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Study on the initial velocity distribution of exhaled air from coughing and speaking

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ABSTRACT

Increasing concerns about the spread of airborne pathogens such as severe acute respiratory syndrome (SARS) and novel swine-origin influenza A (H1N1) have attracted public attention to bioaerosols and protection against them. The airborne pathogens are likely to be expelled from coughing or speaking, so the physical data of the exhaled particles plays a key role in analyzing the pathway of airborne viruses. The objective of this study was to analyze the initial velocity and the angle of the exhaled airflow from coughing and speaking of 17 males and 9 females using Particle Image Velocimetry (PIV) and acrylic indoor chamber. The results showed that the average initial coughing velocity was 15.3 m/s for the males and 10.6 m/s for the females, while the average initial speaking velocity was 4.07 m/s and 2.31 m/s respectively. The angle of the exhaled air from coughing was around 38° for the males and 32° for the females, while that of the exhaled air from speaking was around 49° and 78° respectively. Also, the linear relation between the tested subject's height and their coughing and speaking velocity was shown in this study.

1. Introduction

The necessity of understanding the infection mechanism of airborne transmission is proven from the epidemic cases reported by WHO such as SARS (severe acute respiratory syndrome) in 2003 and H1N1 (novel swine-origin influenza A) in 2009 (WHO, 2004, 2010). Olsen et al. (2003) reported the transmission of SARS on an aircraft by interviewing passengers and crew members who were on the spot and noted that passengers who were seated in the same row with the index patient had higher risk. Especially, higher number of infected passengers seated in front of the index patient than behind him possibly implied the airborne transmission through respiratory activities such as coughing and sneezing. Efficiency of respiratory transmission of H1N1 virus was tested by conducting animal experiments using ferrets (Maines et al., 2009; Munster et al., 2009; Perez et al., 2009). Prediction on the transmission airborne contaminants including SARS inside an enclosed space such as an airliner cabin (Mazumdar and Chen, 2009) and a hospital ward (Qian et al., 2009) have been made, providing a reasonable prediction for applications when the infection occurred and the virus was transmitted to a person staying at the same location in an enclosed space.

Airborne transmission refers to the passage of microorganisms from a source to a person through aerosols, causing possible illness of the person in consequence of infection. Aerosolized disease transmission can be classified into two groups (Gralton et al., 2011); one is the droplet transmission, which is defined as disease transmission through the expelled particles that are likely to settle down quickly due to their size. The other is aerosol transmission, which is defined as disease transmission through the expelled particles that range relatively smaller in size. Such aerosols can be transmitted over short and long distances. Short-range transmission occurs across the short distance (less than 1 m) from person to person and can be moderated by using of personal protective equipment such as gloves and facemasks with precautions to avoid the usual contact transmission from touching of the eyes, nose and mouth. Long range transmission occurs between distant locations and is primarily governed by air flows generated from ventilation systems or movement of people (Tang et al., 2006). Wang and Chow (2011) reported that human walking disturbs the local velocity field influencing the droplet dispersion and the increase of walking speed could effectively cut down the number of suspended droplets ranged 0.5–20 μm.

Large droplets can evaporate to become small droplets that can further evaporate, eventually becoming droplet nuclei suspended for prolonged periods (Parienta et al., 2011), if this evaporation process is fast enough to occur before the droplets settle down. Morawska et al. (2009) showed that evaporation to the equilibrium droplet size occurred within 0.8 s for particles between 0.5 and 20 μm. Redrow et al. (2011) also demonstrated that a 10 μm sputum droplet evaporated to become a droplet nucleus (3.5 μm) in

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0.55 s at 80% RH. According to Chao et al. (2009), the geometric mean diameter of the droplets expelled from human activities such as coughing and speaking was 13.5 μm and 16.0 μm, respectively, thus they are likely to remain airborne in the indoor air flow after the complete evaporation. Duguid (1946) also demonstrated that respiratory droplets were small enough to remain airborne agreeing with above results.

