(EasyOne; Medical Technologies, Andover, MA, USA) was used to measure the mean coughed aerosol volume and peak air flow during coughing, and a 40-L stainless steel cylinder chamber was used to collect coughed aerosols. The collection chamber was fitted with an inlet port for the spirometer and an outlet linked to the SMPS and OPS.

The subjects participated in two experiments. As shown in Fig. 1(a), the 40-L stainless steel chamber was used to evaluate aerosol emissions. To evaluate the emissions of cough-generated aerosols, the participant was seated in front of the steel chamber and asked to breathe high efficiency particulate air (HEPA)-filtered air normally for 5 min to remove background aerosols from their respiratory tract. At the same time, an air pump was used to remove background particles from the chamber. After breathing for 5 min, the air pump was turned off, and the subject was asked to inhale as deeply as possible and then cough with maximum force through the spirometer mouthpiece, which was connected to the chamber. After coughing, the participant breathed normally and exhaled the aerosol that remained in their respiratory tract, but the aerosol emitted during this stage was not included in the concentration per cough shown in Table 2. After analysis, the chamber was evacuated for 10 min using the air pump, and the subject was asked to repeat the coughing procedure two more times for a total of three coughs. After each participant finished the procedure, the spirometer mouthpieces and equipment, including the chamber, were cleaned with disinfectant and UV

157 light.

158 The second experiment to evaluate the characteristics of the cough-generated
159 aerosol in an indoor environment was conducted in a clean room, which controlled
160 background particulates to <10 particles/cc using a HEPA filter-equipped ventilation
161 system. The volume of the clean room was 40.32 m^3 (7.0 m [W] × 2.4 m [L] × 2.4 m
162 [H]). The participant was asked to put on dustproof clothing and to take an air shower
163 to exclude the possibility of any particulate matter from other sources, such as dust
164 dispersion. The temperature and relative humidity were constantly monitored using a
165 real-time thermo-hygrometer (Model TR-72U; T&D Inc., Redmond, WA, USA) to
166 ensure that the room conditions were maintained.

167 Figure 1(b) shows the sampling system. Direct reading instruments for measur-
168 ing the particle concentration and size distribution were placed in each sampling loca-
169 tion. Based on the reported respiratory disease air transmission from previous studies,
170 the clean room area was divided into a near field (<1 m) and far field (>2 m). The
171 SMPS-1 was located 0.5 m from the participant to evaluate the aerosol emissions in
172 the direct contact transmission range. The SMPS-2 and OPS were located 3 m from
173 the participant to measure particle dispersion and airborne exposure. The OPS was
174 placed in the far field to observe the transmission of larger particles and their overall

size distribution and concentration. Due to a lack of monitoring devices, we did not use the OPS in the near field.

Relative humidity and temperature were maintained at 30–50% and 21–25°C, respectively, to represent the indoor air conditions in a hospital or emergency room (Ninomura and Hermans, 2008; Geshwiler, 2003). When the subjects had a cold, the mean temperature in the clean room was 24.0°C (standard deviation [SD] = 0.59) and mean relative humidity was 38.3% (SD = 3.42). After the subjects had recovered, the mean temperature in the clean room was 23.8°C (SD = 0.36) and the mean relative humidity was 37.2% (SD = 1.28).

Each experiment was divided into three phases. Before the cough, the HEPA-filtered air circulation system was operated for at least 60 min to remove contaminants from the clean room. After the particulate concentration level was stabilized, the ventilation system was stopped and 30 min of sampling was conducted to obtain a background aerosol concentration. Cao *et al.* (2015) reported that the existence of a downward air flow from a ventilation system attached to the ceiling can greatly affect aerosol transmission. For this reason, the ventilation system was shut down prior to the experiment, and we assumed that there was no air movement apart from the air flows due to coughing and the sampling instrument intake. The air changes per hour (ACH) of the system during the sampling process were 0.0037 and there were 0.0056 air exchanges per sampling interval. We therefore considered the air flow low enough

to be ignored, and assumed that the inlet flow of the monitoring devices did not affect the transport efficiency in the clean room.

The coughing phase comprised both coughing and rest periods. The participant was asked to cough continuously for 1 min and then rest for 5 min to exhale the aerosol remaining in the respiratory tract. This cough cycle was repeated five times for 30 min of cough-generated aerosol emissions.

After the cough, real-time monitoring was conducted for 30 min to monitor the residence and diffusion of cough-generated aerosols.

Calculations and data analysis

The concentration and size distribution data measured by the SMPS and OPS were used to estimate particle number concentrations and the size distribution. The SMPS provided aerosol particle counts in 13 size bins and the OPS provided five bins. The particle concentrations of 18 optical bins in the 10 nm to 10 μm diameter range were monitored. Data from the SMPS and OPS channels were merged using the Multi Instrument Manager software (MIM-2 ver. 2.0; TSI Inc.) provided by the manufacturer. For effective observation of the characteristics of nano-size aerosol, data was converted from a number concentration into a surface concentration, assuming that the particles were ideal spheres.

All data acquired from real-time monitoring were analyzed statistically. Descriptive statistics were recorded to compare the aerosol concentrations during and after coughing. The number and surface area of aerosol particles per cough were presented as arithmetic means (AM) ± SD because the results were acquired from experiments that were repeated three times. The particle concentrations in the clean room experiment are shown as AMs ± SD because data for each phase and location were normally distributed and the size distribution was proven to be unimodal.

Because the individual data of subjects were not normally distributed when we tested them with a Shapiro-Wilks Test, the results of each subject's coughing while ill were compared to coughs done after recovery using the Mann–Whitney U test. However, because the normalized aerosol concentration data in the clean room were normally distributed, the number of data per experimental phases was the same. A one-way analysis of variance was conducted to compare the particle concentration according to elapsed time (before, during, and after the cough) and Tukey's HSD test was applied because it is the most reasonable way to control type 1 error and has a lot of statistical power. Tukey's test was applied to determine the differences in particle concentration by elapsed time. A result was considered significant at $P \leq 0.05$. All analyses were conducted using SAS software (v. 9.4; SAS Institute, Cary, NC, USA). SigmaPlot software (ver. 10; Systat Software, San Jose, CA, USA) was used to visualize the results.

The particulate concentrations in the chamber were assumed to be the same everywhere and it was also assumed that the aerosol dispersed equally when the concentration was highest 5 min after the cough. Equation (1) was used to estimate the aerosol emissions for each subject:

$$Number\ of\ aerosol\ per\ cough = (C_{particle,max} - \overline{C}_{particle,bg}) \times V_{chamber} \quad -(1)$$

where $C_{particle,max}$ is the particle concentration inside the chamber 5 min after the cough, V is chamber volume (m^3), and $\overline{C}_{particle,bg}$ is the mean background concentration inside the chamber 5 min before the test. There are several assumptions in Eq. 1 that may lead to inaccuracies when estimating aerosol emissions. Size-resolved particle dynamics, coagulation, and constant particle loss rates were ignored. Because we did not use ventilation systems while sampling, the ventilation rate of each experiment was determined only by the inlet flow of the sampling devices. In the chamber experiment, the total inlet flow of the sampling devices was 1.75 L/min. The ACH of the system was 2.5 and there were 0.20 air exchanges per sampling period. Because of dilution and deposition, we considered the use of average aerosol number concentration during sampling inappropriate, and therefore $C_{particle,max}$ was used as the representative value of a well-mixed state.

