Experimental and Theoretical Study of Early Detection and Isolation of Influenza

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AGEM	Aerosol Generation and Entrainment Model
BSA	Bovine serum albumin
CFD	Computational Fluid Dynamics
CFM	Cubic feet per minute
DGM	Droplet Generation Model
DNA	Deoxyribonucleic acid
ESB	Engineering sciences building
F	Filter stage in the bio-sampler
GSD	Geometric Standard Deviation
HVAC	Heating, Ventilation and Air Conditioning
ILI	Influenza like illness
LS	Lagrangian Stochastic walk model
NETL	National Energy Technology Laboratory
NIOSH	National Institute for Occupational Safety and Health
PCR	Polymerase Chain Reaction
PDF	Probability density function
PTM	Pseudo Two-dimensional Model
qPCR	Quantitative polymerase chain reaction
RANS	Reynolds averaged Navier-Stokes
RFG	Random flow generation
RH	Relative humidity
RNA	Ribonucleic acid
RNG	Re-Normalization Group
RSV	Respiratory syncytial virus
SARS	Severe acute respiratory syndrome
SD	Standard Deviation
T1	First stage in the bio-sampler
T2	Second stage in the bio-sampler
TDR	Turbulent dissipation rate
TKE	Turbulent kinetic energy
UC	Urgent care
URANS	Unsteady Reynolds Averaged Navier-Stokes
WHO	World Health Organization
WVU	West Virginia University

1 ABSTRACT

The overall goal of this study was to characterize aerosol droplets produced by human subjects while coughing, and then use this information to better understand the mechanisms of influenza transmission and make recommendations for reducing the extent of influenza transmission. A more specific goal was to quantify the extent of viral-laden aerosols in health care settings by using experimental and theoretical techniques. Aerosols produced by 16 adults coughing were measured using a real-time droplet nuclei measurement system. The results of these experiments were compared with a fluid dynamics model developed for simulating the air flow and particle dynamics in the larynx, and to predict the number and size distribution of the aerosols generated during coughing. The droplet size distribution obtained by this model was consistent with the measurements. Furthermore, a saline solution containing the FluMist influenza vaccine was aerosolized by an apparatus capable of reproducing the flow rate and particle size distribution of a human cough into a simulated medical examination room. These flu-laden particles were collected using NIOSH two-stage cyclone bio-aerosol samplers, while particle concentrations were monitored using an optical particle counter. Airborne influenza and RSV viral particles were collected in a hospital emergency department and in an urgent care medical clinic using mobile and stationary samplers during the winter months. Further tests indicated occurrence of viruses within the particles collected. In another study, a breathing manikin representing a healthcare worker was used to test the ability of masks and respirators to block infectious aerosols. Small aerosols were effectively blocked by N95 respirators but not so well by surgical masks. Additionally, the transport and dispersion of cough generated aerosols in the NIOSH simulated medical room, the WVU Ruby Memorial Hospital children's waiting room, and the WVU urgent care waiting and examination rooms were numerically simulated using a commercially available CFD software called Ansys-Fluent. These simulations showed the importance of ventilation on reducing the concentration of airborne particles. A numerical model was also developed in Matlab to investigate the evaporation rate, velocity, temperature and position of a sputum droplet introduced into a turbulent jet representing a human cough issued into a stagnant air room. The evaporation of water, saline solutions, and saliva was also investigated experimentally and successfully compared to theoretical and numerical models. Another semi-empirical model was developed to predict the variation of airborne virus viability with relative humidity and time. Weather measurements in different US cities and the number of influenza like illness cases reported in those cities are used to correlate the indoor relative humidity and the ILI cases in temperate regions.

2 HIGHLIGHTS/SIGNIFICANT FINDINGS

- The peak in influenza like illness cases in temperate regions occurs when the inside relative humidity is around 10-30%.
- Forty six percent of the influenza virus-laden particles collected in a hospital emergency department had a diameter>4 μm, 49% had a diameter between 1-4 μm, and 4% had a diameter <1 μm.
- Fifty nine percent of the influenza virus collected in an urgent care clinic was in particles>4μm, 30% in particles 1-4 μm, and 11% in particles <1 μm in diameter.
- Seventeen percent of the stationary samplers in an urgent care clinic contained influenza A RNA, 1% contained influenza B RNA, and 32% contained RSV RNA.
- Small aerosols (<0.5μm) penetrate through many surgical masks in significant numbers. N95 respirators block small aerosols better than surgical masks, but coughing pushes the respirator away from the face allowing some particles to leak around the edges.
- Sick people produce more particles per cough volume than healthy ones without a significant change in the droplet size distribution.
- A new two-stage cyclone sampler was developed and tested to collect bio-aerosols.
- In a region close to a coughing source, the Lagrangian stochastic simulations showed that the peak concentration of aerosols occurred close to the floor; the peak concentration of aerosols appeared close to the ceiling in a region away from the coughing source.
- Numerical models indicate that lipids in sputum droplets may reduce the evaporation rate significantly.
- The mucus surface tension seems to affect the aerosol size distribution much more than its density and viscosity, according to our numerical models.
- The influence of relative humidity on models of pure water droplet evaporation seems to be stronger than on models of sputum droplet evaporation.
- The number and size distribution of cough generated aerosols can be predicted by a fluid dynamics model developed in-house.
- Simulations of a 10 μm water droplet show that it can remain airborne in the WVU Ruby Memorial Hospital children's waiting room for up to 28 min, before being removed by the HVAC system.
- A mathematical model was developed which can predict the viability of airborne viruses at different relative humidities.

3 TRANSLATION OF FINDINGS

Inside relative humidity should be maintained between 40-60% in temperate regions during winter months to decrease the viability of influenza virus when airborne, and therefore, decrease the number of influenza like illness cases.

Due to the small size of a higher percentage of the particles containing influenza virus collected in health care facilities, it is anticipated that these particles could remain airborne for a long time before being extracted by the HVAC system. One possible solution is to increase the number of air-exchange rates in health-care rooms when the infection risk is higher (i.e., during the winter months).

Surgical masks do not prevent the inhalation of small viral-laden droplets. Therefore, N95 respirators are recommended for health care personnel dealing with influenza infected patients.

4 OUTCOMES/RELEVANCE/IMPACT

This project lead to improvements in occupational safety and health by providing additional scientific proof that inside relative humidity affects the viability and transmissibility of influenza in temperate regions.

The fact that small droplets containing influenza virus were collected in an urgent care facility and a hospital emergency department provides more evidence to the importance of small droplets in influenza transmission. This also implies that long range transmission, infection at distances greater than about two meters (up to 6 feet), may be significant.

The findings from this research seems to indicate that strategies for prevention of health care workers should focus more on environmental factors such as controlling humidities, air exchange rates, ultraviolet light, etc., than on using surgical masks if wearing N95 respirators is not an option.

5 SCIENTIFIC REPORT

5.1 BACKGROUND FOR THE PROJECT

Millions of people worldwide become infected with seasonal influenza virus every year. Recently, an influenza pandemic (2009 H1N1) has caused about 57 million infections, 257,000 hospitalizations, and 11,690 deaths as of January 16, 2010 (CDC, 2010a). In the United States alone, about 36,000 people die (CDC, 2010b; Thompson et al., 2003; Simonsen et al., 1997; Dushoff et al., 2006), and 114,000 are hospitalized (Bridges et al., 2003a; Barker, 1986) every year from influenza-related illnesses. The estimated cost of building-influenced respiratory infections (influenza, rhinovirus, tuberculosis) amount to about $10 billion in healthcare costs, $19 billion in costs arising from absence caused by illness, and $3 billion in other performance losses per year (Morawska, 2006). From the health cost perspective alone, it is imperative that the transmission of influenza and similar respiratory viruses must be better understood and preventive measures be taken.

The airborne transmission of disease is of great concern to the public health community because of the pandemic potential of newly-emerging diseases like avian influenza, the increasing prevalence of drug-resistant strains of Mycobacterium tuberculosis, and the threat of bioterrorism using agents such as Yersinia pestis. Health-care workers and emergency responders face a much greater exposure to these hazards than does the general public. During an outbreak of SARS in Toronto in 2003, over one-third of the victims were hospital staff. An investigation into the Toronto epidemic concluded that SARS was spread primarily through contact with respiratory droplets (Varia et al., 2003). Another study demonstrated the presence of airborne particles containing viable SARS corona virus in patient rooms (Booth et al., 2005). Additionally, influenza immunization rates among healthcare workers continue to be low and employees often continue to work with respiratory illnesses. During outbreaks in nursing homes, attack rates greater than 60% have been reported (Bridges et al., 2003b). Therefore, there is a need to investigate ways of reducing the transmission of diseases in health-care facilities.

Influenza is transmitted either by contact with contaminated surfaces, large respiratory droplets, or small droplet nuclei that remain airborne for a long time. Bean et al. (1982) demonstrated that influenza A and B survived for 24 to 48 hours on nonporous surfaces and 8 to 12 hours on cloth, paper and tissues. The virus also survived on hands for up to 5 minutes after transfer from the environmental surface. Influenza is also spread by dissemination and inhalation of aerosols of small droplet nuclei that are produced by coughing and remain airborne for an extended

time (Bridges et al., 2003a). Using a mouse model, Schulman (1968) showed that mice with influenza generated airborne particles carrying the virus, and that these particles could transmit virus to other mice. In one human event, an aircraft grounded for 6 hours with mechanical problems contained a woman who began to experience fever, chills, and cough. While few passengers had close contact with her, 72% of the 54 people on the aircraft became ill within 72 hours, suggesting airborne spread of the virus (Moser et al., 1979). However, the airborne transmission of influenza is not well understood in part because cough-generated aerosols in general have not been well-characterized. If a pandemic occurred, it is unlikely that enough facilities would be available to carry out isolation in rooms with negative air flow and the required number of air exchanges. Thus, a better understanding of the exact role of the various modes of transmission of influenza virus is extremely important. This information is also needed even for the recurring annual influenza outbreaks in terms of planning and resource allocation in healthcare facilities.

Coughing is a ubiquitous symptom of respiratory illnesses. Several studies have shown that coughing can produce aerosols containing infectious materials (Gerberding, 1996). Gerone et al. (1966) showed that humans infected with Coxsackie virus produce aerosols when they cough that contain viable viral material. They later showed that the virus could be transmitted from person to person through the air (Couch et al., 1970). Riley et al. (1962) established that tuberculosis is spread by inhalation of respirable particles generated by infected individuals. British studies of classrooms and offices found aerosols containing viable salivary streptococci and other oral bacteria that were thought to be created during speaking, coughing, and sneezing (Lidwell, 1974). Severe acute respiratory syndrome (SARS) and avian influenza are known to spread through infectious aerosols (Yu et al., 2004; WHO, 2004), and this may include cough-generated aerosols as well (WHO, 2004; Wong et al., 2004).

