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The Size and Concentration of Droplets Generated by Coughing in Human Subjects

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ABSTRACT

This work investigated the size distribution of the droplet nuclei and coughed droplets by test subjects. The size distributions of droplet nuclei coughed by test subjects were determined with an aerodynamic particle sizer (APS) and scanning mobility particle sizer (SMPS) system (system 1). Coughed droplets were only sampled with the APS system (system 2). Two different schemes were employed in system 2. Furthermore, the size distribution of coughed droplets of different ages and gender was investigated to identify the effects of age and gender on droplet size distribution. Results indicated the total average size distribution of the droplet nuclei was 0.58–5.42 μm, and 82% of droplet nuclei centered in 0.74–2.12 μm. The entire average size distribution of the coughed droplets was 0.62–15.9 μm, and the average mode size was 8.35 μm. The size distribution of the coughed droplets was multimodal. The size distribution of coughed droplets showed three peaks at approximately 1 μm, 2 μm, and 8 μm. These analytical findings indicate that variation for average droplet size among the three age groups was insignificant ($p > 0.1$). Moreover, the variation in average droplet size between males and females was also insignificant ($p > 0.1$). Also, the variation in droplet concentration between males and females was significant ($p > 0.1$). Droplet nuclei concentrations from male subjects were considerably higher than that from females. Comparison of the droplet concentrations for subjects in different age groups demonstrated that subjects in the 30–50-year age group have the largest droplet concentrations.

Key words: coughed droplet, droplet nuclei, size distribution, age, gender

INTRODUCTION

Severe acute respiratory syndrome (SARS) is the latest in a series of emerging infectious diseases, and certainly one of the most widely publicized. This acute and often deadly respiratory illness first emerged in southern China in late 2002, and spread rapidly throughout China, and to Singapore, Vietnam, Thailand, Indonesia, Taiwan, and the Philippines, as well as to several Western countries, including Canada, the United States, and Germany. When the SARS outbreak was contained on July 31, 2003, over 8000 probable cases worldwide had caused more than 700 deaths.[(1)] No specific remedy exists for SARS, which is an infectious disease with a high death

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rate. During its transmission period, this disease caused widespread panic as a result of limited understanding of its transmission route. Several researchers believed that droplet transmission was the principal means of transmission.[2,3] Droplet transmission limited the spread of SARS to individuals near the carrier, that is, those who directly inhaled droplets coughed by carriers, or ingested diseased droplets spread to the hands. Hawkey et al.[4] suggested that the primary at-risk group comprised medical personnel caring for SARS patients or their families. However, some studies questioned the likelihood of airborne transmission.[5] Airborne transmission is a process by which droplets are spread into air and those who inhale this ambient aerosol are infected. Several other infectious diseases are spread by droplet and airborne transmission. Mumps, flu, and enteroviruses are spread through droplet transmission, whereas tuberculosis is spread via airborne transmission. Transmission of such diseases is dependent upon the size of droplets from coughs or sneezes. Large droplets might settle rapidly, thus limiting disease transmission to individuals in the proximity of the carrier. As small droplets generally remain airborne for a longer period than large droplets, thereby contributing to airborne transmission, small droplets have sufficient time for droplet nuclei evaporation.

Although disease transmission depends on droplet size, few studies have explored the droplet size. Furthermore, some existing data is extremely out of date. Jennison[6] employed high-speed photography to measure the size of droplets generated by sneezing and coughing. This technique only measured droplets with diameters >10 μm. Duguid,[7] who utilized a microscope to measure droplet sizes on stain masks created by holding the slides up to a subject who sneezed, coughed, and spoke, measured droplet sizes of 1–2000 μm with 95% <100 μm. Duguid's measurement results also determined that droplet nuclei were 0.25–42 μm with the majority being 1–2 μm. Fairchild and Stamper,[8] who used an optical particle counter (OPC) to measure exhaled droplets, found that almost all droplets were <0.3 μm. Papineni and Rosenthal[9] utilized OPCs and an analytical transmission electron microscope (AEM) to measure the size of droplets produced when breathing through the nose and mouth, coughing, and talking. Although larger droplets were found, the OPC-based results demonstrated that most droplets were <1 μm. Measurement results obtained with AEM verified the existence of large-sized droplets exhaled during breathing. The principal difference from earlier investigations is that sampling instruments in recent studies have increased sensitivity accuracy.

Although previous studies investigated droplet size, only Duguid[7] examined the size of droplet nuclei, a primary contributor to airborne disease transmission. However, few studies evaluated the size distribution of coughed droplets and droplet nuclei. Therefore, the aim of the present study was to measure the size distribution of coughed droplets and droplet nuclei, and to compare the differences. Furthermore, we also clarified the size distribution and concentration of droplets coughed by test subjects of different ages and gender to identify the effect of age and gender on coughed droplet size distribution and concentration.

MATERIALS AND METHODS

Test subjects and age distribution

Herein, we investigated the size distribution of coughing droplets from 54 healthy test subjects. The subjects' ages ranged from 10 to 50 years of age and were divided into three age-based groups: 10 to 12 years, 20 to 30 years, and 30 to 50 years of age. There were 18 subjects in each group, of which nine were male and nine were female.

