1 Aerosol emission is increased in professional 2 singing

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8 ABSTRACT

In this study, emission rates of aerosols emitted by professional singers were measured with a laser particle counter under cleanroom conditions. The emission rates during singing varied between 753.4 and 6095.37 P/s. Emission rates for singing were compared with data for breathing and speaking.
9 Significantly higher emission rates were found for singing. The growth rates between singing and speaking were between 3.97 and 99.54. Further, effects of vocal loudness and gender were investigated. The present study should support the efforts to improve the risk management in cases of possible aerogenic virus transmission, especially for choir singing.

10 Introduction

11 The respiratory system is the main transmission route for SARS-CoV-2-viruses^{1,2}.

12 Depending on particle size, a distinction can be made between droplets with a diameter greater than
13 5 µm and particles smaller than 5 µm (aerosols or droplet nuclei)^{3–5}. Droplets and aerosols differ according
14 to the influence of gravity. For example, droplets of a size of 100 µm sink to the ground within a short
15 time and are transported up to a distance of 1.5 m^{6,7}.

16 When aerosols are exhaled, the fluid component of the pathogen-containing particles evaporates more
17 and more. They become lighter, can float in the air for longer periods and spread in closed rooms by
18 air flow and diffusion⁸. As the basis of a possible aerogenic transmission of the SARS-CoV-2-virus, the
19 spatial distribution of aerosols is dependent on several factors of the surrounding air, such as temperature
20 and humidity⁹.

21 Droplets and aerosols are also produced during speaking and singing, because the respiratory tract

22 has a dual function: it is not only the main tool for ventilation, but also the source of voice and spoken
23 language production. Particle formation in the pulmonary alveoli¹⁰, flow effects of the vibrating vocal
24 folds and adjustments of the articulation instruments are regarded as aerosol generating mechanisms¹¹.

25 In comparison to breathing, a stronger formation of aerosols is known for speaking, whereby also
26 a dependence of the number of the arising particles on vocal loudness is described^{12,13}. For singing,
27 a significantly higher aerosol production is assumed, probably due to the underlying physiological
28 mechanisms and the greater continuity of voice production over time. This assumption is supported by
29 reports of high infection rates during choir rehearsals in closed rooms¹⁴.

30 Previous measurements focus on fluid mechanical aspects in the near-field plume of the mouth during
31 singing^{6,15}. The spread of the emitted droplets is investigated, hence distance rules can be derived for
32 protection against droplet infection. However, a risk assessment including the distribution of aerosols in
33 larger rooms is not possible with this method.

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

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

41 Results

42 Particle size distribution

43 The particle count measurement method detects different sizes of particles from 0.3 μm to 25 μm . As
44 shown in the log-probability plot (Fig. 1), > 99 % of all detected particles were $\leq 5 \mu\text{m}$ (> 80 % of all
45 particles $\leq 1 \mu\text{m}$). Based on this observation, and following the agreement that aerosol particles of size
46 $\leq 5 \mu\text{m}$ are referred to as aerosol particles, the following results are given for particles of size 0.3 μm –
47 5 μm .

48 Experiment I

49 Figure 2 illustrates both the emission rates for the different test conditions (breathing, speaking, and
50 singing) and the maximum sound pressure levels for singing.

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

While the individual median values for singing ranged from 753.36 P/s (S5) to 6095.37 P/s (S2) (Table 1), those for speaking ranged from 14.13 P/s (S6) to 390.84 P/s (S1) (Table 1). The individual median values for breathing ranged from 4.71 P/s (S1) to 428.55 (S2) (Table 1).

The growth rate of the emission rates for singing in comparison to speaking was between 3.97 (S1) and 99.54 (S2). Moreover, the growth rate of the emission rates for singing in comparison to breathing was between 14.22 (S2) and 329.61 (S1) (Table 2).

The evaluation of the sound pressure levels showed that the higher voice classifications soprano (female) and tenor (male) had 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 were always positively correlated with the particle emission rate, there was no clear correlation in this respect for the female voices.

