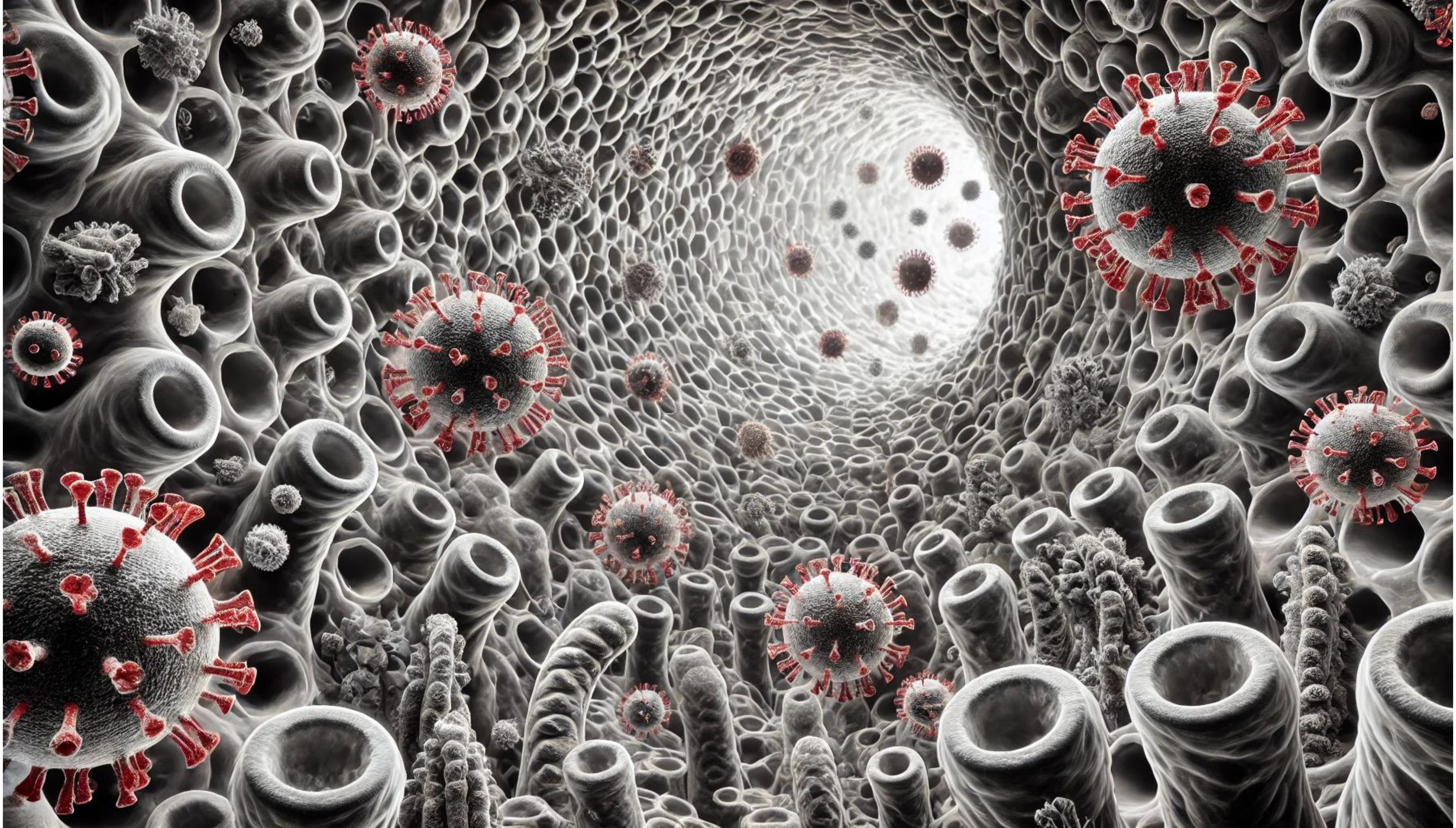
There are two known physical mechanisms to generate the particles emitted from the human respiratory tract: turbulent aerosolization, and the breakage or burst of a fluid film, filament or bubble (FFBB).

Turbulent aerosolization is referred to as atomization in fluid mechanics literature and is characterized by turbulent flows stripping particles from a fluid film.

The FFBB process generates particles during normal breathing due to clearance of fluid closures in respiratory bronchioles, and during speaking when vocal cords adduct and vibrate in the larynx and when lips open and the tongue separates from the teeth in the mouth.



Morawska, L., Buonanno, G., Mikszewski, A. et al. The physics of respiratory particle generation, fate in the air, and inhalation. Nat Rev Phys 4, 723–734 (2022). https://doi.org/10.1038/s42254-022-00506-7



In both turbulent aerosolization and FFBB, particles originate from the airway's surface liquid film, which is a bilayer with the top layer a mucus gel consisting of water (97%) and a mixture of mucins, non-mucin proteins, salts and cellular debris (3%), and the bottom, low-viscosity periciliary layer containing the cilia.

Turbulent aerosolization in the conventional sense is thought to be most active in large bronchi and the larynx owing to airflows that are partly turbulent even during breathing and with increasing velocity during speaking and coughing owing to partially adducted vocal folds.

In the deepest small airway bronchioles, FFBB is the dominant mechanism for particle generation.

It is unlikely that the diameter of generated particles will exceed the thickness of its parent fluid film.

The airway epithelial thickness is greatest, of the order of hundreds of micrometres, in the oral cavity where it also includes an overlying salivary layer.

This thickness decreases on moving deeper into the respiratory tract.

Particle quantities and composition

Particles derived from the film of airway lining fluid contain components of the film itself, such as the aforementioned non-volatile material including mucins, non-mucin proteins, salts and cellular debris.

Adding to the complexity of the composition, the particle mixture also contains saliva, nasal secretions, serum and blood from oral lesions, and even food debris and may contain pathogens such as bacteria, viruses and fungi.

In total, the typical mass or volume proportion of non-water content in a particle generated in the respiratory tract is 1–10%.

Measurements have indicated there are of the order of 10^5 particles of 2–4 µm and 10^7 particles of 0.2–0.4 µm for a single average cough.

With respect to the SARS-CoV-2 virus, when considering that viral loads in respiratory fluids can exceed 10^9 RNA copies per millilitre in certain infected individuals, a single cough can potentially generate thousands of 3-µm particles containing a virion that would be emitted into ambient air.

In the field of aerosol science, the convergence towards developing an understanding of the initial instant of emission of respiratory particles has been long and has not yielded definitive answers, mainly owing to the complexity of physical processes such as evaporation and the difficulty of measuring the particle emission in situ.

In addition, different techniques are used to measure somewhat different parameters, often making comparisons of the outcomes difficult.

Furthermore, when considering airborne disease transmission, the interaction of the respiratory particles with the airflow is a crucial issue, which makes the process more complex.

Measurement techniques

The exhaled airflow measurement techniques can be divided into two categories: global flow-field measurements (high-speed photography, schlieren photography and PIV), and pointwise measurements.

The global flow-field measurement techniques provide information on the whole flow field and help us to understand the interactions between the exhaled flow, the thermal plume and the room airflow.

The pointwise measurements are instead used to measure the initial temperature, initial humidity and velocity.

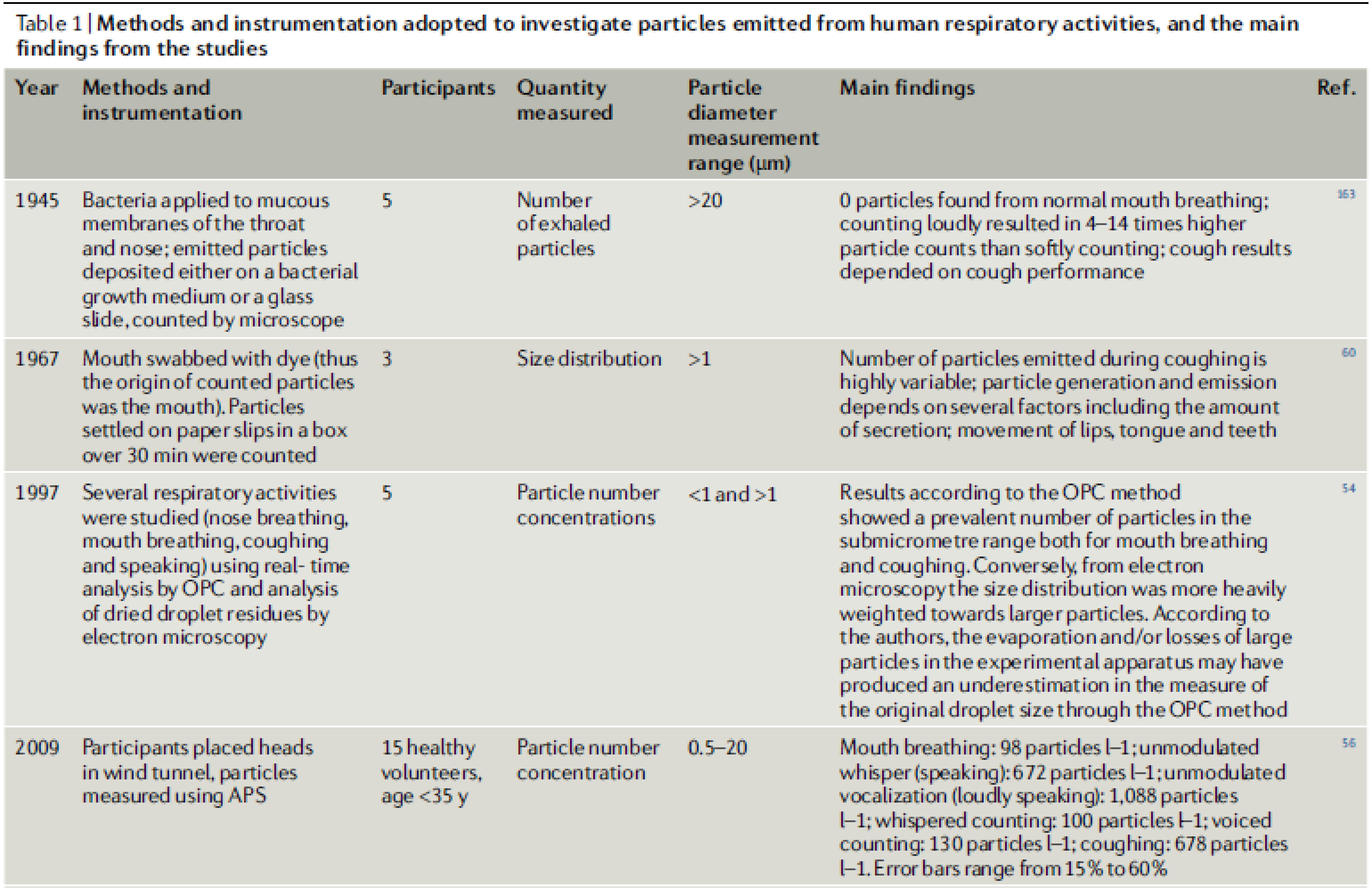


Table 1 | **Methods and instrumentation adopted to investigate particles emitted from human respiratory activities, and the main findings from the studies**

