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Predicting Spatial Distribution of Infection Risk of Airborne Transmission Diseases in a Hospital Ward

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Summary: *This study attempt to integrate the Wells-Riley equation and computational fluid dynamics for analyzing the risk of airborne transmission diseases in a building. The new method can predict the spatial distribution of the infection risk of the airborne transmission diseases in a large hospital ward, while the Wells-Riley equation alone can only predict the overall infection risk in the whole building assuming a uniform distribution of the droplet nuclei concentration. This new method is applied to analyze the transmission risk in the well documented 8A ward SARS outbreak in a Hong Kong hospital in 2003.*

Keywords: *Wells-Riley equation, SARS, airborne transmission of diseases, CFD*

1 Introduction

Avian flu has become a new threat as we just escaped from the terror of the 2003 SARS outbreak. Considerable attention has been paid recently on the potential high-risk transmission of infectious diseases in public areas such as hospital wards, schools, airplanes etc. Furthermore, there still exists the risk of outbreak of airborne transmission diseases, such as measles, chickenpox, TB and so on. It was estimated there were up to 8.8 million new cases and 3 million deaths annually on the worldwide only for TB, which contributed to 6% of all deaths [1]. Analyzing the outbreak case and accurately estimating the infection risk of infectious diseases can help us understand the transmission route of infectious diseases and take method to decrease it.

This study focuses on the prediction of spatial distribution of infection risk of airborne transmission of infectious diseases. It is well known that the droplet nuclei are the vehicles to transmit airborne transmission diseases [2]. Droplet nuclei, the residuals of dried-out droplets, are small in size of generally less than 5 μm in diameter. The settling velocity for the particles less than 5 μm in still air is less than 1 m/h, which make its distribution pattern in the air close to that of gaseous pollutants. In order to estimate the risk of airborne transmission diseases, Wells (1955) introduced the concept of quantal infection [3]. A quantum is the dose which is necessary to cause infection to a new susceptible, and a quantum may be one or more airborne pathogens, which can attach in the droplet nuclei.

The most successful prediction model for the infection risk of an airborne transmission disease is the so-called Wells-Riley equation which is based on the concept of quantal infection [4]:

$$P = \frac{C}{S} = 1 - e^{-Iqpt/Q} \tag{1}$$

where p is the pulmonary ventilation rate of each susceptible per second (m^3/min); Q is the room ventilation rate (m^3/min); q is the quanta produced by one infector (quanta/min); and t is the duration of exposure (min).

The Wells-Riley equation works well when droplet nuclei of infectious particles were randomly distributed in the room air, which means that the air is fully mixed in the enclosed space and the average concentration is Iq/Q. It implies that the chance of infection is equal spatially indoors.

The largest nosocomial SARS outbreak in Hong Kong occurred in 8A ward in a public hospital in 2003. The spatial distribution of infection cases was not even and it was related to airflow pattern in the 8A ward [5, 6]. The traditional Wells-Riley model cannot interpret the spatial distribution of the infection cases in a large space in spite that it may interpret the temporal distribution. Li et al (2005) showed the relationship between the infection cases and airflow pattern using computational fluid dynamics simulations and field measurement [5]. Li et al. (2005) did not predict the infection risk distribution in the space. We propose a method here to integrate the Wells-Riley model into CFD. The

new model can calculate the spatial risk distribution in a large space.

2 Integrating Wells-Riley equation into CFD

The viability of airborne organisms differs under different environmental conditions (temperature, humidity, UV etc). Dunklin and Puck (1948), Ferry et al. (1958) and Riley and O'Grady (1961) noted that when organisms were atomized into air, the rate of their death was at first rapid and then subsequently slowed down [7,8,9]. The first rapid decay (high death rate) occurred within a very short time, which also means that the rapid decay only occurred within close vicinity from the infector's exhaled mouth or nose. In order to simplify the model, the first rapid death is dealt with the source and the death rate of microorganism at any given condition in the pasteurizing range can be treated as proportional to the number of living cells present [10], the viability of the airborne organisms in a closed space can be written as:

$$\frac{dN}{dt} = -kN \tag{2}$$

Where N is the concentration of the quanta (quanta/m^3)

Airborne organisms are assumed to be attached in particles or in droplet nuclei, which are very fine particles or the residual of dried-out droplets. The governing equation for the airborne organisms transport in indoor air can be written as following:

$$\frac{\partial(\rho N)}{\partial t} + \nabla \bullet (\rho(V + V_s)N) = \nabla \bullet (\Gamma \nabla N) - k\rho N \tag{3}$$

The above equation is based on a drift-flux particle model [11]. *Vs* is the settling velocity for the particles.