Statistical analysis by means of linear mixed modeling (Equation 2) showed significant differences of the (logarithmic) emission rate $\log_{10}P_M$ between the different test conditions breathing, speaking and singing. Condition affected $\log_{10}P_M$ ($\chi^2(2)=37.797$, $p=6.2\cdot 10^{-9}$) increasing it by a factor of 0.5230 ± 0.2664 (standard errors) from breathing to speaking and by a factor of 1.7740 ± 0.1211 (standard errors) from breathing to singing. By-subject analysis turned out that S2 and S6 showed a decrease of emitted particles from breathing to speaking (see Fig. 2).

Further, female singers showed significantly higher emission rates than males. Gender affected $\log_{10}P_M$ ($\chi^2(1)=4.3035$, $p=0.03803$) lowering it by a factor of -0.3453 ± 0.1246 (standard errors) from female to male.

Experiment II

The results of measurements with the sustained vowel /a/ at different loudness conditions are presented in Fig. 3. Seven of the eight subjects showed an increase in the emission rate with increasing loudness. The comparison of piano (Table 3) and forte (Table 3) showed a growth rate up to 114.29 (S3) (Table 2). There were higher emission rates for singing in forte for females (from 2023.02 P/s (S1) to 8072.35 P/s (S3)) compared to males (from 376.7 P/s (S5) to 2851.02 P/s (S7)). The same implications were made during the increase from piano to mezzo-forte (see also Table 2).

Statistical analysis by means of linear mixed modeling (Equation 2) showed significant differences of

81 the emission rate $\log_{10}P_M$ for the different vocal loudness conditions piano, mezzoforte and forte. Vocal
82 loudness affected $\log_{10}P_M$ ($\chi^2(2)=12.47$, $p=0.00196$) lowering it by a factor of -0.45994 ± 0.11196
83 (standard errors) from forte to mezzoforte and by a factor of -1.25514 ± 0.23734 (standard errors) from
84 forte to piano. The described higher emission rates for females than for males failed to reach statistical
85 significance.

86 For all subjects, the intended increase in loudness from piano to forte was reflected in the measured
87 values of the sound pressure level. Additionally, [Figure 4](#) shows the relationship between the emission
88 rate and the maximum sound pressure level (only the median values for experiment II – sustained vowel
89 /a/ – were considered). An increase in the sound pressure level was accompanied by a mean increase in
90 the emission rate $\log_{10}P_M$ by a factor of 0.06. With regard to sustained vowels, it could be stated that the
91 emission rates can vary by more than two orders of magnitude.

92 Discussion

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

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

101 An alternative or supplemental method to investigate the size distribution of droplets during breathing,
102 speaking and singing is the imaging technique of Particle Image Velocimetry (PIV). This is based on
103 high-resolution photos of the particles, which are illuminated with a laser light, for example. Studies
104 using PIV also show that more particles are emitted when speaking loudly than speaking with low voice¹⁵.
105 However, mainly qualitative statements can be made here, due to several influencing factors. Size and
106 number of particles can only be estimated, because of the background concentration of particles in the
107 room and some drops can only be picked up in a blurred way. In a recent study¹⁶, particles of the sizes 1,
108 10, and 100 μm were measured with PIV and high accuracy was shown for particles greater than 6 μm .
109 This may be a reason why investigations of the size distribution of droplets with PIV lead to significantly
110 higher mean particle diameters¹⁷. Recent studies show that with PIV, particles in the order of 1 μm can

111 be examined⁶. For particles, in the order of 0.3 – 20 μm , the laser particle counter used in cleanroom
112 conditions offers higher accuracy in determining the number and size of particles.

113 It should be noted, that the relative humidity of about 40%, the initial velocity at the mouth, and
114 constant airflow in the glass pipe lead to biased particle sizes as measured by the laser particle counter.

115 According to Nicas et al.¹⁸, particles with an initial diameter of 20 μm shrink by a factor of 2, and
116 according to Wei & Li⁷ particles up to 1000 μm shrink by a factor of 3 to the equilibrium diameter, nearly
117 independently of the relative humidity in the room.

118 The size of this final state is dependent on the amount of non-soluble residues, on the humidity, and
119 the residual respiratory fluid. This final state, called droplet nuclei, is what is referred to as a particle in
120 the context of this article.