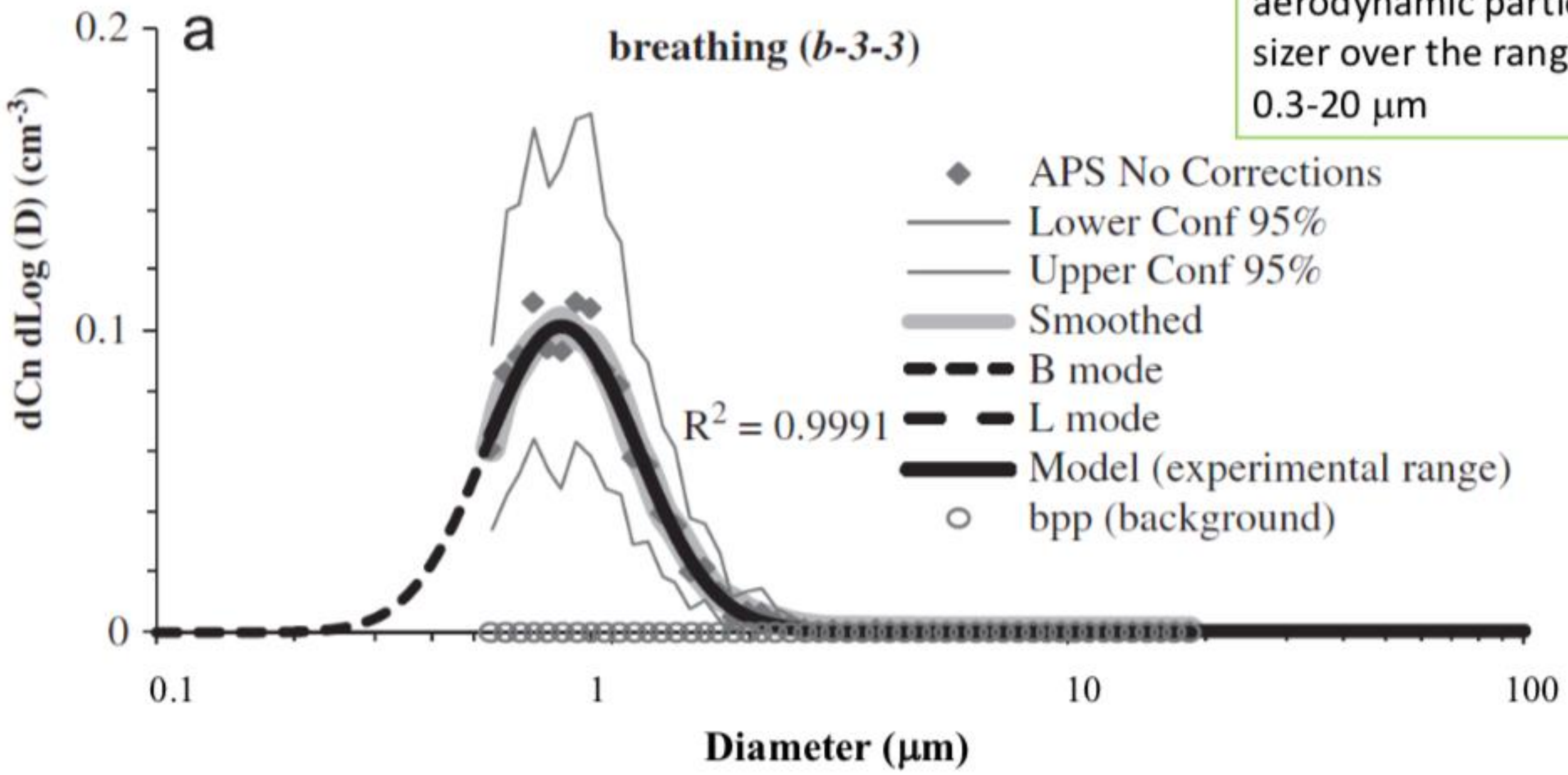
Year	Methods and instrumentation	Participants	Quantity measured	Particle diameter measurement range (µm)	Main findings	Ref.
1945	Bacteria applied to mucous membranes of the throat and nose; emitted particles deposited either on a bacterial growth medium or a glass slide, counted by microscope	5	Number of exhaled particles	>20	0 particles found from normal mouth breathing; counting loudly resulted in 4–14 times higher particle counts than softly counting; cough results depended on cough performance	163
1967	Mouth swabbed with dye (thus the origin of counted particles was the mouth). Particles settled on paper slips in a box over 30 min were counted	3	Size distribution	>1	Number of particles emitted during coughing is highly variable; particle generation and emission depends on several factors including the amount of secretion; movement of lips, tongue and teeth	60
1997	Several respiratory activities were studied (nose breathing, mouth breathing, coughing and speaking) using real- time analysis by OPC and analysis of dried droplet residues by electron microscopy	5	Particle number concentrations	<1 and >1	Results according to the OPC method showed a prevalent number of particles in the submicrometre range both for mouth breathing and coughing. Conversely, from electron microscopy the size distribution was more heavily weighted towards larger particles. According to the authors, the evaporation and/or losses of large particles in the experimental apparatus may have produced an underestimation in the measure of the original droplet size through the OPC method	54
2009	Participants placed heads in wind tunnel, particles measured using APS	15 healthy volunteers, age <35 y	Particle number concentration	0.5–20	Mouth breathing: 98 particles l−1; unmodulated whisper (speaking): 672 particles l−1; unmodulated vocalization (loudly speaking): 1,088 particles l−1; whispered counting: 100 particles l−1; voiced counting: 130 particles l−1; coughing: 678 particles l−1. Error bars range from 15% to 60%	56

2009	Particle size measured with IMI; air velocity measured by PIV close to mouth during coughing and speaking (loudly counting)	11 healthy volunteers, age <30 y	Particle size; air velocity	>1	Measurement of wide size range (2–2,000 μm) with the same measuring system near the point of emission, when the effect of evaporation/condensation was still negligible. Size measurements at 10 mm from the mouth negligibly influenced by evaporation and condensation and can be considered as representative of the 'original' emitted size profile	58
2009	Number and size of respiratory droplets produced from the mouth of healthy individuals during talking and coughing, with and without a food dye, were measured using glass slides and a microscope, and an aerosol spectrometer	25 healthy volunteers	Size distribution and particle number concentration	>1	Mean size of droplets captured using glass slides and microscope was ~50–100 μm	164
2011	Results from APS and DDA were integrated into a single composite size distribution	15 healthy volunteers, age <35 y	Size distribution	0.7–1,000	The most prominent modes in particle number distribution were identified and linked to distinct sites of origin and mechanisms of generation: one deep in the lower respiratory tract, another in the region of the larynx and a third in the upper respiratory tract including oral cavity	5
2012	Laser diffraction system; participants asked to give best effort to reproduce a 'real cough'	45 healthy non-smokers	Size distribution and particle number concentration	0.5–20	Emitted particles 0.1–900 μm. 97% of total number of measured particles had diameter <1 μm. The particle number distribution was not statistically influenced by age, gender, weight, height or corporal mass	21
2019	Emission measured using APS during speaking and breathing	48 healthy volunteers	Rate of particle emission	0.5–20	The rate of particle emission during normal human speech is positively correlated with the loudness (amplitude) of vocalization	44
2020	Real-time visualization of particle emissions speech was conducted with laser light scattering method	–	Airborne lifetime	–	At least 1,000 droplet nuclei that remain airborne for >8 min were estimated for 1 min of loud speaking	17

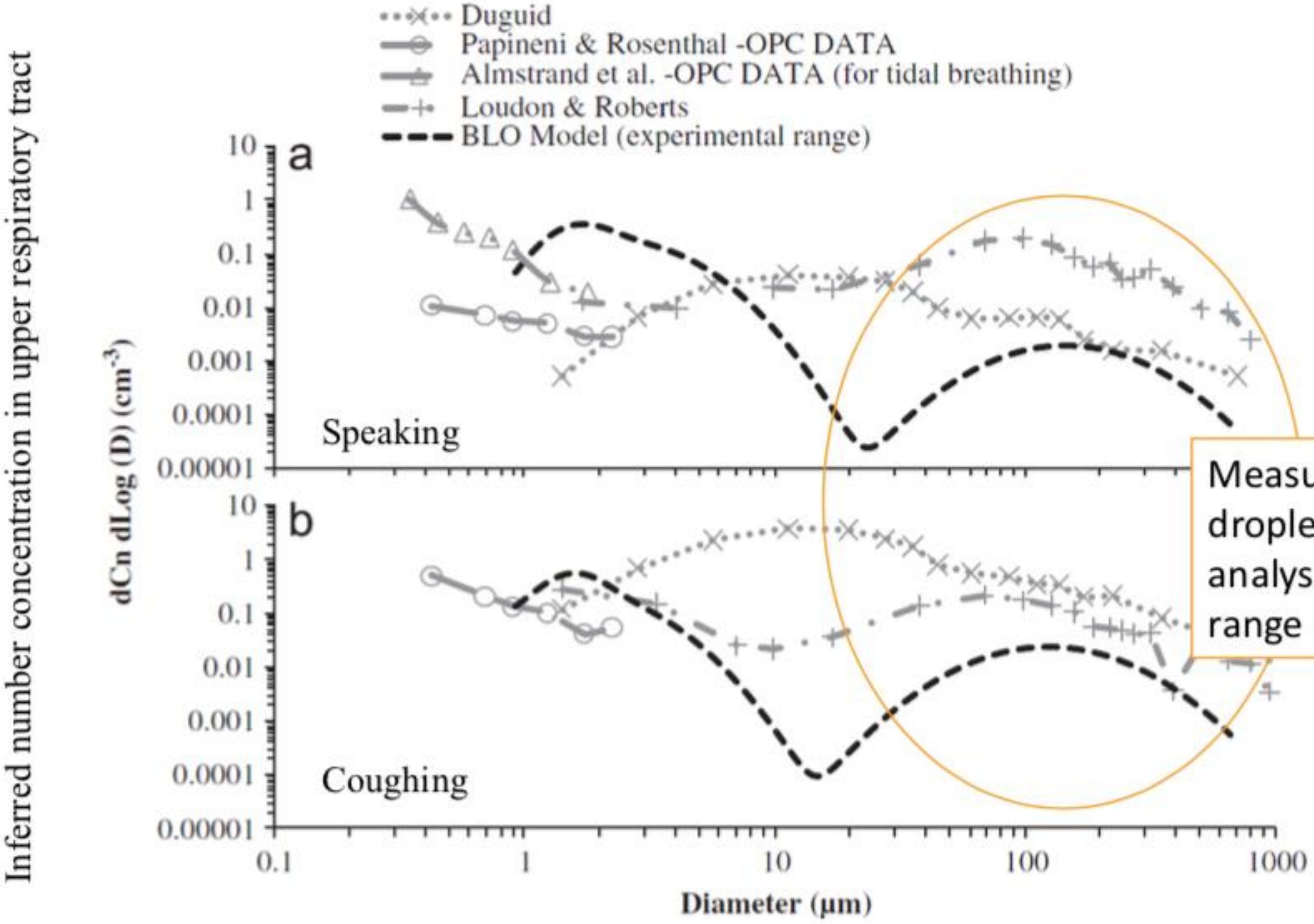
APS, aerodynamic particle sizer; DDA, droplet deposition analysis; IMI, interferometric Mie imaging; OPC, optical particle counter; PIV, particle image velocimetry.

