Risk assessment for airborne infectious diseases in aircraft cabins

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Abstract
Passengers in an aircraft cabin can have different risks of infection from airborne infectious diseases such as influenza, severe acute respiratory syndrome (SARS), and tuberculosis (TB) due to the non-uniform airflow in an aircraft cabin. The current investigation presents a comprehensive approach to assessing the spatial and temporal distribution of airborne infection risk in an aircraft cabin. A case of influenza outbreak was evaluated in a 4 hour flight in a twin aisle, fully occupied aircraft cabin with the index passenger seated at the center of the cabin. The approach considered the characteristics of the exhalation of the droplets carrying infectious agents from the index passenger; the dispersion of these droplets; and the inhalation of the droplets by susceptible passengers. Deterministic and probabilistic approaches were used to quantify the risks based on the amount of inhaled influenza virus RNA particles and quanta, respectively. The probabilistic approach indicated that the number of secondary infection cases can be reduced from 3 to 0 and, for the influenza cases, 20 to 11 if N-95 respirator masks are used by the passengers. The approach and methods developed can easily be implemented in other enclosed spaces such as buildings, trains, and buses to assess the infection risk.

Key words: Infectious disease transmission, airliner cabin, influenza, deterministic approach, probabilistic approach, mask

Practical implications:
Airborne infectious disease transmission could take place in enclosed environments such as buildings and transport vehicles. The infection risk is difficult to estimate and very few mitigation methods are available. This study used a 4 hour flight as an example in analyzing the infection risk from influenza and in mitigating the risk with an N-95 mask. The results will be useful to the airline industry in providing necessary protection to passengers and crew and the results can also be used for other enclosed spaces.

Introduction
Researchers and practitioners from both the medical and engineering disciplines have been collectively addressing the issue of transmission of airborne infectious diseases (Mangili and Gendreau, 2005 and Nachega and Chaisson 2003). Enclosed spaces such as buildings and transport vehicles are more susceptible to the transmission of airborne infectious diseases

than the outdoors due to the low air exchange rate and low sunlight (Houk et al. 1968 and Mangili and Gendreau, 2005). Among enclosed spaces, a greater risk of infection is possible in aircraft cabins due to the high occupant density and long exposure time. Some of the outbreaks of TB (Kenyon et al., 1996), influenza (Moser et al., 1979), SARS (Olsen et al., 2003), and norovirus transmission (Kirking et al., 2010) are alleged to have happened during air travel. The swine flu epidemic in 2009 also created a panic among air travelers and caught the attention of researchers (Khan et al., 2009). These transmissions could have happened through direct contact, indirect contact, droplets or airborne route. The infection spread to rows away from the infected person indicated the transmission to these places may have happened through airborne route (Olsen et al., 2003 and Kirking et al., 2010). Our studies were limited to the airborne route of transmission. With such a never ending series of airborne infectious diseases (TB, influenza, and flu) and the rapidly growing number of air passengers (800 million air passengers in 2010, US DOT 2011), it is essential to predict and mitigate the risk of infection from airborne infectious diseases in aircraft cabins.

The airborne disease transmission process starts from droplets carrying the infectious agents. These droplets are exhaled by an infected person through various respiratory exhalations (Cole and Cook, 1998). They then disperse in the enclosed environment and can be inhaled by susceptible fellow occupants. The droplet dispersion depends on the airflow in the cabin and the exhalation process. The airflow in the aircraft cabins is not uniform (Yan et al., 2009). The pulse release of infectious agents by the index passenger through coughing, breathing, or talking exhalations is transient (Gupta et al., 2009 and 2010). Therefore, the expiratory droplet distribution and the risk of infection in an aircraft cabin are not homogeneous and are temporal.