Setup for droplet nuclei sampling (system 1)

When droplets are coughed, they are affected by low atmospheric relative humidity (RH) and evaporate by either becoming droplet nuclei or merely disappearing. To simulate real environmental conditions and directly sample real droplet nuclei, the coughed droplets were mixed with low RH (35%) clean dry gas. The coughed droplets were then affected by the low RH and evaporated to form the droplet nuclei. Figure 1 shows the droplet nuclei measurement system (System 1). The coughing droplets and the low RH dry gas flowed into a test column. In the coughing droplet nuclei test, the test subjects wore a mask with a P 100 filter (Model 7090, 3M Inc., St. Paul, MN) that eliminated particles flowing into the sampling bag during regular breath-

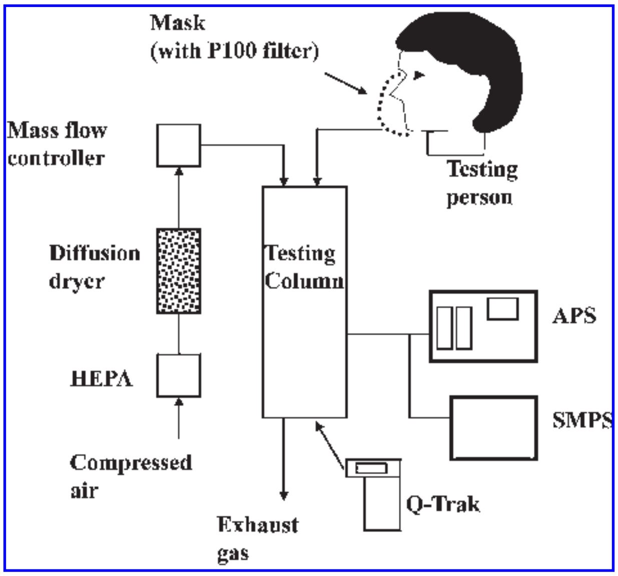

FIG. 1. Schematic diagram of droplet nuclei measurement system.

ing. Thus, flowing-out particles were only produced by the test subjects. In system 1, two subjects (male, aged 20–30 years) were chosen to be the test subjects. The flow of dry gas was limited, as too much gas would overly dilute the particles and the number of droplet nuclei would be too low to sample. Consequently, the flow of dry gas was controlled at 5 L/m^3. After the coughed droplets and the low RH dry gas flowed into a test column, an aerodynamic particle sizer (APS, Model 3310A, TSI Inc., Shoreview, MN) and a Scanning Mobility Particle Sizer (SMPS, Model 3934, TSI Inc.) were used to measure the size distribution of droplet nuclei. The APS can measure particle sizes ranging from 0.6 μm to 30 μm, and the SPMS can measure particle sizes ranging from 0.02 μm to 0.6 μm. A Q-Trak (Model 8550, TSI Inc.) was also utilized to measure the RH in the test column.

Setup of coughed droplet sampling (system 2)

Coughed droplets are first affected by atmospheric humidity, and then evaporate into droplet nuclei or merely disappear. To measure directly initial droplet size, test subjects coughed into a sampling bag that has a higher relative humidity than surrounding air. Consequently, droplets did not evaporate and decrease their original size.

Figure 2 shows the coughed droplet measurement system. Two different schemes were employed during testing. In the first method (method 1), subjects wore a mask with the P 100 filter and the coughed droplets flowed into a sample bag. In the second method (method 2), subjects coughed directly into a sample bag that completely covered the subject's mouth. In the present study, two subjects (male, aged 20–30 years) coughed droplets using these two methods to further understand the differences between these two techniques. However, the second method (coughing directly into the bag) proved simpler and retained more particles than the first method. Thus, the second technique was applied to measure size distribution of particles coughed by subjects of both genders and different age groups. During testing, Q-Trak was utilized to measure the RH in the sample bag. The RH in the sampling bag was approximately 95%. The APS was employed for sampling the original size distribution of coughed droplets that formed droplet nuclei via evaporation.

Subject cough flow rate

To identify the relationship between subject cough flow rate and droplet concentration, the mean cough flow rate was measured. Subjects coughed into a 9-cm^2 square column that was connected to the sample bag. An air velocity meter (Model 8345, TSI Inc.) was employed to mea-

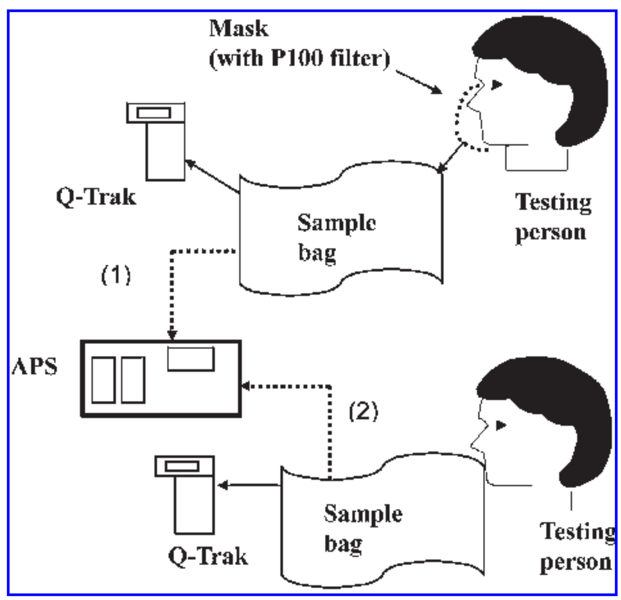

FIG. 2. Schematic diagram of coughing droplet measurement system.

sure cough velocity for calculating mean cough flow rate averaged over the total duration of the cough (i.e., not peak flow rate). These measurements were taken at the same time as droplet sampling.