Size Distributions: Breathing

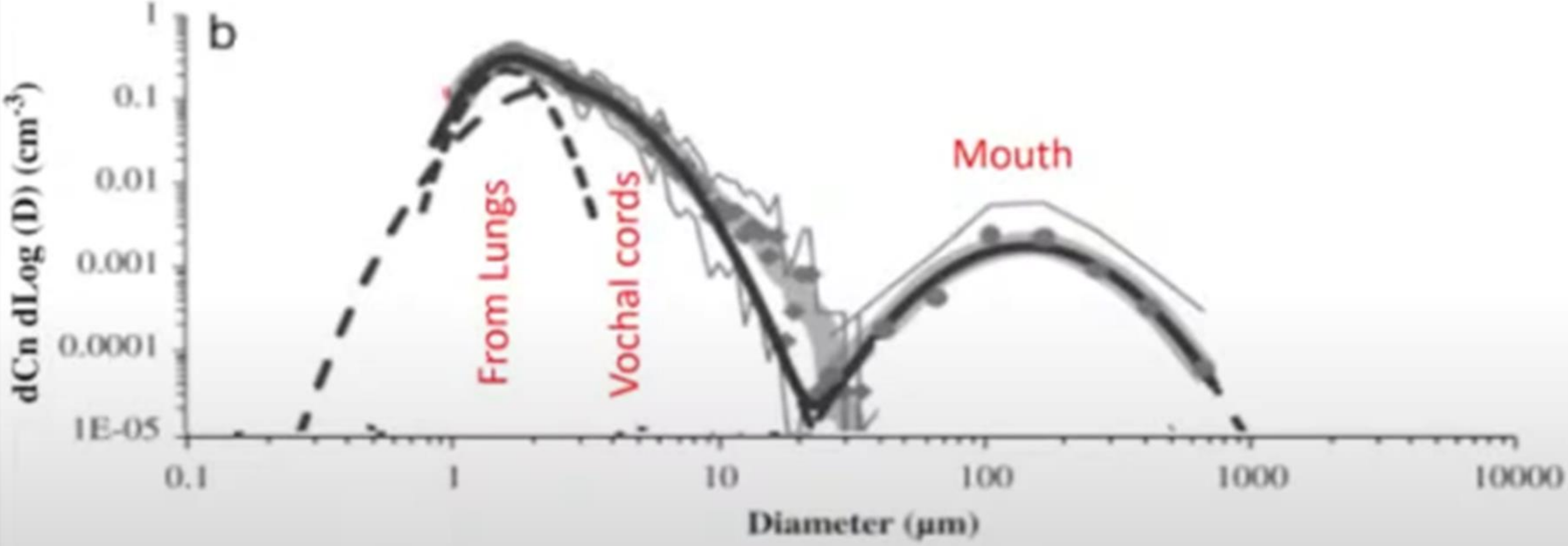
Measured by aerodynamic particle sizer over the range 0.3-20 μm

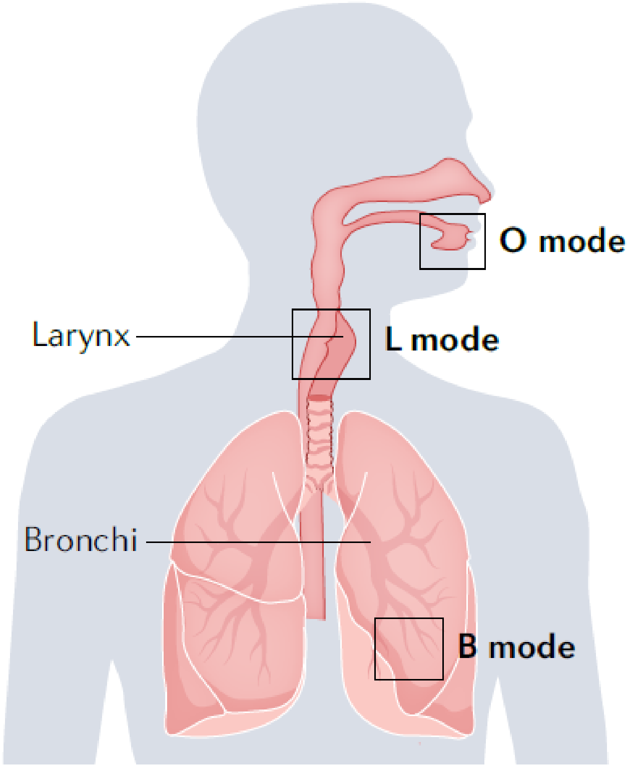


Corrected Size Distributions



Measured by droplet deposition analysis over the range 20-2000 μm


b
dCn dLog (D) (cm^{-3})
1
0.1
0.01
0.001
0.0001
1E-05
From Lungs
Vochal cords
Mouth
0.1
1
10
100
1000
10000
Diameter (µm)


O mode
Larynx
L mode
Bronchi
B mode

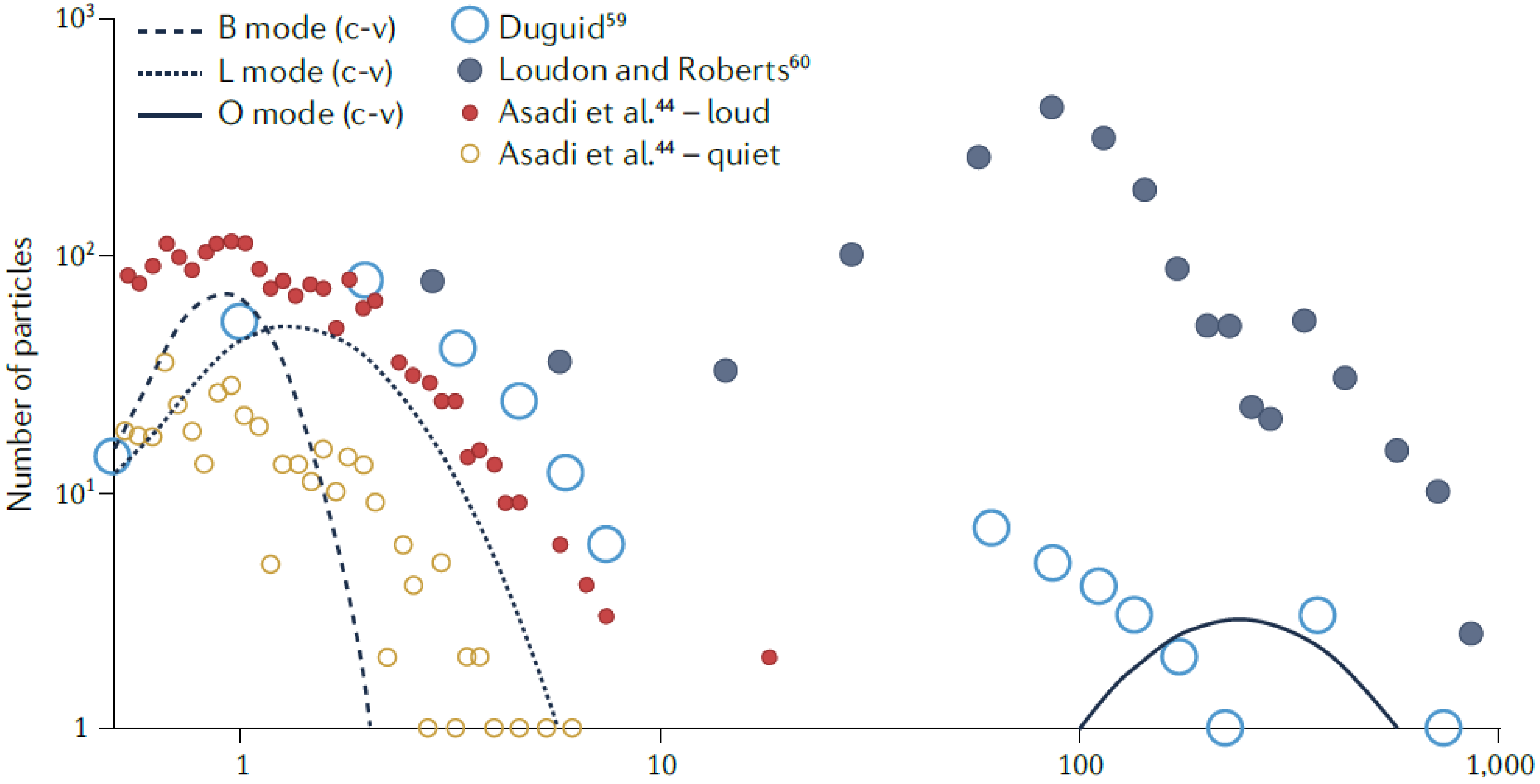
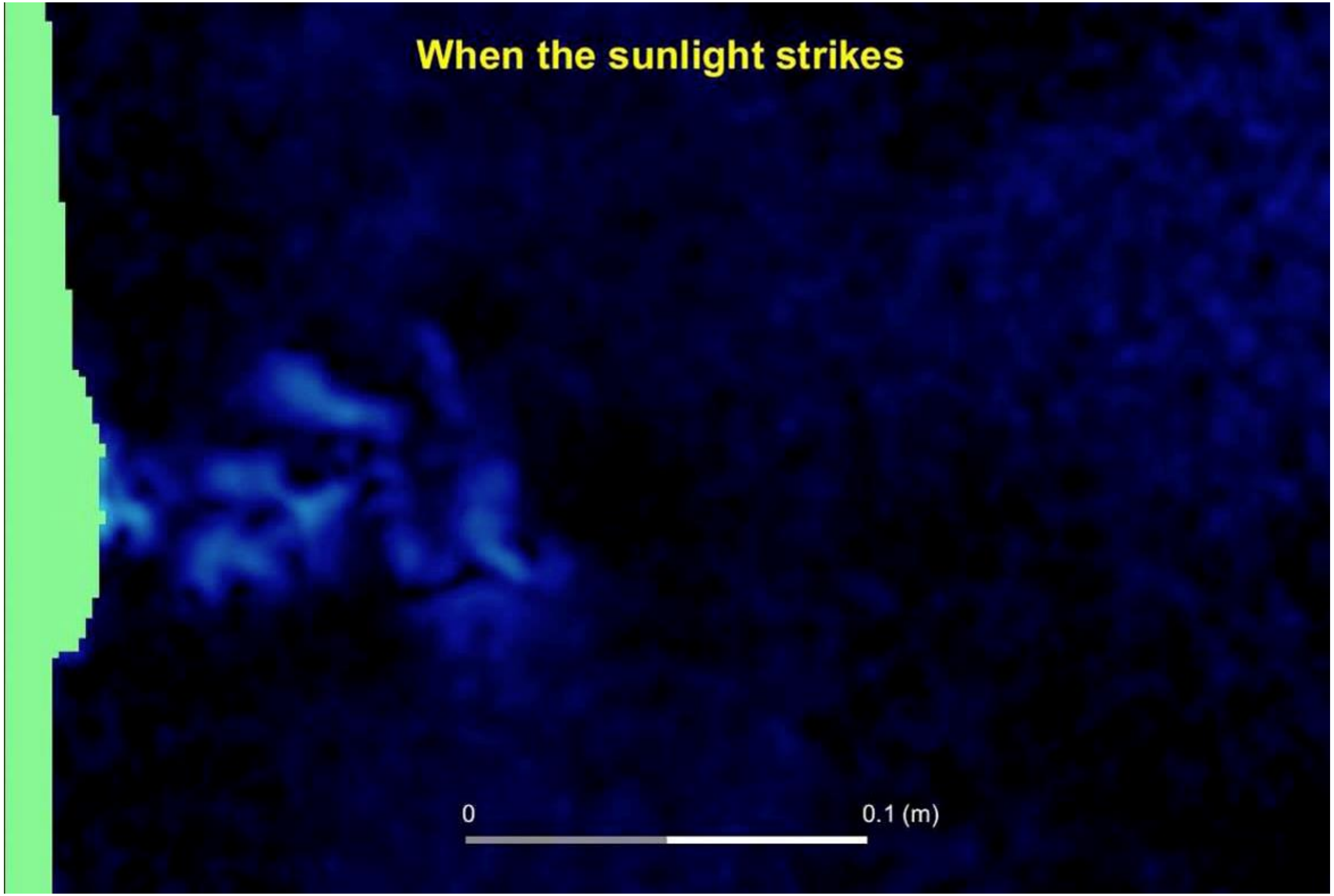
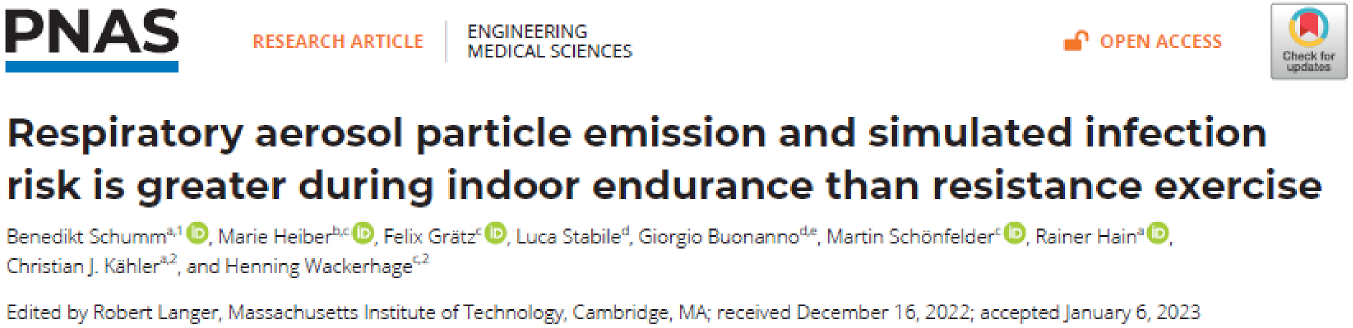

10^3
10^2
10^1
1
Number of particles
1
10
100
1,000
B mode (c-v)
L mode (c-v)
O mode (c-v)
Duguid[59]
Loudon and Roberts[60]
Asadi et al.[44] – loud
Asadi et al.[44] – quiet

Table S1. The methodology and instrumentation adopted to investigate airflow from human respiratory activities and the main findings from the studies.

