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Characterizations of particle size distribution of the droplets exhaled by sneeze

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This work focuses on the size distribution of sneeze droplets exhaled immediately at mouth. Twenty healthy subjects participated in the experiment and 44 sneezes were measured by using a laser particle size analyser. Two types of distributions are observed: unimodal and bimodal. For each sneeze, the droplets exhaled at different time in the sneeze duration have the same distribution characteristics with good time stability. The volume-based size distributions of sneeze droplets can be represented by a lognormal distribution function, and the relationship between the distribution parameters and the physiological characteristics of the subjects are studied by using linear regression analysis. The geometric mean of the droplet size of all the subjects is 360.1 μm for unimodal distribution and 74.4 μm for bimodal distribution with geometric standard deviations of 1.5 and 1.7, respectively. For the two peaks of the bimodal distribution, the geometric mean (the geometric standard deviation) is 386.2 μm (1.8) for peak 1 and 72.0 μm (1.5) for peak 2. The influences of the measurement method, the limitations of the instrument, the evaporation effects of the droplets, the differences of biological dynamic mechanism and characteristics between sneeze and other respiratory activities are also discussed.

1. Introduction

Respiratory infectious diseases, such as influenza and severe acute respiratory syndrome (SARS), are threatening the life of humans around the world. In 1918–1919, the outbreak of Spanish flu (H1N1) caused more than one billion infections and was considered as the most lethal flu pandemic of the twentieth century [1]. During the early twenty-first century, more than eight thousand people were infected by SARS and 774 of them died [2]. Almost four million deaths owing to respiratory infectious diseases and 1.5 million deaths owing to tuberculosis were reported every year [3]. In modern world, respiratory infectious diseases can cause lots of deaths and economic losses, and the significant disruption of social and economic areas will remain much longer even though the outbreak of the diseases ends.

Respiratory infectious diseases can be spread by direct and indirect contacts or airborne transmission [4]. Direct contact of droplet spray produced by coughing, sneezing or talking involves relatively large droplets containing organisms and requires close contact usually within 1 m [5]. Indirect contact may take place after the droplets are removed from the air by surface deposition [6]. Airborne transmission is a major disease transmission mode of respiratory infectious diseases in indoor environments [7,8]. This mode may take place by inhaling the droplets exhaled by respiratory activities or their residues after evaporation [9–14]. These droplets exhaled by infected patients may carry microorganisms and infect other people [15].

By using computational fluid dynamics (CFD) simulation, the dispersion and deposition of the expiratory droplets can be predicted [16–20]. The results indicate that the characteristics of dispersion and deposition of the expiratory droplets are highly dependent upon droplet size [6,21,22]. The size of the droplets can

also influence the possibility of spread of infectious diseases [15,23,24]. Therefore, accurate measurements of the size distribution of expiratory droplets are strongly needed for protection strategy formulation including ventilation system design and infection control planning [14,17,18].

For the size distribution of the expiratory droplets, substantial literature showed the droplet size distribution of cough [25–32], sneeze [26,27,33,34], speech [14,32,35] and breath [25,29,32, 36–41] as well as the concentration and number of the droplets [28,29,42–44]. Table 1 summarizes the method (technology), subjects and results (size range) of the previous literature. Though different methods were employed in these studies, the results were significantly inconsistent. There were also some common problems existing in previous studies, namely the influence of the measurement method, the experimental device and the evaporation effects [4,14,35,45–47].

Sneeze is a common exhalation mode in respiratory tract diseases. Respiratory infectious diseases may cause mucous production, which in turn stimulates various nerves within the nasal mucous membranes and results in sneeze. The biological dynamic mechanism of sneeze is significantly different from that of other respiratory activities. The velocity of the airflow exhaled by sneeze is much larger than that of breath and cough [48–50]. The total number of droplets generated during sneeze is also larger than that of other respiratory activities [26]. Until now, studies on the size distribution of sneeze droplets are still rare [45,51].

In this work, the size distribution of sneeze droplets was measured by using a laser particle size analyser. The measurement was carried out immediately at mouth to reduce the effects of evaporation [35]. A quantitative method was proposed to represent the volume-based size distribution and calculate the number proportion of sneeze droplets. The distribution function and its characteristic parameters were also studied.

2. Material and methods

2.1. Subjects

Twenty healthy subjects including 10 males and 10 females were recruited to participate in the experiment. These subjects were university students and postgraduate students from Tsinghua University, around 16–25 years old. All the subjects had no history or evidence of significant pulmonary diseases (e.g. cystic fibrosis, chronic obstructive pulmonary disease or severe asthma). Smokers and students who had recently experienced respiratory problems or were likely to feel discomfort in confined spaces were excluded. Physiological characteristics including gender (M/F), age (years), height (metres), weight (kilograms) and forced vital capacity (FVC, ml) of these subjects were recorded by face to face interviews and measurements. These physiological characteristics of the subjects are shown in table 2. The means (standard deviations) of age, height, weight and FVC for all the subjects are 21 years (2 years), 1.72 m (0.09 m), 62 kg (15 kg) and 4061 ml (1087 ml), respectively.

2.2. Experimental instrument and principle

In this work, a laser particle size analyser, the 'Spraytec system' (Malvern Instruments Ltd, UK) was used to measure the size distribution of sneeze droplets. This system has been widely used in the measurements of aerosol size distribution [52–55]. Figure 1 shows the measurement set-up of the Spraytec system. During the measurements, a laser beam that passed through the measurement zone was produced by a helium–neon laser transmitter. The diameter of the laser beam was about 0.015 m. Thirty-two detecting optical sensors were installed in the receiver module to detect the light diffraction pattern induced by the spray. The light diffraction pattern was analysed by using a scattering model, and then the size distribution of the spray was calculated by the system. By using a lens with focal length of 0.3 m, the size range that the Spraytec system could measure was from 0.1 to 1000 μm including 60 channels, and the instrumental error was less than 1%. In each measurement, all the droplets ranging from 0.1 to 1000 μm were measured, and the calculated size distribution was recorded immediately. In this experiment, the sampling frequency was set as 2.5 kHz, which means the size distribution of the spray was measured and recorded every 0.4 ms. This sample frequency was high enough to make sure that the measurement was a real-time data acquisition process, and the measured data were also able to be recorded in time.