To predict the evaporation, dispersion, and transport of respiratory droplets in indoor environment using computational fluid dynamics, boundary conditions such as air jet velocity are necessary for the CFD simulations. Gupta et al. (2009, 2010) reported thermo-boundary conditions such as the flow rate, flow direction, and mouth opening area of 25 human subjects for a CFD simulation of coughing, breathing, and talking. Zhu et al. (2006) measured the velocity distribution around the mouth of the three subjects and reported that the exhaled air velocity ranged between 6 and 22 m/s with the average velocity of 11.2 m/s. According to the result, when the maximum velocity of the coughed airflow was 22 m/s, the expelled saliva droplets flew 2 m or longer. Chao et al. (2009) found from measurements that the average expiration air velocity was 11.7 m/s for coughing and 3.9 m/s for speaking. Reliable information on the boundary condition is needed since the simulation results can differ depending on the input condition. Zhao et al. (2005) considered different outlet velocities (20 and 100 m/s) from mouth to simulate the sneezing or coughing process and found that higher coughing velocity will bring on further transport and higher concentration of the exhaled particles.

In this study, initial velocity of exhaled airflow from coughing and speaking was measured with 26 tested subjects using Particle Image Velocimetry (PIV) and analyzed to obtain the angle of the expiration air. The results would be a useful input condition for CFD simulations. Also, the relation between the subject's height and the horizontal velocity of exhaled airflow from coughing and speaking was studied, providing applicable information that can predict the initial velocity of exhaled airflow when the subject's height is known.

Table 1
Physical condition of the test subjects.

Male subject	Age (yr)	Height (m)	Weight (kg)	Female subject	Age (yr)	Height (m)	Weight (kg)
M1	27	1.68	68	F1	24	1.62	55
M2	43	1.69	70	F2	26	1.64	50
M3	35	1.78	86	F3	28	1.64	48
M4	39	1.69	70	F4	26	1.65	49
M5	25	1.72	68	F5	29	1.67	54
M6	33	1.79	85	F6	29	1.67	49
M7	27	1.79	65	F7	32	1.58	42
M8	24	1.77	63	F8	29	1.60	47
M9	29	1.80	70	F9	31	1.59	46
M10	23	1.68	73				
M11	26	1.80	70				
M12	28	1.76	69				
M13	44	1.68	60				
M14	40	1.65	68				
M15	29	1.72	72				
M16	36	1.72	62				
M17	29	1.78	80				
Average	32	1.74	71	Average	29	1.63	49

2. Methods

In order to measure the initial velocity of the exhaled air from coughing and speaking, the PIV was installed in a clean room that can control the constant temperature and humidity (23 °C, 50% RH) as shown in Fig. 1. For the PIV measurements, olive oil particles were nebulized into the acrylic indoor chamber using an atomizer (Oil Droplet Generator, TSI Model 9307) and the thin laser sheet was produced by adjusting the laser (λ = 532 nm Nd: YAG) using a lens. The location of atomized particles resulting from the effect of light scattering was detected using a digital camera (TSI 630057). The sequential two PIV images obtained from a synchronizer (TSI 610035) and a PC were analyzed into a velocity vector by tracking the pathway of the atomized particles. The tested people