Equation (3) allows us to estimate N, the number concentration of quanta in an indoor space after the airflow field is obtained. The infection risk of one susceptible can then be estimated as:

$$P = 1 - e^{-pNt} \tag{4}$$

The total predicted the number of infected cases, C, for S susceptible who may be located at different locations with different quanta concentration N_i will be:

$$C = \sum_{i=1}^{S}(1 - e^{-pN_i t}) = S - \sum_{i=1}^{S} e^{-pN_i t} \tag{5}$$

The escape possibility for one susceptible exposed with different quanta generation for different time duration can be written as:

$$\text{E}scape \text{ possiblity} = e^{-p\sum_{j=1}^{n} N_j t_j} \tag{6}$$

The total predicted cases for S susceptible at different locations with different quanta concentration N_i and different time duration can be calculated as below:

$$C = \sum_{i=1}^{S}(1 - e^{\sum_{j=1}^{n} -pN_{ij}t_j}) = S - \sum_{i=1}^{S} e^{\sum_{j=1}^{n} -pN_{ij}t_j} \tag{7}$$

3 Ventilation parameters and infection distribution patterns in Ward 8A

A total of 39 beds were placed in 4 main semi-enclosed cubicles, each with a dimension of 7.5m× 6m×2.7m, and 2 beds was placed in the isolation cubicle in the ward 8A with overall dimension 24m×18m×2.7m during the period of SARS outbreak there. The ventilation rate was measured on July 17, 2003 when the operation parameter of ventilation system was set as close as possible to that during SARS outbreak. The measured air change rate for the whole ward 8A was 7.8 ACH including 70% recirculated air. The measured airflow rate for each supply diffuser, return, and exhaust outlets and the floor plan of ward 8A during the period of SARS outbreak in 2003 was shown Figure 1, and more details can be found in [5]. The temperature and relative humidity of supply air were at 14^{o}C and 100% respectively and those of return air were at 22 ^{o}C and 75% respectively.

The index patient was admitted into Ward 8A on March 4 and was placed in bed 11 until March 12. His cough was suspected as the main pathogen source [5,6]. Wong et al (2004) and Li et al (2005) studied the infected medical students who examined patients at bed-side with relatively unchanged position during the time [5,6]. They also provided the epidemiological features, spatial distribution pattern among the medical students. Among 16 of 66 medical students developed SARS, there are 10 out of 27 students who reported to enter the index patient's cubicle while 8 of 18 students who could not recall whether they entered the cubicle and 1 out of 20 never entering the cubicle. The relative risk of the same cubicle as the index patient was 7.4 [(10/27)/(1/20)], which clearly describe the association between the infection and position of susceptible. Among all medical students, a group of 20 third-year students was particularly worthwhile for further studying because none of them visited ward 8A for assessment after March 7 or contacted with other SARS patients after their March 6 or 7 visits. The positions of this group of medical students during their bedside clinical assessment are shown in Figure 1, which excluded the ill student

who had an unusually long incubation period (onset on March 23). The time schedule of the clinical assessment of the 19 medical students is shown in Table 1.

Those medical students were assessed by 11 assessors, among which 5 assessors on March 6, 5 on March 7 and only 1 evaluated on both days. The five assessors on March 6 only all developed SARS while three of five assessors for March 7 only developed SARS and the one presented on both days also developed SARS. The infection cases of the group of third-year medical students accessed on March 6 and 7 are chosen here to analyze the infection risk of medical students.