RESULTS

Characteristics of individual subjects

The mean time from the first to the second visit was 32.1 ± 12.1 days. Cough volume and cough peak flow rate were measured during illness and after recovery, whereas the forced vital capacity (FVC), forced expiratory volume in 1 second (FEV1), and peak expiratory flowrate (PEF) of subjects were measured when they were ill.

As summarized in Table 1, the air volume of each cough, and the peak cough flow rate, increased slightly after recovery compared to during the cold (cough volume, $P = 0.57$; peak cough flow rate, $P = 0.27$). Mean air volume and peak cough flow rate during the cold were 1.68 ± 1.19 L and 6.01 ± 1.45 liters/second (LPS), respectively, which increased to 1.96 ± 1.02 L and 6.59 ± 1.98 LPS after recovery. Although patient cough peak flowrates (CPFs) increased overall after recovery, the CPFs of IDs No. 1 and 10 decreased. Compared with the CPF of ID No. 10, in which the "After Recovery" CPF did not decrease much from the "While ill" CPF, the "After Recovery" CPF of ID No. 1 was much lower than the "While ill" CPF, and was outside the normal range. In previous studies, the normal CPF in healthy adults is typically in the range of 360–1,000 L/min, with CPFs under 160 L/min considered ineffective for airway clearance (Bach, 1993). According to these criteria, the CPF of ID

No. 1 (170 L/min) was effective but below the normal range. Although the CPF criteria may vary slightly depending on race and gender, there was a large difference between the CPF of ID No. 1 and the normal value. The results of measurements other than the CPF for ID No. 1 tended to match those of other subjects. The low CPF may therefore have been a measurement error.

The FVC, FEV1, and PEF were significantly higher in males than in females (all *P*-values = 0.01). The mean FVC, FEV1, and PEF values of female subjects were 2.92 ± 0.24 L, 2.52 ± 0.25 L, and 4.59 ± 1.02 L, respectively, whereas they were 4.54 ± 0.65 L, 3.88 ± 0.40 L, and 9.07 ± 1.07 L in males, respectively. The peak cough flow rate and cough volume of each cough during a cold were also significantly higher in males than in females (all *P*-values = 0.04), but the difference disappeared after recovery, although peak cough flow rate and cough volume were still higher in males than in females ($P = 0.09$ and $P = 0.06$, respectively).

Size and quantity of cough-generated aerosol

As shown in Table 2, the number of particles expelled per cough while the subjects had a cold ranged from 731,000 to 18,756,000 (mean, 4,914,600 particles/cough). The number of particles expelled per cough after the subjects recovered ranged from 200,900 to 450,000. The mean number of particles per cough was higher when the subjects had a cold than after they recovered ($P < 0.001$). However, the

mean value was not significantly different between the sexes, either when subjects were ill or had recovered ($P = 0.68$ and $P = 0.21$, respectively).

The surface area of particles expelled per cough when the subjects had a cold varied from 156,000 to 66,824,000 μm^2 (mean, 7,210,000 μm^2/cough). The surface area of particles expelled per cough after the subjects recovered ranged from 39,000 to 2,681,000 μm^2 (mean, 521,000 μm^2). When the subjects had a cold, the mean surface area of particles per cough was higher than after they recovered ($P = 0.002$). However, patient ID No. 10 displayed the opposite trend. This result was induced by an increase in the proportion of particles with larger diameters in the cough of ID No. 10. The mean did not differ between the sexes, either when the subjects were ill or had recovered ($P = 0.40$ and $P = 0.30$, respectively).

Figure 2(a) shows a plot of the number of aerosol particles expelled per cough, as detected in each size bin, and Fig. 2(b) shows a plot of the surface area of aerosol particles per cough in each size bin. Around 99.9 ± 0.3% of all expelled particles had diameters <5 μm (airborne transmission) when the subjects had a cold, which accounted for 90.2 ± 12.2% of the total surface area. The particle number concentration decreased in each respective size channel of instruments.

The mean number of particles per cough and mean surface area of particles per cough were higher within certain diameter ranges (<100 nm, 100–300 nm, 420–1,000

nm, and 1.0–2.5 μm) when the subjects had a cold versus after they had recovered ($P < 0.001$). The diameter distribution of the measured particles varied among patients, especially for larger particles. In particles with diameters under 100 nm and 100–320 nm, the geometric means and standard deviations GM (GSD) of the particle number concentration were 1,467,000 (2.97) and 1,285,000 (2.73), respectively, for patients with positive symptoms, and 421,000 (3.02) and 413,000 (1.6), respectively, for patients with negative symptoms. However, for larger particles, the GSD was larger, ranging from 5.40 to 47.08.

Aerosol characteristics

Table 3 shows a summary of the background particle concentrations during and after coughing in the near field (0.5 m) and far field (3 m) from the source (participant). In the far field, particle concentrations during coughing by subjects with a cold were considerably higher than the background level. After coughing the concentration increased considerably, but not significantly, in the near field. After subjects had recovered, particle concentrations during and after coughing were slightly higher than the background level, but the difference was less than that observed during the period when subjects had a cold (Fig. 4a).

For nine of the ten subjects, the particle concentrations in the far field were higher than the background concentration when they were ill. The arithmetic mean (AM)

of the particle concentration in the far field increased during coughing for infected subjects compared to the AM of the background concentration. The difference in particle number concentration in the clean room between the background and during coughing varied from 65 to 710 particles/cm^3, as shown in Fig. 4(b), and the difference was significant ($P < 0.001$).

The AM of the particle concentration in the near field was higher than the AM of the background concentration. The difference in the particle number concentration in the clean room between the background and during coughing varied from 8 to 448 particles/cm^3 and the difference was not significant ($P = 0.22$). The distribution of particle concentrations during coughing were not different among the 13 different-sized bins, which ranged from 10 to 420 nm ($P = 1.000$).

In exposure chamber experiments, when subjects had cold symptoms, the number of aerosol particles generated from a single cough had no statistically significant correlation with FVC (0.93), FEV1 (0.90), PEF (0.65), volume of cough (0.28), CPF (0.43), body mass index (0.57), or sex (0.63). However, after subjects had recovered, the number of aerosol particles generated from a single cough had a statistically significant correlation with FVC (0.04, $r = 0.65$), FEV1 (0.03, $r = 0.68$), PEF (0.01, $r = 0.78$), and volume of cough (0.02, $r = 0.72$), but did not have a statistically significant correlation with CPF (0.19), body mass index (0.33), or sex (0.19).

