Aerosol emission is increased in professional singing

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Abstract In this study, emission rates of aerosols emitted during singing are presented for professional singers. The results, measured with a laser particle counter, are compared with published data for breathing and speaking. In the investigated cohort of eight volunteers, the particle source strengths during singing are between 753.4 and 6093.14 P/s. The growth rates between singing and speaking are between 3.98 and 99.54. The present study contributes to a more precise assessment of a possible spread of SARS-CoV-2-viruses during singing. It should support the efforts to improve the risk management, especially for choir singing.

Introduction

The respiratory system is the main transmission route for SARS-CoV-2-viruses. (*Asadi et al., 2020a*; *Morawska and Cao, 2020*).

Depending on particle size, a distinction can be made between droplets with a diameter greater than 5 μm and particles smaller than 5 μm (aerosols or droplet nuclei) (*Couch et al., 1966*; *Tellier, 2006*; *Judson and Munster, 2019*). Droplets and aerosols differ according to the influence of gravity. For example, droplets of a size of 100 μm sink to the ground within a short time and are transported up to a distance of 1.5 m (*Kähler and Hain, 2020*; *Wei and Li, 2015*).

When aerosols are exhaled, the fluid component of the pathogen-containing particles evaporates more and more. They become lighter, can float in the air for longer periods and spread in closed rooms by air flow and diffusion (*Stadnytskyi et al., 2020*). As the basis of a possible aerogenic transmission of the SARS-CoV-2-virus, the spatial distribution of aerosols is dependent on several factors of the surrounding air, such as temperature and humidity (*Morawska, 2006*).

Droplets and aerosols are also produced during speaking and singing, because the respiratory tract has a dual function: it is not only the main tool for ventilation, but also the source of voice and spoken language production. Particle formation in the pulmonary alveoli (*Johnson and Morawska, 2009*), flow effects of the vibrating vocal folds and adjustments of the articulation instruments are regarded as aerosol generating mechanisms (*Johnson et al., 2011*).

In comparison to breathing, a stronger formation of aerosols is known for speaking, whereby also a dependence of the number of the arising particles on vocal loudness is described (*Hartmann et al., 2020*; *Asadi et al., 2020b*). For singing, a significantly higher aerosol production is assumed, probably due to the underlying physiological mechanisms and the greater continuity of voice production over time. This assumption is supported by reports of high infection rates during choir rehearsals in closed rooms (*Hamner et al., 2020*).

Previous measurements focus on fluid mechanical aspects in the near-field plume of the mouth during singing (*Anfinrud et al., 2020*; *Kähler and Hain, 2020*). The spread of the emitted droplets is investigated, hence distance rules can be derived for protection against droplet infection. However, a risk assessment including the distribution of aerosols in larger rooms is not possible with this

method.

The current investigations aim to initially determine the number and size distribution of even small particles emitted by professional singers during singing. This information can be the basis for a numerical calculation of the distribution of aerosols in larger rooms, which takes into account the boundary conditions being typical for concert and opera performances.

The present data may contribute to improved risk management strategies in the fields of culture and education. They should be used for specification of hygiene measures and ventilation concepts in order to facilitate performances and events.

Results

As listed in the methods section, the particle count measurement method detects different sizes of particles from > 0.3 µm to > 10 µm. As shown in the log-probability plot (*Figure 1*), > 99 % of all detected particles were ≤ 5 µm (> 80 % of all particles ≤ 1 µm). Based on this observation, and following the agreement that aerosol particles of size ≤ 5 µm are referred to as aerosol particles, the following results are given for particles of size > 0.3 µm – 5 µm.

It should be noted, that the results for breathing and speaking tasks of the subjects considered in this study, have already been analyzed and published within a larger cohort. (*Hartmann et al., 2020*). In order to allow a direct comparison with the data for singing, the data of this subgroup were reused and analyzed.

This study shows considerable differences in the emission rates for the different test conditions.

In *Figure 2* both the medians of the particle source strengths (emission rates) and the maximum sound pressure levels are shown for the different tasks mouth breathing, speaking, and singing.

The results confirm the hypothesis of significantly higher emission rates for singing compared to mouth breathing and speaking.