121 In contrast, humidity has a highly relevant impact on the evaporation time of droplets. In general, the
122 evaporation time is proportional to the square of the initial diameter^{7,8}. Considering the greatest measured
123 particle size of 5 μm in this study and a shrinking factor of 3, one gets droplets of a diameter of 15 μm in
124 maximum. Whereas a droplet of a size of 15 μm in diameter evaporates in dry air in about 0.15 s to its
125 resting state, the evaporation time increases at a relative humidity of 90% by a factor of about 25 to 3.75 s
126 (values were interpolated considering Table 1 in Wei & Li⁷). More than 80% of the particles measured in
127 this study are equal to or smaller than 1 μm (3 μm un-evaporated). For this particle size, evaporation times
128 are in the order of 0.006 s in dry air, and 0.08 s in moist air.

129 Considering an initial fluid volume velocity at the mouth opening of about 0.142 (females) to 0.244
130 (males) liters per seconds for spoken vowels¹⁹, a lip opening area of about 300 to 1100 mm^2 for females²⁰
131 and 214.4 to 830.8 mm^2 for males²¹ one gets fluid velocities in maximum in the order of magnitude of
132 0.47 (females) up to 1.14 m/s (males) for sustained vowels. These values are up to one order of magnitude
133 lower than reported values of 2.31–4.07 m/s²² and 3.9 m/s¹⁷ for speech. Adding these values to the
134 constant fluid flow velocity of 1.63 m/s in the glass pipe used in the experiment, droplets dispersed with a
135 velocity of 5.7 m/s in maximum over the length of 810 mm (Fig. 5).

136 Taking into account the evaporation time of 3.75 s for 15 μm droplets, a characteristic evaporation
137 length of 21.375 m occurs. This length is lowered for droplets of the size of 3 μm to 0.456 m. Assumption
138 of dry air, these values drop considerably to 0.84 m for 15 μm droplets and 0.034 m for 1 μm droplets.
139 Recognizing a relative humidity of about 40% in the cleanroom, it can be expected that most of the emitted
140 droplets evaporates to droplet nuclei before reaching the laser particle counter. Additionally, because of
141 the small initial size of about 15 μm in the maximum of the particles, no dissection is expected and the

142 measured number of particles should be correct. To summarize these assessments, it should be noted
143 that the particle sizes measured are recognized as aerosols which distribute in an environment and not as
144 particles that were emitted by a subject directly at the mouth. Thus, the droplet nuclei represent a realistic
145 measure for possible carrier particles for viruses.

146 Since the aerosols emitted during breathing, speaking¹² and singing are mainly $< 1 \mu\text{m}$ in size, it
147 cannot be assumed that they sink quickly to the ground. It had been shown, that the retention time was in
148 the range of minutes to hours and the sink rate is in the order of $< 1 \text{ mm/s}$ ^{4,7,8}. The determined order of
149 magnitude of the particle size of this study is significantly lower than the results of the only study, where
150 the particle emission during singing was also investigated. In this former study, the estimated particle
151 size during singing was determined with $68 \mu\text{m}$ in median^{23,24}. Furthermore, in the same study, the
152 sizes of the emitted particles for speaking were determined by $81 \mu\text{m}$. Apart from the methodological
153 aspect discussed above, the discrepancy between these and the data presented in this article, is probably
154 due to the high-precision measuring methods not yet available at that time. With regard to the size of
155 emitted particles, one was able to show that they are distinctively smaller than $10 \mu\text{m}$ during speaking and
156 breathing^{25,26}.

157 The present study confirms that higher emission rates of aerosols are produced during singing in
158 comparison to speaking and breathing. A higher emission rate for speaking compared to breathing and an
159 increase of emission rates with raising vocal loudness was found²⁵. One could further show that the range
160 of emission rate ranges from 1 to 50 P/s for speaking²⁵, which roughly confirms our data (14.13 to 390.84,
161 see [Table 1](#)). Furthermore, there is a good agreement in the emission rate in breathing²⁵.