Statistical analysis

To further understand the effects of age and gender on coughed droplet size, two testing methods, the *t*-test and the *F*-test, were used to analyze the experimental data obtained from 54 test subjects. The mode of the coughed droplet sizes from the test subjects was used for the statistical analysis.

The *t*-test was used to analyze the difference in average coughing droplet sizes for males and females in each age group. The males and females in each age group were assumed to be representative of the normal population. The *t*-test was used to determine the difference between the average of two normal populations. This approach is suitable when the sample numbers are lower than 30. The *F*-test was used to analyze the differences in average coughing droplet size between the three age groups. Each age group was assumed to be representative of the normal population. The *F*-test was used to determine the difference between the average of multiple normal populations (>2). Thus, the *F*-test was suitable for application in this test situation.

RESULTS AND DISCUSSION

Size distribution of the droplet nuclei

The whole average size distribution of droplet nuclei for the test subjects, measured using the first system (System 1). Also, we tried to find that what the major part of the droplet nuclei centered. In this System, 2 subjects (male, aged 20–30 years) were chosen to be the test subjects.

Figure 3 plots the total average size distribution of the droplet nuclei was 0.58–5.42 μm, and 82% of droplet nuclei centered in the range of 0.74–2.12 μm. Because 82% of droplet nuclei size range (0.74–2.12 μm) of the droplet nuclei is very small, these droplet nuclei likely contribute to airborne disease transmission. Consistent with results obtained by Duguid,[(7)] 97% of droplet nuclei were 0.5–12 μm, and the primary size distribution was 1–2 μm.

Size distribution of coughed droplets

Herein, we attempted to determine the size distribution of coughed droplets that contribute to

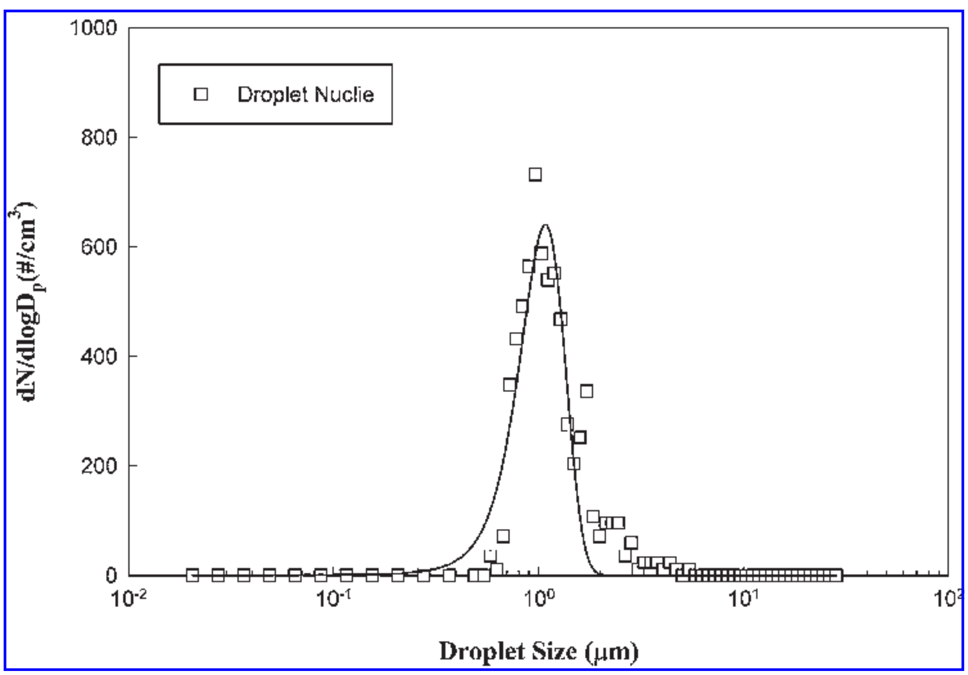

FIG. 3. The size distribution of the coughing droplet nuclei.