While the median values for mouth breathing range from 4.71 P/s (S1, S7 & S8) to 84.76 P/s (S2), those for singing range from 753.4 P/s (S5) to 6093.14 P/s (S2).

The growth rate of the emission rates for singing in comparison to speaking was between 3.98 (S1) and 99.54 (S2). Female singers showed higher particle source strengths than male singers.

Moreover, the growth rate of the emission rates for singing in comparison to breathing was between 15.25 (S6) and 330 (S1).

The evaluation of the sound pressure levels shows that the higher voice classifications soprano (female) and tenor (male) have the expected higher sound pressure levels than the lower voice classifications alto and baritone. While the maximum sound pressure level of males in the selected sample is always positively correlated with the particle emission rate, there was no clear correlation in this respect for the female voices.

The results of measurements with the sustained vowel /a/ at different loudness conditions are presented in *Figure 3*. Seven of the eight subjects showed an increase in the emission rate with increasing loudness. A comparison of soft and loud condition showed a growth rate of up to 114.33 (S3). Again, there are gender differences with higher emission rates for loud phonation for females (from 2024.77 P/s (S1) to 8075.53 P/s (S3)) compared to males (from 376.7 P/s (S5) to 2848.8 P/s (S7)). For all subjects, the intended increase in loudness from piano to forte is reflected in the measured values of the sound pressure level.