Walkinshaw (2010) predicted the risk of infection from influenza in an aircraft cabin. He quantified the amount of influenza virus ribonucleic (RNA) particles inhaled by the passengers assuming perfectly mixed and transient conditions. Ko et al. (2004) and Jones et al. (2009) used multizone models to quantify the risks based on the dose response model under steady and unsteady scenarios, respectively. Wan et al. (2009) performed detailed steady-state computational fluid dynamics (CFD) (Patankar, 1980) simulations and quantified the risk of infection from influenza in an aircraft cabin. Risks from inhalation and surface contact were quantified using the dose-response model. These studies accounted for either the spatial or the temporal variation of risk of infection in an aircraft cabin, but not both variations. Thus, it is necessary to develop methods to predict both the temporal and spatial distributions of the risks of airborne infection in an aircraft cabin.

To evaluate the risk of airborne infection, it is first necessary to quantify the amount of inhaled active infectious agents such as influenza virus or Mycobacterium. These infectious agents are carried by the exhaled droplets. Therefore, it is necessary to predict the distribution of the exhaled droplets in the cabin. The spatial and temporal distributions of the exhaled droplets can be predicted using experiments or CFD methods. Experiments are expensive and less flexible to change in the parameters. On the other hand, CFD models are flexible to change and, with recent developments, can accurately predict the dispersion of infectious agents (Zhang et al., 2009). Therefore, the current study developed an approach based on CFD methods to evaluate the spatial and temporal distributions of the risks from airborne infectious diseases.

Research Methods

The CFD simulation calculated the airflow, temperature distribution, humidity, evaporation, and dispersion of the exhaled droplets. A commercial CFD program, FLUENT (FLUENT, 2005), was used. To obtain these parameters, the CFD simulations needed

information on the flow, temperature, humidity, and droplet content of the coughing from the index passenger. The flow, temperature, humidity, and droplet fate conditions at the aircraft cabin surfaces, cabin ventilation ports, passenger's body, and breathing of the passengers are also needed. Detailed information on all these conditions can be found in Gupta et al. (2011a). In particular, the coughing and breathing flow conditions were obtained from the experimental studies by Gupta et al. (2009 and 2010). They conducted experiments on human subjects to measure the flow of coughing and breathing. And they developed mathematical functions to characterize the flow rate from these exhalations/inhalations and the direction of the exhalation jets. Figures 1 (a) and (b) show the direction of the exhaled jet from the coughing and breathing (Gupta et al., 2009 and 2010).
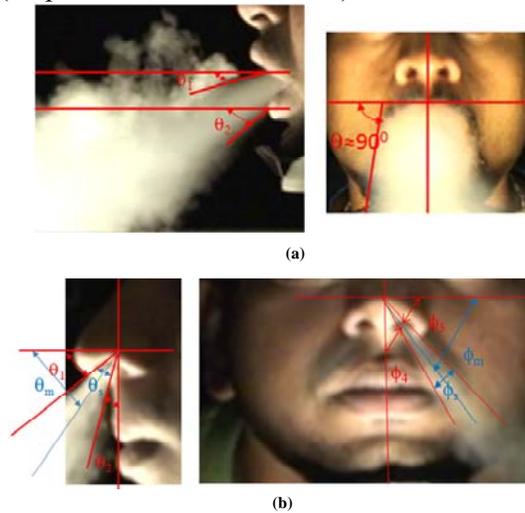

(a)

(b)

Figure 1. Visualization of exhaled jet from the (a) coughing (Gupta et al., 2009) and (b) breathing (Gupta et al., 2010) of a human subject.