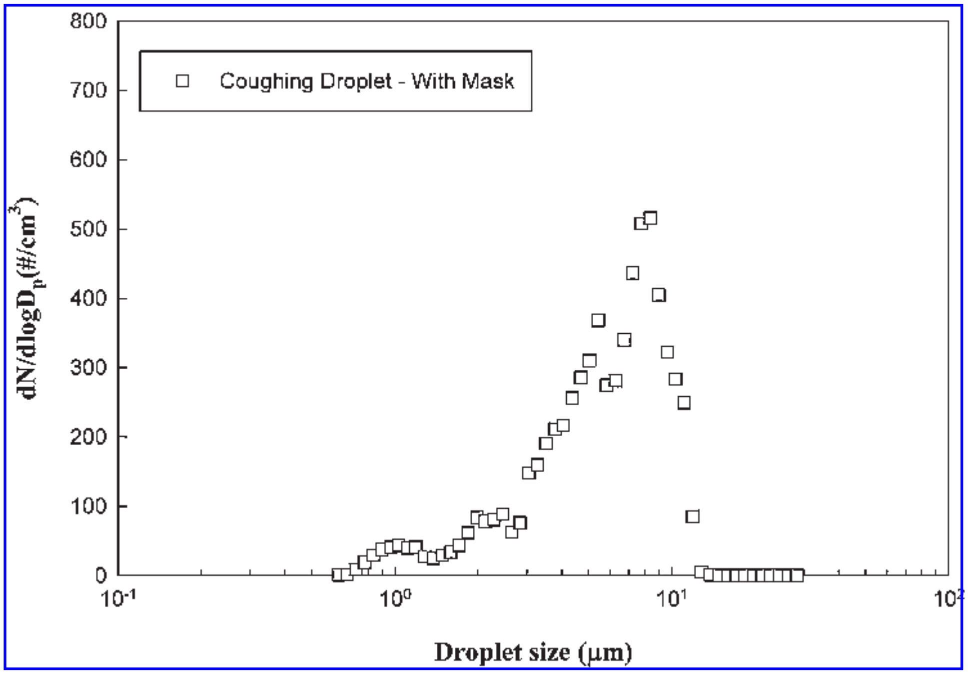

FIG. 4. The size distribution of the coughing droplet (with mask)

the formation of droplet nuclei. The size distribution of coughed droplets is shown in Figure 3. Droplet nuclei were 0.58–5.42 μm. Because the size of coughed droplets must be larger than that of droplet nuclei, it follows that the size of coughed droplets, which evaporate to form droplet nuclei, must be >0.58 μm. Thus, only the APS was used to measure size distribution of coughed droplets (System 2).

The average size distribution of droplets coughed by the two subjects (male, aged 20–30 years, subjects 5 and 6) who wore the mask with

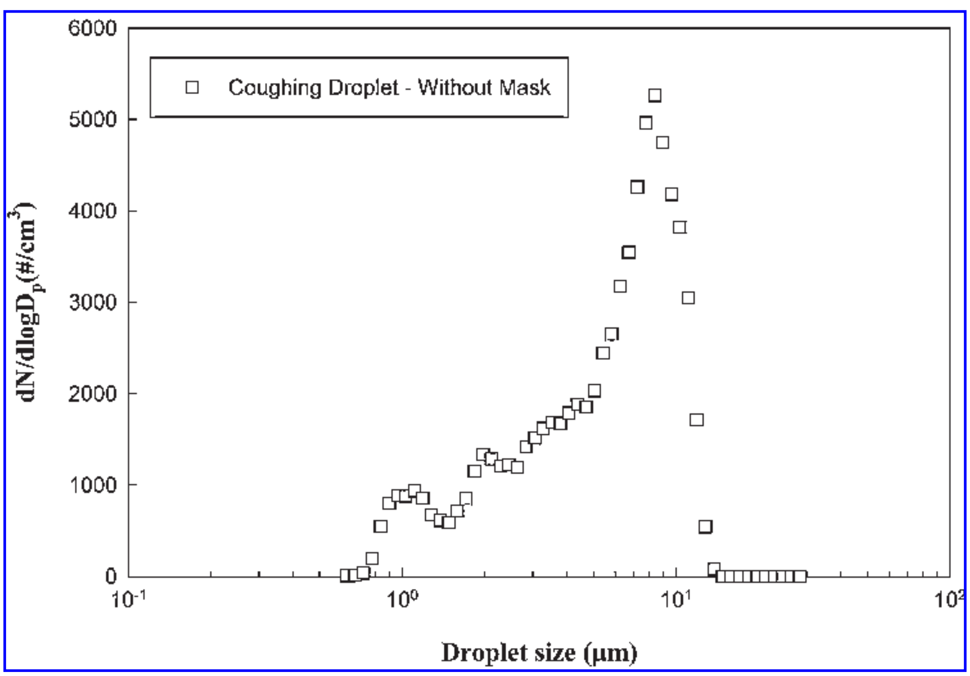

FIG. 5. The size distribution of the coughing droplet (without mask).