In clean room experiments, when subjects had cold symptoms, the ratio of aerosol number concentration during coughing to the background was significantly correlated with the number of coughs (0.04, $r = 0.65$). However, it had no statistically significant correlation with FVC (0.73), FEV1 (0.96), PEF (0.47), volume of cough (0.49), CPF (0.58), body mass index (0.56), or sex (0.27). After subjects had recovered, the ratio of the aerosol number concentration during coughing to the background had no statistically significant correlation with the number of coughs (0.65), FVC (0.75), FEV1 (0.85), PEF (0.65), volume of cough (0.38), CPF (0.38), body mass index (0.99), or sex (0.38).

DISCUSSION

In this study, we found that patients with a cold can release cough-generated airborne transmission-available particles. Transmission was detected at a distance of 3 m, which is considered to be beyond the contact transmission distance. Furthermore, we found that the number of particles expelled by coughing decreased after patients recovered, and most of the particles generated from coughing were <5 μm in size. Particles of this size can remain suspended in the air for at least 1 h. These results suggest that the airborne spread of pathogens based on aerosol diffusion or the forceful airflow produced by coughing may be possible even at distances >3 m from a patient

with a respiratory disease.

The possibility of airborne transmission of pathogen-containing aerosols is a critical issue for the public health community. However, many questions remain unanswered regarding potentially infectious aerosols produced by ill people. Many recent studies have focused on the generation of aerosols expelled from the respiratory system, and their transmission possibility has usually been studied using models, such as those suggested by Xie *et al.* (2007), Redrow *et al.* (2011), and Wei and Li (2015), rather than experimental methods. The results of this study indicate that people produce more fine aerosols <5 μm, as well as aerosols containing a larger number of particles, when they have a cold compared to after they have recovered. As in several similar studies, the number of cough-generated aerosol particles expelled by the test subjects in this study varied considerably from person to person (Lindsley *et al.*, 2010; Stelzer-Braid *et al.*, 2009; Fabian *et al.*, 2008).

As shown in Table 2, the number concentration and surface area concentration varied greatly. The reason the variation was large even though the participants were of similar ages, i.e., in their 20s and early 30s, was due to differences in gender, spirometric differences (FVC, FEV1, PEF), and differences in the amount of coughing and CPF. For this reason, we found that the number of particles released when suffering from a cold was higher than that after recovery for the same individual. The range of generated particles was 731,000 to 18,756,000

391 particles/cough when subjects had an infection. This suggests a “superspreader”
392 effect, i.e., if a person expels large quantities of infectious particles, they may spread
393 a virus or other infectious agents to others at a much higher rate. When calculating the
394 number of particles per cough, the maximum concentration within 5 min after
395 coughing was assumed to represent the conditions under which the aerosol was
396 completely diffused in the air. We considered that the aerosol would be dispersed
397 from a subject’s mouth over time and diffusion of the aerosol would cease when the
398 aerosol reached the end of the chamber.
399 Because of its ability to reach the alveoli, the respirable fraction of cough-generated
400 aerosols is of great concern. Compared with particles deposited in the nasal region, a
401 considerably lower dose of infectious particles deposited in the lungs can lead to in-
402 fection (Tellier, 2006). Approximately 99.9% of the total number of particles expelled
403 by the subjects in this study were <5 μm in diameter (airborne-transmitted particles),
404 accounting for 90.2% of the total surface area. As seen in Figs. 3(a) and (b), most aer-
405 osols were <5 μm, which meant they could enter and deposit in the alveolar region
406 rather than the upper respiratory tract and branchiloles. Most cough-generated aero-
407 sols are in the respirable particle size range and can enter the alveolar region. We also
408 found that the mean number of particles per cough and mean surface area of particles
409 per cough were higher within certain size ranges (<100 nm, 100–300 nm, 420–1,000
410 nm, 1.0–2.5 μm), but the reason for a lack of statistical difference for particles in the

411 other size ranges (300–420 nm and >2.5 μm) was unclear. This may be due to the
412 physical or chemical properties of particles with specific diameters or simply due to
413 the lack of a sufficient sample size. We found no previous studies that reported the
414 same result, and therefore this observation requires further study.

415 There were some differences between the results of this study and those of pre-
416 vious studies. Yang *et al.* (2007) found that small droplet nuclei had a size distribution
417 of 0.58–5.42 μm and 82% of droplet nuclei were centered in the range of 0.74–
418 2.12 μm. This contrasted with the results of our study, in which a modal diameter of
419 <100 nm was obtained. Yang *et al.* (2007) used a novel process to transfer a respirato-
420 ry-originating warm and water vapor-saturated cough aerosol to a dry bag at room
421 temperature. This would have involved a disturbance to the original equilibrium size
422 of the aerosol due to saturation on the walls of the bag. Therefore, the size distribu-
423 tion would have been larger than that of the aerosol in the respiratory tract. According
424 to Johnson and Morawska (2009), particles of 8–10 μm are the most common size in
425 a droplet distribution. The size of droplets in their study varied from 0.1 to 16 μm and
426 the number concentration varied from 0.001 to 5.5 #/cc. These differences were at-
427 tributed to differences among monitoring devices. The lower diameter limit of the
428 SMPS (10 nm) is much smaller than the device (aerodynamic particle sizer [APS],
429 TSI Inc.) used by Johnson and Morawska (2009), which has a lower diameter limit of
430 0.5 μm. We recorded the proportion of nanosized particles, which made a large differ-

ence to the aerosol number concentration. The size of pathogens may be informative regarding the size of particles that carry them. For example, larger pathogens, such as bacteria (1–2 μm), are found in larger particles (Wainwright *et al.*, 2009), whereas smaller pathogens, such as viruses (20–30 nm), are found in smaller particles (Fabian *et al.*, 2008; Hersen *et al.*, 2008). Hence, measuring aerosols with instruments capable of detecting a wide range of particle sizes is likely to be the most effective way to identify the particles that can induce viral infection.

From the results of the exposure chamber experiments, when subjects had a cold, the number of aerosol particles generated from a single cough had no statistically significant correlation with FVC (0.93), FEV1 (0.90), PEF (0.65), or volume of cough (0.28). However, after subjects recovered, the number of aerosol particles generated from a single cough had a statistically significant correlation with FVC (0.04, r = 0.65), FEV1 (0.03, r = 0.68), PEF (0.01, r = 0.78), and volume of cough (0.02, r = 0.72). This raised the question of whether infection affects the emission characteristics of cough aerosols. From the results of the clean room experiments obtained with cold patients, we found that there was a correlation between the ratio of the aerosol number concentration during coughing and the background concentration, and the number of coughs (0.04, r = 0.65). However, other factors had no correlation with the aerosol emissions of cold patients. Our correlation analysis results were similar to those of Zayas *et al.* (2010). They reported that the concentration of droplets was not

related to age, sex, weight, height, or body mass index in 45 subjects. However, Yang *et al.* (2007) found a significant difference in concentration depending on sex in three age groups. Their 30–50 year age group produced the highest aerosol concentration, and there was also a higher airborne droplet concentration in males than in females. Johnson *et al.* (2009) reported a significant correlation between the droplet concentration and age in 15 individuals, and the concentration differed markedly by particle size. In our study, the participants were all young and healthy adults; thus, our results may not be representative of the entire population. Furthermore, the total number of subjects was small, and aerosol production varied significantly from person to person. This study suggests that within the same age groups, the particle number concentration can vary significantly. According to several studies, relative humidity may also play a role in affecting particle trajectory. Yang and Marr (2011) showed that the total concentration of influenza A virus contained in aerosol particles decreased with increasing relative humidity across all particle sizes. Generally, evaporation can control droplet size, with fine droplets evaporating faster than large droplets. A high relative humidity slows the evaporation process. Yang and Marr (2011) showed that the total concentration of influenza A virus contained in aerosol particles decreased with increasing relative humidity across all particle sizes.