The studies described above have provided important information on the transmission of disease by cough-generated infectious aerosols. However, large gaps remain in understanding the spread of illness by coughing. Only a few studies have examined the size distribution of cough-generated aerosols, and none have looked at aerosol particles below 0.3 μm (Jennison, 1942; Loudon and Roberts, 1967; Papineni and Rosenthal, 1997; Fennelly et al., 2004). Only few studies have collected virus-laden aerosols in healthcare facilities. Finally, very little is known about how and where aerosols of respiratory fluids are actually produced in the respiratory system. This lack of information hampers the ability of health scientists to model and predict the generation of infectious aerosols by coughing and to reduce the potential spread of particular diseases by cough-generated aerosols. In healthcare settings, standard

precautions such as wearing surgical masks and droplet isolation are recommended for treating influenza patients. However, the effectiveness of such measures has not been methodically assessed.

Experiments on animals and humans are often costly and sometimes impossible due to restrictions and dangers involved in studying infectious disease. Properly verified and validated computer models can supplement, and in many cases can be used as a stand alone alternative tool in studying transmission of influenza in occupational settings. The generation and dissemination of infectious droplets by coughing is a very complex problem that requires a joint experimental and theoretical study.

Although there are many investigations concerning the break up of relatively large droplets under various air flow conditions (Hinze, 1955; Narsiman et al., 1979, 1984; Sathyagal et al., 1996), these studies are aimed at aerodynamics problems that have unique features related to the specific application such as chemical reactors (Konno et al., 1983), bubbly flows (Hesketh et al., 1991), and automotive engine combustion and atomization (Castelman, 1931; Reitz and Bracco, 1982). In relation with the present study, there is a need to have two separate models, one for entrainment and transport of infectious liquid droplets within the upper respiratory track, another model that would take the droplets generated by the first model and determines the distribution within a working room.

A thorough literature review (Ersahin, 2007; Celik et al., 2004; Ersahin et al., 2004, 2005) indicated that there is no physics-based computer modeling work that aimed at prediction of droplet properties produced as a result of coughing. Most work in this area seems to be related to drug delivery problems rather than spread of infectious diseases (Martonen, 1983; Katz and Martonen, 1996; Katz et al., 1999; Gemci et al., 2000; Renotte et al., 2000; Martonen et al., 2002). In this regard, the work by Ersahin et al. (2004, 2005) constitutes the first work on this topic. As for simulation of droplet/particle dispersion in working environments, there are numerous applications regarding mostly worker exposure (Su et al., 2001; Li et al., 2003, 2005; Hu and Celik, 2006; Peneau et al., 2000; Saamanen et al., 2000) to hazardous particulates. The work in this project is an application of existing CFD tools with refinements so that the most significant factors such as the temperature, humidity, evaporation and deposition for the droplets are properly accounted for.

The review paper by Bridges et al. (2003a) indicates that droplet transmission (i.e., direct contact of droplets ejected by the infected person with another person in the vicinity) and airborne droplet nuclei transmission (i.e., small

aerosol particles suspended in the circulating air in the occupied room) are the most significant mechanisms of influenza transmission. Both of these processes can be simulated by way of computational models based on equations governing the dynamics of gas-droplet two-phase flows. Validation studies of gaseous contaminant transport in a wind tunnel equipped with a human manikin have been performed by Li (2005) and Guffey et al. (2001) and bubble dispersion in turbulent flows by Hu (2005). These previous studies were extended to include droplets accounting for evaporation in a humidified room setting. The boundary conditions for the transport model were obtained from experiments and the AGEM developed. The two computer models when used in conjunction with experimental study will be valuable tools in investigation of various prevention studies of the spread of influenza virus. For example, the minimum distance to be kept from the infected person, the influence of room temperature and humidity, and the strength of ventilation can all be investigated without resorting to costly experiments and or sampling. To this end a computational study has been performed to determine the sphere of influence by a breathing person (see section 4.4.2.7).

In summary, the purpose of this project was to gain a better understanding of the production of potentially infectious aerosols by coughing via a joint experimental, clinical and theoretical study. We studied the generation of aerosols during coughing and the dissemination of cough-generated aerosols in the working environment. Because of the critical need for information about the role of cough-generated aerosols in the spread of influenza, our work was focused on the influenza virus, and included laboratory experiments, field studies in a health care facility, and computer modeling of aerosol generation and dissemination mechanisms. The major results of this study have been disseminated by publishing journal articles, conference papers and posters (see section 7). Most recent results which have not yet been published are included in the main text of this report.

5.2 SPECIFIC AIMS

The overall objective of this study was to first characterize the size and quantity of aerosol droplets produced by humans while coughing, and then use this information to better understand the mechanisms by which influenza is transmitted from infected individuals to others. This objective was accomplished using well-established experimental and theoretical techniques in conjunction with laboratory experiments and actual clinical studies.

5.2.1 Specific Aim I: Characterize Aerosol Production by Coughing

Aerosols produced by humans during voluntary coughs were characterized using aerosol measurement instruments. Human subjects coughed through masks and respirators, and these were tested using an artificial cough generator with test aerosols. This information was required to develop experimental conditions to study dissemination of virus-laden aerosols (aim II) and for modeling cough aerosols (aim III).

In addition some preliminary experiments were performed to determine evaporation rates of droplets made of human saliva. The evaporation rate changed significantly depending on the composition of the droplet.

5.2.2 Specific Aim II: Study the Dissemination of Virus-Laden Aerosols Produced by Coughing

A newly developed two-stage personal sampler was utilized to characterize aerosols containing virus. The trivalent influenza vaccine known commercially as FluMist was used as a surrogate for wild-type influenza. FluMist contains a live, attenuated, cold-adapted influenza virus. This work involved optimizing PCR and quick detection tests for the influenza virus, simulating the cough dissemination of the virus by pumping aerosols of FluMist into a closed laboratory environment using an artificial cough generator, and collecting the airborne viral particles with the two-stage personal aerosol sampler. Because the sampler fractionates the aerosol particles by size, this information helped to determine if the virus is transported in larger droplets and/or smaller droplet nuclei. The two-stage sampler was tested under field conditions. Samplers were worn by healthcare workers during their normal work routine and were deployed in fixed locations. Collected samples were evaluated for the presence of potentially infectious influenza virus. Results were analyzed methodically to deduce by which mechanisms the virus is transmitted, e.g., by (i) contacting contaminated surfaces/objects, (ii) large droplet contact, and/or (iii) small droplet nuclei in circulating air.

5.2.3 Specific Aim III: Develop a Computer Model of the Aerosol Generation and Transmission

A computer model based on relevant physical properties (such as surface tension, viscosity and density) of mucus and flow parameters pertaining to coughing was developed to be able to predict the size distribution and exhalation (ejection) properties of aerosol materials produced by humans who may have infectious disease. This droplet generation model (DGM) helped to understand aerodynamic properties of the aerosol particles which in turn were used in calculation of the diffusion and dispersion processes within the work place. The results from the DGM were used as boundary conditions in a computational tool that was developed for virtual sampling and detection of concentration of aerosol material in work rooms. Furthermore, environmental data consisting of relative humidity, pressure and temperature during the months when influenza has occurred were collected. This data has been analyzed in connection with the occurrence of influenza cases. A strong correlation has been found between indoor relative humidity and the number of influenza cases.

The outcome of this theoretical study, when combined with the experimental study, will help in identifying the most plausible influenza transmission mechanisms and help formulate effective prevention guidelines for possible outbreak of influenza in work places, specifically in health care facilities. It will also be used to investigate strategies for ventilation of the work place to minimize exposure to infectious airborne materials by modifying ventilation.

5.3 METHODOLOGY AND RESULTS

5.3.1 Aim I: Characterize Aerosol Production by Coughing

5.3.1.1 Masks and respirators study using a cough simulator

A cough simulator was built to test the ability of masks and respirators to block simulated cough-generated aerosols (Lindsley, 2010). Preliminary results indicate that small aerosols (0.5 µm) are able to penetrate through many surgical masks in significant numbers (Figure 1). Larger aerosol particles (1.5 µm and 3 µm) are filtered out more effectively, but a substantial quantity of particles are still able to penetrate around or through the masks. Particle penetration also varies considerably between different models of masks. N95 respirators are able to block small aerosols from passing through them, but coughing pushes the respirator away from the face and allow particles to leak around the edges of the respirator.

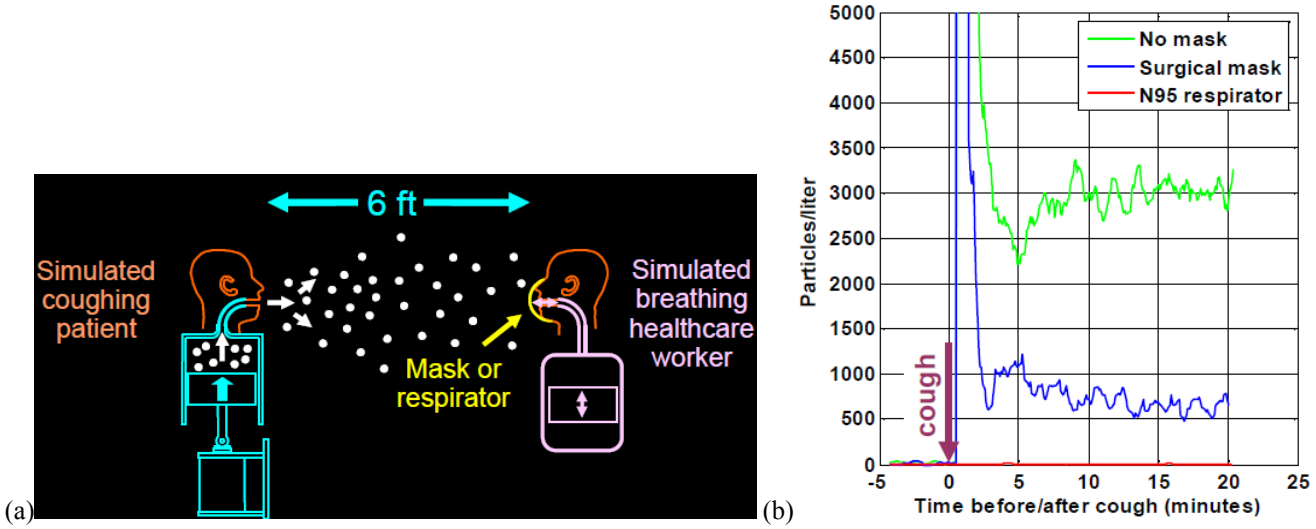


Figure 1. (a) Sketch of the experiments done by NIOSH on the efficacy of surgical masks and N95 respirators, (b) concentration of 0.3 to 0.4 µm KCl aerosol particles at mouth of breathing mannequin (Lindsley, 2010).