These mathematical functions were used in the CFD simulations. The temperature and humidity information for the breathing and coughing was obtained from the studies by Hoppe (1980). The information on the droplet content of the coughing was obtained from the studies by Yang et al. (2007). Using this information, one can predict the dispersion of droplets exhaled from the coughing of an infected passenger (Gupta et al. 2011a) seated at the center of the cabin using CFD methods. Figure 2 shows the dispersion pattern of the exhaled droplets from coughing over a period of time. The nomenclature for the passenger can be found in Gupta et al., 2011a. The seat starts with A on the extreme left and ends at G extreme right. The rows are named from 1 to 7 in the order of sitting.
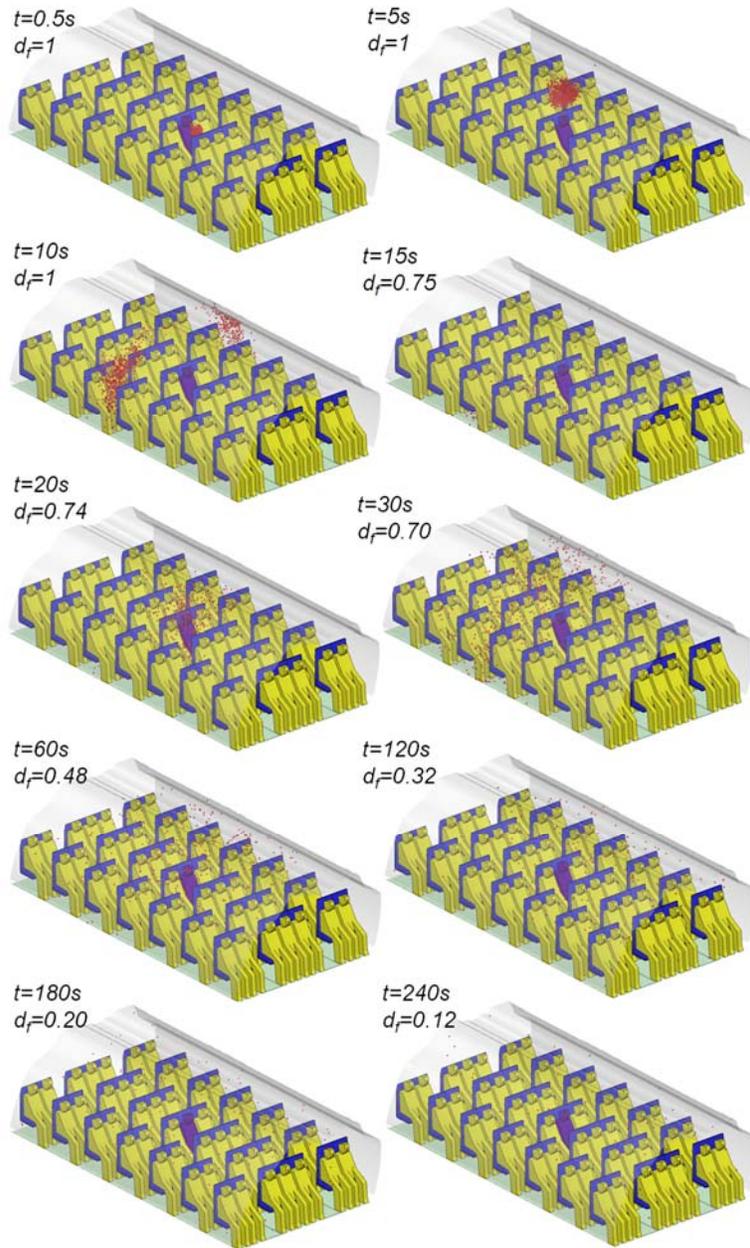
Figure 2. Transport of exhaled droplets from the coughing of an index passenger seated in the center of the cabin section (Gupta et al., 2011a).

The CFD simulations are complex. It took 4 weeks of computational time over eight parallel processers to simulate 4 minutes of dispersion. Therefore, it is not practical to perform CFD simulations for realistic flight durations. Gupta et al. (2011b) developed methods to predict the distribution of droplets for a realistic flight time and for multiple exhalations from an index passenger. They observed that the amount of droplets reduced to about 10% of the amount exhaled within 3-4 minutes and that the distribution became almost homogeneous. Therefore, the droplet distribution in the cabin can be obtained using CFD methods for within 3-4 minutes after the exhalation and assuming perfectly mixed conditions beyond 4 minutes after the exhalation. They also pointed out that the droplet distribution

obtained from a single exhalation CFD study can be superimposed with appropriate time differences to obtain the distribution of exhaled droplets from multiple exhalations. Therefore, the CFD simulation of a single cough exhalation was carried out for 4 minutes of time. Based on the droplet distribution obtained from the 4 minutes of CFD simulation and the perfectly mixed conditions, the distribution of the droplets was calculated for a realistic flight duration. Then using the method of superposition, the droplet distribution was calculated for a multiple coughing exhalation case. As not all of the exhaled droplets may contain infectious agents, we first need to characterize the amount of infectious agent dose present in the exhaled droplets.