There were some limitations of this study. First, the number of participants was small and the study could therefore not reflect all age groups. Second, all subjects

were infected with a cold at the time of the initial test, but their illnesses were in different stages. Some subjects were more ill than others, although all participants were diagnosed at a hospital. These factors may account for the wide variation in aerosols per cough within the same age group and gender.

Third, we attempted to determine the difference in aerosol concentration between the near and far field distances, but it was negligible. This was because the background concentration fluctuated, and the number of subjects was not large. We therefore normalized the concentration data, but further observations of changes in the cough aerosol size distribution with distance should be made with more patients under more stable background concentration conditions. Fourth, relatively large particles, i.e., >10 μm, were likely deposited by impaction on the walls of the exposure chamber and then sedimented in the clean room, resulting in an underestimation compared to smaller particles. In the exposure chamber experiment, the distance from a participant's mouth to the measuring instrument was less than 60 cm and the cough particles were propagated as a conical plume, which might have reduced the potential for impaction on the walls of the chamber, although some large particles would inevitably be deposited. In the clean room experiment, large droplets might have sedimented out over a short distance. However, the purpose of the study was to determine the potential for cough-generated aerosol transmission to the far field as well as the near field. The transmission of cough-generated aerosol over a long distance (>3 m)

491 in this study suggests that the assumption that most cough-generated aerosol consists
492 of large droplets that are deposited in the near field (<2 m) is wrong.

493 Although these limitations could lead to an underestimation of particles size in
494 the study, we detected airborne particles that were small enough for transmission and
495 a temporary increase in the particle number concentration in the far field by airborne
496 transmission. We found no difference in size distribution between the direct contact
497 range (0.5 m) and the airborne transmission range (3.0 m), which may have been due
498 to a lack of monitoring according to distance. We only used the OPS for the far field
499 measurement, whereas in the near field the upper limit of the SMPS (420 nm) was too
500 small to detect changes in the size distribution of large particles, such as droplets or
501 larger droplet nuclei. However, as shown in Fig. 3(a), most of the aerosol particles
502 expelled from coughing were in the droplet nuclei size range. Thus, this result may
503 not differ from the results obtained with the simultaneous use of monitoring devices
504 with wide particle size detection ranges.
505

506 **CONCLUSIONS**

507

508 Individuals infected with a cold release potentially infectious aerosols when they
509 cough, sneeze, and speak. Coughing is the most important and most common source

of transmission of infectious agents. The results of this study show that most of the particles generated from coughing are small enough to be suspended in the air. Furthermore, patients with a cold can release airborne transmission-available particles, with transmission detected at a distance of 3 m. These results suggest that the airborne spread of pathogens may be possible even at a distance >3 m from a patient with a respiratory disease. Hence, more attention should be given to airborne infections to prevent the spread of disease.

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REFERENCES

Bach, J,R., Smith W,H., Michaels J, Saporito, L. Alba, S,A., Dayal, R., Pan, J. (1993). Airway secretion clearance by mechanical exsufflation for post-poliomyelitis ventilator-assisted individuals. *Arch Phys Med Rehabil, 74*, 170-177

Beggs, C. (2003). The airborne transmission of infection in hospital buildings: fact or fiction?. *Indoor and Built Environ, 12*, 9-18

Blachere, F., Lindsley, W. G., Pearce, T. A., Anderson, S. E., Fisher, M., Khakoo, R.

and Celik, I. (2009). Measurements of airborne influenza virus in a hospital emergency department. *Clin Infect Dis, 48*, 438.

Cao, G. Y., Liu, S. C., Boor, B. E., and Novoselac, A. (2015). Characterizing the dynamic interactions and exposure implications of a particle-laden cough jet with different room airflow regimes produced by low and high momentum jets. *Aerosol and Air Qual. Res., 15(5)*, 1955-1966.

Choi, J., Kim, K., Cho, Y. and Kim, S. (2015). Current epidemiological situation of Middle East respiratory syndrome coronavirus clusters and implications for public health response in South Korea. *J Korean Med Assoc, 58(6)*, 487-497.

Fabian, P., McDevitt, J. J., DeHaan, W. H., Fung, R. O., Cowling, B. J., Chan, K. H. and Milton, D. K. (2008). Influenza virus in human exhaled breath: an observational study. *PLoS ONE, 3(7)*, e2691.

Geshwiler, M. (2003). HVAC design manual for hospitals and clinics. (2nd ed.). *American Society of Heating, Refrigerating, and Air-Conditioning Engineers*, (pp 28).

Gralton, J., Tovey, E., McLaws, M. L. and Rawlinson, W. D. (2011). The role of particle size in aerosolised pathogen transmission: a review. *J Infect, 62(1)*, 1-13.

Hamburger, M. and Robertson, O. (1948). Expulsion of group A hemolytic streptococci in droplets and droplet nuclei by sneezing, coughing and talking. *The American Journal of Medicine, 4(5)*, 690-701.

Hersen, G., Moularat, S., Robine, E., Géhin, E., Corbet, S., Vabret, A. and Freymuth,

F. (2008). Impact of health on particle size of exhaled respiratory aerosols: case-control study. *Clean, 36(7)*, 572-577.

Johnson, G. R. and Morawska, L. (2009). The mechanism of breath aerosol formation. *J Aerosol Med Pulm Drug Deliv, 22(3)*, 229-237.

Li, Y., Leung, G. M., Tang, J. W., Yang, X., Chao, C. Y. H., Lin, J. Z., Lu, J. W., Nielsen, P. V., Niu, J., Qian, H., Sleigh, A. C., Su, H. J. J., Sundell, J., Wong, T. W. and Yuen, P. L. (2007). Role of ventilation in airborne transmission of infectious agents in the built environment–a multidisciplinary systematic review. *Indoor Air, 17(1)*, 2-18.

Lindsley, W. G., Blachere, F. M., Thewlis, R. E., Vishnu, A., Davis, K. A., Cao, G. and Beezhold, D. H. (2010). Measurements of airborne influenza virus in aerosol particles from human coughs. *PLoS ONE, 5(11)*, e15100.