By using the Spraytec system, the volume-based size distribution can be obtained, which is the ratio of the volume of all the particles with the diameters in each size range and the total volume of all the particles with any diameter in the spray. Assuming that all the droplets exhaled by sneeze are spherical, then the number size distribution which is the ratio of the number of all the particles with diameters in this size range and the total number of all the particles with any diameter in the spray can be calculated as follows:

$$P_{n,i} = \frac{N_i}{N} = \frac{P_{V,i} \cdot V \cdot (\frac{1}{6}\pi D_i^3)^{-1}}{\sum_i P_{V,i} \cdot V \cdot (\frac{1}{6}\pi D_i^3)^{-1}} = \frac{P_{V,i} D_i^{-3}}{\sum_i P_{V,i} D_i^{-3}}, \qquad (2.1)$$

where $P_{n,i}$ is the number size distribution of sneeze droplets. N_i is the total number of the droplets in size class i, $i = 1, 2, \ldots, n$. N is the total number of all the droplets. V is the total volume of all the droplets. D_i is the geometric mean of size class i, μm. $P_{V,i}$ is the ratio of the volume of all the particles with diameters in size class i and the total volume of all the particles with any diameter in the spray, %.

2.3. Measurement protocol

The experiments with volunteers and the use of the laser particle size analyser were approved by the Human Subjects Committee of Tsinghua University. All the measurements were carried out in an indoor test room during the daytime. During the experiment, the room temperature was 23–24°C and the relative humidity (RH) was 32–33%. Adequate ventilation was provided by the ventilation system located on the ceiling of the test room. Fresh air was supplied by the ventilation system to keep the air circulation in the test room. The velocity of the airflow in the experimental environment was small and could not be felt by the subjects (less than 0.05 m s^{-1}). Before each measurement of sneeze droplets, the background particles in the measurement environment were measured first, which was also a part of the standard operating procedure (SOP) of the Spraytec system. The measurements of the background particles lasted for 15 s and the size distribution of all the background particles was measured $15 \times 2500 = 37\,500$ times. Then, the average of the 37 500 size distributions was calculated and recorded automatically by the Spraytec system as the size distribution of the background particles. In the measurement of sneeze droplets, the size distribution of the background particles was excluded from the measured results of sneeze droplets by the Spraytec system automatically. So the Spraytec system directly gave the size distribution of sneeze droplets with background particles excluded. In addition, if the subjects did not sneeze successfully within 15 s after the measurement of the background particles, the SOP would be restarted and the background particles would be measured again.

Before the experiment, the subjects were asked to drink water, gargle and take a rest. Snuff, small cotton swabs, soft hair and wools were supplied to the subjects for inducing sneezes. The snuff used in this work was made in the form of skin lotion

Table 1. Previous literature on droplet size distribution of respiratory activities.

author, reference	method or technology	subjects	respiratory behaviours	results
Jennison [33]	high-speed photograph	—	cough and sneeze	most droplets ranged from 7 to 100 μm
Duguid [25,26]	solid impaction (celluloid-surfaced slide for collection)	one healthy subject	cough and sneeze	size ranged between 1 and 2000 μm and 95% were between 2 and 100 μm
Buckland & Tyrrell [34]	liquid impaction (impinger)	two subjects infected with unknown bacteria	cough, sneeze and speech	size ranged from 50 to 860 μm, and 76% were between 80 and 180 μm
Gerone *et al.* [27]	solid impaction (chamber for collection)	one patient infected with coxsackievirus A	cough and sneeze	most were less than 1 μm (large droplets not measured)
Loudon & Roberts [28]	solid impaction (chamber with bond paper for collection)	three healthy subjects	cough and speech	geometric mean of 55.5 μm for cough and 85 μm for speech
Papineni & Rosenthal [29]	solid impaction (glass slide for collection) and optical technology (optical particle counter)	five healthy subjects	cough	85% of the particles had diameters of less than 1 μm
Fennelly *et al.* [30]	cough aerosol sampling system and solid impaction	16 patients infected with tuberculosis	cough	most particles were in the respirable size range
Hersen *et al.* [15]	electrical impaction (electrical low pressure impactor)	35 healthy subjects and 43 patients	cough	the number and size of the droplets that exhaled by infected subjects and healthy subjects are different
Edwards *et al.* [36]	optical technology (optical particle counter)	12 patients infected with influenza	breath	size range from 0.15 to 0.19 μm
Yang *et al.* [31]	time-of-flight technology (aerodynamic particle size) and charge separation (scanning mobility particle sizer)	54 healthy subjects	cough	size range from 0.62 to 15.9 μm with the average mode of 8.35 μm
Fabian *et al.* [37]	optical technology (optical particle counter)	12 patients infected with influenza	breath	over 87% of particles exhaled were under 1 μm in diameter
Chao *et al.* [35]	interferometric Mie imaging technique	11 healthy subjects	cough and speech	geometric mean of 13.5 μm for cough and 16 μm for speech
Johnson *et al.* [32]	aerodynamic particle sizer and droplet deposition analysis	17 healthy subjects	breath and speech	a BLO tri-modal model was found for the droplet size distribution
Xie *et al.* [14]	solid impaction (glass slide with microscopy) and optical technology (dust monitor)	seven healthy subjects	cough and speech	average size is about 50 to 100 μm
Fabian *et al.* [44]	optical technology (optical particle counter)	three healthy subjects and 16 patients infected with human rhinovirus	breath	82% of particles detected were 0.300–0.499 mm.