The infectious agent dose could be represented as the tissue culture infectious dose ($TCID_{50}$), colony forming unit (cfu), virus RNA particle, or quanta (Wells, 1955). There are a few studies that quantified the dose exhaled for some of the airborne infectious diseases. Alford et al. (1966) quantified the dose exhaled by influenza patients in terms of $TCID_{50}$. Yeager et al. (1967) measured the amount of cfus in patients with TB. Recently, Fabian et al. (2009) and Milton et al. (2010) conducted controlled experiments and quantified the amount of influenza virus RNA particles exhaled from the breathing and coughing of influenza infected people. The dose exhaled during various epidemics was also calculated in terms of quanta (Qian et al., 2009 and Rudnick and Milton, 2003). Quanta is a term defined by Wells, 1955 that indicates that if a person inhales one quanta, the probability of his getting infected is 1-1/e.

Any of these quantities can be used to define the amount of dose exhaled, then the dose inhaled can be calculated using equation (1) (Gupta et al., 2011b).

$$d_i(t) = \sum In_f d_{ex} \alpha(t - t_0) \; p_i(t) \; c_i(t) \; \Delta t \qquad (1)$$

where, $d_i(t)$ is the infectious agent dose inhaled by the ith passenger until time t, In_f is the inhalability (Millage et al., 2010), d_{ex} is the infectious agent dose exhaled by the index passenger, and α is the viability of the infectious agent, i.e., the fraction of total infectious agents that are active at time t. This is generally defined with reference to the time the infectious agents are exhaled. The t_0 is the time when the infectious agents are exhaled; therefore, it is a function of $t-t_0$. The p_i is the rate of inhalation (volume/time) for the ith passenger and is zero during exhalation. (Gupta et al., 2010) and the c_i is the fractional concentration of expiratory droplets in the vicinity of the ith passenger. The fractional concentration of droplets in the vicinity of the ith passenger was obtained by dividing the average concentration of droplets in a zone around the nose of the ith passenger with the droplets exhaled by the index passenger during the exhalation.

The risk was calculated using the deterministic and the probabilistic (stochastic) models. Haas et al. (1999) discussed these models in detail. The dose inhaled by the susceptible passengers was calculated using equation (1) and fed into these models to quantify the risk.

Deterministic models are based on the inhaled dose of infectious agents. A person can get infected only when he/she inhales more than or equal to his/her tolerance dose (Haas et al., 1999). This tolerance dose can vary based on the type of infectious agent and the immunity of the susceptible person. But to our knowledge, there is no study that quantifies the tolerance dose in terms of $TCID_{50}$, cfu, or influenza virus RNA particles. Therefore, even though the dose inhaled can be quantified, the risk cannot be quantified. But the inhaled dose can give an indication of the relative risk of infection.

On the other hand, the probabilistic models are based on probability distribution such as Poisson's or Beta-Poisson's distribution. The probabilistic models do not tell if a person will get infected or not, but can estimate the probability of a person getting infected. Some of

the most popular probabilistic models are the dose-response model (Haas, 1983) and the Wells-Riley model (Riley et al., 1978). Recently, Sze To and Chao (2010) have reviewed the advantages and disadvantages of these models. Equation (2) shows the mathematical form of the probability of risk given by the Wells-Riley equation and is given by:

$$P = \frac{D}{S} = 1 - \exp\left(-\frac{n_i qp}{Q}t\right) = 1 - \exp\left(-d_{i_s}\right). \tag{2}$$