Additionally, *Figure 4* shows the relationship between the emission rate and the maximum sound pressure level. In tendency, an increase in the sound pressure level is accompanied by an increase in the emission rate. Concerning this tendency, males behave similarly to females. With regard to sustained vowels, it can be stated that the emission rates can vary by more than two orders of magnitude.
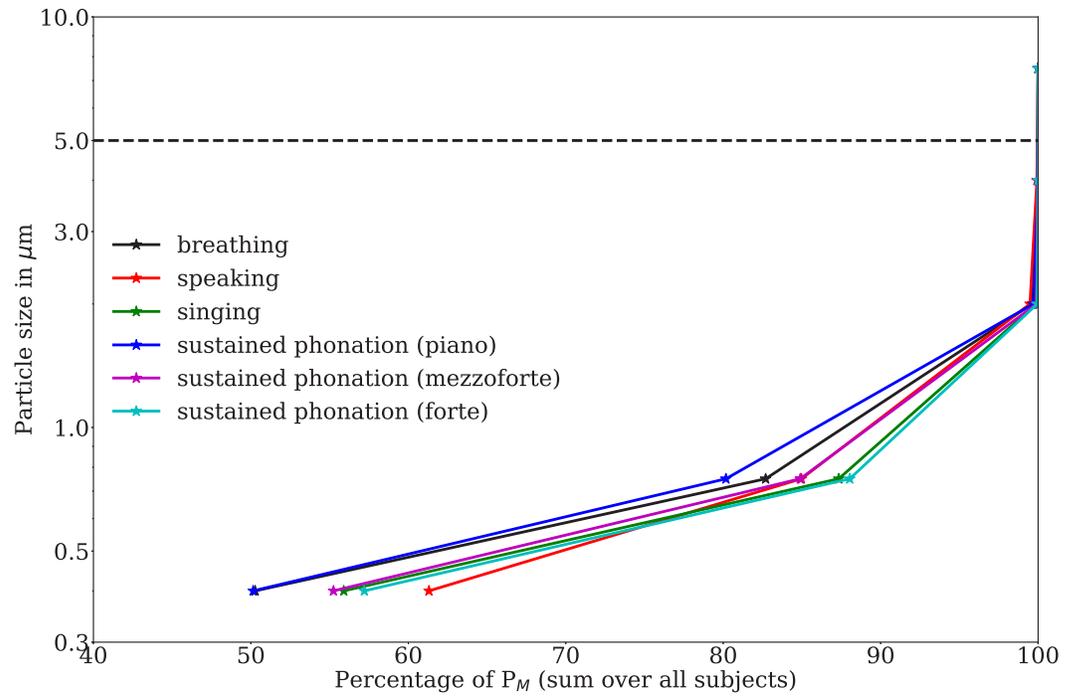
Figure 1. Log-probability plot of the frequency distribution of the size of the detected particles. Regardless of the task, > 99 % of all detected particles are ≤ 5 µm (dashed line). Furthermore all tasks show that > 80 % of all particles are ≤ 1 µm.
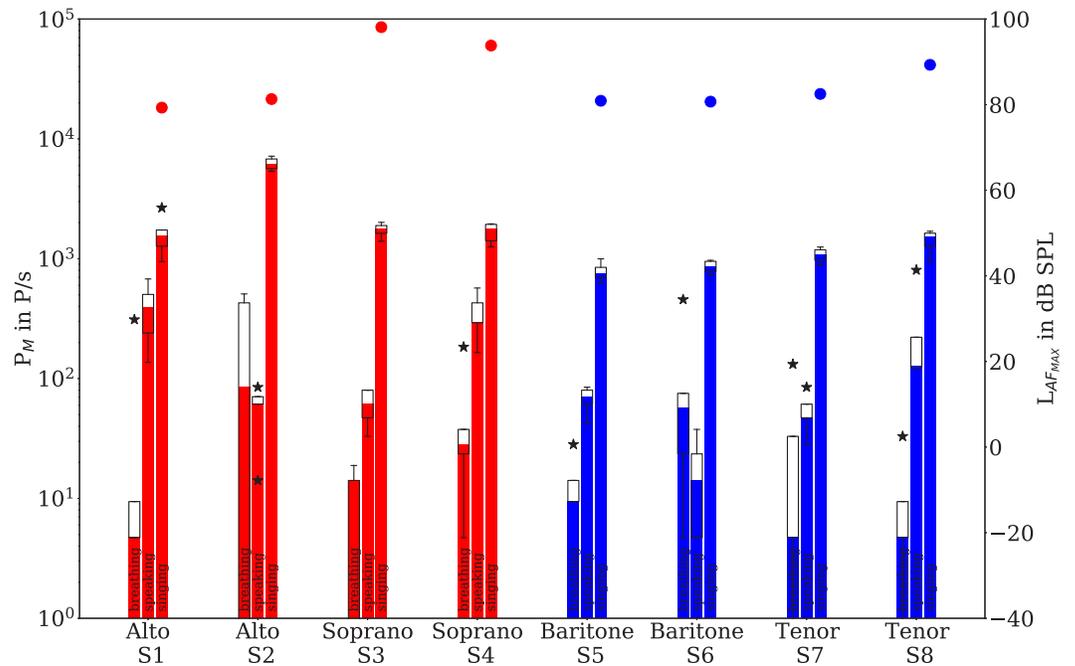
Figure 2. Boxplots of the particle source strengths (bars represent the median) for different gender, voice classifications and tasks: mouth breathing, speaking and singing (left y-axis). Only particles ≤ 5 µm were considered. For singing, the maximum sound pressure levels LAF_{MAX} are also shown (full circles, right y-axis).