4 Results and Discussion

Calculation quanta generation by the Wells-Riley Equation

In order to calculate the risk of the medical students, some assumptions should be made. We first assume that the pulmonary ventilation for each patient is 6 l/min. The total airflow rate of the ventilation system is 77.4 m^3/min or 7.9 ACH. There are no data on the fine particle (droplet nuclei) removal efficiency of the filter in the air conditioning system and the survival rate of virus as they pass through the ductwork or filter. If the combined filtration efficiency (considering the virus death rate) is 0%, 50% and 100%, the equivalent airflow rate from outdoor is 23.22, 50.31 and 77.4 m^3/min respectively. We assume that the quanta generation is steady and same for each day. The results of quanta generation are also summarized in Table 1. We use the obtained quanta generation to estimate the infected cases in assessors, which results were shown on Table 2. The predicted results agreed very well with the real cases.

Integrate the Wells-Riley Equation into CFD analysis

There are no data of the spatial distribution of the medical students for each session or each day. The locations of 19 medical students on March 6 and March 7 are shown in Figure 1. We assume the quanta generation during the whole examining period is a constant. As we cannot find any data on the viability of SARS Co-virus in air, the death rate of SARS Co-virus here is assumed to be zero. The process of droplet evaporation is also ignored and the size of droplet nuclei size was assumed to be same as the gaseous pollutant. Due to no data on the efficiency of filters installed in Ward 8A, we calculated risk with three filter efficiencies and compared the results.

The calculated risk of each medical student was summarized in Table 3. The spatial risk distribution for three ventilation systems is shown in Figure 2. The data agreed well with the infection cases for three ventilation efficiencies. The predicted spatial risk distribution at high efficiency filter seems agree better than the lower ones. A low filter efficiency make the risk distribute more even in the hospital ward. It should be noted here that the calculated spatial risk distribution is based on each calculated quanta generation. At same quanta generation, the risk for a high efficiency filter is obviously greater than that for a low efficiency filter.

5 Conclusions

The classical Wells-Riley model is a powerful tool for analyzing and predicting the infection risk of airborne transmission diseases in spite of that it cannot predict the spatial distribution of risk in a room. Integrating the Wells-Riley equation to CFD can predict the spatial distribution of infection risk of airborne transmission diseases. Using a SARS outbreak in a large hospital ward, we demonstrated that such an integrated method can predict the infection risk distribution of airborne transmission diseases in a large space when the susceptible is at relative unchanged locations, such as a hospital ward or an air plane.

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Table 1: Calculated quanta generation using the Wells-Riley equation and the cases of medical students (Those highlighted in gray color means the calculated results)

NO. of infected cases (*C*)	**No. of susceptible involved (*S*)**	**C/S**	**Filter efficiency**	**Equivalent airflow rate (m^3/min)**	**Exposure period (min)**	***Iqpt/Q***	***q* (quata/min)**
7	19	0.37	0	23.52	40	0.010q	148.2
			50%	50.96	40	0.005q	96.3
			100%	78.4	40	0.003q	44.5

Table 2: Predicted number of infected cases of assessors using the quanta generation in Table 1

Filter efficiency	**Equivalent airflow rate (m^3/min)**	**Exposure period (min)**	***Q* (quata/min)**	***Iqpt/Q***	**No. of susceptible involved (*S*)**	**Predicted infected cases**	**Actual infected cases**
0	23.52	160	44.5	1.84	10	8.4	8
50%	50.96	160	96.3	1.84		8.4	8
100%	78.4	160	148.2	1.84		8.4	8

Table 3 Calculated risk of each medical student and the predicted total infected cases (those in brackets are the actual infected cases)

Cubicle	**Close to Bed No.**	**Filter Efficiency =100% *q*=148.2**	**Filter Efficiency =50% *q*=96.3**	**Filter Efficiency =0% *q*=44.5**
Same Cubicle	12a	0.82	0.73	0.59
	12b	0.9	0.82	0.66
	12c	0.94	0.87	0.7
	9	0.58	0.53	0.47
	14	0.57	0.52	0.47
	15a	0.44	0.43	0.42
	15b	0.57	0.52	0.47
	16	0.66	0.57	0.5
	16xa	0.52	0.48	0.45
	16xb	0.54	0.5	0.46
	16xc	0.68	0.61	0.52
	Total infected cases	7.22(9)	6.58(9)	5.71(9)
Adjacent Cubicle	24a	0.29	0.34	0.38
	24b	0.31	0.35	0.39
	17xa	0.35	0.37	0.4
	17xb	0.39	0.4	0.41
	17xc	0.4	0.41	0.41