Lindsley, W. G., Pearce, T. A., Hudnall, J. B., Davis, K. A., Davis, S. M., Fisher, M. A. and Coffey, C. C. (2012). Quantity and size distribution of cough-generated aerosol particles produced by influenza patients during and after illness. *J Occup Environ Hyg, 9(7)*, 443-449.

Milton, D. K., Fabian, M. P., Cowling, B. J., Grantham, M. L. and McDevitt, J. J. (2013). Influenza virus aerosols in human exhaled breath: particle size, culturability, and effect of surgical masks. *PLoS Pathog, 9(3)* e1003205.

Morawska, L., Johnson, G. R., Ristovski, Z. D., Hargreaves, M., Mengersen, K.,

570 Corbett, S. and Katoshevski, D. (2009). Size distribution and sites of origin of
571 droplets expelled from the human respiratory tract during expiratory activities.
572 *J Aerosol Sci*, *40*, 256-269.
573 Ninomura, P. and Hermans, P. (2008). Ventilation standard for health care facilities,
574 ANSI/ASHRAE/ ASHE Standard 170–2008. *ASHRAE J*, 52–58.
575 Noti, J., Lindsley, W. G., Blachere, F. M., Cao, G., Kashon, M. L., Thewlis, R. E. and
576 Beezhold, D. H. (2012). Detection of infectious influenza virus in cough aerosols
577 generated in a simulated patient examination room. *Clin Infect Dis*, *54*, 1569.
578 Redrow, J., Mao, S., Celik, I., Posada, J. A. and Feng, Z. G. (2011). Modeling the
579 evaporation and dispersion of airborne sputum droplets expelled from a human
580 cough. *Build Environ*, *46*, 2042-2051.
581 Roy, C. J. and Milton, D. K. (2004). Airborne transmission of communicable
582 infection-the elusive pathway. *N Engl J Med*, *350(17)*, 1710-2.
583 Stelzer-Braid, S., Oliver, B. G., Blazey, A. J., Argent, E., Newsome, T. P., Rawlinson,
584 W. D. and Tovey, E. R. (2009). Exalation of respiratory viruses by breathing,
585 coughing, and talking. *J Med Virol*, *81(9)*, 1674-1679.
586 Tellier, R. (2006). Review of aerosol transmission of influenza A virus. J *Emerg*
587 *Infect Dis*, *12(11)*, 1657-1662.
588 Wainwright, C., France, M. W., O'Rourke, P., Anuj, S., Kidd, T. J., Nissen, M. D. and
589 Rose, B. R. (2009). Cough-generated aerosols of *Pseudomonas aeruginosa* and other

590 Gram-negative bacteria from patients with cystic fibrosis. *Thorax*, *64*, 926-931.
591 Wei, J. and Li, Y. (2015). Enhanced spread of expiratory droplets by turbulence in a
592 cough jet. *Build Environ*, *93*, 86-96.
593 Wells, W.F. (1934). On air-borne infection. Study II. Droplets and droplet
594 nuclei. *American Journal of Hygiene*, *20*, 611-18.
595 Wong, B. C., Lee, N., Li, Y., Chan, P. K., Qiu, H., Luo, Z., and Yu, I. T. (2010).
596 Possible role of aerosol transmission in a hospital outbreak of influenza. *Clinical*
597 *Infectious Diseases*, 51(10), 1176-1183.
598 World Health Organization. Infection prevention and control of epidemic-and pan-
599 demic-prone acute respiratory infections in health care : WHO Guidelines, pp 6-8.
600 *World Health Organization*. 2014.
601 Xie, X., Li, Y., Chwang, A. T. Y., Ho, P. L. and Seto, W. H. (2007). How far droplets
602 can move in indoor environments – revisiting the Wells evaporation-falling curve.
603 *Indoor Air*, *17*, 211-225.
604 Yang, S., Lee, G. W., Chen, C. M., Wu, C. C. and Yu, K. P. (2007). The size and
605 concentration of droplets generated by coughing in human subjects. *J Aerosol Med*,
606 *20(4)*, 484-494.
607 Yang, W. and Marr, L. C. (2011). Dynamics of airborne influenza A viruses indoors
608 and dependence on humidity. *PloS ONE*, *6(6)*, e21481.
609 Zayas, G., Chiang, M. C., Wong, E., MacDonald, F., Lange, C. F., Senthilselvan, A. and King,

M. (2010). Cough aerosol in healthy participants: fundamental knowledge to optimize droplet-spread infectious respiratory disease management. *BMC Pulm Med, 12(1)*, 1-11.

Table Captions

Table 1. Characteristics of the individual test subjects.

Table 2. Number and surface area of particles expelled per cough – Chamber (n = 3).

Table 3. Particle number concentration by experimental phase – clean room (#/cc, SMPS only).

Table 1. Characteristics of the individual test subjects.

ID	Gender	Age	Height (cm)	Weight (kg)	FVC (L)	FEV1 (L)	PEF (LPS)	Cough volume (L)		Cough peak flowrate (LPS)	
								While ill	After re-covery	While ill	After re-covery
1	F	25	158	49	2.75	2.61	4.00	0.81	1.33	4.56	2.83
2	F	24	160	49	2.52	2.30	4.59	0.45	0.44	3.58	3.90
3	F	24	158	46	3.03	2.45	4.22	0.73	0.95	5.84	6.37
4	F	29	162	52	3.10	2.28	3.59	1.12	1.60	5.35	6.02
5	F	22	158	63	3.18	2.97	6.53	1.53	2.37	5.92	6.45
Subtotal	F	24.8±2.3	159.2±1.6	51.8±5.9	2.92±0.24	2.52±0.25	4.59±1.02	0.93±0.36	1.34±0.64	5.05±0.88	5.11±1.47
6	M	26	177	77	4.75	4.26	9.29	1.23	3.39	6.28	8.25
7	M	25	173	75	4.77	4.09	10.37	3.87	3.30	8.11	9.19
8	M	30	174	77	3.24	3.12	7.10	1.61	1.50	6.12	8.43
9	M	26	182	90	4.97	3.85	9.18	1.44	1.37	5.52	5.88
10	M	33	174	77	4.95	4.07	9.40	4.02	3.39	8.79	8.58
Subtotal	M	28±3.0	176±3.2	79.2±5.4	4.54±0.65	3.88±0.40	9.07±1.07	2.43±1.24	2.59±0.94	6.96±1.25	8.07±1.13
Total	-	26.4±3.1	167.6±8.8	65.6±14.8	3.73±0.94	3.20±0.75	6.83±2.47	1.69±1.18	1.96±1.02	6.01±1.44	6.59±1.98
P-value		0.07	0.01	0.01	0.01	0.01	0.01	0.04	0.09	0.04	0.06

LPS, liters per second; FVC, forced vital capacity; FEV1, forced expiratory volume in 1 second; PEF, peak expiratory flowrate.

Table 2. Number and surface area of particles expelled per cough—Chamber (n = 3).