162 However, phonation of sustained vowels, characterized by a periodic collision of the vocal folds
163 correlating with pitch, does not reflect the ordinary situation in choral singing. Here, the order of
164 consonants and vowels alternate in a sung passage and are interrupted by pauses. Therefore, in the present
165 study, a sequence of 50 seconds of the choir piece “Abschied vom Walde” by Felix Mendelssohn Bartholdy
166 was selected. Each line of the four-part choral movement was sung by the individually appropriate voice
167 classification (soprano, alto, tenor, baritone). These data were compared with the tasks ‘breathing’ and
168 ‘speaking’ (reading the standardized text corpus). Again, there is an increase of the emission rate for
169 singing in comparison to speaking. Probably, this is due to the higher ratio of voiced segments to pauses
170 and the increased sound pressure level in singing. Further, these findings agree with the observation that
171 voiced vocalizations lead to higher aerosol emissions^{1,13}.

172 Apart from the influence of vocal loudness on the emission rate, we found gender differences with

173 higher emission rates for female singers. One reason for a stronger aerosol generation might be the
174 higher frequency of the vibrating vocal folds. This counts both, for the higher soprano and alto line of the
175 four-part choral movement and for the selected higher pitch for females during sustained phonation.

176 However, the data presented here show no clear homogeneity within the cohort. For example, the
177 emission rate determined for singing fluctuates by almost one order of magnitude. Also, the increase
178 of P_M between singing and speaking fluctuates by almost two orders of magnitude. Thus, the aspect of
179 high-emitters or super-emitters might be considered²⁵.

180 Of course, the determined emission rate does not provide any information about a possible concentra-
181 tion of SARS-CoV-2 viruses yet. However, at present this number can not serve to estimate the probability
182 of infection²⁷.

183 It should be noted that in the course of the actual pandemic so far, numerous situations seem to be
184 related to a high probability of aerogenic virus transmission, among them choir rehearsals. There is also
185 initial evidence of viable SARS-CoV-2 viruses in indoor air²⁸. However, comprehensive information on
186 the transmission quantity and survivability of SARS-CoV-2 viruses in aerosols is still missing²⁹.

187 Therefore, the present study contributes to one component in the risk assessment of singing, which in
188 turn is largely determined by the current prevalence. Finally, there is a lack of data on whether specific
189 breathing characteristics of singing (deep inhalation, higher intrapulmonary pressures) influence the risk
190 of transmission when singing loudly. In any case, the data should support all efforts to improve the risk
191 management, especially in choir singing.

192 **Methods**

193 **Subjects**

194 Eight singers (ages 22 to 62 years; professional choir experience between 1 to 34 years) of a professional
195 chamber choir (RIAS Kammerchor Berlin) took part in the investigations. To each of the different voice
196 classifications belonged two of the subject group: alto (S1 & S2), soprano (S3 & S4), baritone (S5 & S6),
197 and tenor (S7 & S8). This study was conducted according to the ethical principles based on the WMA
198 Declaration of Helsinki and to the current legal provisions. It was approved by the ethics committee of
199 the TU Berlin, and informed written consent was obtained from all subjects. It should be noted, that
200 the results for breathing and speaking tasks of the subjects considered in this study, have already been
201 analyzed within a larger cohort¹². In order to allow a direct comparison with the data for singing, the data

202 of this subgroup were reused and analyzed.

203 Particle measurements

204 The investigations were carried out in a cleanroom at the Hermann Rietschel Institute of the Technical
205 University of Berlin.

206 The supply air was introduced via a vertical low-turbulence displacement flow (TAV) over the entire
207 ceiling area of $4.8 \times 4.8 \text{ m}^2$. The supply air velocity was 0.3 m/s and thus prevented thermal lift at the
208 people. The exhaust air was also discharged from the room over the entire surface via a raised floor. The
209 room temperature was $295.15 \text{ K} \pm 0.50 \text{ K}$, the relative humidity was $40 \% \pm 2 \%$ and the room had 15 Pa
210 overpressure to the surrounding rooms.

211 The actual test stand was located in this highly pure environment (Fig. 5). It consisted of a glass
212 pipe, in which a constant airflow of $400 \text{ m}^3/\text{h}$ was generated by a filter fan unit (Ziehl-Abegg, Künzelsau,
213 Deutschland). The measuring probe of a laser particle counter (Lighthouse Solair 3100 E, Lighthouse
214 Worldwide Solutions, Fremont, CA) was placed centrally in the pipe.