The dose response model can be written mathematically as:

$$P = \frac{D}{S} = 1 - \exp\left(-rd_i\right) \tag{3}$$

where P is the probability of infection, D is the number of developed (secondary) infection cases, S is the number of susceptible cases, n_i is the primary infected cases, q is the quanta release rate, p is the pulmonary ventilation rate, Q is the ventilation rate, r is the contact rate (or capacity to cause infection), and d_i is the inhalation dose. $d_{i,s}$ represents the infectious inhalation dose under a perfectly mixed steady state scenario. The value of r depends on the human response to the airborne infection. Some of the studies on mice for tubercle found that the best fitting r value is one (Wells, 1955). Recently, Jones et al. (2009) suggested a value of 0.0218 based on infections in monkeys. Therefore, the accuracy of the probability of risk will depend on the value of r. Similarly, the calculation of risk using the Wells-Riley approach requires information on quanta. The information on quanta for various epidemics was calculated (Riley et al., 1978; Rudnick and Milton, 2003 and Qian et al., 2009) using the Wells-Riley equation (Riley et al., 1978). The quanta values were back calculated by substituting the number of susceptible and infected people, the ventilation rate and pulmonary rate, and the time of exposure. Therefore, the quanta calculations were not direct. As the method on predicting the quanta exhaled is not direct, people have debated about its accuracy (Sze To and Chao, 2010). But even though the method is not direct because the information (quanta) is the infectious dose, it can characterize the risk.

We used both the approaches, deterministic and Wells- Riley equation to evaluate the risk. The dose inhaled was calculated using equation (1) for deterministic method in terms of influenza virus RNA particle. The quanta inhaled by each passenger were obtained using deterministic approach (equation (1)) by replacing the dose with quanta. The quanta inhaled by each passenger was then substituted in equation (2) in place of $d_{i,s}$ to obtain the probability of infection. Figure 3 shows all the steps involved in the approach. The risk can be reduced using N-95 masks as they can reduce the amount of inhaled infectious agents (Weiss et al., 2007). The total leakage through the N-95 masks was observed to be less than 10% (Grinsphun et al., 2009). This means that the inhaled dose can be reduced to 10% if passengers wear an N-95 mask; also, the risk of infection would be lower.
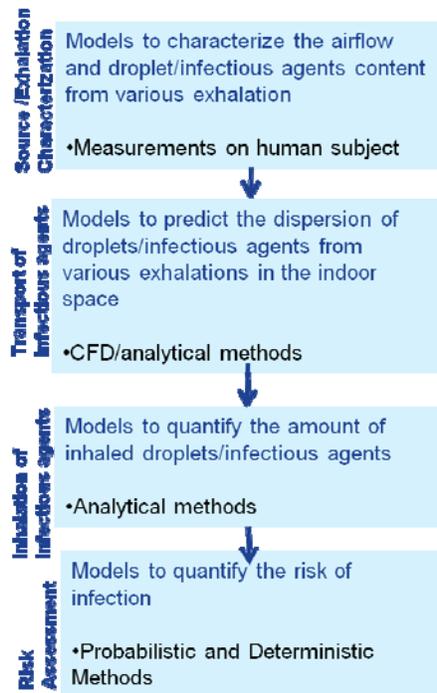
Figure 3. Total approach to predicting the airborne infection risk.

Case Description

A case of influenza spread was studied in a fully occupied twin aisle cabin with the index passenger seated at the center of the cabin. The risk of infection was calculated for the passengers seated in the row of the index passenger and the neighboring rows for 4 hours of flight under a total ventilation rate of 33.7 ACH (Air Change per Hour, considering 9 l/s flow per passenger). The ventilated air consisted of a half of air from outside and another half recirculated air.

The risk of infection was calculated for passengers in scenarios with wearing and then not wearing N-95 masks. We used influenza virus RNA particles and quanta of influenza as units to define the dose for the deterministic and probabilistic approaches, respectively.

The amount of influenza virus RNA particle exhaled by the index passenger was obtained from the studies of Fabian et al. (2009) and Milton et al. (2010). They measured the rate of exhalation of influenza virus RNA particles from the coughing and breathing of influenza infected patients. It was observed that an influenza infected subject can exhale 0.01 to 2 influenza virus RNA particles per minute (geometric mean 0.1) through breathing. The amount of such influenza virus RNA particles for a cough combined with one minute of breathing ranged from 0.1 to 20000 per minute (geometric mean 3.1) and 0.1 to 100000 per minute (geometric mean 5) for coarse and fine particles, respectively. Therefore, a cough alone can contain 8 (geometric mean) influenza virus RNA particles. An average of 25 coughs per hour was considered as Hsu et al. (1994) and Loudon and Brown (1967) indicated that the cough frequency can vary from 12 to 35 and 3 to 48 per hour, respectively. No breathing exhalations were considered as the amount of infectious agents exhaled from coughing was higher than from breathing. The viability of the influenza virus was assumed to be 1 (α=1) as Harper (1961) found that the viability of the influenza virus does not change significantly in 4 hours. This information was used in equation (1) to calculate the inhaled amount of influenza virus RNA particles.