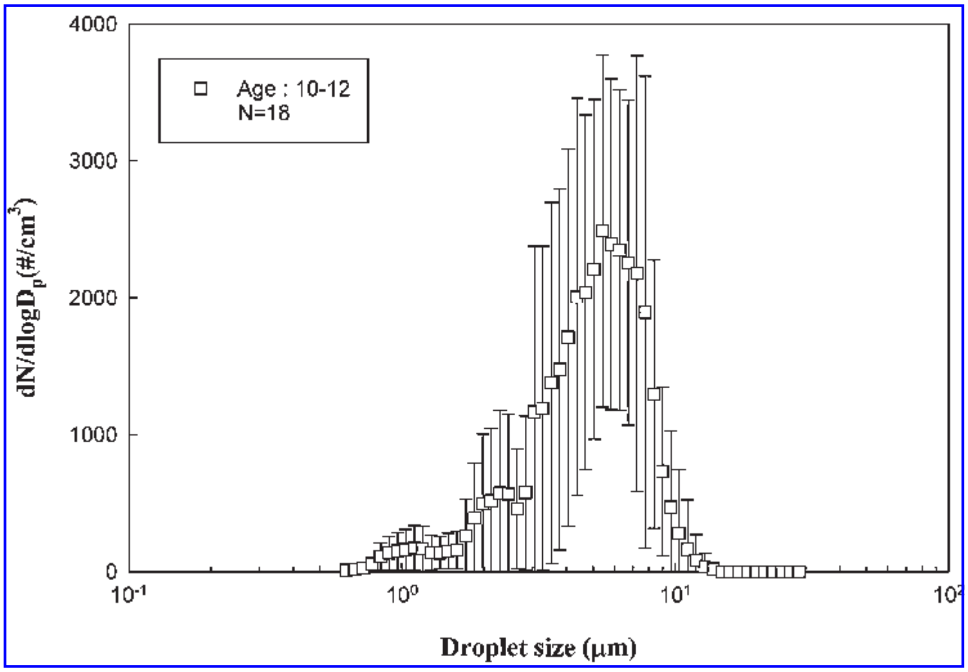

FIG. 6. The size distribution of coughing droplet for the first group (age: 10–12).

a P 100 filter (method 1) is shown in Figure 4. Measurement results suggest that the mode of coughed droplets was 8.35 μm and geometric standard deviation (GSD) was 1.801. The entire size distribution was 0.62–13.8 μm. The average size distribution of droplets coughed directly into the sample bag (method 2) by the same two test subjects (male, 20–30 years old, subjects 5 and 6) is shown in Figure 5. Measurement results indicate that the mode of coughed droplets was 8.35 μm and GSD was 2.205. The whole size distribution of the droplets was 0.62–15.9 μm. The predominant size range of coughed droplets was large; consequently, coughed droplets may contribute to droplet transmission.

Comparison of results for subjects 5 and 6 (male, 20–30 years old) wearing the P 100 filter mask with direct coughing into the sample bag indicated that the size of coughed droplets were the same and the size-distribution curves were markedly similar. These analytical findings demonstrated that the size distribution of coughed droplets was not affected by outside particles for subjects 5 and 6 (male, 20–30 years old) when they did not wear the P 100 filter mask. This finding is likely due to the sampling bag tightly covering the subjects' mouths. Additionally, a comparison of particle concentrations of coughed droplets obtained by method 1 and method 2, noted that the average concentration of coughed droplets from subjects 5 and 6 (male, 20–30 years old) wearing the P 100 filter mask was 53 droplets/cm^3, and the average concentration of droplets coughed directly into the sample bag was 586 droplets/cm^3. The difference in droplet concentration was markedly large, that is, the droplet concentration when wearing the mask was substantially lower than that when not wearing the mask. This finding likely results from coughed droplets impacting directly on the mask

Table 1. The Droplet Modes for Males and Females of Different Age Groups

	10–12 Years		*20–30 Years*		*30–50 Years*	
	Nine males	*Nine females*	*Nine males*	*Nine females*	*Nine males*	*Nine females*
Droplet mode (μm)	4.37–7.77	4.23–7.23	4.37–8.35	4.37–8.35	4.37–6.73	4.37–6.73
Average size (μm)	5.99	5.84	6.29	6.46	5.46	6.01

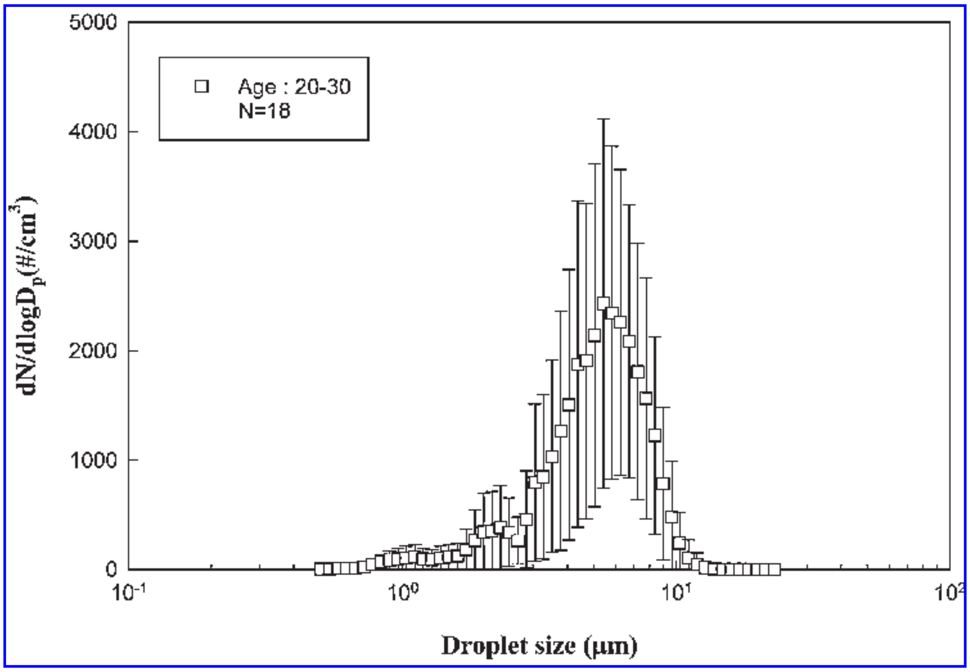

FIG. 7. The size distribution of coughing droplet for the second group (age: 20–30).