Table 2. Physiological characteristics and sneeze number of each subject.

no.	gender (M/F)	age (years)	height (m)	weight (kg)	FVC (ml)	number of sneezes
1	M	24	1.72	70	4500	2
2	M	21	1.81	73	6500	1
3	M	25	1.82	75	5000	1
4	M	25	1.85	104	5000	5
5	M	21	1.8	65	4000	2
6	M	21	1.85	75	5100	1
7	F	22	1.63	48	3250	2
8	F	19	1.68	57	2980	2
9	M	20	1.8	76	4500	3
10	F	21	1.64	54	3300	2
11	F	20	1.63	49	3690	3
12	M	20	1.75	67	5200	2
13	F	21	1.58	42	2920	2
14	F	16	1.71	56	3250	2
15	F	20	1.62	49	2750	1
16	M	20	1.77	70	5980	1
17	M	19	1.81	70	4130	3
18	F	21	1.65	53	3240	3
19	F	21	1.65	45	3220	1
20	F	20	1.65	48	2700	5

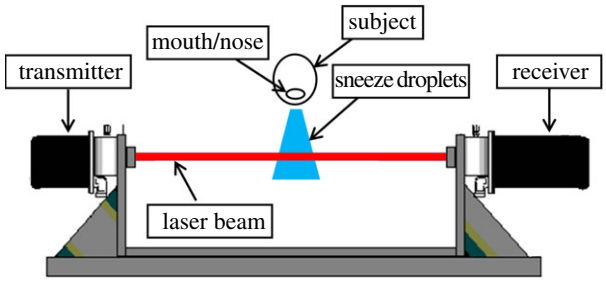

Figure 1. Measurement set-up of the Spraytec system. (Online version in colour.)

which had been widely used in ancient East Asia. During the experiment, it was stirred well as skin lotion or moisturizer and spread evenly in the nasal vestibule. Sneeze was induced by the pungent odour which smelt like mint. When using it, it was not in the form of powder or smoke and would not disperse in the room air. The cotton swabs used in this work were normal cotton swabs, with cotton on wooden sticks (about 5–6 cm in length, 0.5–0.7 cm in diameter). The soft hair and wools used in this work were long (about 5 cm in length) but tiny with a small diameter. Sneeze was induced by the physical stimulation inside the nasal cavity. After each measurement, the cotton swabs, soft hair and wools were still held in the subjects' hands, so they would not affect the measurement results. The subjects were free to choose any of these materials to induce a sneeze. During the experiment, the subjects were allowed to take a brief rest, drink water, gargle and wash face whenever they needed. After each measurement, there was a break which lasted at least 5 min for the subjects to have a rest. The duration of this break was also long enough for the removal of the dispersed particles of the original sneeze. After the break, the subjects were asked to sneeze again and the measurement was repeated following the same protocol. The repeated measurement would not begin until the subjects were ready. Therefore, the subjects were well prepared before each sneeze and the sneeze behaviours were almost the same. Before the repeated measurement, the background particles were also measured and recorded.

In each measurement, the subjects were asked to stand comfortably in the correct position with mouths right towards the laser beam and close to the measurement zone. Before each sneeze, the distance between the mouths of the subjects and the laser beam was measured and kept around 0.05 m. The head of the subjects was not firmly fixed, because the firmly fixed situation may make the subjects feel uncomfortable and result in changes of sneeze behaviour. During the measurement, there was no collection device (i.e. slide, mask or other sampler) used for avoiding the influences of the collection device.

3. Results

3.1. Distribution characteristics of volume-based size distribution

In the experiment, six subjects sneezed once and 14 subjects sneezed twice or more times. There were altogether 44 sneezes measured in the experiment. The mean (standard deviation) of the numbers of sneezes of all the subjects is 2.2 (1.2). The sneeze number of every subject is presented in table 2. By observing the measured results, two types of volume-based size distributions of sneeze droplets are found: unimodal and bimodal, as shown in figures 2 and 3. Twenty-one sneezes have unimodal volume-based size distributions, and 23 sneezes have bimodal size distributions, and the ratio is 1 : 1.1. Of the subjects, 12 have unimodal volume-based size distributions and 11 have bimodal

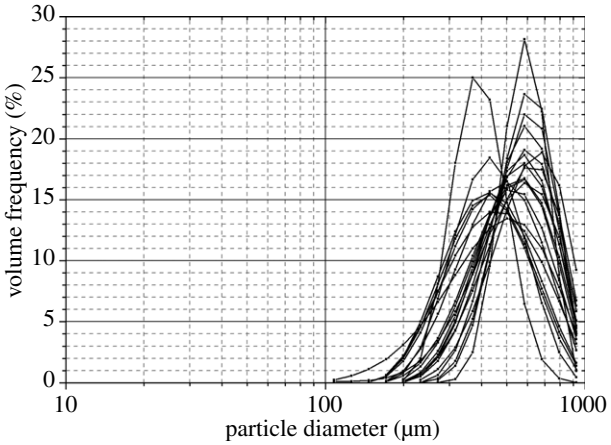

Figure 2. Unimodal distribution measured in the experiment (21 sneezes of 12 subjects).

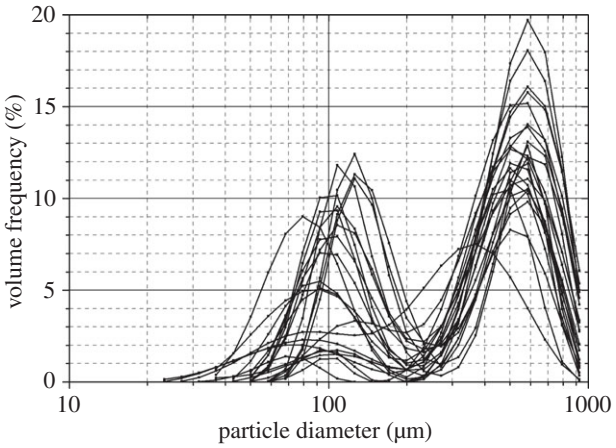

Figure 3. Bimodal distribution measured in the experiment (23 sneezes of 10 subjects).

size distributions. So there are three subjects who have both unimodal and bimodal size distributions in their sneezes: subject 4 has four unimodal distributions and one bimodal distribution, subject 14 has one unimodal distribution and one bimodal distribution, and subject 20 has one unimodal distribution and four bimodal distributions. Figure 2 shows the 21 sneezes that have unimodal distributions. Figure 3 shows the 23 sneezes that have bimodal distributions.