	Methodology and instrumentation	Main findings
Savory et al. (2014)	Particle image velocimetry, an experimental cough chamber facility has been developed to study the far-field aerodynamics and aerosol transport of particles produced by the coughs from 12 humans naturally-infected with influenza	The spatially averaged maximum velocity was determined and the average value was 0.41 m s^{-1} across 27 coughs of good data quality.
Kwon et al. (2012)	To analyze the initial velocity and the angle of the exhaled airflow from coughing and speaking of 17 males and 9 females using Particle Image Velocimetry (PIV) and acrylic indoor chamber.	The average initial coughing velocity was 15.3 (10.6) m s^{-1} for the males (females), while for speaking it was 4.07 (2.31) m/s, respectively. The angle of the exhaled air from coughing was around 38° (32°) for the males (females), while from speaking it was around 49° and 78° respectively.
VanSciver et al. (2011)	The velocity field of human cough was measured using particle image velocimetry (PIV). 29 subjects coughed into an enclosure seeded with stage	Maximum cough velocities ranged from 1.5 m s^{-1} to 28.8 m s^{-1}. The average width of all coughs ranged between 35 to 45 mm.


When the sunlight strikes
0
0.1 (m)

Cortellessa et al. (2021)	Particle image velocimetry (PIV) technique was employed for the determination of speak velocity for a "face-to-face" interaction. Speaking activity was recorded for the duration of 50 s (500 images).	Peak velocities ranged from 1.5 m s^{-1} to 5 m s^{-1}.
Zhu et al. (2006)	The transport characteristics of saliva droplets produced by 3 subjects coughing are examined through PIV in a calm indoor environment	More than 6.7 mg of saliva is expelled and travel further than 2 m at speeds of up to 22 m s^{-1} during each individual cough
Bourouiba et al. (2014)	A visualization of the real human coughs and sneezes is presented through an experimental set-up using high-speed cameras.	The turbulent multiphase cloud plays a critical role in extending the range of the majority respiratory particles that can remain suspended long enough to reach heights where ventilation systems can be contaminated (4-6 m).
Gupta et al. (2009) Gupta et al. (2010)	A spirometer based on Fleish type pneumotachograph was used to measure the flow rates generated over time with a frequency of 330 Hz. The flow directions were visualized through moderate-speed photography (120 Hz) with 1 Mega Pixel resolution.	The flow rate, flow direction, and mouth opening area were measured for 25 human subjects during breathing, coughing and speaking.
Xu et al. (2017)	Airflow dynamics of human exhalation were obtained through nonhazardous schlieren photography technique. The visualization and quantification of turbulent exhaled airflow was estimated from 18 healthy human subjects whilst standing and lying.	The mean peak centerline velocity was found to decay with increasing horizontal distance and the mean propagation velocity was found to correlate with physiological parameters of human subjects.
Tang et al. (2009)	Video records are obtained of human volunteers coughing with and without wearing standard surgical and N95 masks through the schlieren optical method	Wearing a surgical or N95 mask blocks the formation of the jet (N95 mask) or redirect it in a less harmful direction (surgical mask) during human coughing.



PNAS RESEARCH ARTICLE | ENGINEERING MEDICAL SCIENCES OPEN ACCESS

Respiratory aerosol particle emission and simulated infection risk is greater during indoor endurance than resistance exercise

Benedikt Schumm[a,1], Marie Heiber[b,c], Felix Grätz[c], Luca Stabile[d], Giorgio Buonanno[d,e], Martin Schönfelder[c], Rainer Hain[a], Christian J. Kähler[a,2], and Henning Wackerhage[c,2]

Edited by Robert Langer, Massachusetts Institute of Technology, Cambridge, MA; received December 16, 2022; accepted January 6, 2023

Intensive endurance exercise can increase respiratory particle emission by over 100-fold and there is evidence that SARS-CoV-2 has spread during indoor group exercise.

Many exercisers do resistance exercise (i.e. weightlifting) in gyms and data on respiratory particle emission during resistance exercise and for "real life" endurance or resistance training sessions do not exist.

To fill this knowledge gap, we measured respiratory particle emission during resistance exercise and "real life" exercise sessions.

We used measured respiratory particle emission data to calculate the infection risk for a "real life" spinning class (i.e. cycle ergometer exercise)

We conducted an observational, monocentric human cohort study with the main aim to continuously measure respiratory ventilation, the concentration of aerosol particles in the expired air and aerosol particle emission at rest and during a realistic spinning class and a realistic resistance exercise with three exercises, each with three sets at 80% of the maximal voluntary contraction.

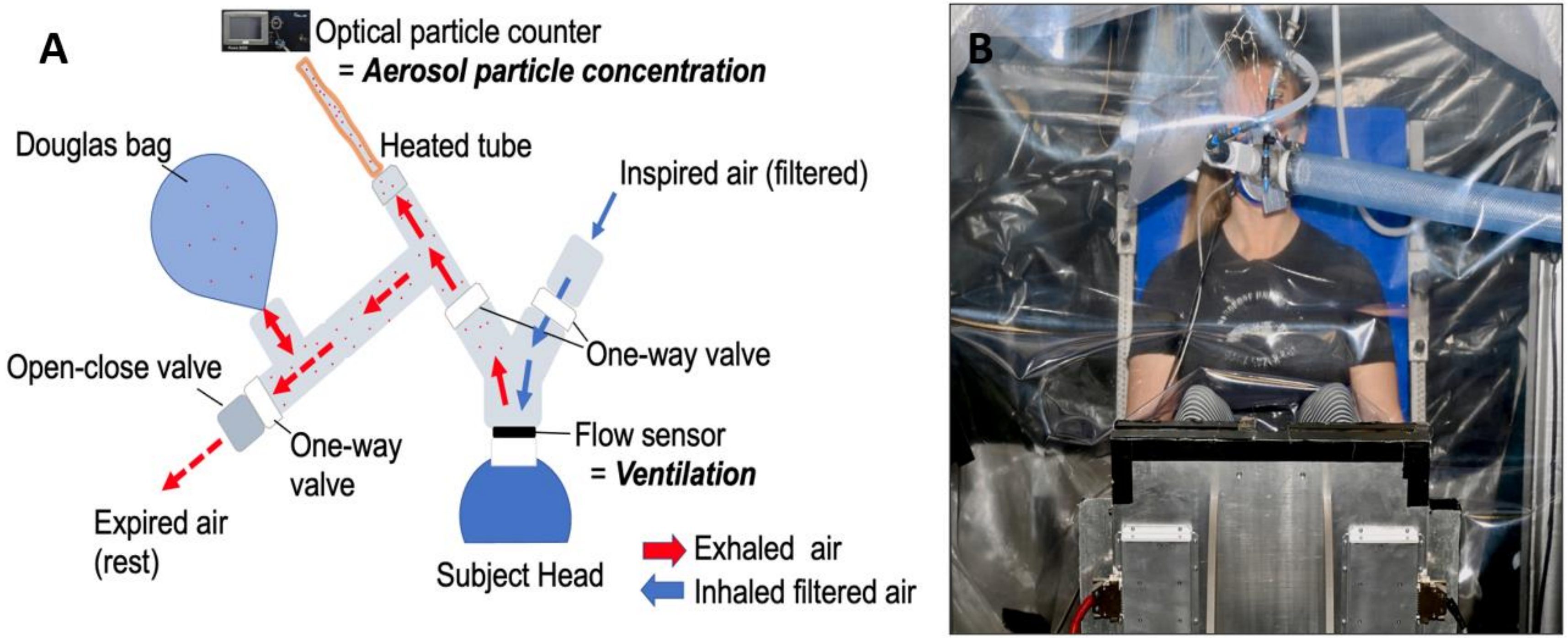


Figure 1 Experimental set up. **A** Detailed image of the aerosol particle and ventilation measurement system – including flow sensor, mask and the tubes leading to the optical particle counter (Palas Promo 3000). **B** Photo of a subject with spiroergometry mask, during a set of resistance exercise in clean air space.

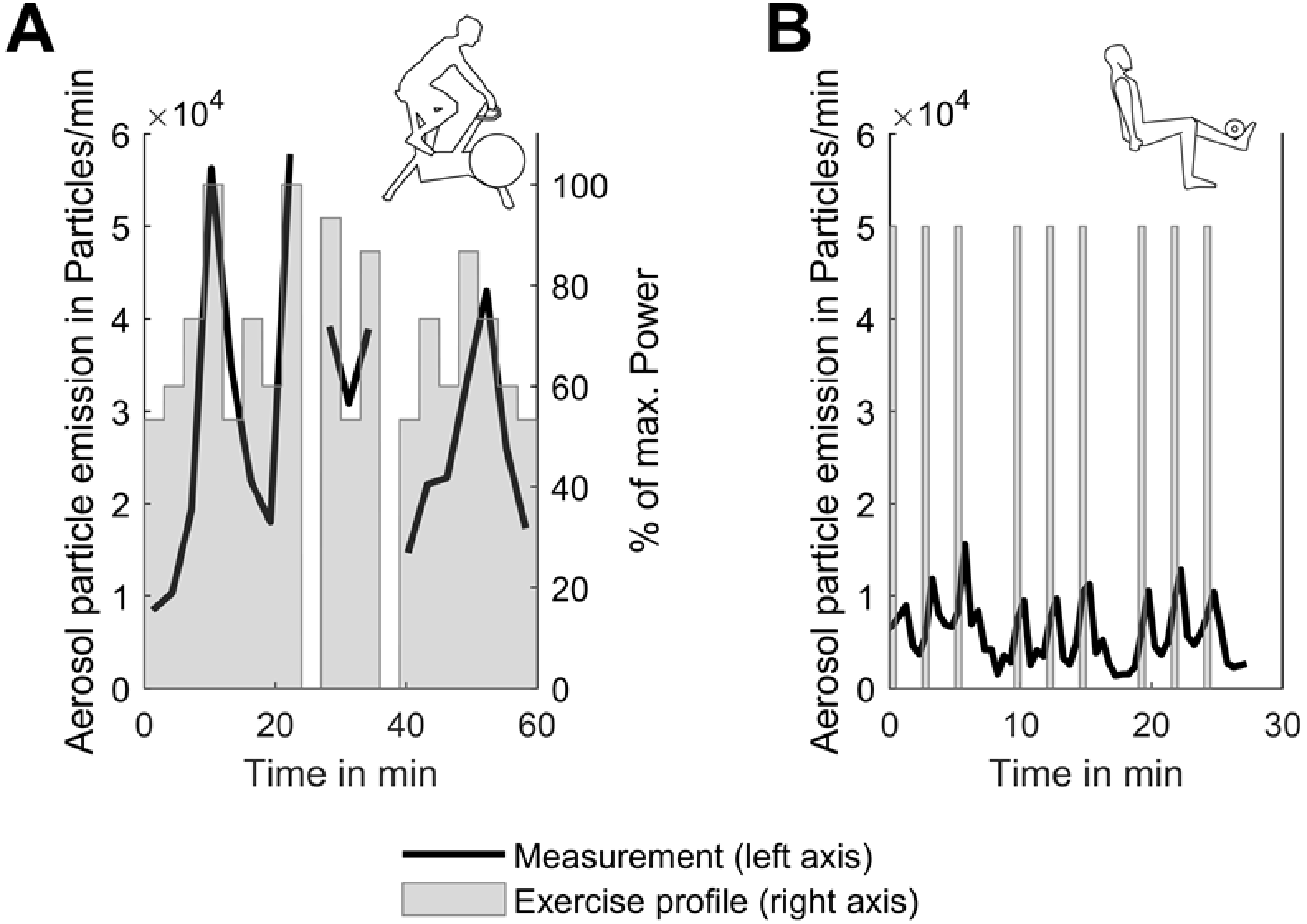


Figure 3: Mean aerosol particle emission during **A** the spinning class and **B** the resistance exercise (note that the Y-axis for aerosol particle emission is identical). The intensity profile for the spinning class is shaded in the background. For the resistance exercise the sets 1 – 3 were leg extensions, 4 – 6 biceps curls and 7 – 9 overhead presses. Note the different time scales between **A** and **B**.