inner surfaces, thereby significantly reducing droplet concentrations. Therefore, method 1 and method 2 were effective techniques for sampling coughed droplets. However, method 2, during which subjects coughed directly into the sample bag, obtained dramatically more correct data than method 1 for coughed droplet concentration.

The size distribution of coughed droplets sampled via APS was multimodal, indicating that the size distribution has three peaks, at approximately 1 μm, 2 μm, and 8 μm. A previous study (Papineni and Rosenthal,)[9] also determined that droplet size distribution was multimodal, peaking at 0.6 μm and 1.0–1.5 μm.

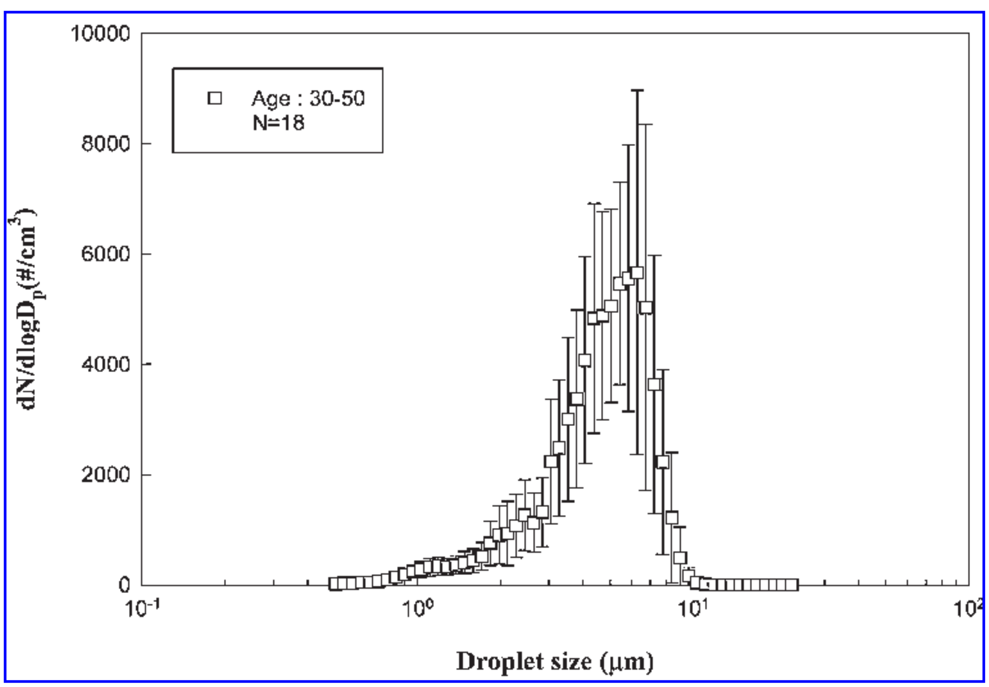

FIG. 8. The size distribution of coughing droplet for the third group (age: 30–50).

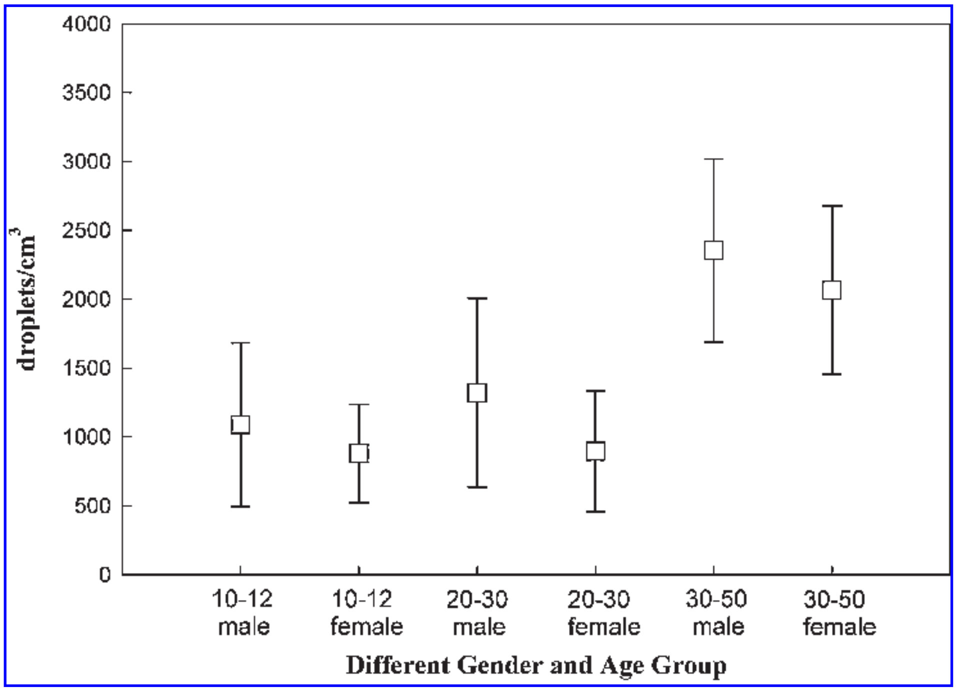

FIG. 9. The concentration of coughing droplet for different gender and age group.