5.3.1.2 NIOSH two-stage bio-aerosol sampler

A personal sampler was built to collect bioaerosols (Lindsley et al., 2006, 2007). This sampler uses a two-stage cyclone to collect bioaerosols into disposable 1.5 ml Eppendorf-type microcentrifuge tubes (Figure 2a). Samples can be processed in the tubes for polymerase chain reaction (PCR) or immunoassays, and the use of multiple stages fractionates aerosol particles by aerodynamic diameter. The sampler was tested using fluorescent microspheres and aerosolized fungal spores. The sampler had first and second stage cut-off diameters of 2.6 mm (GSD=1.45) and 1.6 mm (GSD=1.75) at 2 l min^{-1}, and 1.8 mm (GSD = 1.42) and 1 mm (GSD=1.55) at 3.5 l min^{-1}. The trajectory of a 2

μm particle through the sampler when the flow rate is 3.5 l min^{-1} is obtained using CFD-Fluent (Figure 2b). Numerical modeling of this sampler has been conducted using Fluent, and the results were used to compare to experimental collection efficiency of the cyclone sampler (Parsons et al., 2007). For 6.2 μm particles, the aspiration efficiency was 89% at 2 l min^{-1} and 96% at 3.5 l min^{-1} (Figures 2c and 2d; Parsons et al., 2007). At 3.5 l min^{-1}, the sampler collected 92% of aerosolized Aspergillus versicolor and Penicillium chrysogenum spores inside the two microcentrifuge tubes, with less than 0.4% of the spores collecting on the back-up filter.

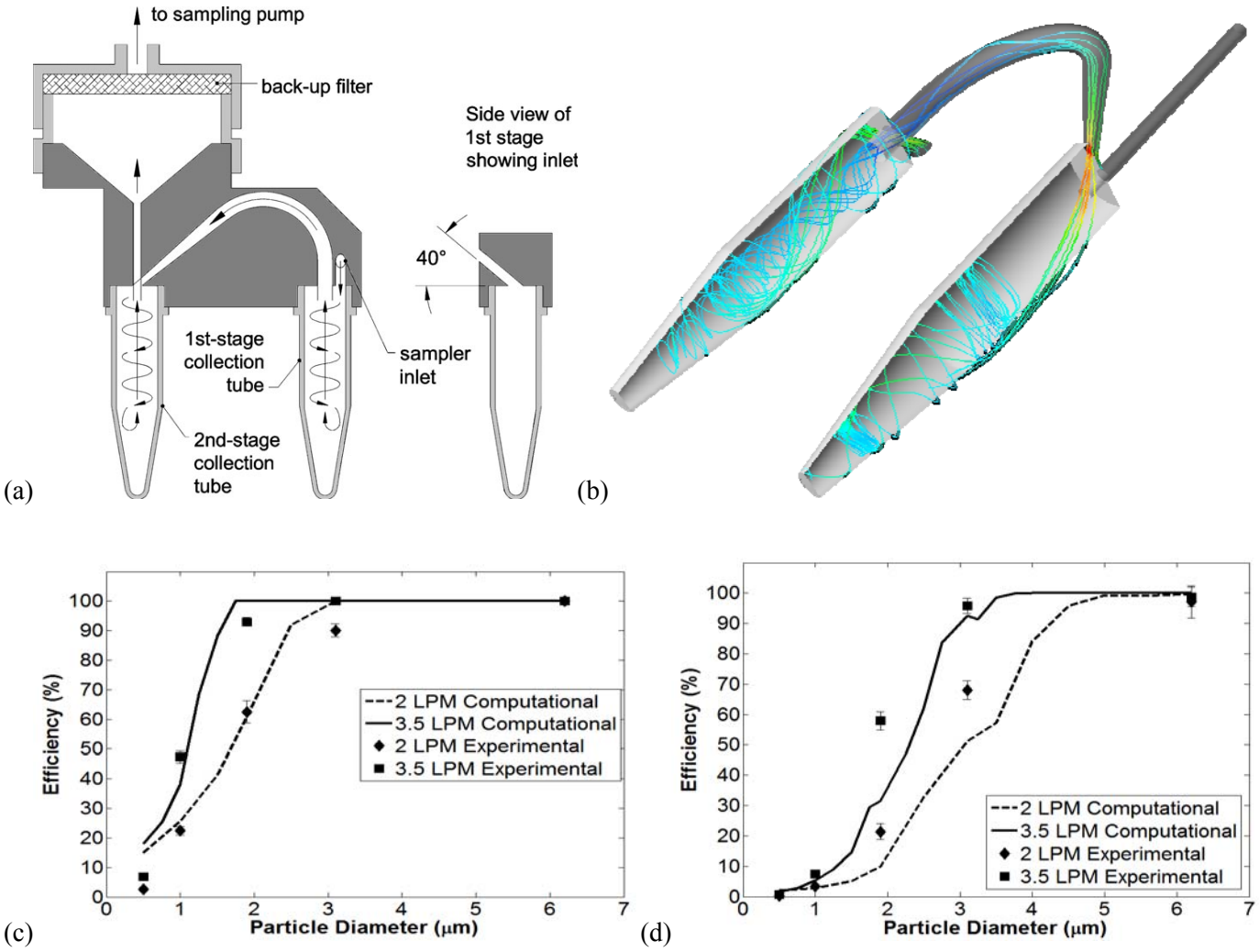


Figure 2. NIOSH two-stage cyclone bio-aerosol sampler: (a) geometry, (b) particle trajectories for 2 μm particle at 3.5 liters per minute (LPM), (c) collection efficiency of first stage, and (d) collection efficiency of second stage (Lindsley et al., 2006; Parsons et al., 2007).

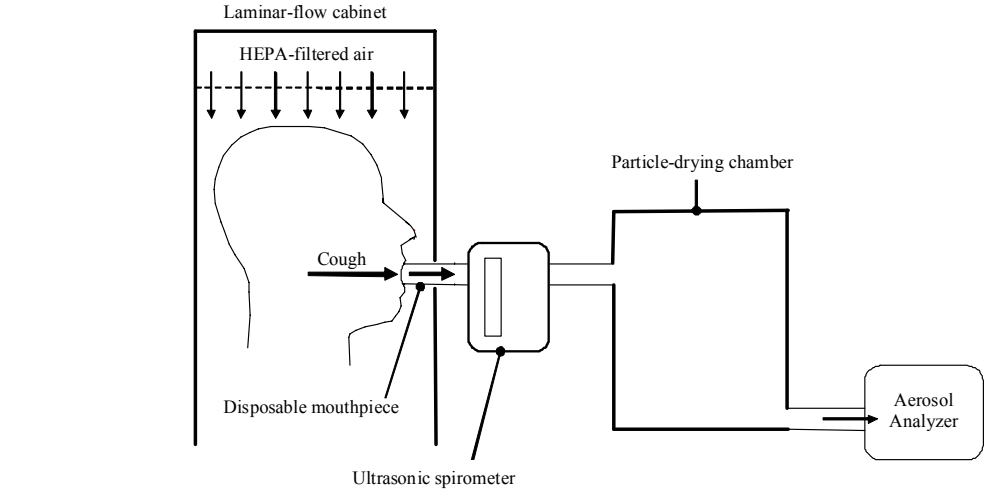
5.3.1.3 Collection and separation of influenza viral particles

Bioaerosols studies were performed within a calm-air settling chamber using the two-stage sampler to capture aerosolized FluMist vaccine (Blachere et al., 2007a, 2007b). Quantitative polymerase chain reaction (qPCR) assays

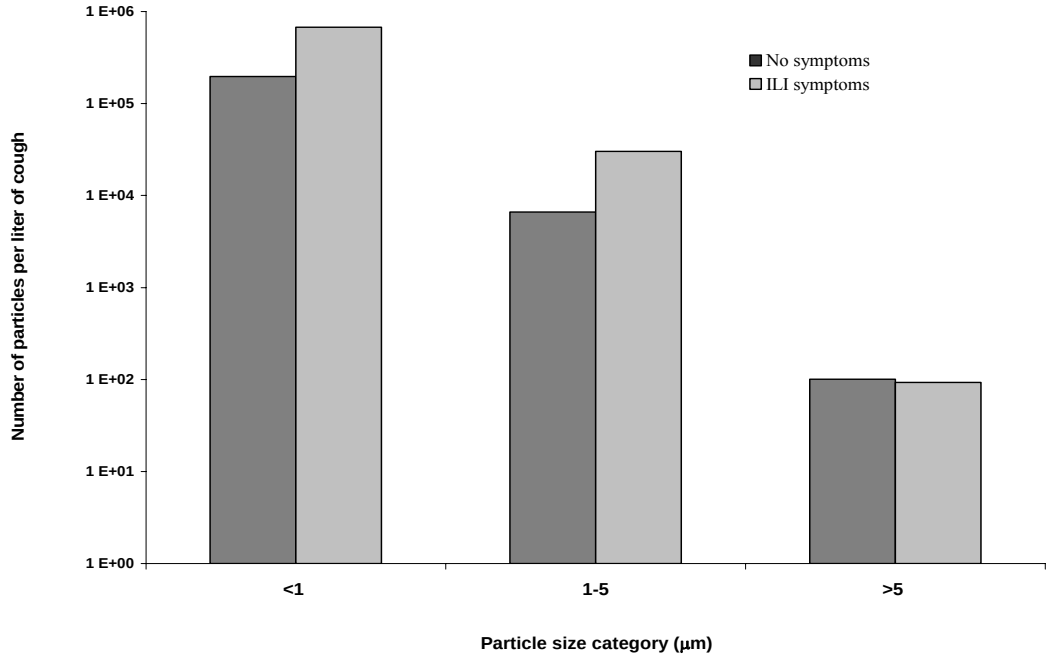
confirmed that the NIOSH two-stage sampler efficiently collected and separated influenza viral particles. Aerosolized influenza viral particle numbers were greatest in the second stage (T2, 1-1.8 μm) and the after-filter (F, < 1 μm) of the two-stage sampler. In order to simulate a more biologically complex aerosol, we also co-aerosolized FluMist with *Aspergillus versicolor* spores in the calm-air settling chamber and captured particles using the two-stage sampler. Previous work demonstrated 95% of Aspergillus spores accumulate in the first stage. In co-aerosolization experiments, qPCR results confirmed that both influenza and spore particles were successfully separated, however, an overall shift in deposition did occur. Namely, in the presence of fungal spores concentrations of viral particles were increased in the first stage (T1, >1.8 μm) of the sampler from approximately 20% to 40%.

5.3.1.4 Characterization of droplets released during coughing by persons infected with influenza

Sixteen otherwise-healthy adults experiencing influenza-like symptoms were recruited from among patients accessing care through a university student health service (Pearce et al., 2010). The participants coughed into a system constructed for real-time droplet nuclei measurement and returned to repeat the coughs when they were no longer exhibiting symptoms (Figure 3a). Sick versus healthy cough volumes for the same person were generally consistent although the participants varied considerably in the volume of their individual coughs. Not all participants produced more cough particles when sick but those who did produced at least ten times the number per liter of cough than when healthy with no obvious difference between the particles sizes measured in a sick versus a healthy cough (Figure 3b). Considerable variation in cough volume and the number of droplet nuclei present in a cough was shown among the small number of participants in this study but the findings did indicate that influenza-like infection does increase the number of droplet nuclei produced. Such a finding indicates that droplet nuclei could play a role in influenza transmission and that further exploration of this mode is necessary. The study also shows that the size distribution of droplets produced by healthy and non-healthy individuals did not change significantly.