Based on the high sampling frequency of the Spraytec system, plenty of data were obtained and recorded. So the time stability of the droplet size distribution of every sneeze was also studied. By observing the volume-based size distributions measured at different time of each sneeze, good similarity and time stability are found both for the unimodal and bimodal distributions. So the distribution characteristics of sneeze droplets will remain almost the same in the duration of a sneeze. More detailed information can be found in the electronic supplementary material.

Until now, investigations on dynamic flow of sneezes are still rare in previous works. According to the studies on flow dynamics and characterization of cough, the maximum velocity of exhaled airflow can be found at $t = 57$–110 ms for different persons which is most likely to occur at 100 ms [49]. So in this work, the volume-based size distribution measured at 100 ms after the sneeze began was chosen as the size

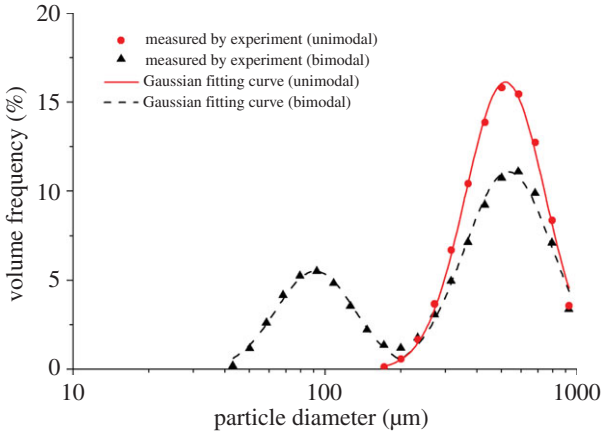

Figure 4. Measured data and fitting curves of two sample sneezes (unimodal and bimodal distributions, respectively). (Online version in colour.)

distribution of this sneeze and used for analysis. The results shown in figures 2 and 3 are the size distributions measured at $t = 100$ ms after the sneezes start. Usually, sneeze lasts 0.3–0.7 s, so $t = 100$ ms is in the duration of the sneeze. As the velocity of the airflow exhaled by sneeze is really high, it can be assumed that the droplets that are exhaled at $t = 0$–100 ms will not re-enter the measurement zone before $t = 100$ ms.

From figures 2 and 3, it can be seen that the single peak of the unimodal distribution and the two peaks of the bimodal distribution obviously meet the distribution characteristics of lognormal distribution. Therefore, each peak of the volume-based size distributions can be represented by the lognormal distribution function, as follows.

For unimodal distribution

$$P_{V,i,U} = A_U \left(\frac{1}{\sqrt{2\pi}\sigma_U} \right) e^{-(\log_{10}(D_i)-\mu_U)^2/2\sigma_U^2}. \tag{3.1}$$

For bimodal distribution

$$\left.\begin{aligned} &P_{V,i,B} = \mathrm{Max}[P_{V,i,B_1}, P_{V,i,B_2}], \\ &P_{V,i,B_1} = A_{B_1} \left(\frac{1}{\sqrt{2\pi}\sigma_{B_1}} \right) e^{-(\log_{10}(D_i)-\mu_{B_1})^2/2\sigma_{B_1}^2} \\ \text{and} \quad &P_{V,i,B_2} = A_{B_2} \left(\frac{1}{\sqrt{2\pi}\sigma_{B_2}} \right) e^{-(\log_{10}(D_i)-\mu_{B_2})^2/2\sigma_{B_2}^2}, \end{aligned}\right\} \tag{3.2}$$

where $P_{V,i,U}$ and $P_{V,i,B}$ are the ratio of the volume of all the particles with diameters in size class i and the total volume of all the particles with any diameter in the spray, %. P_{V,i,B_1} and P_{V,i,B_2} are the ratio for peak 1 and peak 2, respectively. i is the number of the size class, $i = 1, 2, \ldots, n$. The diameter range of size class i is (d_i, d_{i+1}), μm. D_i is the geometric mean of size class i, μm. μ_U, μ_{B_1}, μ_{B_2}, σ_U, σ_{B_1}, σ_{B_2}, A_U, A_{B_1}, A_{B_2} are the characteristic parameters of the lognormal distribution, for means, variances and coefficients, respectively, and $\mu_{B_1} > \mu_{B_2}$.

A nonlinear least-square curve fitting analysis is performed to obtain the optimum values of the characteristic parameters required to define the lognormal distribution function for each sneeze. The fitting results of two sample sneezes are shown in figure 4, including the measured data and the fitting curve of one unimodal distribution and one bimodal distribution. It is clear that the lognormal distribution fitting curve is capable of accurately representing the

Table 3. Lognormal distribution fitting results of the unimodal volume-based size distribution.

no.	mean μ_U	variance σ_U	coefficient A_U
1A	2.7552	0.1730	7.0469
1B	2.7480	0.1452	6.8704
2A	2.8046	0.1500	7.0463
3A	2.6822	0.2103	7.0442
4A	2.6252	0.1681	6.7221
4B	2.6413	0.1657	6.5569
4C	2.7420	0.1703	5.9714
4D	2.5917	0.1045	6.7022
9A	2.7680	0.0882	6.2960
9B	2.7914	0.0925	6.3650
9C	2.7428	0.1330	6.8488
10A	2.7779	0.1177	6.6457
10B	2.7801	0.1116	6.8133
12A	2.6323	0.1381	6.4667
12B	2.6264	0.1631	6.3996
13A	2.7342	0.1599	6.8163
13B	2.7447	0.1609	7.0530
14B	2.7155	0.1587	6.4132
15A	2.6829	0.1639	6.8879
19A	2.7761	0.1549	6.9070
20A	2.7390	0.1486	6.3150

volume-based size distributions of sneeze droplets, both for unimodal and bimodal distributions.