We found that during a set of isokinetic resistance exercise the increase in aerosol particle emission is 1.3-fold lower compared to the value at maximal exercise in an endurance graded exercise test.

Comparing "real life" exercises the difference is even bigger with 4.9-fold higher aerosol particle emissions during the endurance spinning session compared to a resistance exercise.

This is mainly due to 2.7-fold lower ventilation rates and different training intervals.

Maximum aerosol particle concentration values measured are 2-fold higher during resistance exercise, when comparing isokinetic resistance exercise to the values at maximum intensity at the graded exercise test, but when comparing the "real life" exercises, aerosol particle concentrations during endurance exercise are 1.9-fold higher.

Even though exercise seems to impose a higher risk of getting infected, exercise holds many health benefits and should not simply be avoided. Thus, during periods with many consequential infections, the first focus should be to, for example, limit the number of people in endurance exercise classes, increase the air exchange rate of the facility or to perform high intensity workouts such as training outdoors.

Respiratory particle emission rates from children during speaking

Elisa Caracci[1], Luca Stabile[1*], Andrea R. Ferro[2], Lidia Morawska[3] & Giorgio Buonanno[1,3]

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[2]Department of Civil and Environmental Engineering, Clarkson University, Potsdam, NY, USA.

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Aims of the study

More than 400 children attending primary and secondary schools (aged 6 to 12) were involved in an experimental study aimed at providing emission rates of respiratory particles while speaking at two different intensity levels—"speaking" and "loudly speaking". To this purpose experimental apparatus and testing protocol were optimized and, indeed, respiratory particle emission rates were obtained by directly measuring respiratory particle concentration and exhaled flow rate while subjects pronounced a phonetically balanced word list.

The findings of this study are of great significance as they could be applied to existing models to provide predictive estimates of the risk of infection in indoor environments and/or in close-proximity configurations.

Materials and methods

Human subjects

371 measurements/children were considered valid for data post-processing children attending primary and secondary schools (aged 6 to 12) in Cassino (FR), Central Italy (in accordance with relevant guidelines and regulations of the ethical committee).

Entire population		371
Gender	Male	49.9 %
	Female	50.1 %
Age (yrs)	6	11.1 %
	7	11.3 %
	8	14.8 %
	9	10.2 %
	10	9.4%
	11	27.5 %
	12	15.6 %

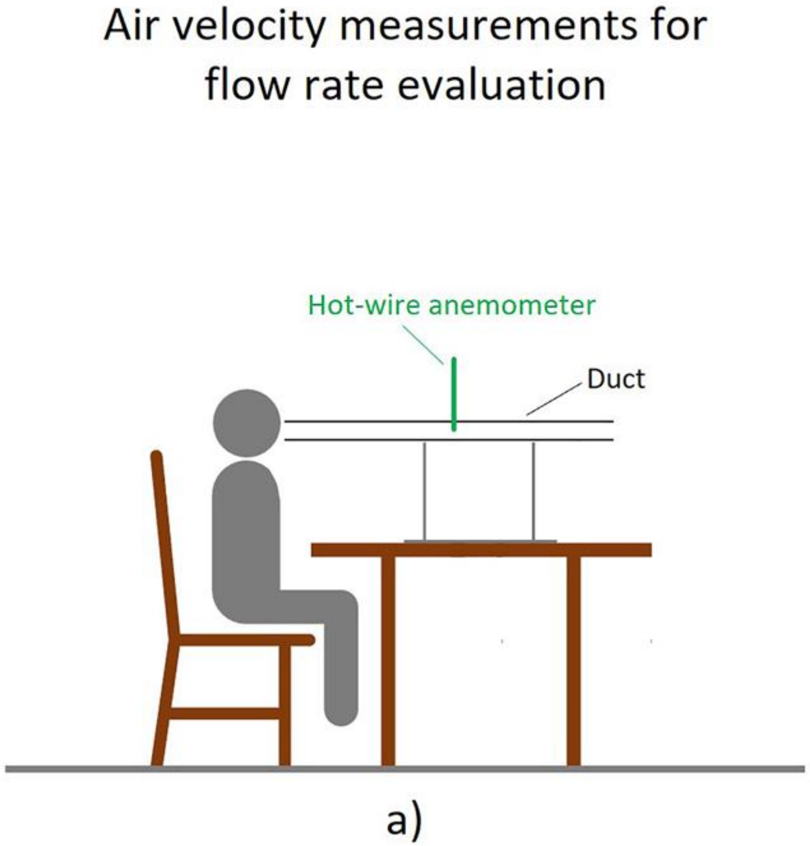
Children read the phonetically balanced word list at "speaking" and "loudly speaking" levels:

PAPA'
BABBO
TETTO
DADO
COCCO
LAGO

CICCIO
GIGI
MAMMA
NONNA
FIFA
VIVA…

Materials and methods

Evaluation of the exhaled air flow rate (test a)

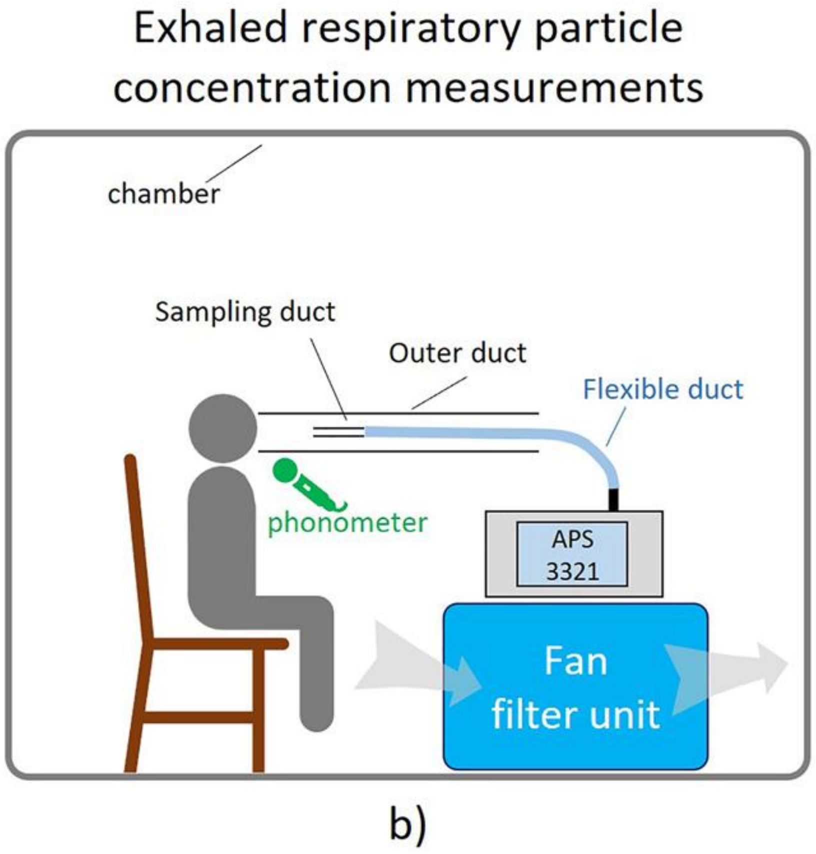


- Measurement of exhaled air velocity (at a distance of 40 cm from the inlet) with a Testo 450i Smart Probe hot-wire anemometer (measurement range 0–30 m s^{-1}; resolution 0.01 m s^{-1};

- Duct characteristics: diameter 0.045 m; lenght 1 m;
- The children were asked to read the word list twice consecutively at their normal intensity level (referred to as "speaking") and twice at a higher intensity level (referred to as "loudly speaking").

Materials and methods

Measurement of the respiratory particle concentration (test b): *experimental set-up*



- The respiratory particle concentration exhaled by children while speaking (test b) was measured by an aerodynamic particle sizer spectrometer (APS 3321, TSI Inc.);

- A fan filter unit (FFU) to reduce the background particle concentration level HEPA H14 filter plus an F7 pre-filtration stage and characterized by an adjustable flow rate (up to 850 $m^3\ h^{-1}$);

- Phonometer Delta Ohm Class 1 HD2110 (Geass; declared uncertainty < 0.7 dB) to record the voice intensity level during the tests.

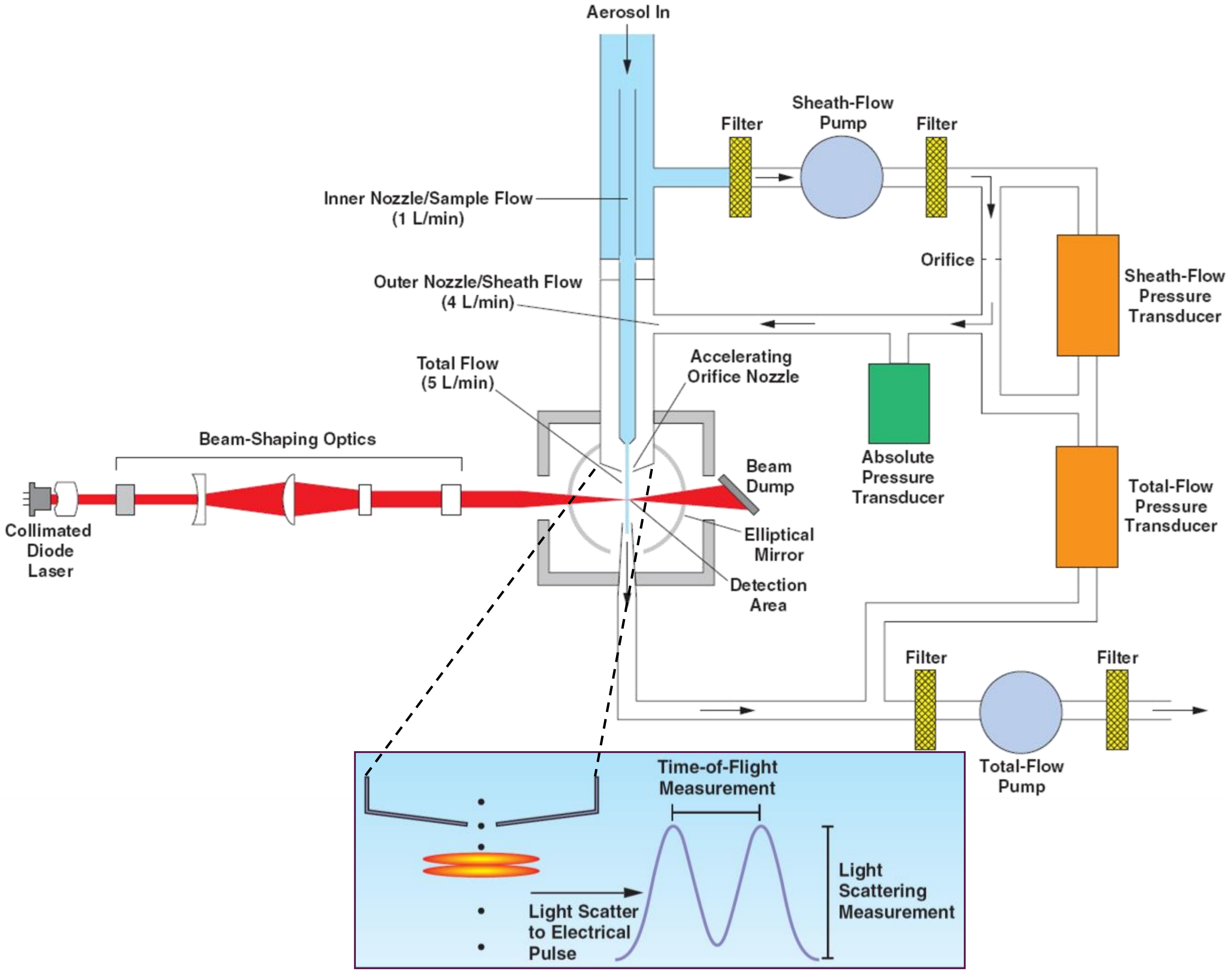
Materials and methods

Measurement of the respiratory particle concentration (test b): *experimental set-up*