(a)



(b)

Figure 3. (a) Schematic diagram of the cough particle measurement system, and (b) number of particles per liter of cough for a participant during and after influenza (Pearce et al., 2010).

5.3.1.5 Characterization of bio-aerosol droplets

The viability of viruses when airborne depends on the environmental conditions of temperature and relative humidity (Schaffer et al., 1976). These conditions would affect the evaporation rate of the viral-laden droplets, making the droplet solution more or less beneficial for the virus viability. The evaporation rate is affected by the density and surface tension of the solution. Several experiments have been performed to measure these properties on different solutions.

The density of five solutions (Table 1) were measured using a Finn pipette II 1-5 ml (Fisherbrand, Pitssburgh, PA, USA), and an electrical balance Adventurer TM Pro AV264 (Ohaus, Pine Brook, NY, USA).

Table 1. Measured density of five different solutions.

Solutions	Measured Density [kg/m^3]
0.3% NaCl Water Solution	1004.29
0.6% NaCl Water Solution	1007.82
0.9% NaCl Water Solution	1009.49
Brewed Coffee	972.00
Human Saliva	1001.73

The surface tension was measured with the help of a capillary tube which has an inside diameter of 1.12 mm. High resolution pictures were taken with a Canon EOS 450D camera (Canon, Ōta, Tokyo, Japan) which has a Tokina AT-X 100mm f/2.8 PRO D Macro Lens (Tokina, Tokyo, Japan). The height of the liquid in the capillary tube and the contact angle between the meniscus and the wall were obtained from these pictures (Figure 4). Then, the surface tension is computed using Equation (1).

$$\sigma = \frac{h\rho g \cdot R}{2\cos\theta} \qquad (1)$$

where σ is surface tension [N/m], ρ is density of liquids [kg/m^3], g is gravity [m/s^2], and R is the inner radius of the capillary tube [m], and θ is the contact angle. The results are presented in Table 2 and shown in Figure 5. Human saliva shows a surface tension similar to a 0.6% glucose-water solution.

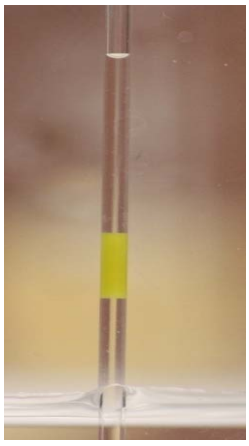


Figure 4. Capillary tube used to measure the surface tension.

Table 2. Surface tension of various solutions.

Solutions	σ [N/m]
Distilled water	0.0692
0.3% Glucose	0.0680
0.6% Glucose	0.0650
5%milk	0.0576
10%milk	0.0540
Brewed Coffee	0.0561
Tap water	0.0659
Saliva	0.0657
0.3%_NaCl	0.0782
0.6%_NaCl	0.0806
0.9%_NaCl	0.0845

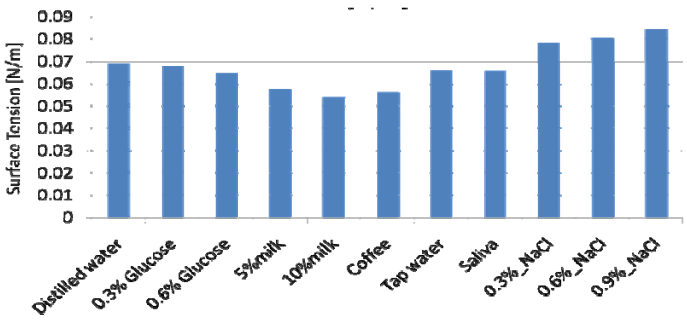
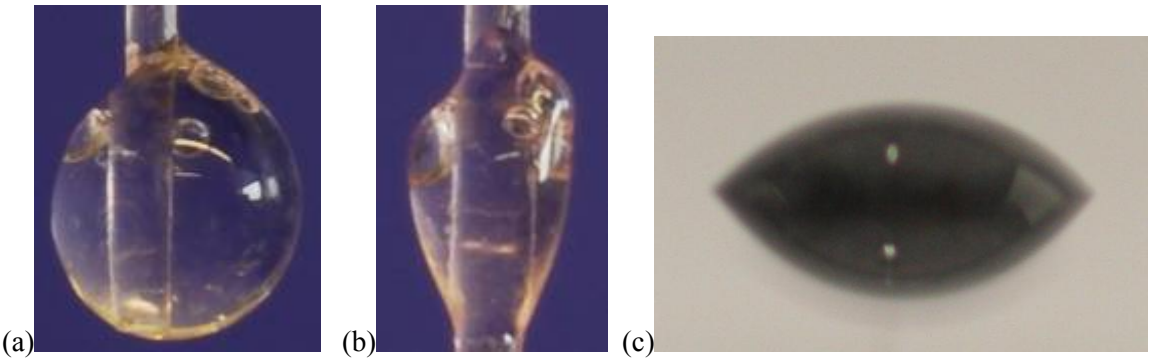
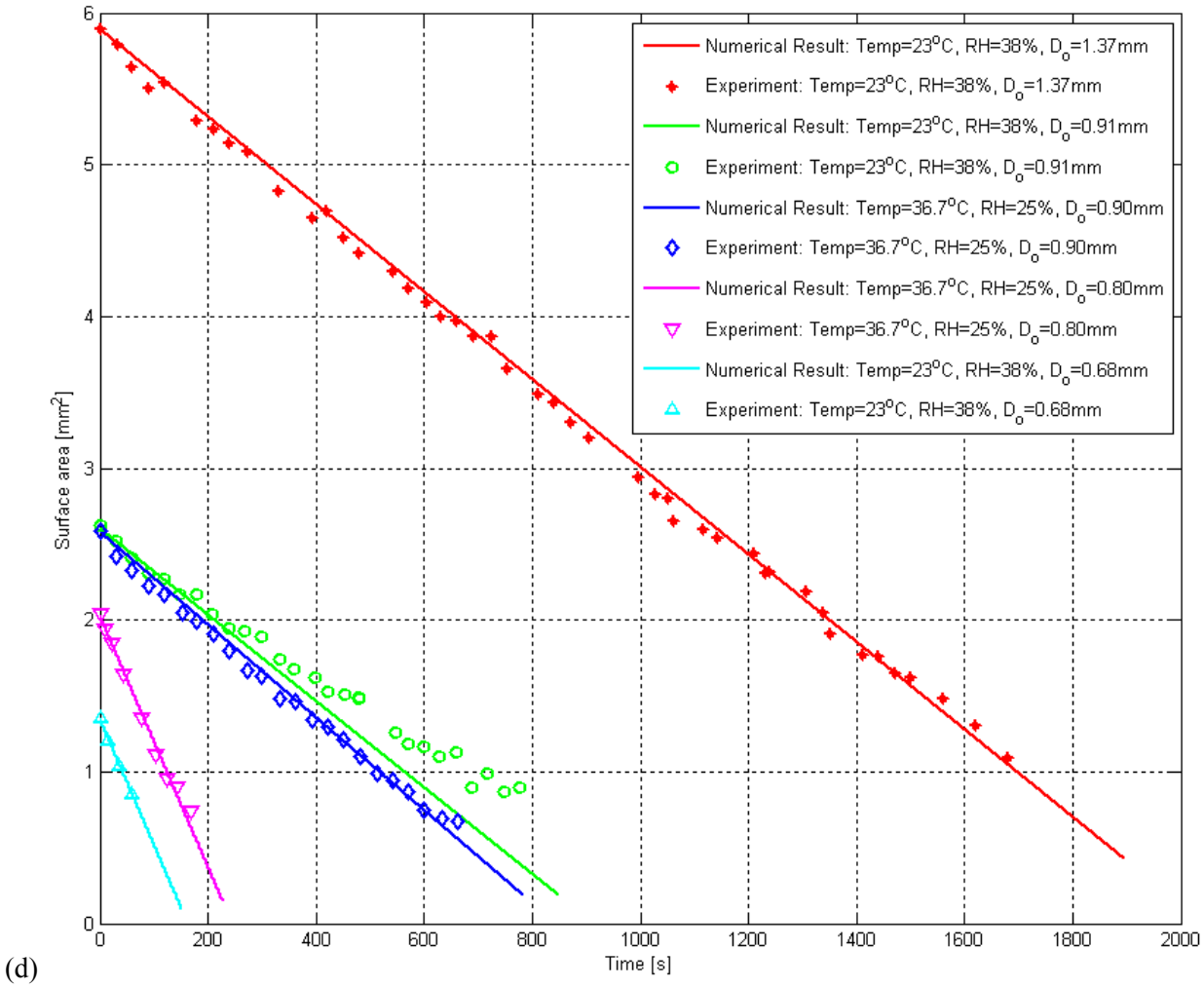


Figure 5. Surface tension of various solutions.

The evaporation of saliva droplets under different environmental conditions has been investigated. Some previous results are shown in Figure 6. An analytical model was developed to determine evaporation rates to be used later in the CFD model. Figures 6a and 6b show a saliva droplet hanging from a nylon filament at different times. Some air bubbles inside the droplet can be seen in these figures. Figure 6c shows a picture taken while investigating the evaporation of saliva droplets on flat surfaces. The results of these experiments and the analytical model at different initial diameters and environmental conditions of temperature and relative humidity are shown on Figure 6d. These preliminary results show that an increase in the environmental temperature from 23 to 36.7ºC increases significantly the evaporation rate. It can also be seen from this figure that a change in RH from 25 to 38% does not affect a lot the evaporation rate of human saliva droplets. These results may shed some light into the mechanisms by which influenza is transmitted via indirect contact.



(a) (b) (c)



(d)

Figure 6. Evaporation of large saliva droplets: Pictures of saliva droplets on nylon (a) at initial time, (b) intermediate time, (c) on a flat surface, and (d) experimental and numerical results of saliva droplet evaporation at different temperature and RH conditions.

On another front, preliminary numerical results were obtained regarding evaporation of small bio-aerosol particles after coughing. A time scale was found based on standard single-droplet equation model. Three different sizes of aerosol particles were chosen to test. The maximum time scale for the evaporation of an aerosol particle from 5~10μm to 1.5μm is found to be less than 0.1s.

An improved and relatively complex single droplet model has been successfully implemented to study the evaporation and dispersion of bio-aerosol particles after coughing (Redrow, 2009; Redrow et al., 2010). Starting with the simple case of a pure water droplet, evaporating or condensing in air of a constant temperature, relative humidity, and velocity, we built upon this model to develop a detailed model of a droplet with the properties of sputum, introduced into a turbulent, buoyant jet (representative of a human cough), which is issuing into and mixing with stagnant ambient surroundings. This model has been proven to be quite accurate at predicting the properties of binary aqueous solution droplets containing sodium chloride, glucose, or bovine serum albumin. For ternary or higher order solutions, it is difficult to assess with certainty the accuracy of the model, as there is little experimental data available pertaining to solutions of interest. For humidity above 85% the model can predict properties of glucose + NaCl + water systems exceptionally well, but no experimental data for this system could be found below this humidity for validation. For solutions of NaCl + BSA + water our model compares reasonably well with the experimental data, though the error increases as the NaCl/BSA ratio moves closer to 1, apparently due to an interaction between the solutes that is not included in the model. Compared with pure water droplets, a lipid film can significantly reduce the rate of evaporation as shown in the modified single droplet model. The influence of relative humidity on pure water droplet is stronger than that on sputum droplet. There is a definite need for more experimental work to determine the properties of multi-component droplets of biological significance under different conditions.