By using the data fitting method, the volume-based size distributions of all the 44 sneezes can be processed and fitted. Especially, the two peaks of the bimodal volume-based size distribution are divided as two single peaks and fitted, respectively. Tables 3 and 4 show the fitting results, including the means, variances and coefficients of all the sneezes. The average values (standard deviations) of the means and variances of the unimodal distributions are 2.7264 (0.0526) and 0.1523 (0.0247), respectively. For the bimodal distributions, the average values (standard deviations) of the means and variances of peak 1 are 2.7331 (0.0236) and 0.1524 (0.0231) and those of peak 2 are 1.9834 (0.0807) and 0.1644 (0.0447), respectively. In the calculation of the average values and standard deviations of the distribution parameters, the distribution parameters of the multiple sneezes from one subject are averaged before combining with those of the others. It can be seen that the means of the single peak of the unimodal distributions have the same range with the larger peak of the bimodal distributions, and the variances of the three peaks have the same range, which can be expressed as $\mu_U \approx \mu_{B_1}$ and $\sigma_U \approx \sigma_{B_1} \approx \sigma_{B_2}$.

3.2. Comparison of number size distribution

According to equation (2.1), the number size distribution of the droplets of all the 44 sneezes can be obtained, both for unimodal and bimodal distributions. Then the average number size distribution can be calculated for the two types of distributions. The average number size distributions per person are shown in figures 5 and 6, for unimodal and bimodal distributions, respectively. More details of the number size distribution can be found in the electronic supplementary material. In figures 5 and 6, the average number size distribution is the average of the results measured at 100 ms of the sneezes. As 14 subjects contributed more than one sneeze, the number size distributions of the multiple sneezes from one subject are averaged before combining with those of the others.

From figures 5 and 6, it can be seen that the size class that has the most droplets is 341.5–398.1 μm for unimodal distribution and 73.6–85.8 μm for bimodal distribution. And the geometric mean of droplet size of all the sneezes is 360.1 μm for unimodal distribution and 74.4 μm for bimodal distribution with geometric standard deviations of 1.5 and 1.7, respectively. Especially, for the two peaks of the bimodal distribution, the geometric mean is 386.2 μm for peak 1 and 72.0 μm for peak 2 with geometric standard deviations of 1.8 and 1.5, respectively. Figures 5 and 6 also show that the sneeze droplets of the unimodal distribution are much larger than those of the bimodal distribution.

Comparing with previous studies, the predominant size range of the bimodal size distribution given in this work is similar to that given by Jennison, Duguid and Buckland & Tyrrell, and much larger than the results given by Gerone *et al*. The result of the unimodal size distribution is significantly larger than that of all the previous works. For the results reported by Jennison and Buckland & Tyrrell, predominant diameter range was evaluated but no detailed size distribution was obtained [34,51]. For the results reported by Gerone *et al*., only the size distribution of the particles smaller than 15 μm was given and the particles above 15 μm in diameter were not successfully measured [27]. So the results given by Duguid are the most closely related to the current study and used for comparison, as shown in figure 5. In addition, to demonstrate the differences of size distribution of different respiratory activities, the results of this work are also compared with those of cough and speech, as shown in figures 5 and 6. As the detailed size distribution rather than the predominant size range is needed for this comparison, the results given by Duguid, Loudon & Roberts, Chao *et al*. and Xie *et al*. are chosen in which the detailed size distributions were reported [14,26, 28,35,51]. For the works using the solid impaction method, almost all the expiration droplets were measured and counted. That means that the total numbers of the droplets measured and counted in different measurements were significantly different. So the number size distribution is used in this comparison. The geometric mean of each size class is used to represent the results.

Figure 5 illustrates the comparison of the number size distribution of droplets exhaled by sneeze and speech. It shows that the result of this work is significantly larger than that measured by Duguid. According to Duguid, 34.9% of the droplets are in the range 4–8 μm, while the bimodal distribution of this work shows that 31.2% of the droplets are in the range 80–100 μm, which is similar to the result given by Buckland & Tyrrell [26,34]. As given by Duguid, more droplets with diameter smaller than 80 μm have been found based on the measurement of droplet nuclei. So the proportion of sneeze droplets in this diameter range given by Duguid is significantly larger than the result of this work. Comparing with

Table 4. Lognormal distribution fitting results of the bimodal volume-based size distribution.

	peak 1			peak 2		
no.	mean μ_{B_1}	variance σ_{B_1}	coefficient A_{B_1}	mean μ_{B_2}	variance σ_{B_2}	coefficient A_{B_2}
4E	2.6992	0.2104	6.0464	1.9034	0.2465	1.2623
5A	2.7598	0.1641	5.7726	1.9148	0.2345	1.3541
5B	2.7420	0.1703	5.9714	1.8633	0.2096	1.0838
6A	2.7223	0.1683	6.5595	1.8414	0.1099	0.3934
7A	2.7080	0.1559	5.1387	1.9744	0.1354	1.7766
7B	2.7154	0.1316	6.0027	2.1248	0.1248	6.7081
8A	2.7780	0.1431	4.4846	1.9394	0.1946	2.5307
8B	2.7452	0.1392	3.4715	1.9069	0.1460	3.3623
11A	2.7811	0.1138	3.8270	2.0535	0.1359	2.9633
11B	2.7243	0.1406	3.5679	2.1446	0.1806	1.5595
11C	2.7015	0.1851	5.8431	2.1204	0.1597	1.3867
14A	2.7170	0.1297	3.9804	2.0058	0.1123	2.7410
16A	2.7629	0.1545	6.3267	1.9974	0.1616	0.6949
17A	2.7576	0.1425	6.5223	1.9788	0.0963	0.4351
17B	2.7637	0.1330	6.6521	1.9955	0.0759	0.2639
17C	2.7606	0.1631	6.4701	2.0253	0.1754	0.6731
18A	2.7517	0.1012	3.2626	2.1032	0.1088	3.3664
18B	2.7258	0.1154	3.4791	2.1207	0.1183	3.2220
18C	2.7377	0.1361	3.5040	2.0455	0.1378	3.2362
20B	2.7283	0.1472	3.8752	2.0187	0.1455	2.9316
20C	2.6574	0.1314	3.4873	2.0642	0.1116	3.2493
20D	2.7279	0.1763	4.8957	1.9615	0.1557	2.1520
20E	2.7005	0.1491	4.3855	2.0012	0.1355	2.4474