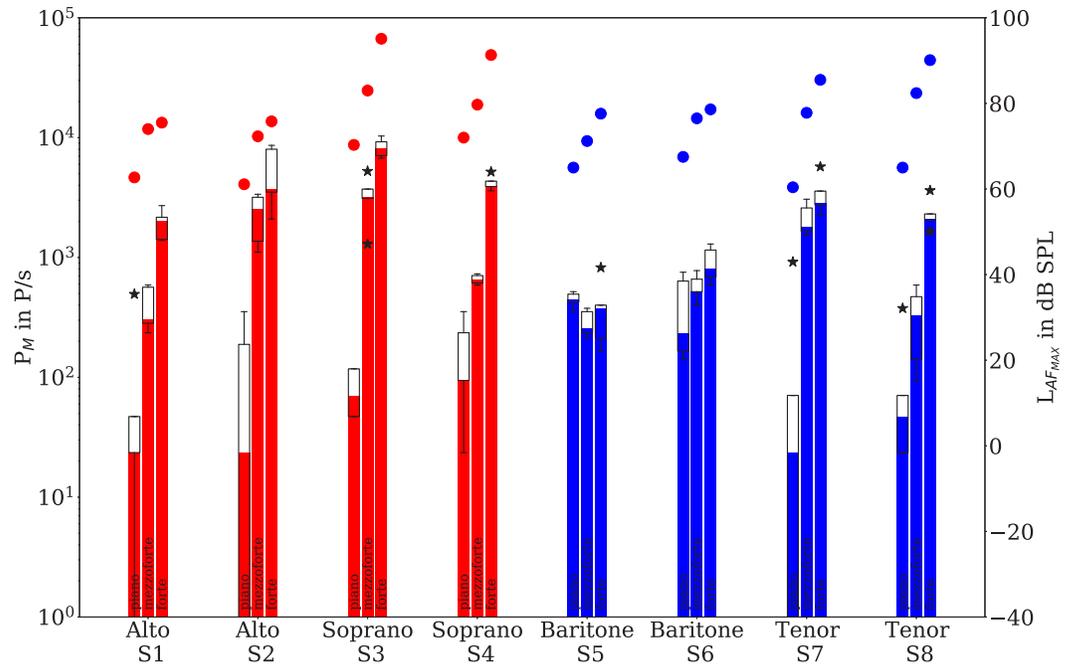
Figure 3. Boxplots of the particle source strengths (bar represents the median) for different gender, voice classifications and vocal loudness conditions while sustaining the vowel /a/ (left y-axis). Only particles ≤ 5 µm were considered. For the different loudness conditions, the maximum sound pressure levels LAF_{MAX} are also shown (full circles, right y-axis).
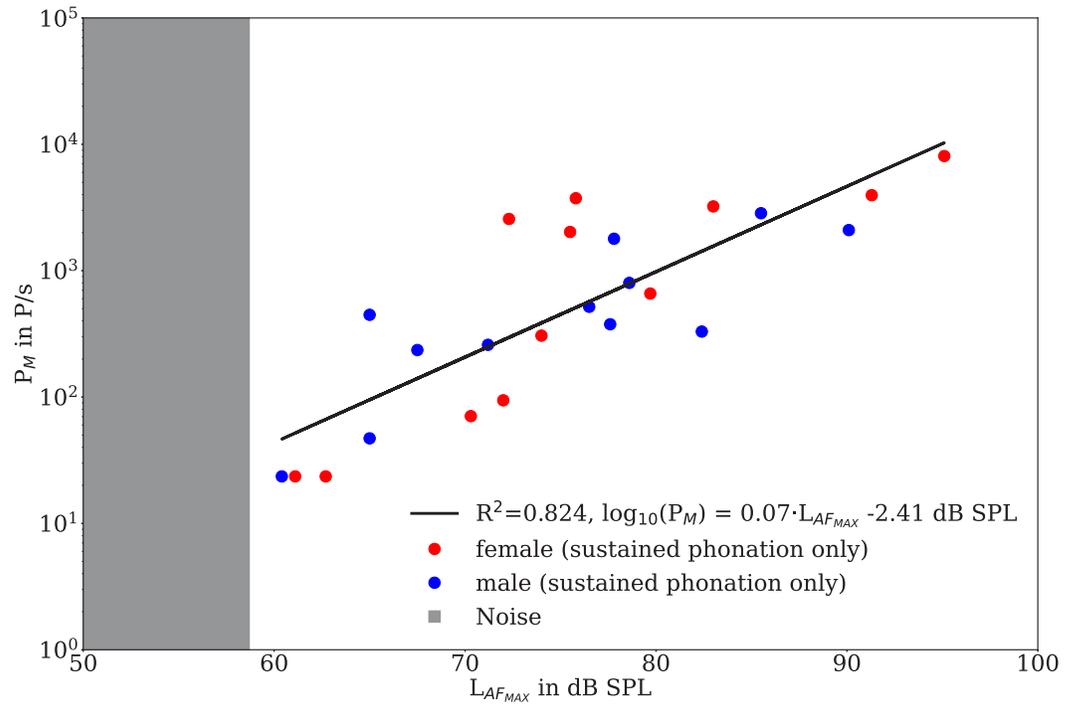
Figure 4. Relationship between particle source strength and the maximum sound pressure level for the test condition of sustained vowel /a/ for all three loudness conditions separated by gender including linear regression of the logarithmic particle source strengths (black line). Only particles ≤ 5 µm were considered. The grey field represents the sound pressure level resulting from the environmental conditions (primarily particle counter) alone.