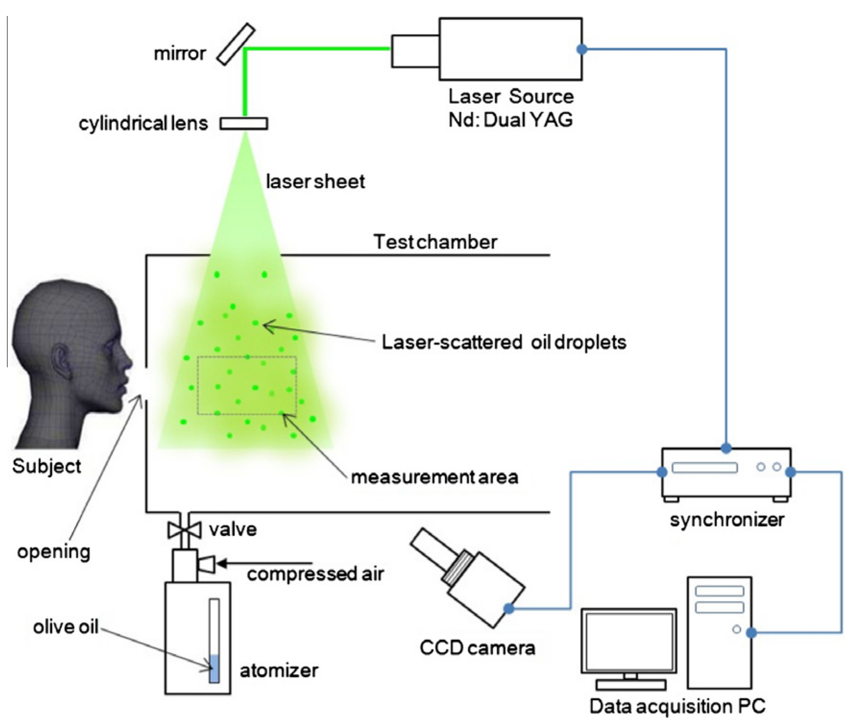

Fig. 1. Schematic diagram of the measurement system.

Table 2
The measurement condition of the PIV system.

PIV parameters	Values
Pulse rep rate (Hz)	14.50
Laser pulse delay (μs)	400.00
Delta *T* (μs)	100.00
PIV exposure (μs)	490
Field of view	247 mm × 184 mm
Image dimensions	1487 pixels × 1039 pixels
Cylindrical lens	FL: −15 mm
Image interval (ms)	70

were instructed to cough or speak in a certain protocol on a side of rectangular chamber made of transparent acryl with a dimension of 500 mm width, 500 mm height and 1500 mm length. To prevent the tested persons from being exposed to the laser, a galvanized steel base plate was installed.

26 tested persons including 17 adult males aged between 23 and 44 (avg age 32, avg height 1.74 m, and avg weight 71 kg) and nine adult females aged between 24 and 32 (avg age 29, avg height 1.63 m, and avg weight 49 kg) were selected for testing (Table 1). When each person repeated coughing and speaking at the front side of the chamber, the velocity distribution around the mouth was measured using the PIV system. The following expiratory activities were tested; coughs with the mouth closed initially and voluntarily performed three times as much as the subject can generate with a sufficient rest period between each cough, Speech instructed to speak out the words *hana* (meaning one in Korean), *dul* (two) and *set* (three) for around 3 s each with a rest period between them. The measurement area was 247 mm × 184 mm located in front of the mouth opening and the PIV images were taken with the 70 ms interval of continuous shots and the shot exposure time was 490 μs (Table 2).

3. Results and discussion

3.1. Coughing velocity vector measurement

17 males and 9 females were instructed to cough three times at the front side of the rectangular chamber in order to measure the initial exhalation velocity distribution. Fig. 2 shows an example of the coughing velocity vector change per time when a person