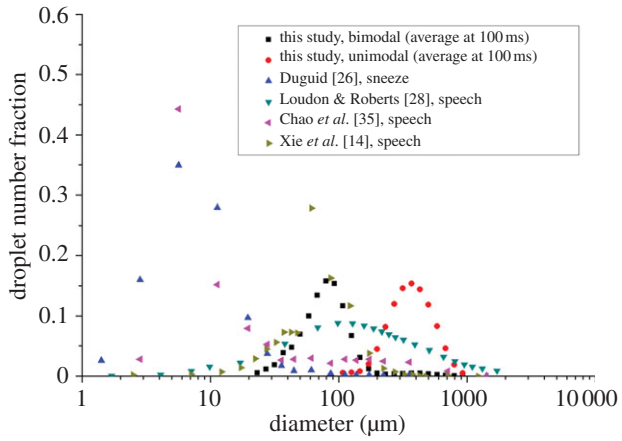

Figure 5. Comparison of the number size distribution of the droplets exhaled by sneeze and speech. (Online version in colour.)

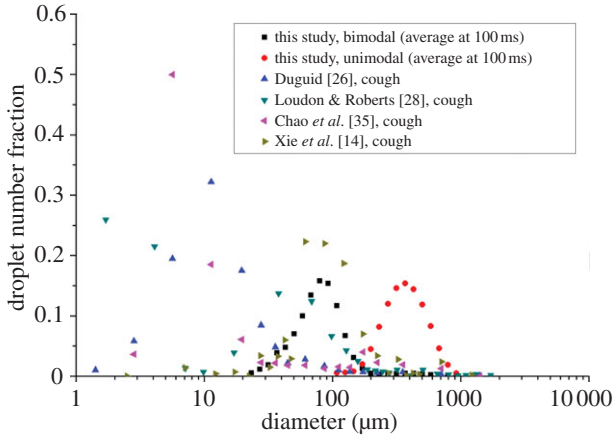

Figure 6. Comparison of the number size distribution of the droplets exhaled by sneeze and cough. (Online version in colour.)

the number size distribution of speech, it can be seen that the predominant droplet size range of the bimodal distribution of this work is significantly larger than the result of Chao *et al.* and smaller than the result of Loudon & Roberts [28,35]. And figure 5 also indicates a good similarity between the profiles of the bimodal distribution of this work and the result given by Xie *et al.* [14]. However, the droplet size of the unimodal distribution is much larger than that of all the other works. Figure 6 illustrates the comparison of the number size distribution of droplets exhaled by sneeze and cough. Similar predominant particle size range can be found between the bimodal distribution of this work and the results given by Loudon & Roberts and Xie *et al.* but more droplets are found in the size range of 5–20 μm according to the results

of Chao *et al*. and Duguid. Many reasons may cause these significant differences.

3.2.1. The effects of evaporation

After the droplets are exhaled into the indoor environment, the evaporation effects will strongly influence the size and mass of the droplets. The final equilibrium diameter of expiratory droplets after evaporation is highly dependent upon the temperature and RH of the environment [45,47,56]. In the indoor environment, the RH and temperature are much lower than those in the respiratory tract. So the volatile content of these droplets will keep evaporating and result in the shrinkage of the droplets. For the measurements of Duguid, the celluloid-surfaced slide was held at 6 inches in front of mouth. This distance was long enough for evaporation and a change in the size distribution of the droplets [35,45]. For the measurements of Loudon & Roberts [28], the subjects coughed into a chamber in which bond paper was placed to collect the droplets. After the cough, the chamber was sealed for 30 min to permit particles to deposit onto surfaces, which was long enough for complete evaporation. For the measurements of Xie *et al*., the subjects also coughed into a chamber which was similar to that used by Loudon & Roberts, and each measurement took up to 20 min and the evaporation effects may also influence the measured results of the droplet size [14,28]. For the measurements of Chao *et al.* [35], the droplets were measured immediately at mouth, so the evaporation effects may have much less influence on the measurement results. In this work, to reduce the effects of evaporation, the measurements were carried out immediately at mouth when the droplets were exhaled. The distance between the mouths of the subjects and the laser beam was quite small. So the evaporation of the droplets had limited effects on the measurement results of this work, which was much less than that of Duguid, Loudon & Roberts and Xie *et al.* and similar to that of Chao *et al*.

3.2.2. The difference of measurement method

Different measurement methods also influence the results. For the measurements of Duguid, Loudon & Roberts and Xie *et al*., the solid impaction method was used. In their studies, the collection device (celluloid-surfaced slide, paper and glass slides) changed the shape of the droplets so the size distribution of the droplets was inaccurate [51]. And also, Duguid applied a potentially incorrect evaporation correction and was not reported in enough details for an appropriate adjustment to be retrospectively applied to the reported data. The two data produced by different techniques were combined together without explaining or justifying the approach [32]. For the measurements of this work, no collection device was used and the droplets would not be impacted by anything before they were measured.