Discussion

Due to the increased risk of transmission of SARS-CoV-2 viruses during singing and the described accumulation of these infections during choir rehearsals, the survey of particle emissions and the assessment of aerosols in rooms are key elements in the risk management of ensemble and choir singing in enclosed rooms.

The measuring method used (laser particle counter) provides very high accuracy concerning the absolute number of particles and their size because sources of interference have been reduced to a minimum. Furthermore, the suitability of the peripheral test setup could be proven within the scope of baseline measurements.

An alternative or supplemental method to investigate the size distribution of droplets during breathing, speaking and singing is the imaging technique of Particle Image Velocimetry (PIV). This is based on high-resolution photos of the particles, which are illuminated with a laser light, for example. Studies using PIV also show that more particles are emitted when speaking loudly than speaking with low voice (*Anfinrud et al., 2020*). However, only qualitative statements can be made here, due to several influencing factors. Size and number of particles can only be estimated, because of the background concentration of particles in the room and some drops can only be picked up in a blurred way. In a study of *Chen-Yu et al.* (*2000*), particles of the sizes 1, 10, and 100 μm were measured with PIV and high accuracy was shown for particles greater than 6 μm. This may be a reason why investigations of the size distribution of droplets with PIV lead to significantly higher mean particle diameters (*Chao et al., 2009*). Recent studies show that with PIV, particles in the order of 1 μm can be examined (*Kähler and Hain, 2020*). For particles, in the order of 0.3 – 20 μm, the laser particle counter offers higher accuracy in determining the number and size of particles.

Since the aerosols emitted during breathing, speaking (*Hartmann et al., 2020*) and singing are mainly < 1 μm in size, it cannot be assumed that they sink quickly to the ground. It had been shown, that the retention time is in the range of minutes to hours and the sink rate is in the order of < 1 mm/s (*Stadnytskyi et al., 2020*; *Tellier, 2006*). The determined order of magnitude of the particle size of this study is significantly lower than the results of the only study, where the particle emission during singing was also investigated. In this former study, the estimated particle size during singing was determined with 68 μm in median (*Loudon and Roberts, 1967*, *1968*). Furthermore, in the same study, the sizes of the emitted particles for speaking were determined by 81 μm. The discrepancy between these and the data presented in this article, is probably due to the high-precision measuring methods not yet available at that time. With regard to the size of emitted particles, *Asadi et al.* (*2019*) was able to show that they are distinctively smaller than 10 μm during speaking and breathing (see also *Papineni and Rosenthal* (*1997*)).

The present study confirms that higher emission rates of aerosols are produced during singing in comparison to speaking and breathing. *Asadi et al.* (*2019*) found higher emission rates for speaking compared to breathing and an increase of emission rates with raising vocal loudness. He could further show that the range of emission rate ranges from 1 to 100 P/s for speaking, which roughly confirms our data (14.13 to 390.83). Similar rates of 330 P/s (particle size ranges between 0.8 to 5.5 μm) were obtained by *Morawska et al.* (*2009*) for sustained vowels. Whereas for unvoiced plosives significantly larger droplets of up to 500 μm were determined (*Anfinrud et al., 2020*). Furthermore, there is a good agreement of the particle source strength in breathing with *Asadi et al.* (*2019*).

However, phonation of sustained vowels, characterized by a periodic collision of the vocal folds correlating with pitch, does not reflect the ordinary situation in choral singing. Here, the order of consonants and vowels alternate in a sung passage and are interrupted by pauses. Therefore, in the present study, a sequence of 50 seconds of the choir piece "Abschied vom Walde" by Felix Mendelssohn Bartholdy was selected. Each line of the choir part was sung by the individually appropriate voice classification (soprano, alto, tenor, baritone). These data were compared with the tasks 'breathing' and 'speaking' (reading the standardized text corpus). Again, there is an increase of

the emission rate for singing in comparison to speaking. Probably, this is due to the higher ratio of voiced segments to pauses and the increased sound pressure level in singing. Further, these findings agree with the observation that vocalizations lead to higher aerosol emissions (*Asadi et al., 2020a*,b).

However, the data presented here show no clear homogeneity within the cohort. For example, the emission rate determined for singing fluctuates by almost one order of magnitude. Also, the increase of P_M between singing and speaking fluctuates by almost two orders of magnitude. Thus, the aspect of high-emitters or super-emitters might be considered (*Asadi et al., 2019*).