215 The particle counter was counting with a volume flow $\dot{V}_{PC}$ of 28.3 l/min , with a measuring time of 10
216 seconds each and detected particles in six size classes: $> 0.3 \mu\text{m} - 0.5 \mu\text{m}$, $> 0.5 \mu\text{m} - 1.0 \mu\text{m}$, $> 1.0 \mu\text{m} -$
217 3.0 , $> 3.0 \mu\text{m} - 5.0 \mu\text{m}$, $> 5.0 \mu\text{m} - 10 \mu\text{m}$ and $> 10 \mu\text{m}$.

218 The emission rate P_M presented in Figs. 2 – 4 was computed based on the measured particle concentra-
219 tion c_M and the volume flow through the filter fan unit (FFU) $\dot{V}_{FFU}$, i.e.

$$P_M = c_M \cdot \dot{V}_{FFU}. \quad (1)$$

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

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

227 The counting efficiency for particles of the size $0.3 \mu\text{m}$ is $50 \% \pm 20 \%$ and for particles of the size
228 $0.5 \mu\text{m}$ it is $100 \% \pm 10 \%$ according to ISO 21501-4. To investigate how many particles were separated

229 over the measuring distance, comparative measurements were made over a short distance from the particle
230 counter. For this case, the particles were directly collected through a 150 mm high funnel while breathing
231 and speaking and directed to the particle counter. The same size distribution was found as in the finally
232 used configuration.

233 **Audio measurements**

234 The sound pressure level was determined using a calibrated sound level meter (CENTER 322_ Datalogger
235 Sound Level Meter, Center Technologies, Houston, TX). During all measurements, the sound level meter
236 was located approximately 60 cm anterior-laterally away from the mouth of the test persons due to limited
237 accessibility. The measuring arrangement of the particle counter did not allow a standard positioning of
238 30 cm mouth distance of the measuring device. Furthermore, the high sensitivity of the particle counter did
239 not allow a frontal positioning of the sound level meter inside the glass tube. Consequently, the determined
240 levels were not to be considered as absolute levels but are lowered by a constant value of approx. 10 dB
241 SPL.

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

245 **Test conditions**

246 The subjects were in a sitting position at the entry of the particle measurement setup. Two experiments
247 were carried out:

248 Experiment I: Comparison of three different test conditions

- 249 a) Breathing through the mouth
- 250 b) Reading a standardized text
- 251 c) Singing a line of a four-part choral movement

252 Experiment II: Singing a sustained vowel (/a/) at three loudness conditions

- 253 a) piano
- 254 b) mezzo-forte

c) forte

For experiment I, respectively, a time window of 50 seconds was analyzed. Further, for experiment II the time window was set to 10 seconds. For reading in a comfortable loudness condition (Ib), the text “Der Nordwind und die Sonne” by Äsop was selected. To pass Ic) 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 all tasks were repeated five times.

The following pitches were selected for experiment II: 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.

Statistical Analysis

Besides the description of the data, a confirmative analysis was carried out. Therefore, a linear mixed effects analysis of the relationship between $\log_{10}P_M$, gender, condition and subject was performed by means of the freely available software package R³⁰ including the package lme4^{31,32}. The model used was

$$\log_{10}P_M \sim \text{Condition} + \text{Gender} + (1 + \text{Condition}|\text{Subject}) + (1 + \text{Gender}|\text{Subject}) \quad (2)$$

(R model syntax). Condition and gender were incorporated as fixed effects into the model. Intercepts for subject were incorporated as random effects. To keep the model maximal³³, by--subject random slopes for the effect of gender and condition were additionally incorporated as random effects. The interaction term between condition and gender was identified as not significant and therefore not regarded. Careful visual inspection of residual-plots and Q-Q-plots did reveal obvious deviations from homoscedasticity and normality. Therefore, log-transform of P_M was considered which overcomes these problems. To avoid infinite values in the analyses, only $P_M > 0$ were taken into account. To test significance, the P-values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question. For this reason, linear mixed models were fit by maximum likelihood to enable comparison.

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356 **Acknowledgements**

357 We thank the members of the RIAS Kammerchor Berlin for their support.

358 **Author contributions statement**

359 D. M., M. F., and M. K. designed research. J. L., H. R. and M. F. made measurements. M. F., J. L., D. M.
360 and M. K. wrote the paper.