Moreover, the whole average size distribution of coughed droplets observed in the present study was 0.62–13.8 μm. Duguid[7] and Papineni and Rosenthal[9] both found that coughed droplets measured microscopically, consisted of a large range of particle sizes. Duguid[7] identified that the principal size distribution was 4–8 μm. Papineni and Rosenthal[9] showed that droplets >2 μm were the predominant distribution. Our results are in agreement with those obtained by Papineni and Rosenthal and Duguid. Additionally, Papineni and Rosenthal,[9] who used an OPC to determine droplet size distribution, found that the predominant droplet size distribution was <1 μm. This result differs dramatically from the results obtained in the present study. A likely rationale is that measurement results obtained by Papineni and Rosenthal[9] may have been based on samples obtained in a lower RH than that used in the present study. Papineni and Rosenthal sampled[9] droplet size in RHs of 24% and RH 45%. However, RH in the mouth is very high (roughly 99%). When droplets are coughed from the mouth in an environment with low RH, they typically form small particles via evaporation. Thus, droplet size measured via an OPC in Papineni and Rosenthal's study[9] may be underestimated. Herein, coughed droplets were collected in a sample bag with a 95% relative humidity. Therefore, droplet size distribution in the present study was higher than that measured in a lower RH in Papineni and Rosenthal's study[9].

Size distribution of coughed droplets in different age and gender groups

Herein, the size distribution of coughed droplets for different age groups and genders was measured. Although Papineni and Rosenthal[9] investigated droplet size for subjects, they did not consider age or gender. Therefore, we examined the size distribution of coughed droplets

TABLE 2. MEAN COUGHING FLOW RATE OF TESTING SUBJECTS

	10–20 Males	*10–20 Females*	*20–30 Males*	*20–30 Females*	*30–50 Males*	*30–50 Females*
Mean coughing flow rate (L/sec)	0.30 ± 0.06	0.23 ± 0.05	0.48 ± 0.09	0.26 ± 0.05	0.90 ± 0.11	0.69 ± 0.09

for three age groups (10–12 years, 20–30 years, and 30–50 years) for males and females.

The size distribution of coughed droplets for the group aged 10–12 years (nine males and nine females) is shown in Figure 6. The average mode of coughed droplets for this group was 5.91 μm. The droplet modes for nine males and nine females were listed in Table 1. A *t*-test comparison of average modes for these two gender groups identified insignificant variation ($p > 0.1$).

The size distribution of coughed droplets for nine male and nine female subjects aged 20–30 years is shown in Figure 7. These analytical results of the nine male and nine female subjects in this age group were also presented in Table 1. The *t*-test comparison of average sizes for the two genders demonstrated that the difference was insignificant ($p > 0.1$).

Figure 8 presents the size distribution of droplets coughed by nine male and nine female subjects aged 30–50 years. The average mode of coughed droplets for this group was 5.73 μm. Table 1 listed the droplet modes of the nine male and nine female subjects in this age group. The *t*-test comparisons for the average droplet size between the two genders indicated that that the difference was insignificant ($p > 0.1$).

Moreover, the *F*-test for average modes between these three age groups indicated that no significant variation existed ($p > 0.1$).

Concentration of coughed droplets for different age and gender groups

The average concentrations of droplets coughed by different gender and age groups are shown in Figure 9. For the group subjects aged 10–12 years, the average concentration of the coughed droplets by the nine male subjects was 1089 $\pm$ 594 droplets/cm^3, and the average concentration of droplets coughed by the nine female subjects was 881 $\pm$ 358 droplets/cm^3. For the group subjects aged 20–30 years, the average concentration of droplets coughed by the nine male subjects was 1323 $\pm$ 685 droplets/cm^3, and the average concentration of droplets coughed by the nine female subjects was 896 $\pm$ 442 droplets/cm^3. The average concentrations of droplets coughed by the nine male subjects and nine female subjects in the group aged 30–50 years were 2355 $\pm$ 663 droplets/cm^3 and 2066 $\pm$ 612 droplets/cm^3, respectively. These analytical findings confirmed that the droplet concentrations for males were significantly higher than those for females. The *t*-test was also applied to compare differences in droplet concentrations for gender-based groups. Comparison results also demonstrated that droplet concentration variation between males and females was significant ($p < 0.1$).