Of course, the determined emission rate does not provide any information about a possible concentration of SARS-CoV-2 viruses. The probability that a 1 μm sized particle contains a virus has been estimated to only 0.01% (*Stadnytskyi et al., 2020*). However, taking into account an average viral RNA load of 7e-6 to 2.35e9 per mm^3 (*Wölfel et al., 2020*), it can be estimated that one minute of loud speech produces at least 1000 virus-containing droplet nuclei that can remain in the air up to several hours. However, at present this number can not serve to estimate the infectivity or the probability of infection. (*Bar-On et al., 2020*).

It should be noted that in the course of the pandemic so far, numerous situations seem to be related to a high probability of aerogenic virus transmission (cruise ships, restaurants, choir rehearsals). There is also initial evidence of viable SARS-CoV-2 viruses in indoor air (*Guo et al., 2020*). However, comprehensive information on the transmission quantity and survivability of SARS-CoV-2 viruses in aerosols is still missing (*van Doremalen et al., 2020*).

Therefore, the present study can only be one component in the risk assessment of singing, which in turn is largely determined by the current prevalence. Finally, there is a lack of data on whether specific breathing characteristics of singing (deep inhalation, higher intrapulmonary pressures) influence the risk of transmission when singing loudly.

In any case, the data should support all efforts to improve the risk management, especially in choir singing.

Materials and Methods

Subjects

Eight singers (ages 22 to 62 years; professional experience between 1 to 34 years) of a professional chamber choir (RIAS Kammerchor Berlin) took part in the investigations. To each of the different voice classifications belonged two of the subject group: alto (S1 & S2), soprano (S3 & S4), baritone (S5 & S6), and tenor (S7 & S8). The subjects were informed about the investigations and gave their written consent.

Particle measurements

The investigations were carried out in a cleanroom at the Hermann Rietschel Institute of the Technical University of Berlin. According to *Figure 5*, the supply air is introduced via a vertical low-turbulence displacement flow (TAV) over the entire ceiling area of 4.8 x 4.8 m^2. The supply air velocity is 0.3 m/s and thus prevents thermal lift at the people. The exhaust air is also discharged from the room over the entire surface via a raised floor. The room temperature is $295.15\,\text{K} \pm 0.50\,\text{K}$, the relative humidity is $40\,\% \pm 2\,\%$ and the room has 15 Pa overpressure to the surrounding rooms.

The actual test stand is located in this highly pure environment (*Figure 5*). It consists of a glass pipe, in which a constant airflow of 400 m^3/h is generated by a filter fan unit (Ziehl-Abegg, Künzelsau, Deutschland). The measuring probe of a laser particle counter (Lighthouse Solair 3100 E, Lighthouse Worldwide Solutions, Fremont (CA)) is placed centrally in the pipe.

The particle counter counts with a volume flow of 28.3 l/min, with a measuring time of 10 seconds each and detects particles in six size classes: > 0.3 μm – 0.5 μm, > 0.5 μm – 1.0 μm, > 1.0 μm – 3.0, > 3.0 μm – 5.0 μm, > 5.0 μm – 10 μm and > 10 μm.

The source strength P_M presented in *Figure 2*, *Figure 3* and *Figure 4* is computed based on the measured particle concentration c_M and the volume flow through the filter fan unit (FFU) $\dot{V}_{FFU}$, i.e.

$$P_M = c_M \cdot \dot{V}_{FFU}. \tag{1}$$

To estimate sources of interference, such as background noise of particles in the room, as well as abrasion on the clothing and hair of the persons investigated, a baseline measurement was carried out at the beginning of the investigation. For particle reduction due to movement artifacts, the test persons wore cleanroom clothing and a headgear with the sealing of the edges with adhesive tape, so that only eyes, nose, and mouth were uncovered.

In this baseline measurement, a count rate of the particle counter of <1 particles/5 minutes was determined within a measurement period of 10 minutes.