ID.	Gender	Number of particles / cough			Surface area of particles / cough (μm²)		
		While ill	After recovery	*P*-value	While ill	After recovery	*P*-value
1	F	4,443,000 ± 2,300,000	661,000 ± 421,000	0.081	438,000 ± 210,000	66,000 ± 53,000	0.081
2	F	774,000 ± 477,000	600,000 ± 180,000	0.190	748,000 ± 786,000	55,000 ± 14,000	0.190
3	F	2,542,000 ± 959,000	546,000 ± 291,000	0.383	160,000 ± 87,000	106,000 ± 109,000	0.383
4	F	4,674,000 ± 1,857,000	566,000 ± 292,000	0.383	818,000 ± 306,000	444,000 ± 531,000	0.383
5	F	18,806,000 ± 6,984,000	1,039,000 ± 604,000	0.081	66,825,000 ± 33,647,000	121,000 ± 114,000	0.081
Subtotal		6,248,000 ± 7,291,000	683,000 ± 182,000	< 0.001	13,805,000 ± 30,498,000	159,000 ± 145,000	< 0.001
6	M	3,226,000 ± 1,525,000	1,178,000 ± 440,000	1.00	127,000 ± 136,000	714,000 ± 863,000	1.00
7	M	1,596,000 ± 1,145,000	4,229,000 ± 2,728,000	0.383	1,212,000 ± 481,000	842,000 ± 629,000	0.383
8	M	3,522,000 ± 2,057,000	363,000 ± 108,000	0.081	492,000 ± 343,000	39,000 ± 17,000	0.081
9	M	1,043,000 ± 490,000	983,000 ± 651,000	0.663	156,000 ± 44,000	113,000 ± 87,000	0.663
10	M	9,326,000 ± 6,181,000	2,940,000 ± 1,910,000	1.00	550,000 ± 330,000	2,681,000 ± 3,132,000	1.00
Subtotal		3,742,000 ± 4,235,000	1,939,000 ± 1,430,000	0.147	512,000 ± 498,000	882,000 ± 958,000	0.481
Total		4,995,000 ± 6,090,000	1,376,000 ± 1,459,000	< 0.001	7,210,000 ± 19,901,000	521,000 ± 774,000	0.002

Table 3. Particle number concentration by experimental phase — clean room (#/cc, SMPS only)

		0.5 m			3.0 m		
ID	Diagnosis	Background (N = 30) AM ± SD	During cough (N = 30) AM ± SD	After cough (N = 30) AM ± SD	Background (N = 30) AM ± SD	During cough (N = 30) AM ± SD	After cough (N = 30) AM ± SD
1	While ill	1,163 ± 173	1,443 ± 330	1,346 ± 90	1,098 ± 56	1,503 ± 192	1,200 ± 103
	After recovery	2,619 ± 202	2,605 ± 162	2,891 ± 171	2,437 ± 173	2,281 ± 130	2,596 ± 145
2	While ill	2,019 ± 110	2,159 ± 113	2,100 ± 98	1,730 ± 96	1,797 ± 96	1,754 ± 77
	After recovery	4,044 ± 163	3,920 ± 161	3,708 ± 173	3,275 ± 160	3,501 ± 139	3,251 ± 395
3	While ill	-	-	-	1,154 ± 100	1,460 ± 141	1,147 ± 74
	After recovery	884 ± 81	944 ± 86	1,037 ± 79	690 ± 63	755 ± 80	789 ± 65
4	While ill	-	-	-	1,282 ± 69	1,488 ± 117	1,202 ± 213
	After recovery	3,732 ± 294	4,001 ± 223	3,917 ± 180	3,494 ± 252	3,758 ± 266	3,605 ± 187
5	While ill	-	-	-	2,277 ± 198	2,987 ± 628	2,260 ± 172
	After recovery	1,627 ± 85	2,011 ± 239	1,752 ± 177	1,270 ± 70	1,454 ± 92	1,340 ± 76
6	While ill	-	-	-	3,329 ± 131	3,955 ± 236	3,162 ± 227
	After recovery	2,137 ± 125	2,401 ± 155	2,645 ± 283	2,032 ± 96	2,102 ± 148	2,314 ± 140
7	While ill	1,968 ± 134	2,141 ± 121	2,314 ± 159	1,611 ± 87	1,881 ± 141	2,061 ± 115
	After recovery	2,786 ± 169	2,815 ± 132	2,542 ± 147	2,547 ± 166	2,661 ± 141	2,350 ± 146
8	While ill	2,753 ± 106	2,761 ± 160	2,730 ± 207	2,515 ± 101	2,231 ± 153	2,429 ± 171
	After recovery	3,980 ± 316	4,006 ± 302	3,655 ± 221	3,548 ± 287	3,430 ± 284	3,150 ± 259
9	While ill	-	-	-	3,244 ± 206	3,873 ± 220	3,928 ± 335
	After recovery	3,881 ± 204	3,997 ± 203	3,978 ± 160	3,421 ± 177	3,534 ± 152	3,382 ± 117
10	While ill	2,893 ± 238	3,341 ± 274	2,559 ± 129	3,495 ± 248	3,800 ± 357	3,124 ± 200
	After recovery	3,622 ± 482	3,747 ± 412	3,703 ± 447	3,293 ± 548	3,830 ± 310	3,397 ± 444

Table 3. Continued.

		0.5 m			3.0 m		
ID	Diagnosis	Background (N = 30) GM(GSD)	During Cough (N = 30) GM(GSD)	After Cough (N = 30) GM(GSD)	Background (N=30) GM(GSD)	During Cough (N = 30) GM(GSD)	After Cough (N = 30) GM(GSD)
1	While ill	1,142(1.26)	1,362(1.54)	1,343(1.07)	1,096(1.05)	1,491(1.13)	1,196(1.09)
	After recovery	2,611(1.08)	2,600(1.07)	2,886(1.06)	2,431(1.07)	2,277(1.06)	2,592(1.06)
2	While ill	2,015(1.06)	2,156(1.05)	2,098(1.05)	1,728(1.06)	1,795(1.06)	1,751(1.04)
	After recovery	4,041(1.04)	3,917(1.04)	3,705(1.05)	3,271(1.05)	3,499(1.04)	3,291(1.09)
3	While ill	-	-	-	1,150(1.09)	1,454(1.10)	1,144(1.07)
	After recovery	881(1.10)	940(1.10)	1,034(1.08)	687(1.09)	751(1.11)	786(1.09)
4	While ill	-	-	,-	1,280(1.06)	1,484(1.08)	1,185(1.18)
	After recovery	3,721(1.08)	3,994(1.06)	3,910(1.05)	3,485(1.07)	3,748(1.07)	3,600(1.05)
5	While ill	-	-	-	2,269(1.09)	2,928(1.22)	2,254(1.08)
	After recovery	1,625(1.06)	1,997(1.13)	1,744(1.10)	1,268(1.06)	1,451(1.07)	1,338(1.06)
6	While ill	-	-	-	3,326(1.04)	3,948(1.06)	3,154(1.07)
	After recovery	2,133(1.06)	2,396(1.07)	2,630(1.11)	2,030(1.05)	2,097(1.07)	2,310(1.06)
7	While ill	2,309(1.07)	2,138(1.06)	1,964(1.07)	1,608(1.06)	1,875(1.08)	2,058(1.06)
	After recovery	2,781(1.06)	2,812(1.05)	2,538(1.06)	2,542(1.07)	2,657(1.06)	2,346(1.06)
8	While ill	2,751(1.04)	2,757(1.06)	2,723(1.08)	2,513(1.04)	2,226(1.07)	2,423(1.07)
	After recovery	3,968(1.08)	3,995(1.08)	3,649(1.06)	3,536(1.08)	3,419(1.09)	3,139(1.09)
9	While ill	-	-	-	3,238(1.07)	3,867(1.06)	3,912(1.09)
	After recovery	3,875(1.05)	3,992(1.05)	3,975(1.04)	3,416(1.05)	3,531(1.05)	3,380(1.04)
10	While ill	2,883(1.08)	3,330(1.09)	2,556(1.05)	3,486(1.07)	3,783(1.10)	3,118(1.06)
	After recovery	3,589(1.15)	3,724(1.12)	3,675(1.14)	3,249(1.18)	3,817(1.09)	3,368(1.14)