A parametric study was conducted using the model, in order to identify and visualize the conditions that a virus housed within such a droplet would be subject to while in the airborne state. This will help us evaluate how well the influenza virus is spread through the air, and can be used for risk assessment in any given environment. The output of this model includes the variation of the droplet's size, temperature, velocity, and concentration of droplet constituents over time, including salt (NaCl), carbohydrate, protein, lipids, and DNA content—the same chemical components found in sputum. The initial concentration of any particular component can be specified. The initial temperature, relative humidity, and velocity of the jet and the temperature and relative humidity of the stagnant ambient air can be prescribed as well. The sputum droplet model was able to accurately predict the change in diameter, velocity, and temperature over time. Different initial conditions for the droplet and the ambient air in the room are shown to have drastically different effects on the droplet's behavior. The numerical modeling has been

conducted using Ansys-Fluent (a commercial CFD software package). The concentration of viral particles highly depends on the initial prediction of the coughing jet.

5.3.2 Aim II: Study the Dissemination of Virus-Laden Aerosols Produced by Coughing

5.3.2.1 NIOSH simulated medical examination room

A simulated medical examination room has been set up to study the spread of virus-laden aerosols in a healthcare setting (Lindsley, 2010). A series of experiments were conducted in which a saline solution containing the FluMist influenza vaccine was aerosolized into the room using a nebulizer. Flu-laden particles were then collected using 4 to 6 NIOSH two-stage cyclone personal aerosol samplers. Particle concentrations in the room were also monitored using an optical particle counter. The amount of viral aerosol collected in each stage of each sampler was determined using real-time PCR. The results indicated that the amount of virus detected was consistent between samplers, the amount of material detected was proportional to the collection time, and the samplers fractionated the aerosol particles by size as expected. A coughing manikin (simulating a patient with influenza) and a breathing manikin (simulating a healthcare worker) were set up to simulate the exposure of a healthcare worker to a potentially infectious aerosol. A computational fluid dynamics model of the aerosol flow patterns in the room was also created and validated using the experimental data (Redrow et al., 2009).

5.3.2.2 Measurement of airborne influenza virus in a hospital emergency department

Size-fractionated aerosols were collected in a hospital emergency department to assess the amount of potentially infectious airborne influenza virus in typical healthcare settings (Lindsley et al., 2008; Blachere et al., 2009). Sampling was conducted on 8 days for 3 to 5 hours per day during influenza season. Fourteen healthcare workers were equipped with personal samplers, and 98 samplers were mounted on stands in waiting rooms, examination rooms and reception areas. RNA in the collected material was isolated, reverse-transcribed and amplified using real-time PCR with primers specific to an influenza A matrix protein. Preliminary results indicate that influenza virus was detected in 3 of 14 personal samplers and 10 of 98 stationary samplers. The 3 personal samplers in which influenza was detected contained an average of 2697 (SD 2194) viral particles per sampler, while the 10 stationary samplers in which influenza was found contained 6282 (SD 6809) viral particles per sampler. 53% of the viral particles were detected in the respirable aerosol fraction. These results suggest that a significant amount of airborne influenza virus can be found within a typical healthcare facility, and that the amount of airborne virus varies considerably both spatially and temporally.

5.3.2.3 Airborne influenza virus in an urgent care clinic

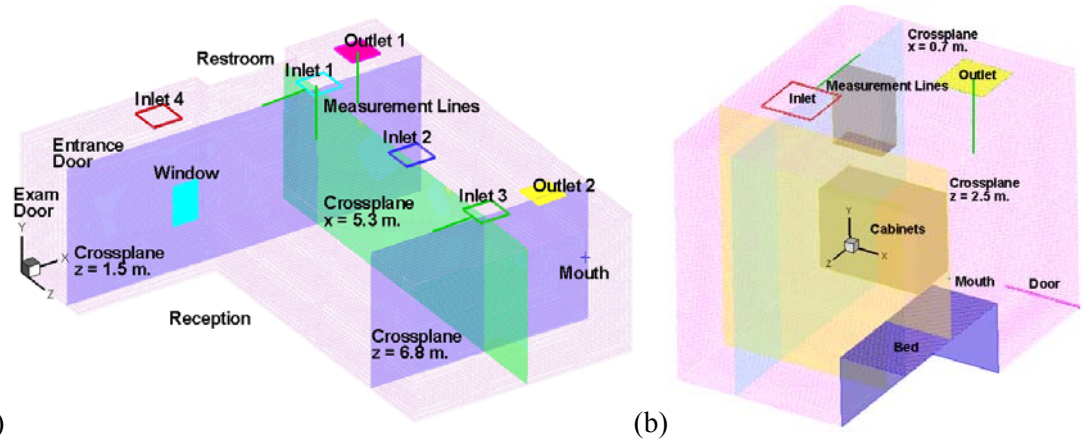
To assess the amount of potentially infectious airborne influenza and RSV virus in typical healthcare settings, size-fractionated aerosols were collected in an urgent care medical clinic during 2009 influenza season (Lindsley et al., 2010). This study was amply broadcasted by West Virginia news stations (Courtney, 2009; Moniot, 2010). Sampling was conducted on 11 days for 3 to 5 hours in the afternoon and evening. During each day, two healthcare workers were equipped with personal samplers, and 24 samplers were mounted in pairs on tripods in the waiting room, exam rooms, procedure rooms and next to the patient scale in the corridor. RNA in the collected material was isolated, reverse-transcribed and amplified using real-time PCR with primers specific to an Influenza A matrix protein and an RSV protein. Fifty-nine percent of the influenza virus was detected in the first tube of the sampler (particles greater than 4 micrometers), 30% of the influenza was detected in the second tube (particles 1 to 4 micrometers), and 11% was detected on the filter (< 1 micrometer). During the collection time, 15 patients had a positive test result for influenza. In 13 of these cases, at least one of the aerosol samplers in the exam or procedure room occupied by the patient was found to contain influenza virus. Influenza virus was also detected in 11 exam or procedure rooms that did not contain patients with confirmed influenza (most but not all patients were tested for influenza). Sampler locations during the study are shown in Table 3. Seventeen percent of the stationary samplers contained influenza A RNA, 1% contained influenza B RNA, and 32% contained RSV RNA. Nineteen percent of the personal samplers contained influenza A RNA, none contained influenza B RNA, and 38% contained RSV RNA. The number of samplers containing influenza RNA correlated well with the number and location of patients with influenza (r=0.77). Forty-two percent of the influenza A RNA was in particles ≤ 4.1 μm in aerodynamic diameter, and 9% of the RSV RNA was in particles ≤ 4.1 μm. Airborne particles containing influenza and RSV RNA were detected throughout a health care facility. The particles were small enough to remain airborne for an extended time and to be inhaled deeply into the respiratory tract. These results support the possibility that influenza and RSV can be transmitted by the airborne route and suggest that further investigation of the potential of these particles to transmit infection is warranted.

Table 3. Sampler locations and number of samplers containing influenza or RSV virus.

	Sampler locations				
	Personal samplers	Examination rooms	Waiting room	Procedure rooms	Scale in corridor
Number of samplers used	21	132	66	44	22
Number of samplers positive for influenza A	4 (19.0%)	29 (22.0%)	10 (15.2%)	6 (13.6%)	1 (4.5%)
Number of samplers positive for RSV	8 (38.1%)	48 (36.4%)	23 (34.8%)	6 (13.6%)	7 (31.8%)

5.3.2.4 The effect of ventilation on airborne infectious disease transmission in an Urgent Care facility

Airflow velocity and volume flow rate measurements were taken inside the waiting room and one of the examination rooms of the West Virginia University Urgent Care facility during the influenza season of 2009 (Figure 7). The measurements at air inlets were used as boundary conditions for numerical simulations of the airflow patterns using Ansys/Fluent. Diffusers of the HVAC system were modeled as small vertical surfaces providing radial flow. Velocity contours and vectors were plotted at certain cross planes in the rooms with and without a cough to study the effect on the airflow (Figure 8). The dispersion of small droplets representing virus-laden aerosols was also simulated. Possible scenarios of patient exposure to airborne aerosols were assessed. Droplets expelled from the mouth of a person sitting close to the lateral walls would be transported to the center of the waiting room and then extracted by the HVAC system, which may put a person sitting in the center of the room at risk. The velocity and volume flow rates measured compared well with the results obtained in the numerical simulations (Figure 9). The agreement was not as good at low velocities, near the minimum limit of the hot wire anemometer used in experiments.



(a) (b)

Figure 7. Geometry and mesh of: (a) waiting room and (b) examination room of the WVU Urgent Care.

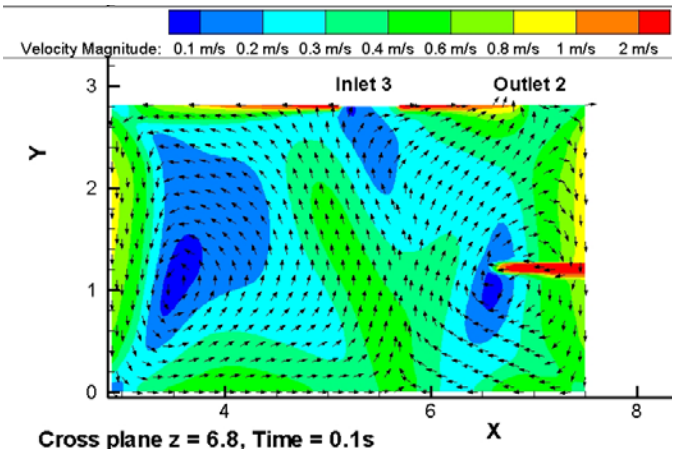


Figure 8. Velocity magnitude contours and vectors at the UC waiting room cross plane z=6.8m at 0.1s from a simulated cough.