Aerodynamic Particle Sizer – APS 3321 TSI

Measurement range: 0.5 – 20 µm
Principle of measurement: time-of-flight

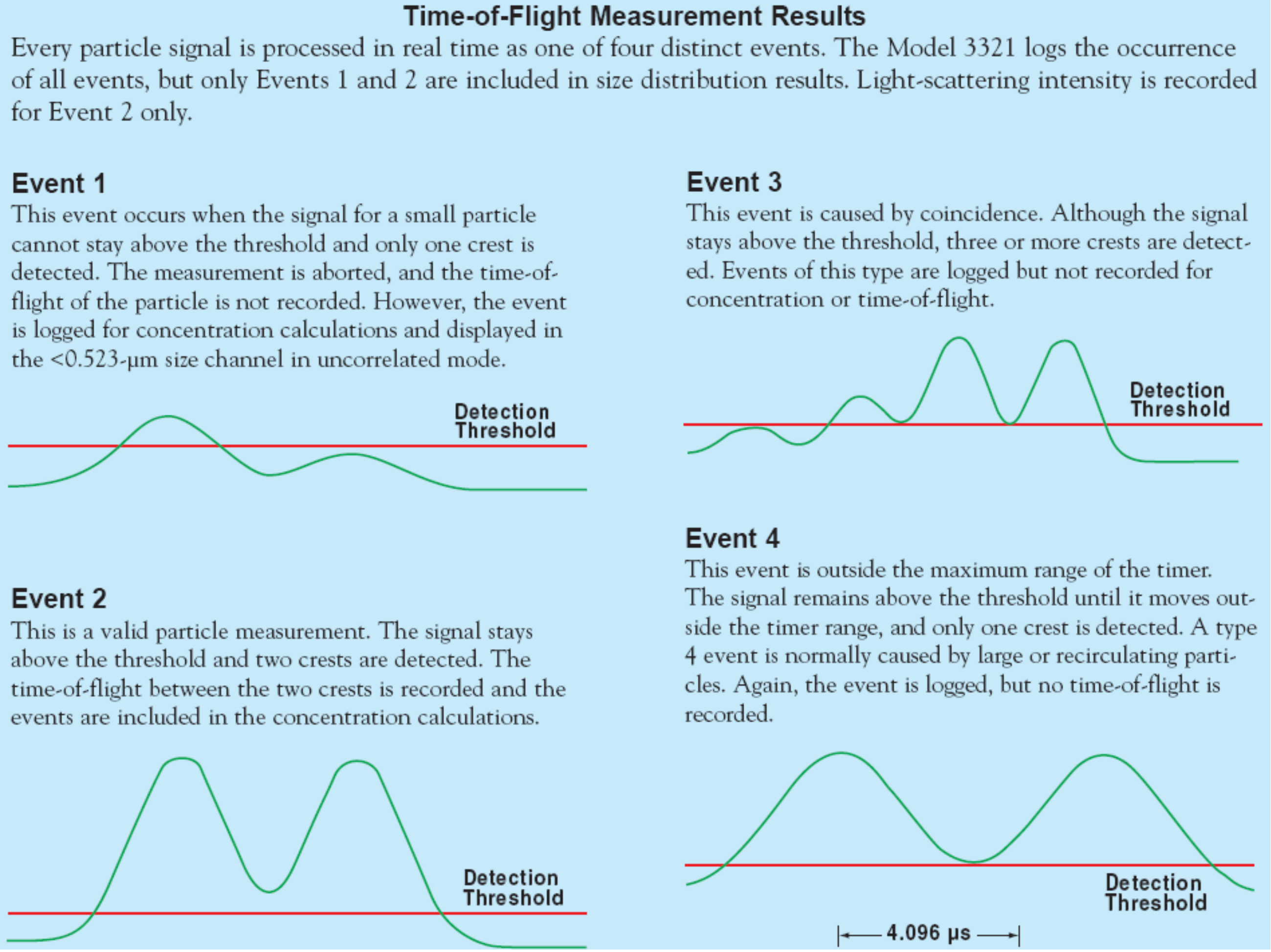
Particle size measurement is performed according to the time-of-flight (TOF) technique by which the acceleration of the particle is measured following an acceleration imposed on the sampled aerosol.



Materials and methods

Measurement of the respiratory particle concentration (test b): *experimental set-up*

Aerodynamic Particle Sizer – APS 3321 TSI



Time-of-Flight Measurement Results

Every particle signal is processed in real time as one of four distinct events. The Model 3321 logs the occurrence of all events, but only Events 1 and 2 are included in size distribution results. Light-scattering intensity is recorded for Event 2 only.

Event 1

This event occurs when the signal for a small particle cannot stay above the threshold and only one crest is detected. The measurement is aborted, and the time-of-flight of the particle is not recorded. However, the event is logged for concentration calculations and displayed in the <0.523-µm size channel in uncorrelated mode.

Event 2

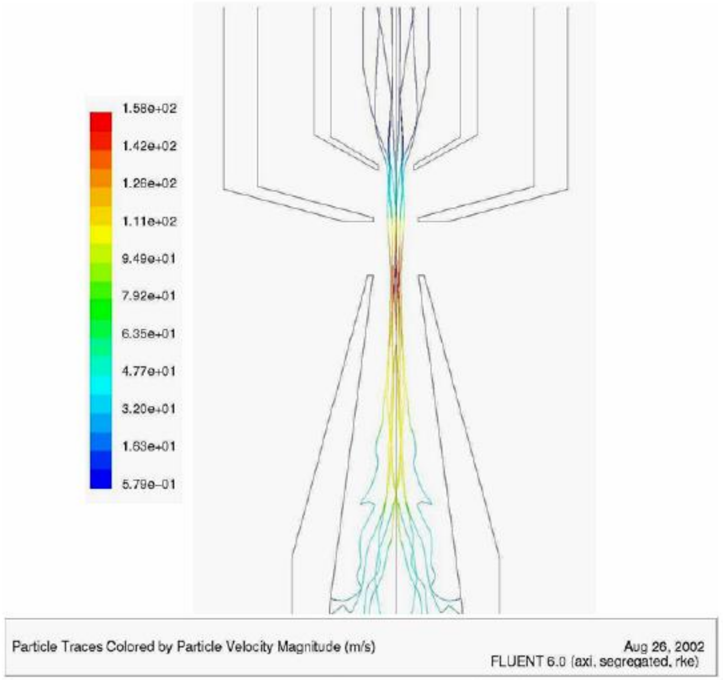
This is a valid particle measurement. The signal stays above the threshold and two crests are detected. The time-of-flight between the two crests is recorded and the events are included in the concentration calculations.

Event 3

This event is caused by coincidence. Although the signal stays above the threshold, three or more crests are detected. Events of this type are logged but not recorded for concentration or time-of-flight.

Event 4

This event is outside the maximum range of the timer. The signal remains above the threshold until it moves outside the timer range, and only one crest is detected. A type 4 event is normally caused by large or recirculating particles. Again, the event is logged, but no time-of-flight is recorded.



Particle Traces Colored by Particle Velocity Magnitude (m/s)

Aug 26, 2002
FLUENT 6.0 (axi, segregated, rke)

Figure 4: Flow recirculation is restricted in Model 3320 APS with a redesigned eduction nozzle[6] that is identical to the nozzle in Model 3321.

Materials and methods

Measurement of the respiratory particle concentration (test b): *testing procedure*

(i) the FFU was run at the maximum flow rate for 3 min to reduce the airborne particle background concentration in the chamber;

(ii) the FFU was switched off and a 30-s background concentration measurement (with a 1-s sampling frequency) was carried out;

(iii) particle concentrations and distributions were measured with a 1-s sampling frequency while the child being tested read the word list twice consecutively at his/her normal intensity level (speaking);

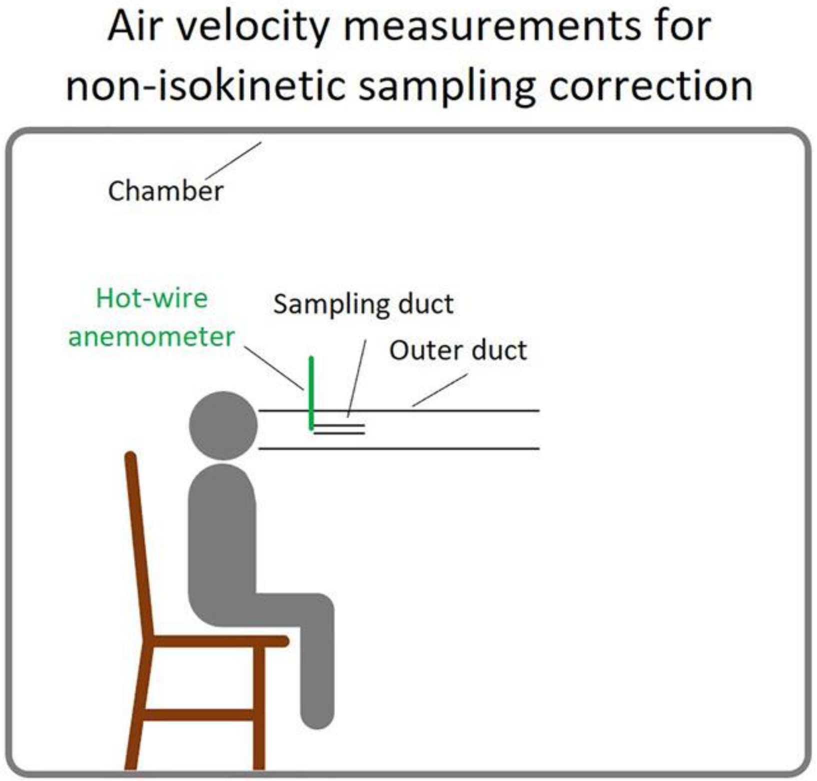
(iv) the FFU was run at the maximum flow rate for 3 min to reduce the airborne particle background concentration in the chamber;

(v) the FFU was switched off and a 30-s background concentration measurement (with a 1-s sampling frequency) was carried out;

(vi) particle concentrations and distributions were measured with a 1-s sampling frequency while the child read the word list twice at a higher intensity level (loudly speaking). The children were asked to speak and loudly speak with the same sound pressure level as during test a. The median duration of each air velocity (test a) and particle concentration/distribution measurement (test b), i.e. reading the word list twice consecutively, was 56 s (with corresponding 5th–95th percentile range of 44–143 s). Nonetheless, the length of the measurement is not expected affecting the results as both, air velocity and particle concentrations/distributions, are measured with a 1-s sampling frequency.

Materials and methods

Measurement of the respiratory particle concentration (test c): *corrections for non-isokinetic sampling and particle losses*



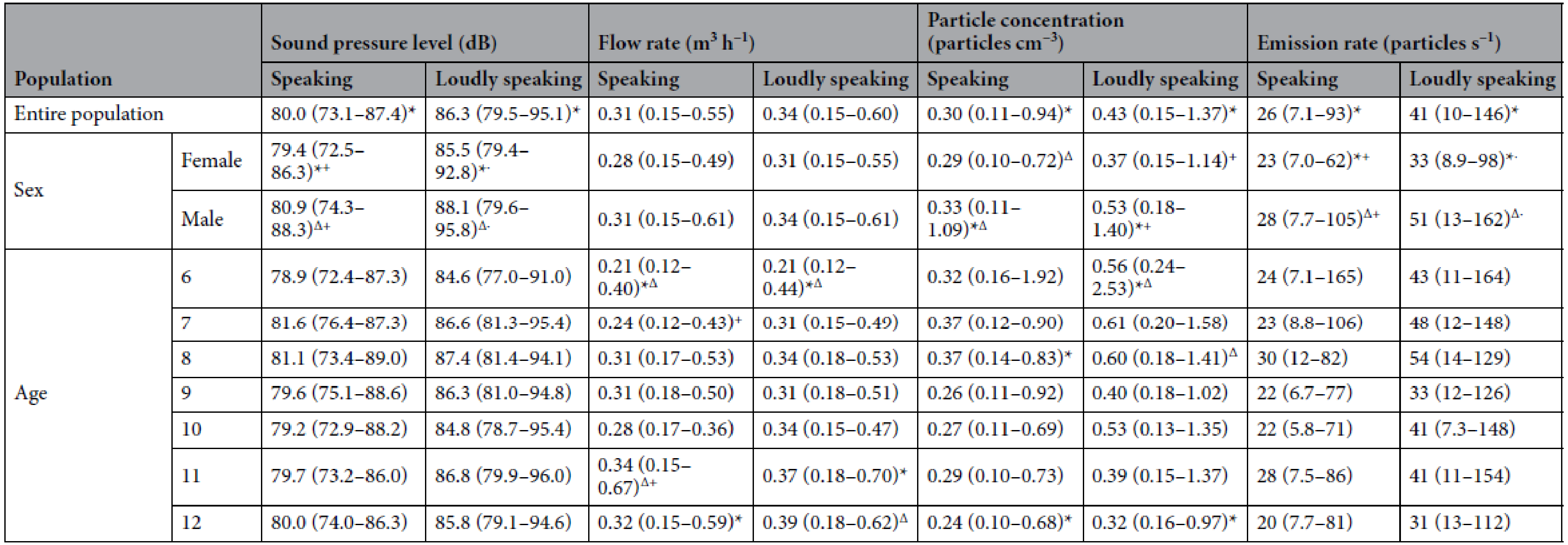
c)

- The air velocity while speaking can vary significantly amongst children, so **corrections for non-isokinetic sampling** need to be considered; the correction factor is a function of the difference between the actual speaking velocity and the sampling velocity and the Stokes number (ranging between **0.8 and 4.0%**);

- **Sampling particle losses** (diffusion, sedimentation, turbulent inertial deposition, inertial deposition due to bend and contraction) occurring in the entire sampling line were all **< 1%**.