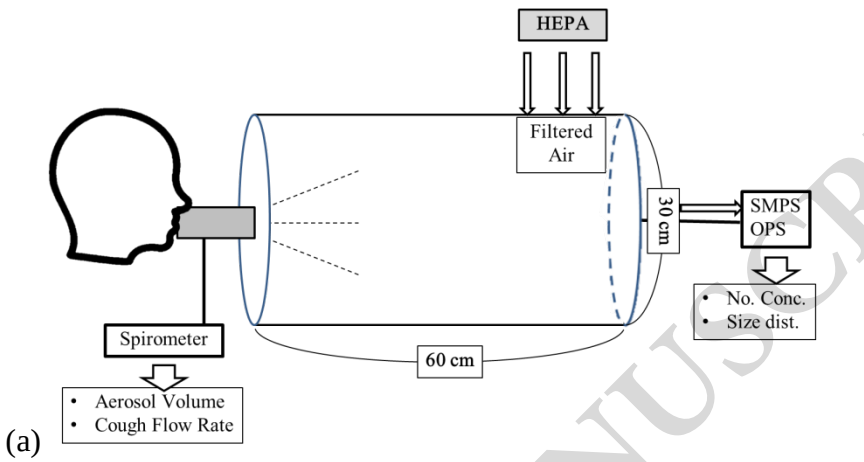
Figure Captions

Fig. 1. Schematic of the exposure chamber (a) for the experiment conducted in the clean room (b). In the experiment (b), filtered air was circulated for approximately 60 min before the experiment to lower the background aerosol concentration. Circulation was suspended during the experiment.

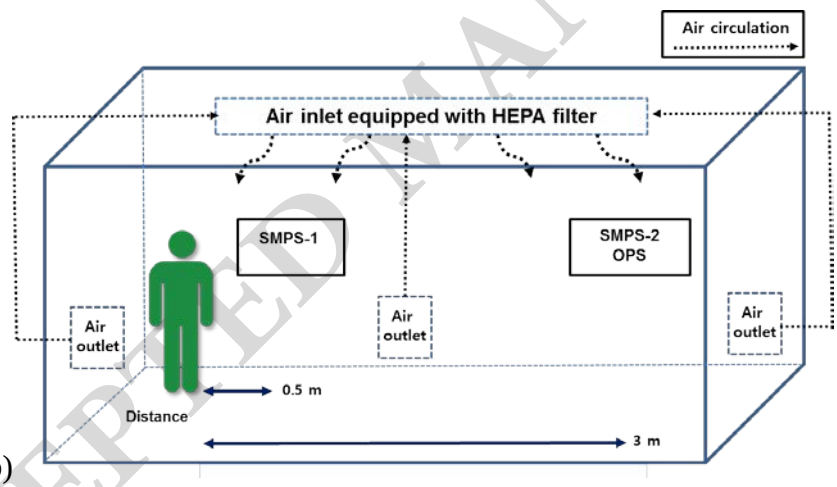
Fig. 2. Number and surface area of particles per cough while ill and after recovery. Results were derived from the chamber experiment. Each bar shows the average of three coughs, and the error bars show the standard error.

Fig. 3. Number (a) and surface area (b) of particles per cough in each size range. Results from the chamber experiment.

Fig. 4. Particle number concentration ratio in the near field (a) and far field (b). The mean number concentration of each phase was normalized by dividing by the mean number concentration of the background. Values shown are medians (line within box), 25th and 75th percentiles (bottom and top of box, respectively), and 10th and 90th percentiles (lower and upper bars on whiskers, respectively).



(a)



(b)

Fig. 1. Schematic of the exposure chamber (a) for the experiment conducted in the clean room (b). In the experiment (b), filtered air was circulated for approximately 60 min before the experiment to lower the background aerosol concentration. Circulation was suspended during the experiment.