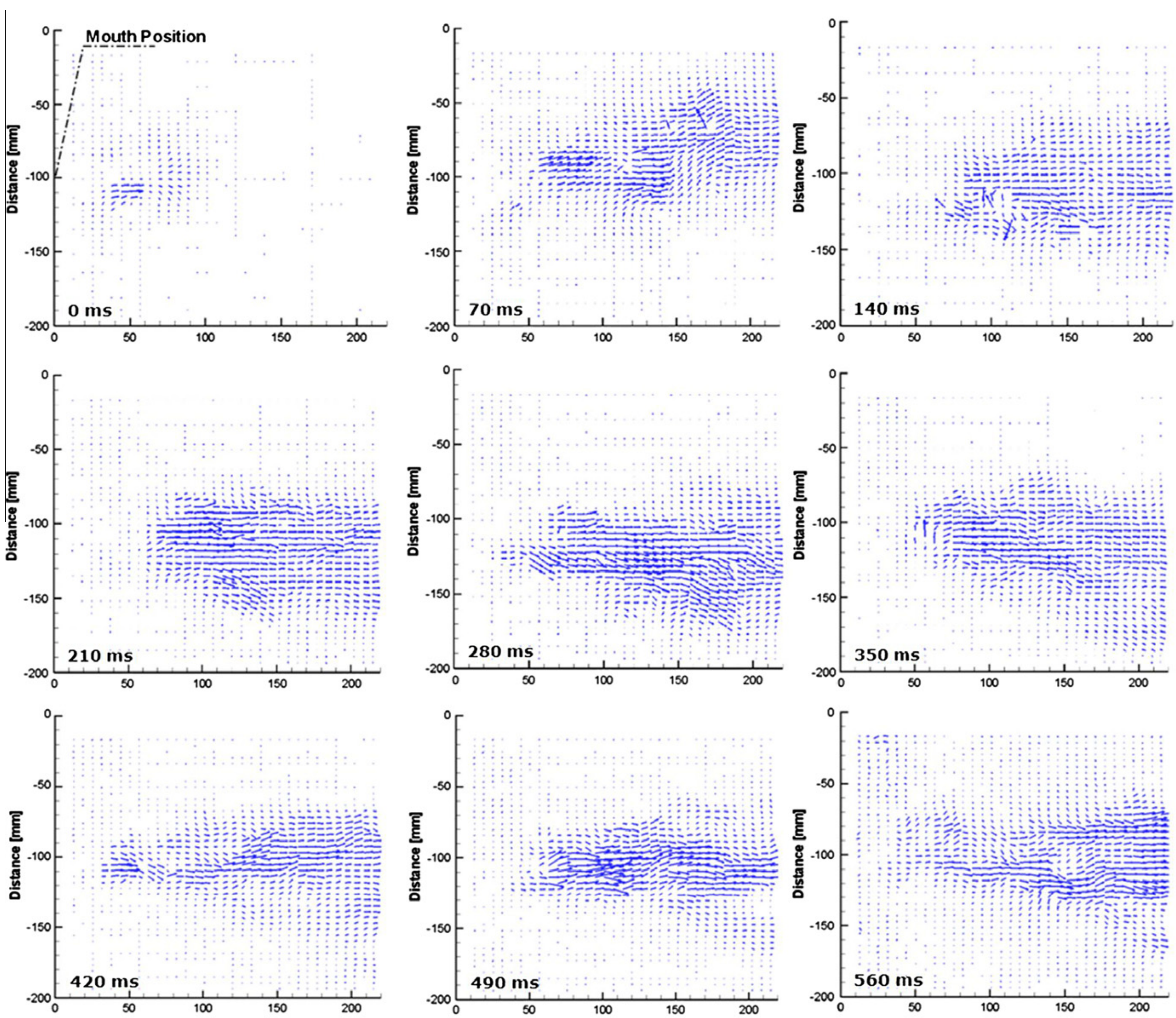

Fig. 2. The velocity vector of coughed airflow change per time.

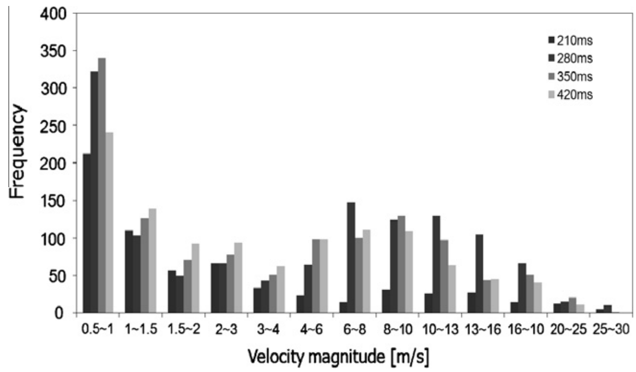

Fig. 3. The velocity size distribution of coughed airflow.

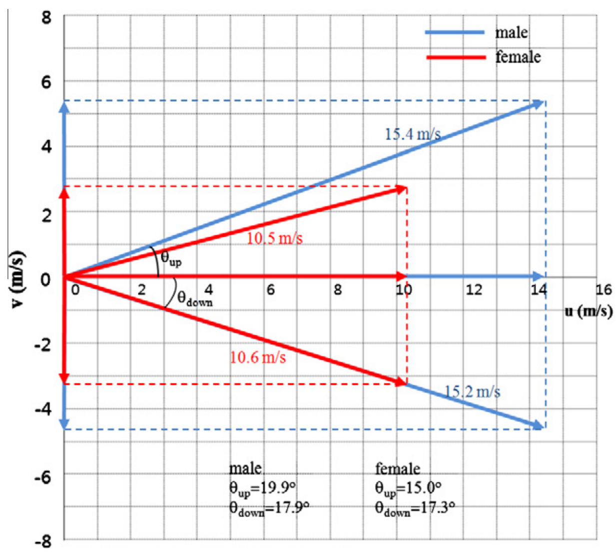

Fig. 4. Initial coughing velocity distribution by males and females.