The dose exhaled for the probabilistic (Wells-Riley) model was defined in terms of quanta. The rate of exhalation of quanta was calculated based on the influenza epidemic case (Moser et al., 1979). A Boeing 737 flight was delayed for 4.5 hours due to engine failure. There were 54 people on board, with 29 remaining on board throughout the delay. One index passenger was on board and 25 secondary infection cases were observed. Rudnick and Milton (2003) formulated an unsteady Wells-Riley equation and back calculated the quanta release rate for this case under a low air exchange rate to have same secondary infected cases. The quanta release rate was 79 and 128 per hour for 0.1 and 0.5 ACH, respectively. We took an average and considered a quanta release rate of 103 per hour. Assuming the same infection spread taking place under a ventilation rate of 33.7 ACH, we found that the quanta release rate would have been 5226 per hour. We studied these cases (103 and 5226 quanta per hour) assuming a ventilation rate of 33.7 ACH. As quanta is an active quantity, we assumed the value of α to be one. The amount of quanta inhaled was then calculated similarly using equation (1). The probability of infection was calculated for both the quanta release rates.

Results

This section presents the risk of infection from influenza as assessed through the deterministic and probabilistic approaches.

Figures 4 (a), (b), and (c) show the risk of infection from influenza for the passengers seated in the same row and the neighboring rows of the index passenger over a 4-hour flight. The risk evaluated using the deterministic approach was represented as inhaled influenza virus RNA particles, as shown in Figure 4 (a). The index passenger was seated in D. It should be noted that the dose inhaled by the passengers seated in the vicinity of the index passenger was high. The dose inhaled by passenger 5A was high even though the seat was far from that of the index passenger. This was because the droplets exhaled moved backwards and then towards the window in the back and index passenger rows (as shown in Figure 2). The amount inhaled was in accordance with the movement of the droplets. The distribution of dose inhaled was not symmetric but the relative pattern on either side of the cabin was similar. This was due to the asymmetric distribution of expiratory droplets on either side of the cabin. We noticed that the dose inhaled increased linearly if significant time was considered for calculations with the same cough frequency. It was to minimize the effect of random occurrence of coughs. For example the dose inhaled by the passengers for a 2-hour flight was a half that for a 4-hour flight. It can be seen that the number of influenza virus RNA particles inhaled for 4 hours of flight was less than one, but this does not mean that the risk was either low or high, as the influenza virus RNA particles can be more than one influenza virus. Moreover, the tolerance dose for influenza for the passengers is not known. Thus, no comments on the risk of infection can be made, but the relative risk of infection to the passengers can be observed.

On the other hand, the risk evaluated using the probabilistic approach is represented as the probability of being infected by influenza (infection probability) from the index passenger. Figures 4 (b) and (c) show the infection probability for the release rate of 103 quanta per hour and 5226 quanta per hour, respectively. The infection probability is proportional to the amount of quanta of influenza inhaled. Therefore, the infection probability was higher for the passengers seated close to the index passenger and 5G and 5A, as explained earlier. The higher the probability, the greater the chance of getting the infection. Considering the average probability for the passengers, 3 out of the 20 passengers (rounded off) could be infected for the quanta release rate of 103 per hour. This is much lower than the observed case of 25 secondary infection cases out of a total of 29 passengers (Moser et al., 1979) because that outbreak happened under little or no ventilation, while our calculations