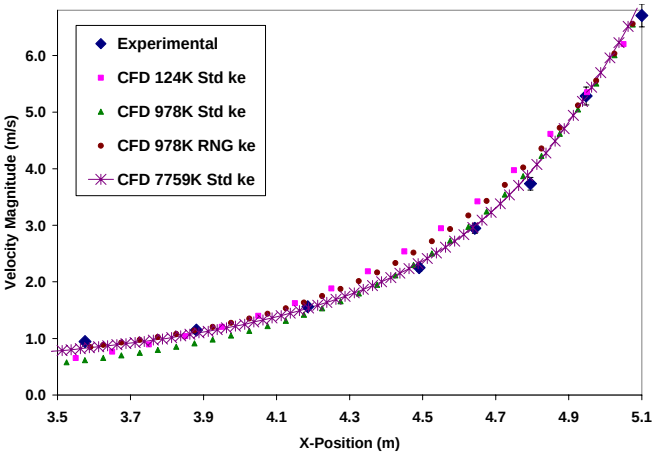
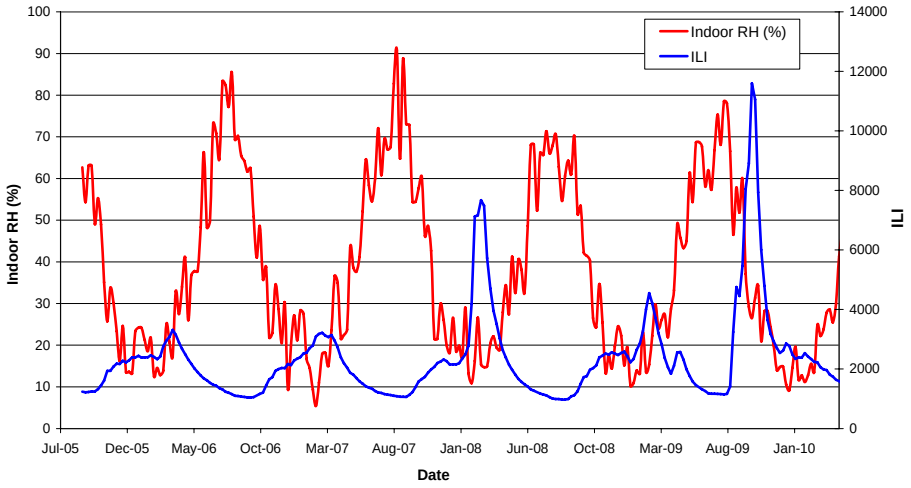


Figure 9. Comparison between the velocity measurements and the CFD simulation results in the waiting room along a horizontal line extending from the center of inlet 3.

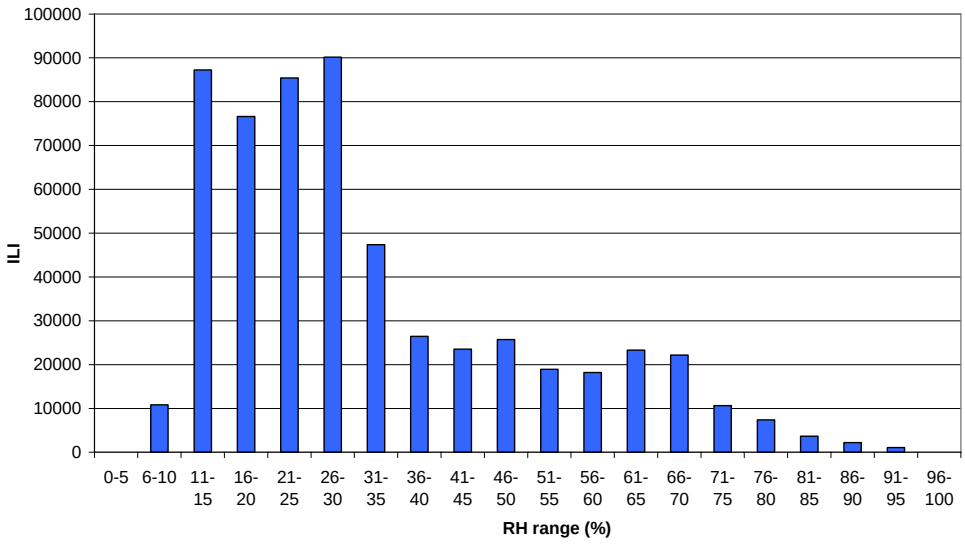
5.3.2.5 Effect of indoor relative humidity on the number of Influenza-Like Illness (ILI) cases

One of the aims of this study was to understand airborne transmission in indoor locations by examining the relation between environmental parameters such as temperature and relative humidity with the number of influenza like illness (ILI) cases. It is proposed that the pattern of influenza activity is primarily a function of indoor relative humidity in temperate regions. This hypothesis is based on previous virus viability experiments (Schaffer et al., 1976; Benbough, 1971). Four weather stations (Vantage Pro2 weather stations, Davis Instruments, Hayward CA and ProWeatherStation, Tycon Power Systems, Draper UT) were installed at various locations at West Virginia University (i.e., Engineering Sciences Building, Residential complex-Towers, Student Health Center, and Urgent Care) to measure the inside and outside weather conditions since September 2009. Additionally a psychrometic procedure is used to obtain indoor relative humidity from outside conditions at four cities in the U.S., namely

Morgantown WV, Cleveland OH, Newark NJ, and Columbus OH. This procedure was validated with weather data measured at WVU and NETL (NETL data was made available to us by responsible authorities and used by permission). The number of influenza like illness cases reported in these cities during the last five influenza seasons is compared to the computed and measured indoor relative humidity trends (Figure 10a). A strong correlation is observed between these two variables which may indicate that indoor relative humidity is the major variable affecting influenza transmissibility. Historical data reveals that the peak in influenza like illness cases occurs when the indoor relative humidity is around 10-30% (Figure 10b). For more details the reader may refer to Panday (2010).



(a)



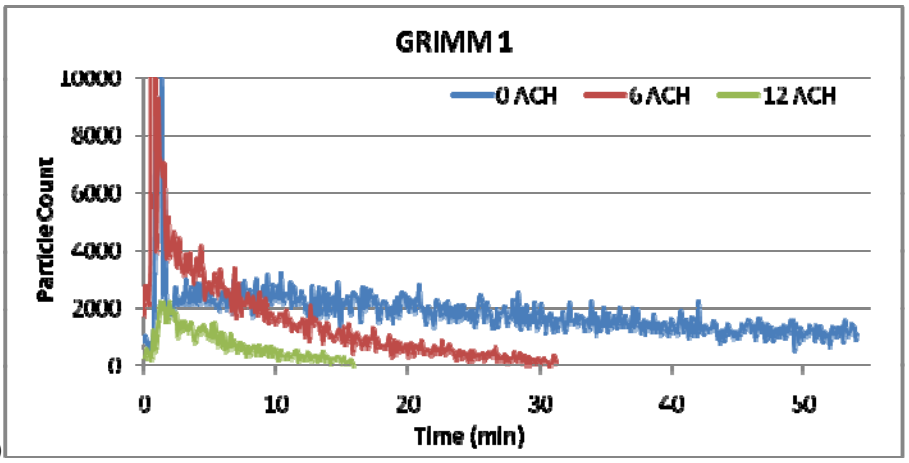
(b)

Figure 10. Indoor RH and ILI cases in Morgantown WV since 2005: (a) Comparison between the indoor RH and the number of ILI, and (b) Histogram of the total ILI cases in each indoor RH range.

5.3.2.6 Effect of air ventilation on particle concentration

The effect of the air exchange rate on the dispersion of simulated cough particles was assessed in the NIOSH environmental chamber. This chamber was ventilated at three air changes per hour (ACH): 0, 6, and 12. Grimm samplers were located across the room and particle count recorded. As expected, the number of airborne particles decreases faster at high air changes per hour (Figure 11).

(a)



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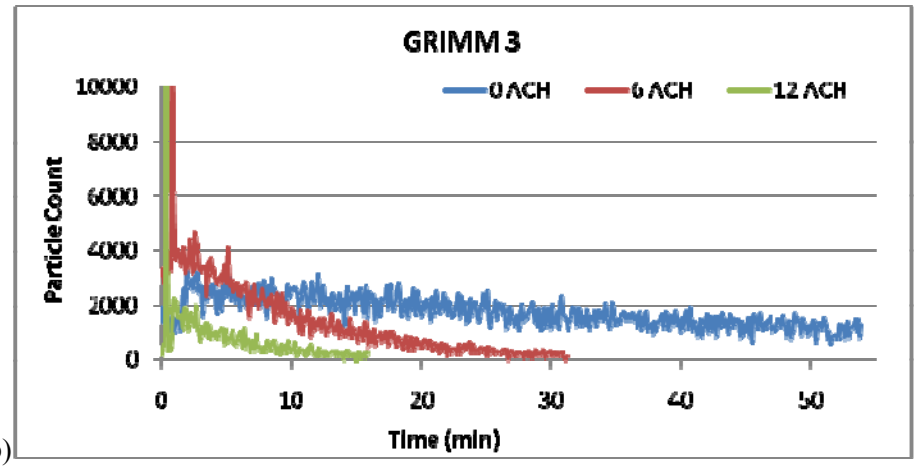

Figure 11. Effect of air ventilation on particle count at various locations in the NIOSH environmental chamber: (a) Grimm 1, and (b) Grimm 2.

5.3.2.7 Determination of the sphere of influence of a breathing person

Infected particles can be inhaled from a certain distance when a healthy person is breathing. The aim of this section is to determine from how far a normal person can pull into his lung airborne particles. A CFD model was created and used to study this problem. This model assumes a breathing cycle of 6 seconds according to the literature review. The total flow rate was set to 14.4 l min^{-1}. The initial concentration of contaminants in the room was assumed equal to one (red in Figure 12). Also, the concentration of contaminants when the simulated healthy person is exhaling is

assumed free of contaminants (dark blue in Figure 12). Preliminary results show that the distance from which a healthy person can pull contaminants into his mouth at the end of inhalation is 8.5 cm from the mouth.

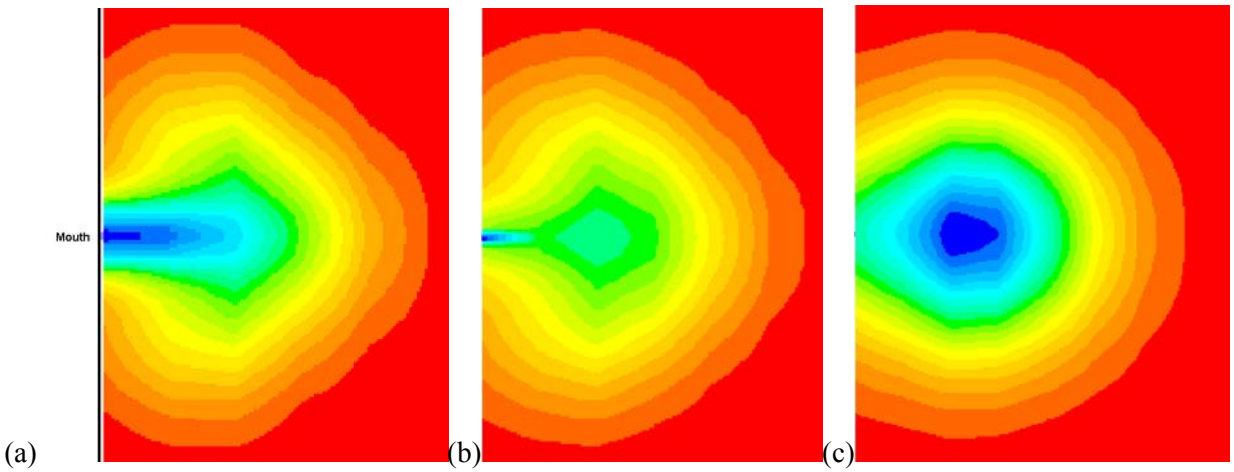

Figure 12. Sphere of influence of breathing at: (a) end of first exhalation-beginning of first inhalation, (b) end of first inhalation, and (c) end of second exhalation – beginning of second inhalation.