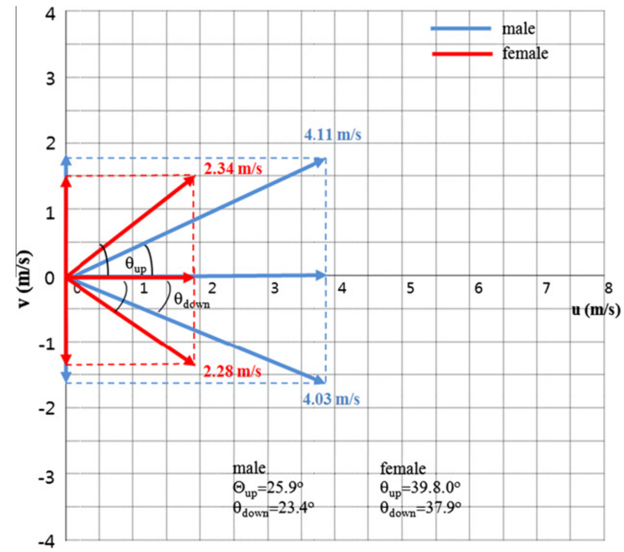

Fig. 5. Initial velocity distribution while pronouncing *Dul* by males and females.

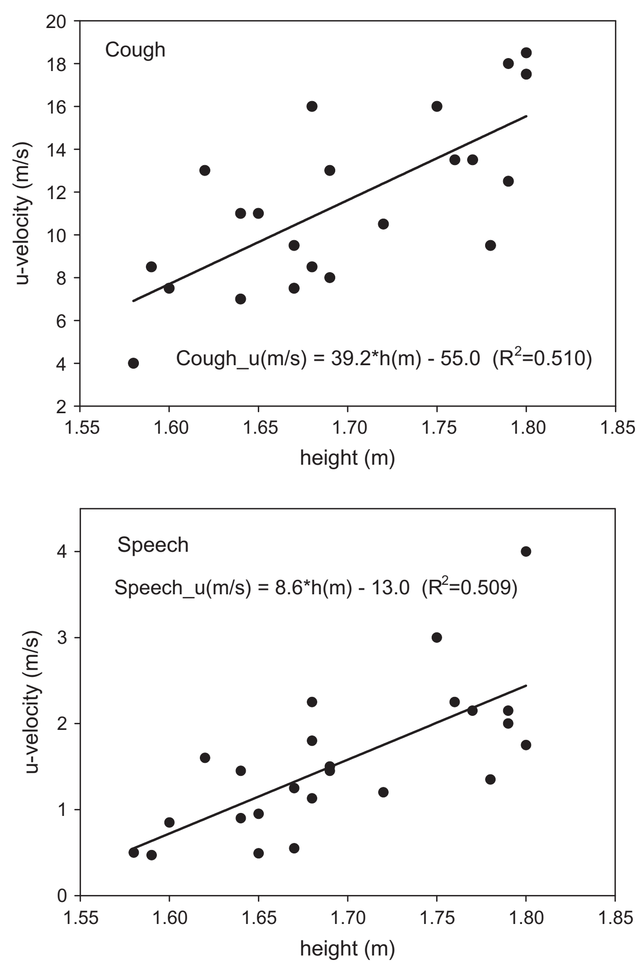

Fig. 6. Relation between height and horizontal coughing and speaking velocity.

coughs once. The position of the mouth of the tested person is at 100 mm on the *y*-axis in the figure, and the *x*-axis represents the distance from the mouth. The velocity vector was captured at each 70 ms as shown in Fig. 2. For all 26 tested persons, 9 shots of velocity vectors for 560 ms were captured from each cough. Of these, three or four continuous shots showing the highest velocity distribution were assumed to be the initial velocity of the exhaled air from coughing. Fig. 3 shows the velocity size distribution in the *x*-axis direction of all velocity vector data obtained from four shots between 210 ms and 420 ms. The velocity at 0.5–1 m/s is most frequently observed possibly due to the addition of velocity vector from surrounding air, and hence, the maximum velocity of the exhaled air from coughing possibly ranges between 6 and 13 m/s.