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were performed assuming a full ventilation of 33.7 ACH. This clearly explains the importance of the ventilation system. Similar calculations on average probability for the quanta release rate of 5226 per hour indicated that all 20 people could be infected with influenza, assuming a full ventilated aircraft and 25 secondary infection cases among the 29 passengers.
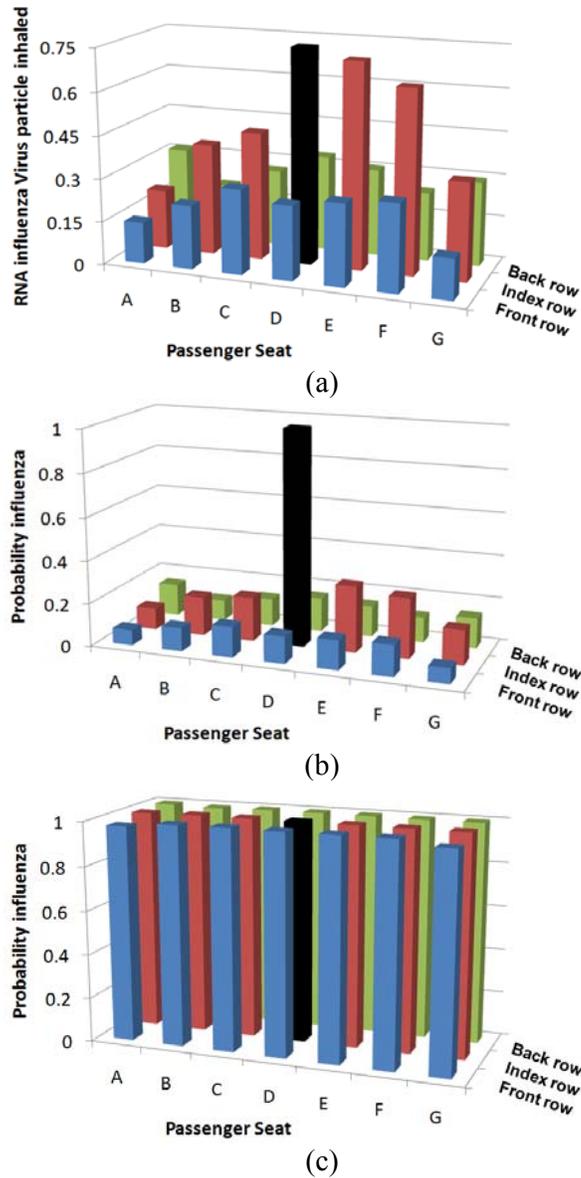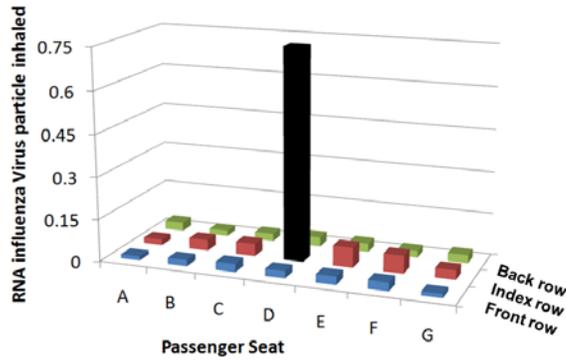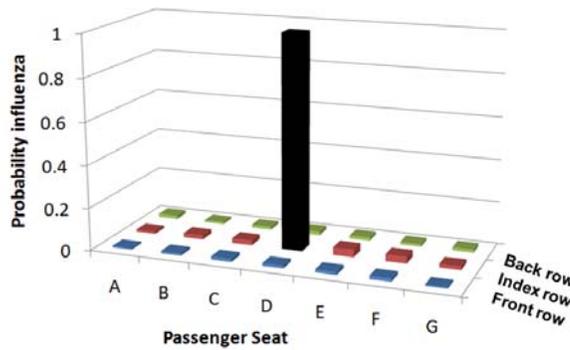

(a)

(b)

(c)

Figure 4. Risk of infection from influenza for the passengers in a 4 hour flight: (a) deterministic approach: inhaled influenza virus RNA particles, (b) probabilistic approach: infection probability at the exhaled dose of 103 quanta per hour, and (c) 5226 quanta per hour.