5.3.3 Aim III: Develop a Computer Model of the Aerosol Generation and Transmission

5.3.3.1 Aerosol generation and entrainment model for cough simulations

For specific aim III, progress was made in five related areas. First, the generation of aerosol particles by coughing was investigated (Ersahin, 2007; Ersahin et al., 2004, 2005, 2006, 2007). A fairly simple yet accurate air flow dynamics model was developed for simulation of the flow inside the upper respiratory tract, focusing on the larynx and its vicinity, and was used to predict the number and size distribution of the aerosol generated during coughing (Celik et al., 2010) (Figure 13).

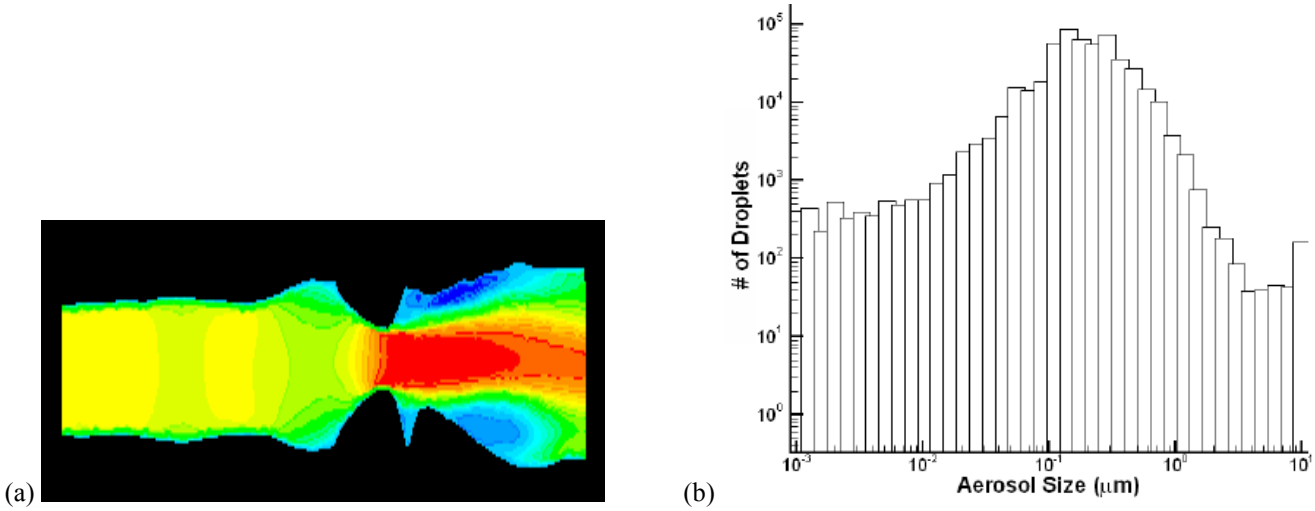

Figure 13. (a) Velocity flow field in the larynx, (b) calculated aerosol size distribution after coughs (Ersahin, 2007).

In order to provide a more complete analysis tool, a secondary objective was to develop a simple reduced order model for the purpose of simulating the air flow and particle dynamics in the larynx. To this end a pseudo two-dimensional model (PTM) has been developed and run for several cases including, sinusoidal laminar and low Reynolds number flow cases including breathing and coughing. The comparison of the PTM model results with FLUENT has shown that the PTM model is capable of producing accurate results within a fraction of execution time needed for the multi-dimensional FLUENT's model.

The aerosol generation and entrainment model (AGEM) was integrated into this validated one-dimensional model. This was done by utilizing a one dimensional turbulent kinetic energy equation. AGEM is then employed to calculate the aerosol formations during a cough, which was simulated by the one dimensional flow solver. The final size distribution of the aerosol droplets was calculated and these findings were compared with laboratory measurements. It is shown that, with appropriate model coefficients, it is possible to obtain size distribution of aerosols that is consistent with the experimental findings (Ersahin, 2007; Ersahin et al., 2006, 2007). A parametric study by variation of physical properties of the mucus has also been carried out. The results show some interesting trend with changing surface tension and varying cough signals. These simulation tools should serve the scientist to do more parametric studies in a fairly quick manner and investigate the aerosol dispersion in the confined areas as well as studying particle deposition patterns within the upper respiratory track.

5.3.3.2 Transport and dispersion of bioaerosols in ventilated rooms

A numerical tool (i.e., DREAM code) based on unsteady Reynolds Averaged Navier-Stokes (URANS) with no turbulence model has been developed at WVU. The large-scale turbulent flow was directly solved by using URANS in a relative coarse grid system. The code was modified by using state-of-the-art techniques to handle complex geometries with a simple computational grid system. A typical ventilated room was modeled by using the code for indoor airflow and dispersion of bioaerosols. A Lagrangian Stochastic (LS) walk model combined with random flow generation (RFG) technique was applied to examine the risk of infection from viral particles in a typical ventilated room (Mao and Celik, 2007, 2010; Mao et al., 2007). The numerical results show the effects of entrainment and deposition of aerosols. The probability distribution of concentration of viral particles provides quantitative information on direct assessment of influence area of germ-laden aerosols due to turbulent diffusion. This result is more useful than that shown in random trajectories of particles as widely reported in the literature. It will help us to re-examine indoor environments in healthcare settings and other work places to limit or prevent viral spread.

The transport and dispersion of bio-aerosol embedded with influenza virus in a positive or negative ventilated room was investigated by Lagrangian stochastic flight model. This model has the advantage of directly tracking these bio-aerosol particles driven by turbulence in indoor environment. Aerosol particle trajectories are generated using a stochastic model. This method is generally more natural and efficient, and has greater potential for application to practical dispersion problems. The probability density function (PDF) and the peak zone of the concentration of aerosol particles in a work place were used to examine influence area. In a region nearby the coughing source, the simulation showed that the peak concentration of aerosols (the maximum probability density) happens at low levels (close to the floor). However, the peak appears at high levels (close to the ceiling) in a region away from the coughing source. The numerical results will be used to benchmark more complicated three-dimensional CFD model in further study. In order to improve the accuracy of probability density function of aerosols, we need detailed fluid flow field and complete droplet evaporation calculation.

5.3.3.3 Simulations of NIOSH Experiments

The commercial CFD solver FLUENT was used to perform simulations of an experimental setup at the Morgantown NIOSH facility involving a specialized room containing an apparatus capable of "reproducing" the flow rate and particle size distribution of a human cough (Redrow, 2009; Redrow et al., 2009). A scenario of a human producing multiple, consecutive coughs within this room was simulated through the use of this software, as well (Figure 14a). In these simulations, small particles were injected into the room at the source of the cough, and their trajectories were tracked over time. The calculated particle dispersion within the room was then compared to experimental data to assess the suitability and accuracy of CFD simulations for such a flow. The spread of coughed droplets within a room was simulated in two different ways and compared with data from experiments performed at the Morgantown NIOSH facility. The particle injection method seems to compare fairly well with Grimms 1 and 5 in the first setup, but no particles were captured during the entire 60 seconds at the other spectrometer locations. This can be justified for Grimms 2 and 4 by assuming the experimental data is just noise, but Grimm 3 seems a bit too high towards the end of the 60 seconds to be excluded as being solely background noise. The second setup proved much more difficult to match the particle simulation with experiments, since there were no longer any Grimms directly on the axis of the inlet. By increasing the virtual volume of the spectrometers in the particle trapping code, we were able to obtain counts in the range of the experiments, though the trends of the data do seem to err significantly from the experiments in some areas. The scalar simulation seems to compare well with the experiments, perhaps even better

than the particle simulation (Figure 14b). The CFD model needs further improvement for accurate prediction of aerosol dispersion in such situations.

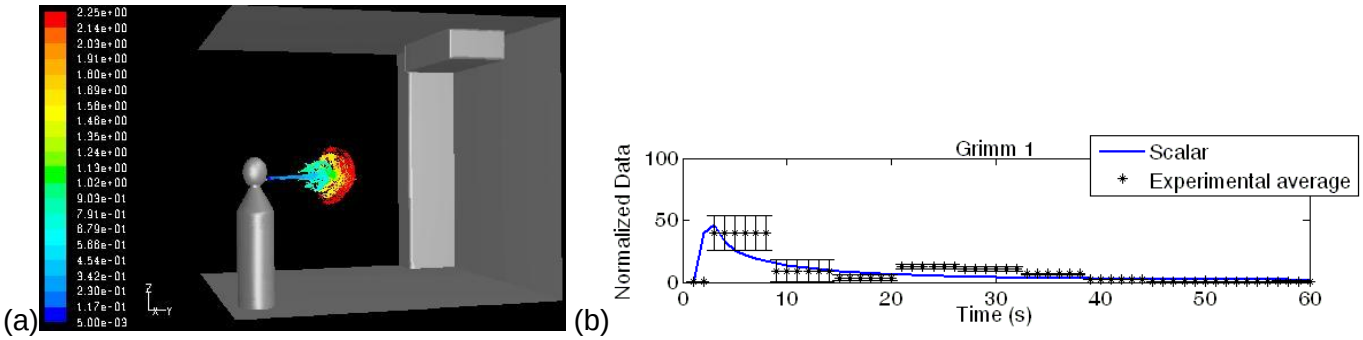

Figure 14. (a) Numerical simulation of a cough inside a NIOSH environmental chamber, (b) comparison between numerical simulations on Fluent and experimental results obtained by an aerosol spectrometer placed 72 inches away from a cough machine in a NIOSH environmental chamber (Redrow, 2009).

5.3.3.4 Droplet residence time in children's waiting room

The residence time of 10 μm water droplets representing a typical cough in the WVU Ruby Memorial Hospital children's waiting room was assessed numerically and experimentally. The volume flow rate of the HVAC system was measured at the inlet with an air capture hood. Dispersion simulations were run using Fluent. Droplets were virtually injected from the HVAC inlet, from a mouth at 10 m/s for 0.75 s (the average velocity and time scale for a human cough). The flow time of a cough droplet cloud released from the inlet and the mouth was calculated. The average residence time measured (6.3 min) in the children's waiting room compared very well with that predicted by the simulations in the range of 4 to 5.6 min. The maximum time that a 10 μm water droplet can remain airborne in the room was 28 min, before being removed by the HVAC system. Around 67% of the 10 μm particles discharged from the room during a cough impinged upon the wall in front of the coughing subject, and the rest were removed by the outlet of the HVAC system.