Results and discussion

Air flow rate and sound pressure level



Population		Sound pressure level (dB)		Flow rate (m^3 h^{-1})		Particle concentration (particles cm^{-3})		Emission rate (particles s^{-1})	
		Speaking	Loudly speaking	Speaking	Loudly speaking	Speaking	Loudly speaking	Speaking	Loudly speaking
Entire population		80.0 (73.1–87.4)*	86.3 (79.5–95.1)*	0.31 (0.15–0.55)	0.34 (0.15–0.60)	0.30 (0.11–0.94)*	0.43 (0.15–1.37)*	26 (7.1–93)*	41 (10–146)*
Sex	Female	79.4 (72.5–86.3)$^{*+}$	85.5 (79.4–92.8)$^{*\cdot}$	0.28 (0.15–0.49)	0.31 (0.15–0.55)	0.29 (0.10–0.72)$^{\Delta}$	0.37 (0.15–1.14)$^{+}$	23 (7.0–62)$^{*+}$	33 (8.9–98)$^{*\cdot}$
	Male	80.9 (74.3–88.3)$^{\Delta+}$	88.1 (79.6–95.8)$^{\Delta\cdot}$	0.31 (0.15–0.61)	0.34 (0.15–0.61)	0.33 (0.11–1.09)$^{*\Delta}$	0.53 (0.18–1.40)$^{*+}$	28 (7.7–105)$^{\Delta+}$	51 (13–162)$^{\Delta\cdot}$
Age	6	78.9 (72.4–87.3)	84.6 (77.0–91.0)	0.21 (0.12–0.40)$^{*\Delta}$	0.21 (0.12–0.44)$^{*\Delta}$	0.32 (0.16–1.92)	0.56 (0.24–2.53)$^{*\Delta}$	24 (7.1–165)	43 (11–164)
	7	81.6 (76.4–87.3)	86.6 (81.3–95.4)	0.24 (0.12–0.43)$^{+}$	0.31 (0.15–0.49)	0.37 (0.12–0.90)	0.61 (0.20–1.58)	23 (8.8–106)	48 (12–148)
	8	81.1 (73.4–89.0)	87.4 (81.4–94.1)	0.31 (0.17–0.53)	0.34 (0.18–0.53)	0.37 (0.14–0.83)*	0.60 (0.18–1.41)$^{\Delta}$	30 (12–82)	54 (14–129)
	9	79.6 (75.1–88.6)	86.3 (81.0–94.8)	0.31 (0.18–0.50)	0.31 (0.18–0.51)	0.26 (0.11–0.92)	0.40 (0.18–1.02)	22 (6.7–77)	33 (12–126)
	10	79.2 (72.9–88.2)	84.8 (78.7–95.4)	0.28 (0.17–0.36)	0.34 (0.15–0.47)	0.27 (0.11–0.69)	0.53 (0.13–1.35)	22 (5.8–71)	41 (7.3–148)
	11	79.7 (73.2–86.0)	86.8 (79.9–96.0)	0.34 (0.15–0.67)$^{\Delta+}$	0.37 (0.18–0.70)*	0.29 (0.10–0.73)	0.39 (0.15–1.37)	28 (7.5–86)	41 (11–154)
	12	80.0 (74.0–86.3)	85.8 (79.1–94.6)	0.32 (0.15–0.59)*	0.39 (0.18–0.62)$^{\Delta}$	0.24 (0.10–0.68)*	0.32 (0.16–0.97)*	20 (7.7–81)	31 (13–112)

- The median exhaled air flow rate values for speaking activities were **0.28 (females) and 0.31 (males) m^3 h^{-1}**;
- no significant differences between females and males in the exhaled air flow rate values for **loudly speaking** (median values of **0.31 and 0.34 m^3 h^{-1}**);
- a **slight age effect** was recognized: older children (11 and 12 years old) recorded statistically higher flow rates than younger children (6 years old);
- **Sound pressure levels** were significantly **different between females and males** for both speaking (median values 79.4 and 80.9 dB, respectively) and loudly speaking (85.5 and 88.1 dB, respectively).

Results and discussion

Respiratory particle concentrations and size distributions

- **Respiratory particle concentrations** values for females and males were significantly different for **loudly speaking** (median values **0.37 and 0.53 particles cm^{-3}**, respectively) but not for **speaking** (median values **0.29 and 0.33 particles cm^{-3}**, respectively);

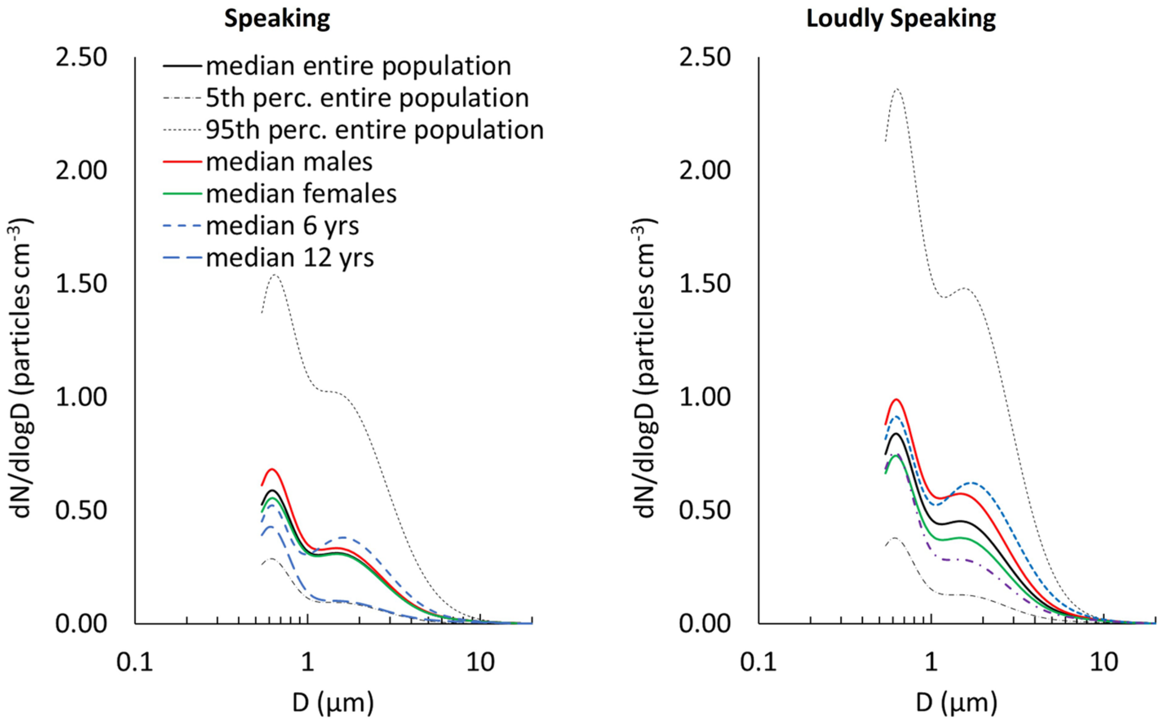
- Despite different methodologies applied in the experimental studies, a rough comparison with previous studies reveals that the particle concentrations we measured for children were within the ranges measured for similar speaking activities performed by adolescents and adults;

- 12-year-old children had significantly lower concentrations than 8-year-old children for speaking, and also 6- and 8-year-old children for loudly speaking. This is a novel finding that should be explored in future research because the few previous studies involving children.

Results and discussion

Respiratory particle concentrations and size distributions

- **Particle size distributions** measured for the entire population investigated for speaking and loudly speaking activities present a main mode at approximately **0.6 µm** and a second minor mode at **< 2 µm**; the main mode is characteristic of the respiratory particles generated in the bronchioles (and it is present also in breathing activities), whereas the second mode is generally associated with the generation occurring in the larynx and pharynx which are more typical of speaking and singing activities;
- a **slight age effect was observed in younger children**, in whom the second mode (at < 2 µm) was more pronounced than in older children.



Results and discussion

Emission rates

- The emission rates for speaking and loudly speaking for the entire investigated population were significantly different, with median values of **26 and 41 particles s^{-1}**;

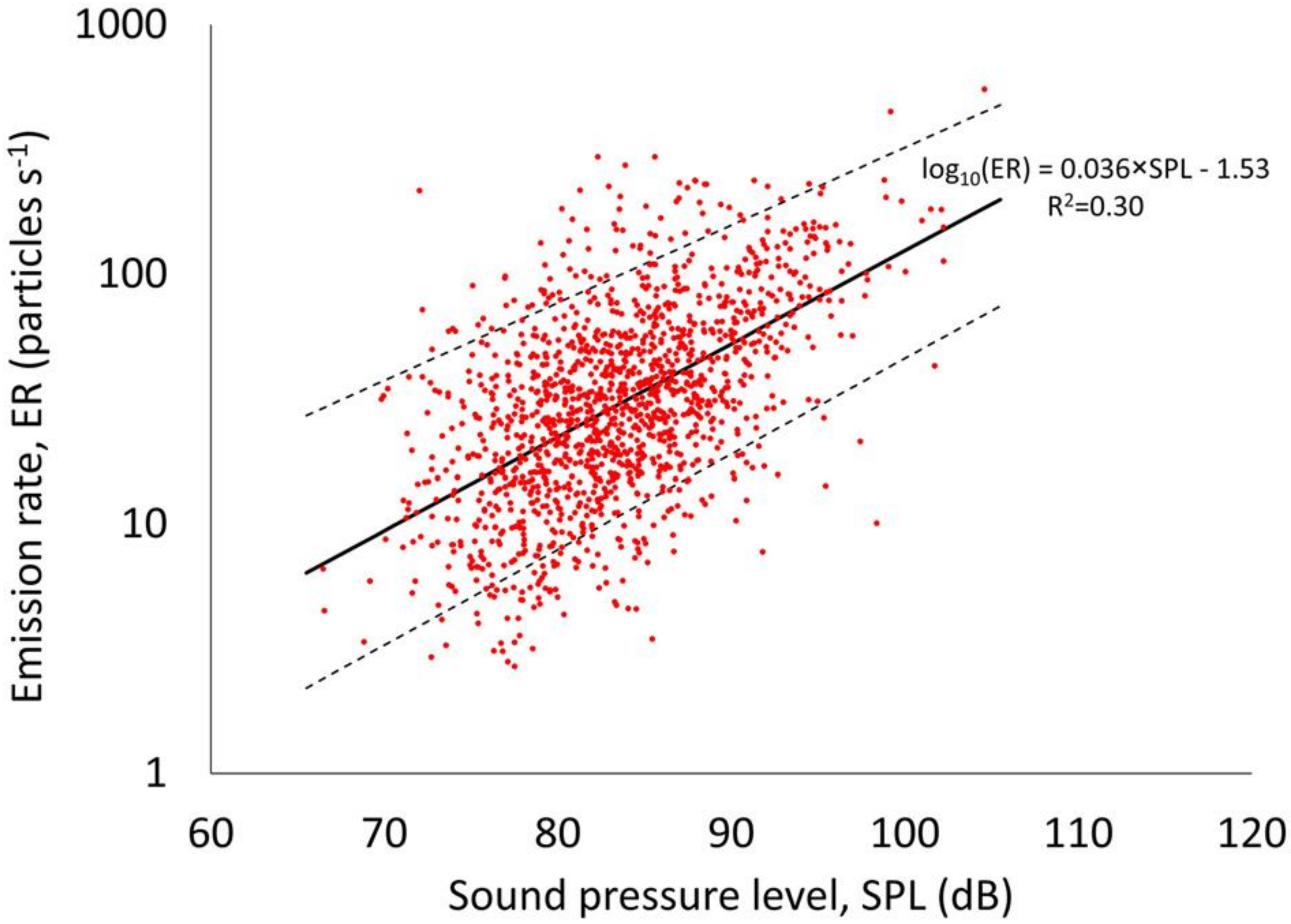
- **Males** had significantly **higher emissions** than females both while speaking (median values of 28 and 23 particles s^{-1}, respectively) and loudly speaking (51 and 33 particles s^{-1}, respectively), consistent with the differences in particle concentrations;