The velocities of the exhaled air from coughing by the adult males and females were separated into the *x*-axis direction velocity (u) and two *y*-axis direction velocity (v upward and downward). Each u and v velocity averaged from three times cough data was analyzed for all ranges and the sections that showed the highest velocity were selected. The selected velocity was averaged for all tested males and females separately and is shown in Fig. 4. In the case of the males, the maximum u of the exhaled airflow from coughing was 14.4 m/s, while v was 5.2 m/s upward and -4.7 m/s downward. In the case of females, u was 10.1 m/s, while v was 2.7 m/s upward and -3.1 m/s downward. The coughing velocity vector combining u and v was 15.4 m/s (15.2 m/s downward) in the case of males, and the females showed around 70% of that of the males. The result is around 10% higher than the average air velocity (11.7 m/s) for both males and females observed by Chao et al. (2009). The angle of the upward vector and downward vector was 19.9° and 17.9° for the males and 15° and 17.3° for the females, respectively. From the mouth, the angle of the coughed airflow was around 38° for the males and 32° for the females. The result is somewhat lower than the measured average angle (55°) reported by Gupta et al. (2009).

3.2. Speaking velocity vector measurement

In the case of speech, the test subjects were instructed to pronounce the words *hana*, *dul* and *set* then the velocity vector of each word was analyzed. However, there was too large a discrepancy among the test subjects in the case of *hana* and *set*, thus only *dul* was used to analyze the velocity vector. Applying the same procedure as with the coughs, the maximum velocity distribution of the exhaled air when *dul* was pronounced was acquired and as shown in Fig. 5. The velocity vector for the males was 4.11 m/s upward and 4.03 downward, while that for the females was 2.34 m/s upward and 2.28 m/s downward. The angle of the exhaled air was around 78° for the females which was much larger than 49° for that for the males. The average angle of the exhaled air from the mouth for the speech was found to be larger than that for cough.

In the study of speech of 3 males and 9 females by Chao et al. (2009), the average velocity of exhaled air was 4.6 m/s for the males and 3.6 m/s for the females. The results are somewhat higher than that of this study mainly by the difference from the way to speak during the experiments. For the case of Chao et al. (2009), the tested persons were asked to speak by counting 1–100 loudly, so the higher velocity was expected.

3.3. Relation of coughing and speaking velocity with height

Since the expelled particles from coughing or speaking with higher outlet velocity can flow further distances affecting the risk of infection, the relation between a subject's physical condition and the velocity has to be considered. In this study, the relation between the horizontal velocity of the exhaled air from coughing and the subject's height that is known to be related with their lung capacity (Morris et al., 1971) was analyzed regardless of gender. As shown in Fig. 6, the coughing velocity was higher when the test subject was taller. However, the linear relation was weak ($R^2 = 0.510$). The lowest coughing velocity was shown for a female who was 1.58 m tall and weighed 42 kg (F7), while the highest coughing velocity was appeared for a male who was 1.8 m tall and weighed 70 kg (M9). The results with speech also showed similar patterns. The comparison of the horizontal velocity of the exhaled air indicated that the speaking velocity increased with the height of the person.

4. Conclusions

The airborne-transmission of contagious substances expelled by the respiration system of an infected patient is known to be the key contagion mechanism. Contagious substances as droplets or particles are likely to be expelled from coughing or speaking, and thus the physical data of the exhaled particles is important in analyzing the air-borne path of the viruses. Accurately analyzing the initial velocity distribution is particularly important in the study of the fluid dynamics property of the respiratory particles through numerical analysis. This study used a PIV system to analyze the initial velocity of the exhaled air from coughing and speaking of 17 males and 9 females. Each person repeated coughing or speaking in a certain protocol, and the exhalation velocity distribution was measured. From the measurement data, the initial coughing velocity was calculated. The results indicated that the average initial coughing velocity was 15.3 m/s for the males and 10.6 m/s for the females. The angle of the coughed air was around 38° for the males and 32° for the females. It may be difficult to generalize the case of speech since the test result was limited to the pronouncing of a certain word '*dul*'. Still, the result indicated that the speaking velocity was about 22–27% of coughing velocity and the angle of the exhaled air from speaking was larger for the females than the males. The comparison of the test subject's height with their coughing and speaking indicated a linear relation. The coughing velocity was higher when the test subject was taller.

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