The counting efficiency for particles of the size 0.3 μm is 50 % and for particles of the size 0.5 μm it is 100 % ± 10 % according to ISO 21501-4. To investigate how many particles were separated over the measuring distance, comparative measurements were made over a short distance from the particle counter. For this case, the particles were directly collected through a 150 mm high funnel while breathing and speaking and directed to the particle counter. The same size distribution was found as in the finally used configuration.

Audio measurements

The sound pressure level was determined using a calibrated sound level meter (CENTER 322_ Datalogger Sound Level Meter, Center Technologies, www.centertek.com). During all measurements, the sound level meter was located approx. 60 cm anterior-laterally away from the mouth of the test persons due to limited accessibility. The measuring arrangement of the particle counter did not allow a standard positioning of 30 cm mouth distance of the measuring device. Furthermore, the high sensitivity of the particle counter did not allow a frontal positioning of the sound level meter inside the glass tube. Consequently, the determined levels are not to be considered as absolute levels but are lowered by a constant value of approx. 10 dB SPL.

Due to the time variability of the determined sound pressure levels (primarily for speaking and singing), the maximum value $L_{AF_{MAX}}$ of the frequency- and time-weighted acoustic pressure was recorded and evaluated.

Test conditions

The subjects were in a sitting position at the entry of the particle measurement setup. Four test situations were distinguished:

    (1) Breathing through the mouth

    (2) Reading a standardized text

    (3) Singing a line of a four-part choral movement

    (4) Singing a sustained vowel (/a/) for ten seconds at three loudness conditions (piano, mezzo-forte and forte)

For task (1), (2) & (3), respectively, a time window of 50 seconds was analyzed. Further, for task (4) the time window was set to 10 seconds. For reading in a comfortable loudness condition (task (2)), the text "The North Wind and the Sun" by Äsop was selected. To pass task (3) the choral part of the song "Abschied vom Walde" by Felix Mendelssohn-Bartholdy was chosen. The subjects were instructed to sing the line of their individual voice classification. Each of these tasks was repeated five times.

The following pitches were selected for the fourth task: soprano: C5 (523 Hz), alto: F4 (349 Hz), tenor: C4 (262 Hz), and baritone: F3 (175 Hz). The total measuring time for all tasks was about 30 minutes for each subject. Each of the five trials of each task was examined with regard to their median, quantiles, and quartiles. Due to the small sample size, no cross-cohort statistical analyses were carried out, but proband-specific data were computed.
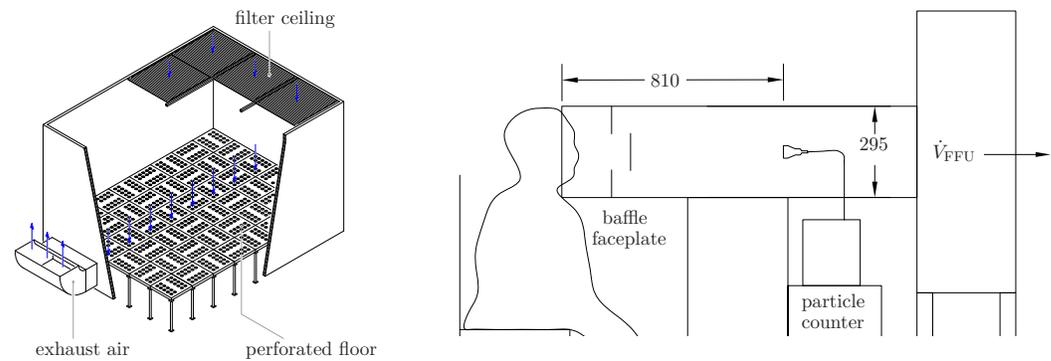
Figure 5. Left: Schematic layout of the cleanroom with vertical displacement flow (Figure adapted from Fig II-37 in *Kriegel et al.* (*2017*)). Right: Schematic test setup with one person in cleanroom clothing whose exhaled air is recorded by the particle counter. The glass measuring section is located on the suction side of a horizontally positioned Filter Fan Unit (FFU). All geometric dimensions are in mm (Figure adapted from Fig 2 in *Hartmann et al.* (*2020*)).

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Contributions

D. M. and M. F. contributed equally to this work. D. M., M. F., and M. K. designed research. J. L., H. R. and M. F. made measurements. M. F., J. L., D. M. and M. K. wrote the paper.

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