- **Differences in emission rates due to the age of the child were not significant** due to the balancing of two opposite effects: the slight increase in the flow rate as a function of age (older children recorded statistically higher flow rates than younger children) and the slight reduction in respiratory particle concentration with age (older children recorded statistically lower particle concentrations than younger children).

Results and discussion

Emission rates

- The emission characteristics clearly highlight an **effect of the vocal loudness** on the concentrations and emission rates, as reported in previous studies.

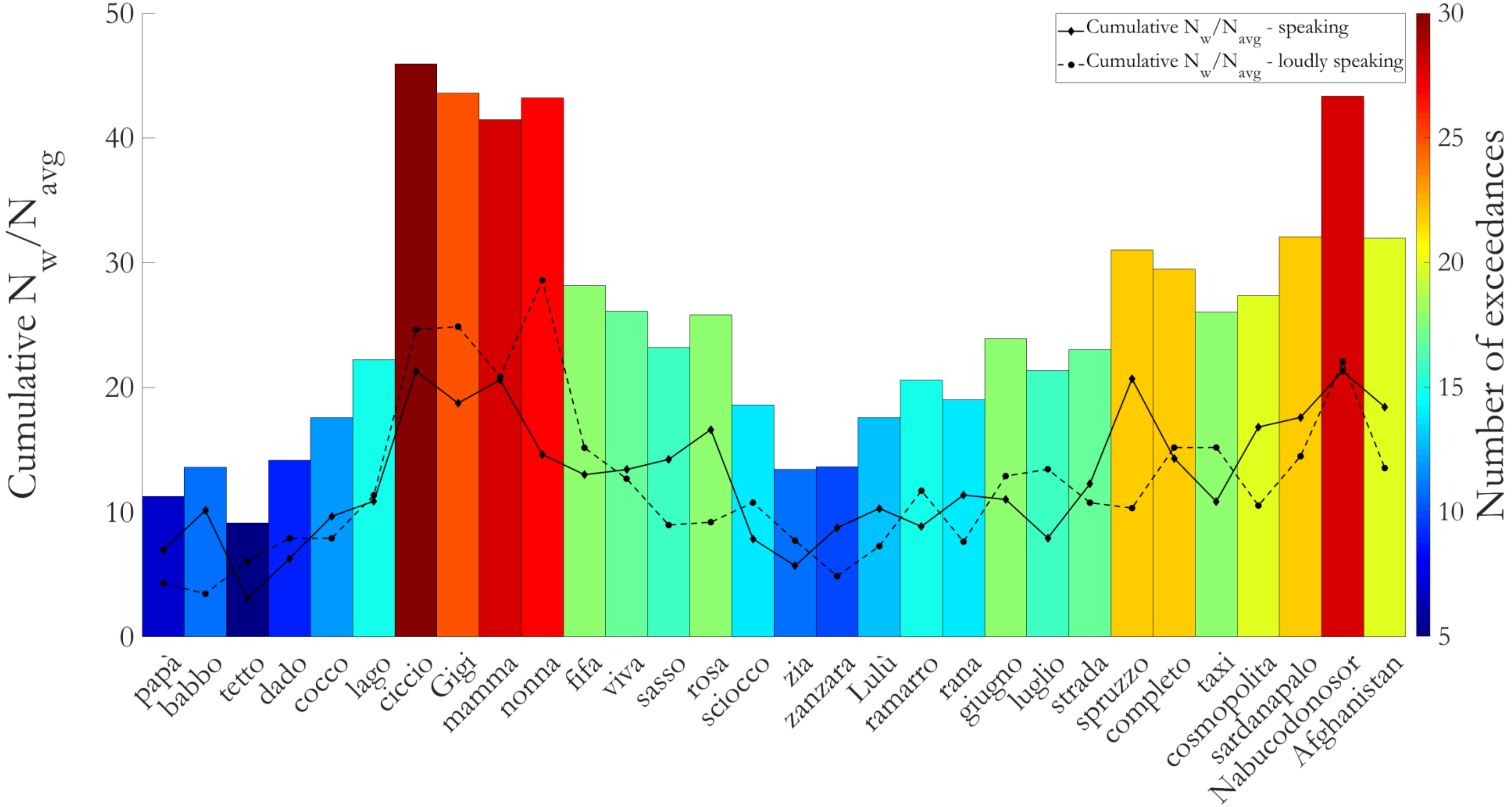


Respiratory particle super-emissive Italian words and effect of articulation manner during children speaking

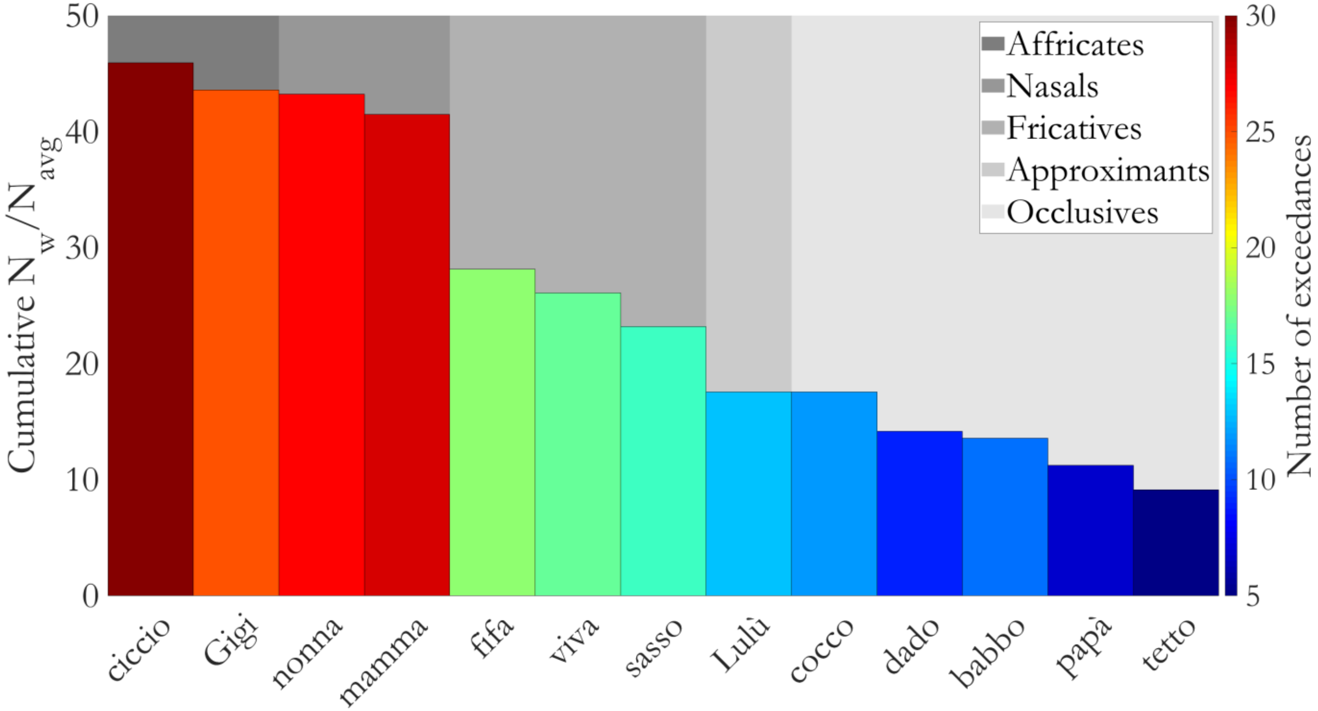
Methodology

1. Evaluation of the average particle number concentration during the single reading of the word list, N_{avg} (part. cm^{-3});
2. Identification of particle number concentrations that exceeded the average particle number concentrations N_{avg}, expressed as N_w (part. cm^{-3});
3. Time synchronization between APS samplings with the audio tracks recorded during the experimental tests;
4. Association of the exceeding particle number concentration N_w with corresponding word included in the list;
5. Calculation of the ratio between the particle number concentrations associated to the super-emissive aerosol words, Nw, and the average particle number concentration, N_{avg}, expressed as N_w/N_{avg};
6. Calculating the cumulative as the sum of all Nw/Navg for each word list and counting the number of times that each word exceeded the average particle concentration value.

Results


Cumulative N_w/N_{avg}
0
10
20
30
40
50
Cumulative N_w/N_{avg} - speaking
Cumulative N_w/N_{avg} - loudly speaking
Number of exceedances
5
10
15
20
25
30
papà
babbo
tetto
dado
cocco
lago
ciccio
Gigi
mamma
nonna
fifa
viva
sasso
rosa
sciocco
zia
zanzara
Lulù
ramarro
rana
giugno
luglio
strada
spruzzo
completo
taxi
cosmopolita
sardanapalo
Nabucodonosor
Afghanistan

Results



Word	IPA notation	Vowels	Consonants		
		quantity	quantity	articulation	Voiced/voiceless
papà	[paˈpa]	2 (50%)	2 (50%)	occlusives	voiceless
babbo	[ˈbab.bo]	2 (40%)	3 (60%)	occlusives	voiced
tetto	[ˈtɛt.to]	2 (40%)	3 (60%)	occlusives	voiceless
dado	[ˈdaːdo]	2 (50%)	2 (50%)	occlusives	voiced
cocco	[ˈkɔk.ko]	2 (40%)	3 (60%)	occlusives	voiceless
ciccio	[ˈkɔk.ko]	3 (50%)	3 (50%)	affricates	voiceless
Gigi	[ˈʤiːʤi]	2 (40%)	3 (60%)	affricates	voiced
mamma	[ˈmam.ma]	2 (40%)	3 (60%)	nasals	-
nonna	[ˈnɔn.na]	2 (40%)	3 (60%)	nasals	-
fifa	[ˈfiːfa]	2 (50%)	2 (50%)	fricatives	voiceless
viva	[ˈviːva]	2 (50%)	2 (50%)	fricatives	voiced
sasso	[ˈsas.so]	2 (40%)	3 (60%)	fricatives	voiceless
Lulù	[luˈlu]	2 (50%)	2 (50%)	approximants	-

Results

- There is not substantial difference between exceedances and cumulative due to speaking and loudly speaking tests;
- The words “*ciccio*, *Gigi*, *mamma*, *nonna*, *Nabucodonosor*” present the highest number of exceedances and cumulative N_w/N_{avg} between all the potentially “super-emissive” words;
- The high respiratory particle emissivity of “*Nabucodonosor*” can be due to the presence of various phonemes in the unit of time;
- *Affricate* consonants contained in “*ciccio*” and “*Gigi*” result in the highest number of exceedances and cumulative due to their complex sound (consisting of an *occlusive* and a *fricative* part).