Figures 5 (a), (b), and (c) show the risk of infection from influenza for the case with everyone except the index passenger wearing a mask. The mask can provide a protection factor of 10 (Gupta 2010); therefore, the amount of influenza virus RNA particles would be $1/10^{th}$ of that inhaled without the masks, as shown in Figure 4(a). If the index passenger is also wearing a mask, the amount would be even lower. Similarly, the quanta inhaled with the

masks would be 10% of the quanta inhaled without the mask and thus the infection probability with the mask would be lower than without the mask, as shown in Figures 4(b) and (c). Considering the average probability of infection for this case, it was found that none of the 20 and 11 out of the 20 passengers may get infected for the quanta release rate of 103 and 5226 per hour, respectively. This is lower than the average probability of infection without the mask case, which was 3 out of 20 and 20 out of 20 for the quanta release rate of 103 and 5226 per hour, respectively. This clearly indicates the usability and importance of N-95 respirator masks against exposure from inhalation.

(a)

(b)
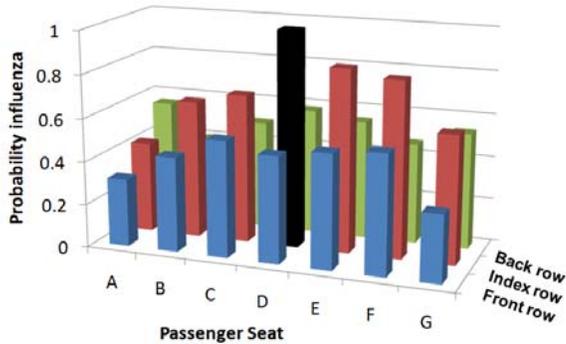
(c)

Figure 5 Risk of infection from influenza for the passengers in a 4 hour flight for a case with all the passengers except the index passenger wearing masks: (a) deterministic approach: inhaled influenza virus RNA particles, (b) probabilistic approach: infection probability at the exhaled dose of 103 quanta per hour, and (c) 5226 quanta per hour.

Discussion

The study quantified the risk of airborne infection for the influenza outbreak case (Moser et al., 1979) based on the inhaled dose, which is a function of the infectious dose exhaled by an index passenger. This investigation used the exhaled dose data collected by Fabian et al. (2009) and Milton et al. (2010) and an influenza outbreak case (Moser et al., 1979). The infectious dose exhaled by the index passenger can vary with the index passenger's infectious condition and so can the dose inhaled by susceptible passengers and the probability of their getting infected. Therefore, the risk to susceptible passengers can be different from that of other cases.

The total protection level provided by the N95 respirator mask was considered to be 10% from the literature (Gupta, 2010 and Grinsphun et al., 2009), but the values can vary based on the fit. Therefore, the reduction in risk if passengers wear N-95 masks can also vary with the fit.

The risk was calculated in a twin aisle cabin configuration under a 33.7 ACH ventilation rate. The risk for other cabin configurations at other operating conditions could be different as the spatial and temporal distributions of infectious agents and thus the risk of infection can vary with the aircraft cabin configuration and the ventilation rate.

The model developed accounted for the risk of infection from an airborne route but did not account for the risk of infection from direct/indirect contact or droplets. We also did not account for infection risk that may come from fomite contamination and possible re-suspension on cabin surfaces.

Conclusions

An approach to predicting the spatial and temporal distributions of airborne infection risk in an aircraft was discussed. Using the exhalation and inhalation models (Gupta et al., 2009 and 2010) and the CFD techniques (Gupta et al., 2011a), this investigation calculated the spatial and temporal distributions of droplets in an aircraft cabin. The dose inhaled by the passengers in the cabin was then determined for a 4 hour flight with an influenza outbreak case. The risk of infection was quantified based on the inhaled dose for the passengers seated in the same row and the neighboring rows of the index passenger.

The deterministic approach quantified the dose as the number of influenza virus RNA particles, because the tolerance dose in terms of influenza virus RNA particles was not available. The probabilistic approach used the Wells Riley equation to quantify the probability of influenza infection based on the spatial distribution of quanta inhaled by the passengers. It was found that the probability of influenza can be reduced by using N-95 respirator masks as it can reduce the amount of inhaled viruses. In addition, the approach and methods developed can easily be extended to other enclosed spaces.

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