361 **Additional information**

362 The authors declare no competing interest.

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 $\leq 5\ \mu m$ (dashed line). Furthermore all tasks show that $> 80\%$ of all particles are $\leq 1\ \mu m$.

Figure 2. Boxplots of the emission rates (bars represent the median) for different gender, voice classifications and the test conditions breathing, speaking and singing in experiment I (left y-axis). Only particles $\leq 5 \mu\text{m}$ were considered. For singing, the maximum sound pressure levels L_{AF_MAX} are also shown (full circles, right y-axis).

Figure 3. Boxplots of the emission rates (bar represents the median) for different gender, voice classifications and vocal loudness conditions while sustaining the vowel /a/ (Experiment II) (left y-axis). Only particles $\leq 5 \mu\text{m}$ were considered. For the different loudness conditions, the maximum sound pressure levels L_{AF_MAX} are also shown (full circles, right y-axis).

Figure 4. Relationship between emission rate and the maximum sound pressure level for the test condition of sustained vowel /a/ (Experiment II) for all three loudness conditions separated by gender including linear regression of the logarithmic emission rates (black line). Only particles $\leq 5 \mu\text{m}$ were considered. The grey field represents the sound pressure level resulting from the environmental conditions (primarily particle counter) alone.

Figure 5. Left: Schematic test setup with one person in cleanroom clothing whose exhaled air was recorded by the particle counter. The glass measuring section was 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.¹²).

Table 1. Minimum, maximum, and median values of emission rates in P/s for breathing, speaking, and singing

ID	breathing			speaking			singing		
	Min	Median	Max	Min	Median	Max	Min	Median	Max
S1	4.71	4.71	310.46	136.46	390.84	677.64	946.24	1552.39	2666.86
S2	84.72	428.55	508.16	14.13	61.24	84.72	5370.32	6095.37	7177.94
S3	14.13	14.13	18.84	32.96	61.24	79.98	1399.59	1761.98	2009.09
S4	4.71	28.25	183.65	164.82	296.48	570.16	1256.03	1761.98	1954.34
S5	9.42	11.53	28.25	42.36	70.63	84.72	630.96	753.36	997.70
S6	4.71	56.49	457.09	4.71	14.13	37.67	734.51	860.99	970.51
S7	4.71	12.47	131.83	28.25	47.10	84.72	881.05	1078.95	1253.14
S8	4.71	6.67	32.96	122.46	127.06	805.38	941.89	1520.55	1694.34

Table 2. Ratios of medians of emission rates for different test and loudness conditions

ID	Speaking/breathing	Singing/breathing	Singing/speaking	Forte/piano	Forte/mezzoforte
S1	82.99	329.61	3.97	60.81	6.61
S2	0.14	14.22	99.54	19.86	1.46
S3	4.34	124.74	28.77	114.29	2.50
S4	10.50	62.37	5.94	41.98	6.00
S5	6.12	65.31	10.67	0.84	1.46
S6	0.25	15.24	60.95	3.40	1.55
S7	3.78	86.50	22.91	40.36	1.59
S8	19.05	228.03	11.97	44.46	6.35

Table 3. Minimum, maximum, and median values of emission rates in P/s for piano, mezzoforte, and forte

	piano			mezzoforte			forte		
ID	Min	Median	Max	Min	Median	Max	Min	Median	Max
S1	23.55	33.27	494.31	235.50	306.20	588.84	1389.95	2023.02	2710.19
S2	23.55	188.36	353.18	1106.62	2564.48	3365.12	2094.11	3741.11	8609.94
S3	47.10	70.63	117.76	1294.20	3228.49	5248.07	6729.77	8072.35	10303.86
S4	23.55	94.19	353.18	588.84	659.17	729.46	3605.79	3953.67	5176.07
S5	353.18	447.71	517.61	211.84	258.82	376.70	164.82	376.70	824.14
S6	141.25	235.50	753.36	399.94	517.61	776.25	588.84	799.83	1294.20
S7	23.55	70.63	918.33	1531.09	1790.61	3061.96	2238.72	2851.02	5714.79
S8	23.55	47.10	376.70	94.19	329.61	588.84	1648.16	2094.11	3622.43