When using solid impaction method, dye was introduced into the mouth of the subjects during measurements. This dye might influence the formation of secretions in the mouth of the subjects and make the respiratory activities 'unnatural' [14]. So the respiratory behaviours of the subjects might be influenced by physiological factors. Then the size distribution and the total number of the droplets exhaled by respiratory activities might also be changed. In this work, no dye was used in the measurement and the sneeze behaviour was not disturbed by any interfering factors.

3.2.3. The differences of biological dynamic characteristics and atomization mechanism

Atomization process is the main reason for droplet formation in respiratory activities [4]. Air-jet atomization, which is the interaction of a high-velocity airstream with that of a relatively slow moving flow of liquid, may occur in the respiratory tract. This atomization process is also governed by many physical forces including surface tension, viscosity and aerodynamic forces [4]. The size of the droplets formed in atomization processes is highly dependent upon the aerodynamic characteristics of the injection system.

For human respiratory activities, different respiratory behaviours may have significantly different biological dynamic characteristics. The maximum velocity of the exhaled airflow of sneeze is around $30–100\ \mathrm{m\ s^{-1}}$, significantly larger than that of cough, breath and speech [19,27,48]. Turbulence can be induced in the respiratory tract by this high-speed airflow and results in the differences in atomization processes of respiratory fluid [29,32,42]. As given by Lasheras *et al*. [57], higher moving speed of the fluid water in a round water jet resulted in larger mean droplet size. So it can be expected that respiratory behaviours with larger exhaled airflow velocity may result in larger exhaled droplets. The high-speed airflow and corresponding turbulence produced by sneeze may also lead to a large number of droplets [32], i.e. the number of the droplets generated by sneeze is about 18 times larger than that of cough [27].

A comprehensive knowledge of the aerosol generation process during respiratory activities including the aerosol size distribution, the droplet production mechanisms and the corresponding sites of production within the respiratory tract is important and helpful for the investigation of disease transmission [32,36]. Studies on the atomization mechanism of droplet formation in respiratory tract and the aerodynamic characteristics of different respiratory activities are still strongly needed. The corresponding theory may also be helpful to explain the formation mechanism of the two types of size distributions of sneeze droplets found in this work.

4. Discussion

4.1. Distribution parameter evaluation and calculation

As shown in tables 3 and 4, the distribution parameters of the size distributions of different subjects are different and the standard deviations are not significantly small. So it can be expected that the distribution characteristics of sneeze droplets of different subjects may be dependent upon the physiological characteristics of the subjects. In this work, the relationships between the distribution parameters of the volume-based size distributions and the physiological characteristics of the subjects are investigated. By using linear regression analysis, the p-value and adjusted R^2-value can be obtained to test the significance level and goodness of the fitting results. As many subjects contributed more than one sneeze, the average values of the means and variances of the multiple sneezes of one subject were used in the linear regression analysis.

By observing the fitting results of linear regression analysis, it seems the distribution parameters of the unimodal distributions have no significant correlation with the physiological characteristics of the subjects. The p-values for the means and variances with the heights, weights and FVCs

are all larger than 0.24 and the adjusted R^2-values are all quite small. For the bimodal distributions, significant correlation can be found between the variances of peak 1 and the heights and weights of the subjects (p-value < 0.02), and also between the means of peak 2 and the heights and weights of the subjects (p-value < 0.04). Therefore, by using the linear regression analysis, the optimum values of the variables required to define the functions can be obtained:

$$\left.\begin{aligned}&\sigma_{B_1} = 0.1920H - 0.1798\ (p\text{-value} = 0.0168, \text{adjusted } R^2 = 0.4313)\\ &\text{or}\\ &\sigma_{B_1} = 1.22 \times 10^{-3}W - 7.75 \times 10^{-2}\ (p\text{-value} = 0.0012, \text{adjusted } R^2 = 0.6733),\end{aligned}\right\} \tag{4.1}$$

$$\left.\begin{aligned}&\mu_{B_2} = -0.7552H + 3.2898\ (p\text{-value} = 0.0042, \text{adjusted } R^2 = 0.5736)\\ &\text{or}\\ &\mu_{B_2} = -3.22 \times 10^{-3}H + 2.1866\ (p\text{-value} = 0.0359, \text{adjusted } R^2 = 0.3363),\end{aligned}\right\} \tag{4.2}$$

where H is the height of the subjects (metre), W is the weight (kilogram) and V is the FVC (millilitre). The fitting results and the corresponding parameters can be found in the electronic supplementary material, with the p-value and adjusted R^2-value included.

By using equations (4.1) and (4.2), the distribution parameters of σ_{B_1} and μ_{B_2} can be calculated. For approximate estimation of the size distribution, the average values of the distribution parameters can be used: $\mu_U = 2.7264$, $\sigma_U = 0.1523$; $\mu_{B_1} = 2.7331$, $\sigma_{B_1} = 0.1524$; $\mu_{B_2} = 1.9834$, $\sigma_{B_2} = 0.1644$. And the coefficients of the distributions can also be calculated according to the means and variances.

For the unimodal distribution, the sum of the volume frequency in all the size classes is 1 (100%), so the coefficient of the unimodal distribution can be calculated according to the mean and variance, as follows:

$$A_{\mathrm{U}} = 100\sqrt{2\pi}\sigma_U \cdot \left(\sum_{i=1}^{n} \mathrm{e}^{-(\log_{10}(D_i)-\mu_U)^2/2\sigma_{\mathrm{U}}^2}\right)^{-1}. \tag{4.3}$$

For the bimodal distribution, the ratio of the average of the coefficients of the two peaks is 3 according to table 4. So the coefficients A_{B_1} and A_{B_2} of the two peaks of the bimodal distribution should be first evaluated according to equation (4.3), respectively (as A'_{B_1} and A'_{B_2}), and then re-scaled based on the ratio of 3, as follows:

$$A_{B_1} = \frac{3A'_{B_1}A'_{B_2}}{3A'_{B_2} + A'_{B_1}} \quad \text{and} \quad A_{B_2} = \frac{A'_{B_1}A'_{B_2}}{3A'_{B_2} + A'_{B_1}}. \tag{4.4}$$

In general, the volume-based size distribution of sneeze droplets of an adult can be calculated by using equations (3.1) and (3.2). The distribution parameter needed in equations (3.1) and (3.2) can be approximately estimated by using equations (4.1)–(4.4) or by using the average values of the distribution parameters as mentioned above. Then the number size distribution can be calculated according to equation (2.1).