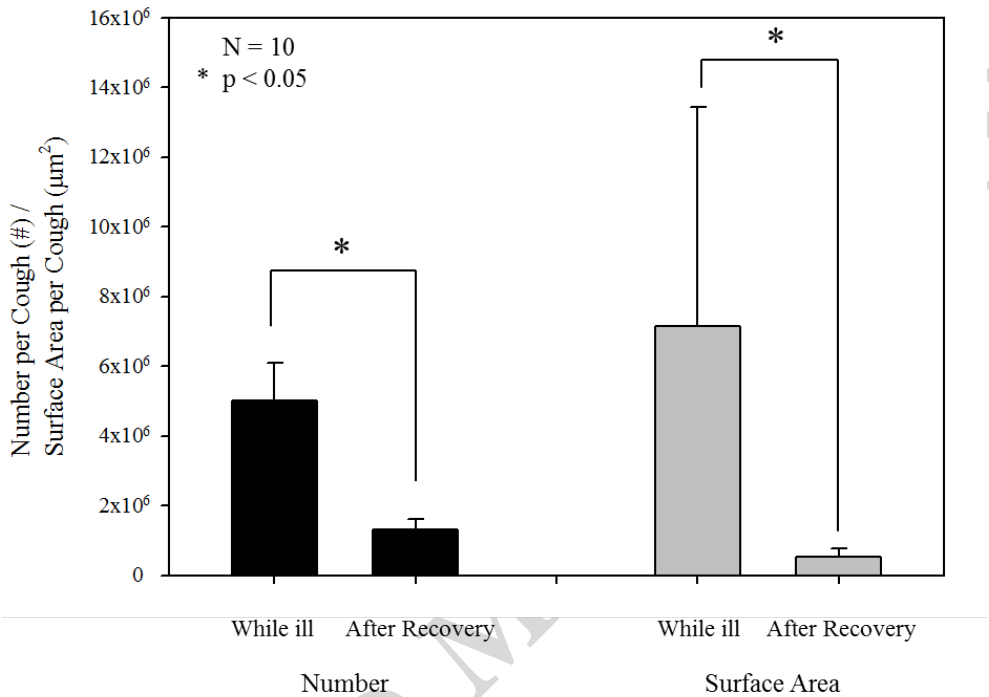
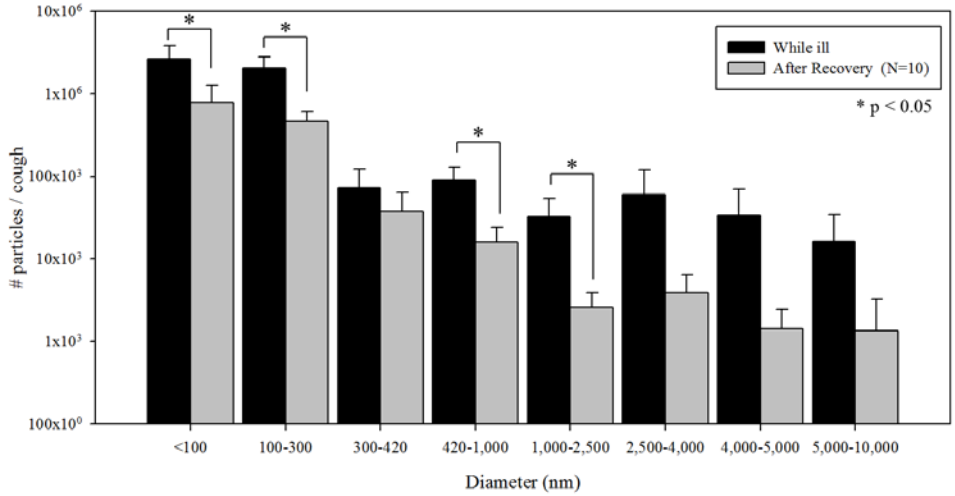
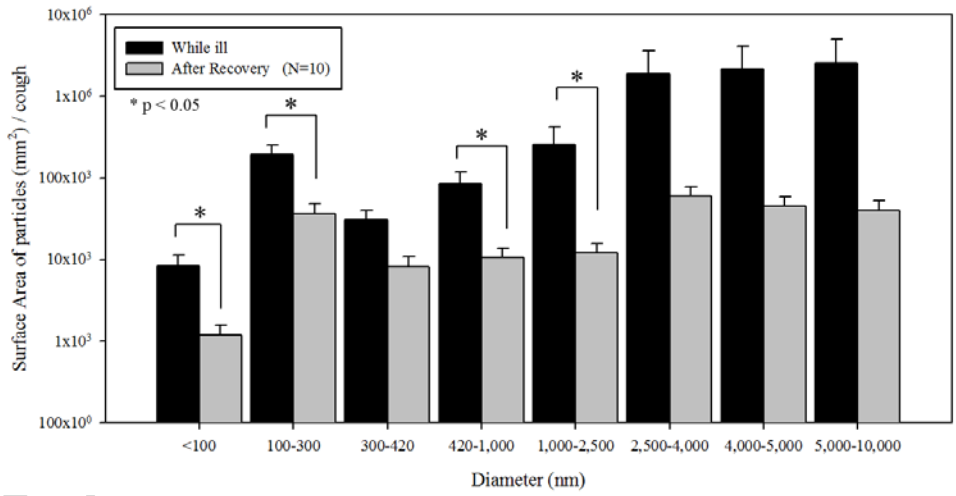


Fig. 2. Number and surface area of particles per cough while ill and after recovery. Results were derived from the chamber experiment. Each bar shows the average of three coughs, and the error bars show the standard error.

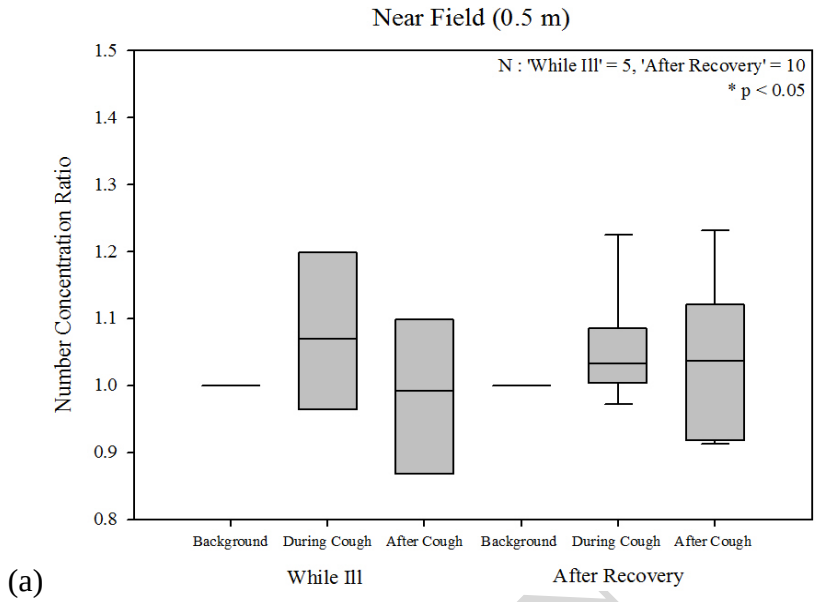


(a)

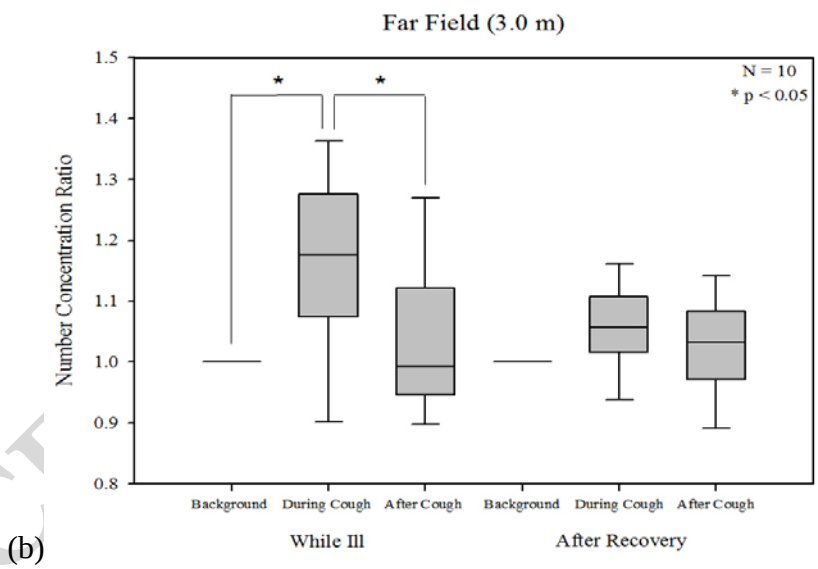


(b)

Fig. 3. Number (a) and surface area (b) of particles per cough in each size range. Results from the chamber experiment.



(a)



(b)

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