This difference in concentration is likely due to males having a larger cough flow rate than fe-

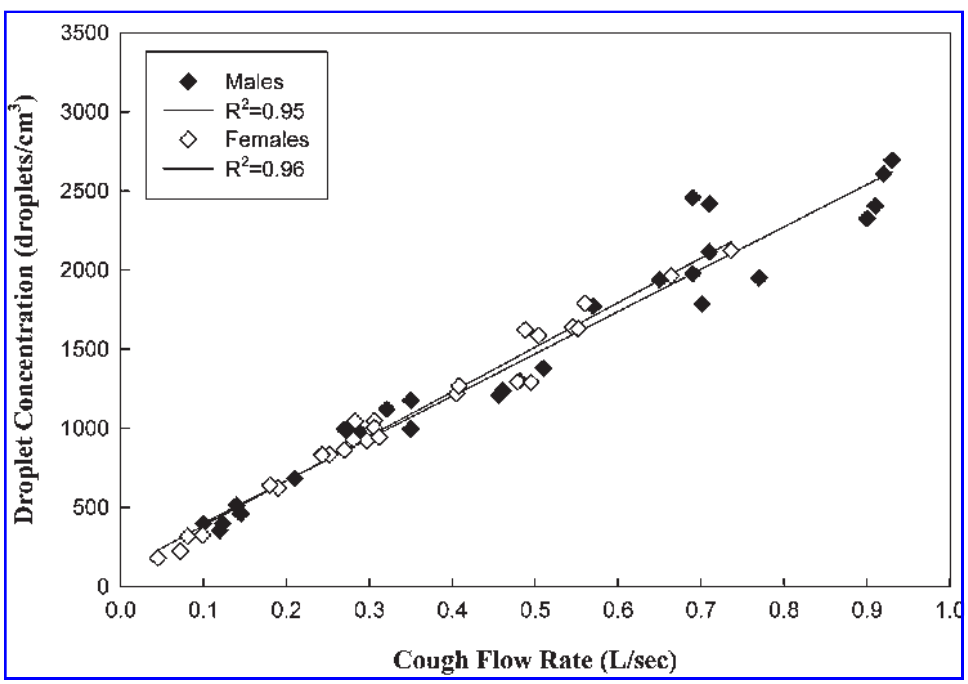

FIG. 10. The concentration of coughing droplet versus the mean cough flow rate with male and female.

males. To prove this assertion, the mean cough flow rate of all test subjects was measured The mean cough flow rate for all test subjects based on gender and age group is shown in Table 2. The cough flow rates of males in the three age groups were larger than those for females, suggesting that droplet concentrations for males were significantly higher than those for females, as males have higher cough flow rates than females. To eliminate the coincidental nature of this finding, the relationship between droplet concentrations and cough flow rate was investigated. The concentration of coughed droplets versus mean cough flow rate for males and females is shown in Figure 10. A linear correlation exists between droplet concentration and cough flow rate. In the regression analysis, the coefficients of determination, R^2, were 0.95 and 0.96 for male and female curves, indicating that droplet concentration increases as cough flow rate increases. The slopes of these two curves were very similar (Fig. 10). These analytical findings confirm that the significantly higher droplet concentration for males than for females is due to the larger cough flow rate of males.

Furthermore, the average concentration of coughed droplets for the group aged 10–12 years was 985 ± 477 droplets/cm^3. The average concentration of droplets coughed by subjects aged 20–30 years was 1109 ± 510 droplets/cm^3, and the average concentration of droplets coughed by the group aged 30–50 years was 2211 ± 636 droplets/cm^3. These measurement results suggest that the droplet concentrations for subjects in the 30–50-year group were the highest. The probably reason is that the mean cough flow rate of subjects in the 30–50-year group is larger than that of the other two age groups (Table 2). However, the each age group only has 18 test subjects. So the representative of these test age groups is weak. Therefore, we would choose more test subjects to measure the droplet concentration and the mean flow rate in the further study to find the representative of the experimental data.

CONCLUSION

Experimental results demonstrated that total average size distribution of the droplet nuclei was 0.58–5.42 μm, and 82% of droplet nuclei centered in the range of 0.74–2.12 μm. The entire average size distribution of coughed droplets by test subjects was 0.62–15.9 μm. Results showed that droplet sizes were nearly the same using the two methods (methods 1 and 2) of measurement; however, the methods differed for droplet concentrations. The coughed droplet concentrations for test subjects wearing the P 100 filter mask were markedly lower that that for subjects who coughed directly into the sample bag. This difference is likely due to coughed droplets easily impacting the inner surface of the mask, reducing significantly the number of coughed droplets measured. The size distribution of coughed droplets was multimodal, not unimodal. Experimental results indicated that the size distribution of coughed droplets peaked at approximately 1 μm, 2 μm, and 8 μm.

These analytical findings indicate that variation for average droplet size among the three age groups was insignificant ($p > 0.1$). Moreover, the variation in average droplet size between males and females was insignificant ($p > 0.1$).

The average droplet concentration for males was significantly higher than that for females, as males have a larger cough flow rate than females. Comparison of the droplet concentrations for subjects in different age groups demonstrated that subjects in the 30–50-year age group had the largest droplet concentrations, as subjects in this age group have the largest cough flow rate.

Herein, we investigated the size distribution of droplet nuclei and coughed droplets, which form droplet nuclei via evaporation. We believe that our results provide useful information for further medical investigations of airborne disease transmission. Moreover, future studies will measure droplets <0.6 μm in order to gain a complete size distribution of coughed droplets.

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