5.3.3.5 Airborne virus viability

A mathematical model was developed to predict the viability variation of airborne viruses with relative humidity (RH) and time (Posada et al., 2010). The model uses the water activity of the carrier aerosol solution as the primary independent variable. The spray mediums were modeled as a binary solution of water and sodium chloride. The water activity was directly related to the solute concentration in this binary solution. Water activity changes with the type of solute(s) within the droplet, and it determines the solute concentration in a droplet at equilibrium with surroundings of a given (constant) temperature and RH. The viability levels obtained by the proposed mathematical

model compared well with the experimental results reported by Benbough (1971) and Schaffer et al. (1976) considering the influenza, Langat, and polio viruses (Figure 15).

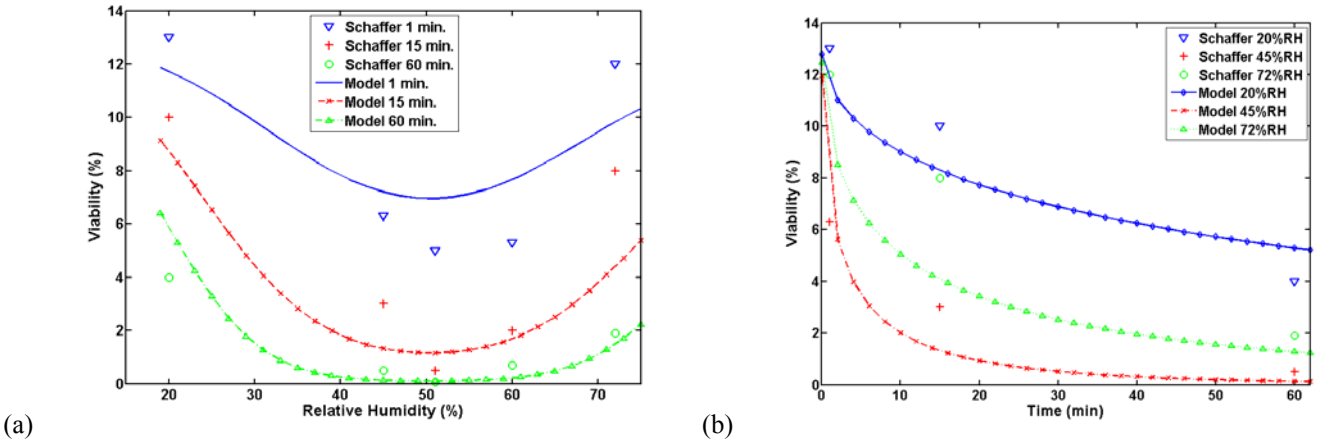

Figure 15. Comparison between the experimental data from Schaffer et al. (1976) and the proposed model for viability of influenza virus in aerosols sprayed from culture fluid: (a) viability versus relative humidity, and (b) viability versus time (Posada et al., 2010).

6 ACKNOWLEDGEMENTS

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9 INCLUSION OF GENDER AND MINORITY STUDY SUBJECTS

Enrollment in this study was not restricted on the basis of gender or racial/ethnic group. Women who are pregnant were not included in the study. All subjects were recruited from the local community (Monongalia County, West Virginia, USA). The women and minority composition of Monongalia County and the State of West Virginia as determined by the US Census Bureau in 2000 are as follows:

Category	***Monongalia County***	***West Virginia***
Female persons	49.6%	51.4%
White persons	92.2%	95.0%
Black or African American persons	3.4%	3.2%
American Indian and Alaska Native persons	0.2%	0.2%
Asian persons	2.5%	0.5%
Native Hawaiian and Other Pacific Islander	<0.1%	<0.1%
Persons reporting some other race	0.3%	0.2%
Persons reporting two or more races	1.4%	0.9%
White persons, not of Hispanic/Latino origin	91.6%	94.6%
Persons of Hispanic or Latino origin	1.0%	0.7%

10 INCLUSION OF CHILDREN

None included

11 MATERIALS AVAILABLE FOR OTHER INVESTIGATORS

All the information is provided in great detail in the publications, so there is nothing additional to provide for it. To obtain from us, email the P.I. at Ismail.Celik@mail.wvu.edu

12 FINAL FINANCIAL STATUS REPORT

This will be provided by the WVU Office of Sponsored Programs.

13 FINAL INVENTION STATEMENT AND CERTIFICATION FORM

None

14 EQUIPMENT INVENTORY

This will be done separately by the WVU Office of Sponsored Programs.

15 APPENDICES — THESES AND DISSERTATION ABSTRACTS

15.1 AEROSOL GENERATION AND ENTRAINMENT MODEL FOR COUGH SIMULATIONS

Cem Ersahin, Ph.D. Dissertation, 2007

The airborne transmission of diseases is of great concern to the public health community. The possible spread of infectious disease by aerosols is of particular concern among health-care workers and emergency responders, who face a much greater risk of exposure to these hazards than does the general public. Some diseases, such as influenza, spread by dissemination and inhalation of aerosols of small droplet nuclei that are generated by coughing and remain airborne for an extended time. For that reason a better understanding of the generation of aerosols is important. Therefore, the main objective of this study is to investigate the flow dynamics and the aerosol generation during coughing. This research aims to develop a fairly simple yet an accurate model for the flow simulation in the upper respiratory tract, mainly in the larynx, and the number and size distribution of the aerosols generated during coughing.

In order to provide a more complete analysis tool, a secondary objective is to develop a simple reduced order model for the purpose of simulating the air flow and particle dynamics in the larynx. To this end a pseudo two-dimensional model (PTM) has been developed and run for several cases including, sinusoidal laminar and low Reynolds number flow cases including breathing and coughing. The comparison of the PTM model results with FLUENT has shown that the PTM model is capable of producing accurate results within a fraction of execution time needed for the multi-dimensional FLUENT's model.

The aerosol generation and entrainment model (AGEM) is integrated into this validated one-dimensional model. This is done by utilizing a one dimensional turbulent kinetic energy equation. AGEM is then employed to calculate the aerosol formations during a cough, which is simulated by the one dimensional flow solver. The final size distribution of the aerosol droplets is calculated and these findings are compared with laboratory measurements. It is shown that, with appropriate model coefficients, it is possible to obtain size distribution of aerosols that is consistent with the experimental findings. A parametric study by variation of physical properties of the mucus has also been carried out. The results show some interesting trend with changing surface tension and varying cough signals.

This study may be considered as a step towards a more complete understanding of aerosol generation mechanisms by coughing, which in turn lead to airborne transmission of diseases. The simulation tools developed should serve the scientist to do more parametric studies in a fairly quick manner and investigate the aerosol dispersion in the confined areas as well as studying particle deposition patterns within the upper respiratory track.

15.2 AN INVESTIGATION INTO THE THEORETICAL AND ANALYTICAL BASIS FOR THE SPREAD OF AIRBORNE INFLUENZA

John B. Redrow, M.Sc. Thesis, 2009

With the threat of a pandemic drawing near and the possibility of a "new", more deadly, form of the influenza virus from genetic re-assortment of avian and human influenza viruses, there is dire need for a better understanding of the transmission mechanisms of this virus. The present study focuses on the aerosol mode of transmission, particularly via the mechanism of human cough. Utilizing computational fluid dynamics (CFD), an in-house code was developed to model the transport of a sputum droplet (cough expectorant) within a jet of air (representative of a human cough). A parametric study was conducted using the model, in order to more thoroughly identify and visualize the conditions that a virus housed within such a droplet would be subject to while in the airborne state. Also, the commercial CFD solver FLUENT was used to perform simulations of an experimental setup at the Morgantown NIOSH facility involving a specialized room containing an apparatus capable of "reproducing" the flow rate and particle size distribution of a human cough. A scenario of a human producing multiple, consecutive coughs within this room was simulated through the use of this software, as well. In these simulations, small particles were injected into the room at the source of the cough, and their trajectories were tracked over time. The calculated particle dispersion within the room was then compared to experimental data to assess the suitability and accuracy of CFD simulations for such a flow.

15.3 A STUDY OF PHYSICAL FACTORS THAT MAY INFLUENCE THE SPREAD AND OCCURRENCE OF INFLUENZA

Kedar V Panday, M.Sc. Thesis, 2010

Influenza is one of respiratory infections causing the highest morbidity and mortality rates. Every day tens of millions of people suffer from virus infection worldwide with varying severity and with a high economic impact. Influenza transmission from person to person occurs in various ways. This study is an attempt to understand airborne transmission in indoor locations by examining the relation between environmental parameters such as temperature and relative humidity with the number of influenza like illness (ILI) cases. It is proposed that the pattern of influenza activity is primarily a function of indoor relative humidity in temperate regions. This conclusion is based on previous virus viability experiments and on our observation of a strong correlation between influenza like illness cases and indoor relative humidity. Historical data reveals that the peak in influenza like illness cases occurs when the indoor relative humidity is around 10-30%. This study also focuses on the aerosol mode of transmission via expelled particles of human cough. Experiments were carried out for concentration measurements at various locations of cough particles in an Environmental Chamber (EC) at a Morgantown NIOSH facility. A simulated cough machine capable of replicating human cough in real time flow and particle size distribution was used for the aerosol injection. A computational fluid dynamics (CFD) model was developed to simulate the human cough in a modeled room. The results of experiments and simulations are compared to assess the suitability and accuracy of CFD simulation for such flow. The last step in this study is to evaluate the potential of inhalation of dispersed cough droplets in room by breathing. Since the primary mechanism of infection transmission is believed to be via inhalation of virus laden droplets, a theoretical study was conducted to define the sphere of influence of human breathing.

15.4 STUDY ON SURFACE TENSION AND EVAPORATION RATE OF DIFFERENT KINDS OF DROPLETS

Tian Zhang, M.Sc. Thesis, 2010

Cough, sometimes containing plenty of germs and virus, is the human body's way of cleaning breathing passages. The virus and germs spread rapidly among humans and may cause influenza. To reduce ultimately the patients caused by human saliva droplets, it is necessary to understand virus transmission. Viruses, shed by an infected person through coughing and sneezing, start to evaporate; once their mucus shell evaporates speedily, the viron, called droplet nuclei, will remain airborne and not drop to the ground, which means that anyone passing by may be infected. In other words, evaporation rate is an important property in virus transmission. Accordingly, the present research is focusing on the evaporation of the virus carrier, human saliva droplets. Experiments and numerical methods are utilized in this research, and two characteristics are monitored, surface tension and evaporation rate. In the experiments, in order to know which component influences the surface tension and evaporation rate of droplet, the distilled water, salt water, etc, are contemplated with the purpose of comparison. In order to comprehend the surface tension, capillary tubes are inserted into solutions to construct 'capillarity'; a high performance camera is used for taking photos; lastly, the influence factors, including different solutes and environmental conditions can be calculated by surface tension equation. As for evaporation, one single droplet is held by a thin needle vertically or lay on a flat surface; a high performance camera is used to take photos of the entire evaporation process of the droplet; after processing the photos, the evaporation rate can be obtained. In the numerical method, a more general equation is derived from the equations of Pruppacher and Klett (1978), Crowe et al. (1997), and Hinds (1982) and then used to model and analyze the evaporation process of multi-component droplets. Eventually, the numerical results compare reasonably well with the experimental measurements. Temperature and relative humidity play an important role in droplet evaporation and therefore virus transmission.