4.2. Uncertainties and limitations

In this work, the size distribution measured by the laser particle size analyser is in the form of the volume-based size distribution. Larger droplets account for greater proportion in the volume-based size distribution than smaller ones, because the volume of the droplets is in direct proportion to the cube of diameter. So, if the size of the droplets covers a wide range, i.e. the diameter of the large droplets is $O(10^2)$ larger than the small droplets (just like the size range of sneeze droplets), and the numbers of the large and small droplets are the same, then the total volume of the large droplets will be $O(10^6)$ greater than that of the small ones (assuming that the shape of the particles is spherical). As the instrumental error of the measurement system is 1%, the instrumental error will account much more in the volume proportion of the small droplets. It will be difficult to give the volume frequency of these small droplets because the total volume of the small droplets is too small [45]. As shown in figures 2 and 3, the volume frequency of the sneeze droplets with a diameter smaller than 20 µm is quite small. And this small volume frequency may lead to a significant uncertainty in the calculation results of the number size distribution of small droplets. Therefore, although the volume-based size distributions measured in the experiment are accurate, the number size distribution may not be accurate enough especially for the small droplets. In addition, the volume frequency of the small droplets can be estimated according to the volume-based size distribution by using equations (3.1)–(4.4) and then the number proportion of the small droplets can be calculated.

Before each sneeze, the distance between the mouth of the subjects and the measurement zone is measured and kept around 0.05 m. However, for avoiding making the subjects feel uncomfortable and influencing the sneeze behaviour, the heads of the subjects are not fixed firmly. It is also difficult to keep the mouth exactly 0.05 m away from the measurement zone during each sneeze. The changes of distance between the mouths of the subjects and the laser beam may also increase the uncertainty. Comparing with that of previous work (2–6 inches or slide in the bottom of chamber), 0.05 m is short enough.

During the measurement, because the plume flow exhaled by sneeze disperses quickly, it is difficult to make sure that all the sneeze droplets successfully pass through the measurement zone of the laser particle size analyser. It implies the assumption that the size distribution of sneeze droplets in different areas of the plume is similar. This assumption may lead to an uncertainty in the calculation of the size distribution. Instruments or technology with larger measurement zone will be a great help to reduce this uncertainty. Experiments that measure and compare the size distributions of sneeze droplets in different areas of the spray will be also useful.

In the measurement of the volume-based size distribution and the calculation of number size distribution of this work,

the shape of the sneeze droplets is assumed as spherical. So the deviation from a spherical particle shape will affect the measurement and the calculation of droplet number, which results in either under-sizing if the particles are non-spherical or overestimating the particle size if the particles are elongated [51].

Healthy subjects were recruited to participate in this experiment. Droplets from infected individuals may be larger than those from healthy individuals owing to the changes induced by disease, such as increases in mucus composition, quantity and viscosity [15,51]. The mucus content in the droplets exhaled by ill subjects will be different from that exhaled by healthy subjects. Higher mucus content may lead to larger final equilibrium diameter of expiratory droplets after evaporation. For simple NaCl solution, the final equilibrium diameter of droplets after complete evaporation is 16% of the initial droplet diameter under the RH of 0%, much smaller than that of 44% of the initial droplet diameter when the content of glycoprotein was considered. So the droplet size distributions of ill subjects are also different from those of healthy subjects. As the dispersion characteristics of aerosols with different size are also different, the changes of original size and content of the expiratory droplets may also influence the transmission of the disease. So studies on contents of expiratory droplets exhaled by infected individual are also strongly needed to understand the transmission characteristics of respiratory infectious disease.

5. Conclusion

In this work, the size distributions of the droplets exhaled by sneezes are investigated. The volume-based size distributions of sneeze droplets of 20 healthy subjects are measured immediately at mouth by using a laser particle size analyser. Forty-four sneezes are measured, and unimodal and bimodal size distributions are found. For each sneeze, the size distribution of the droplets exhaled at different time in the sneeze duration is almost the same, while differences are found among subjects. The volume-based size distributions can be represented by a lognormal distribution function. The geometric mean of the droplet size of all the sneezes is 360.1 μm for unimodal distribution and 74.4 μm for bimodal distribution with geometric standard deviations of 1.5 and 1.7, respectively. For the two peaks of the bimodal distribution, the geometric mean is 386.2 μm for peak 1 and 72.0 μm for peak 2 with geometric standard deviations of 1.8 and 1.5, respectively. These results are compared to that of previous works and other respiratory activities. The result shows that the size of sneeze droplets of the unimodal distribution is significantly larger than that of cough and speech, whereas similarity can be found between the bimodal distribution and that of other respiratory activities. The differences may mainly be because of the influences of the measurement method, the limitation of the instrument, the evaporation effects of the droplets, and the biological dynamic mechanism and characteristic of sneeze. So studies on droplet production process and atomization mechanisms of the respiratory activities are still strongly needed and also necessary for the study of the characterization of sneeze.

This study is the first one that uses a laser particle size analyser to measure the original size distribution of sneeze droplets in recent years. The size distribution of sneeze droplets can be used in CFD simulation for investigations of aerosol transmission, risk assessment and management of respiratory infectious disease. The results shown in this work can also be of help especially for the simulation studies on disease transmission through direct and indirect contacts.

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