	Total infected cases	1.74(0)	1.87(0)	1.99(0)
Distance Cubicle	25x	0.18	0.27	0.35
	30	0.1	0.23	0.34
	4	0.12	0.24	0.34
	Total infected cases	0.4(0)	0.74(0)	1.03(0)
The entire ward	Total infected cases	9.36(9)	9.19(9)	8.73(9)

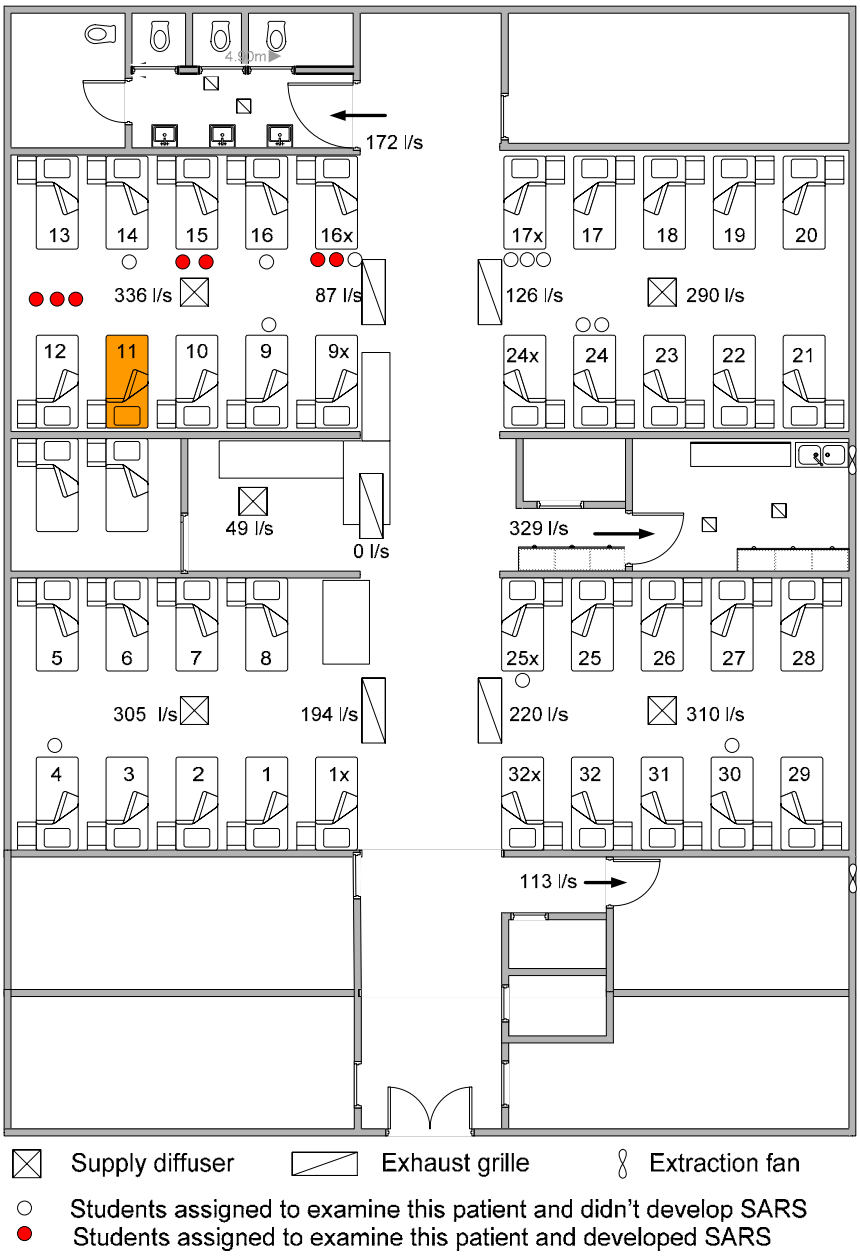

Figure 1 Floor plan of Ward 8A at the time of outbreak in March 2003. Measured supply and exhaust flow rates are also given. The bed no.11 where the index patient stayed is highlighted. The locations of the 19 medical students who attended the 40-min bedside clinical assessments are also highlighted. (Modified from [5]) .

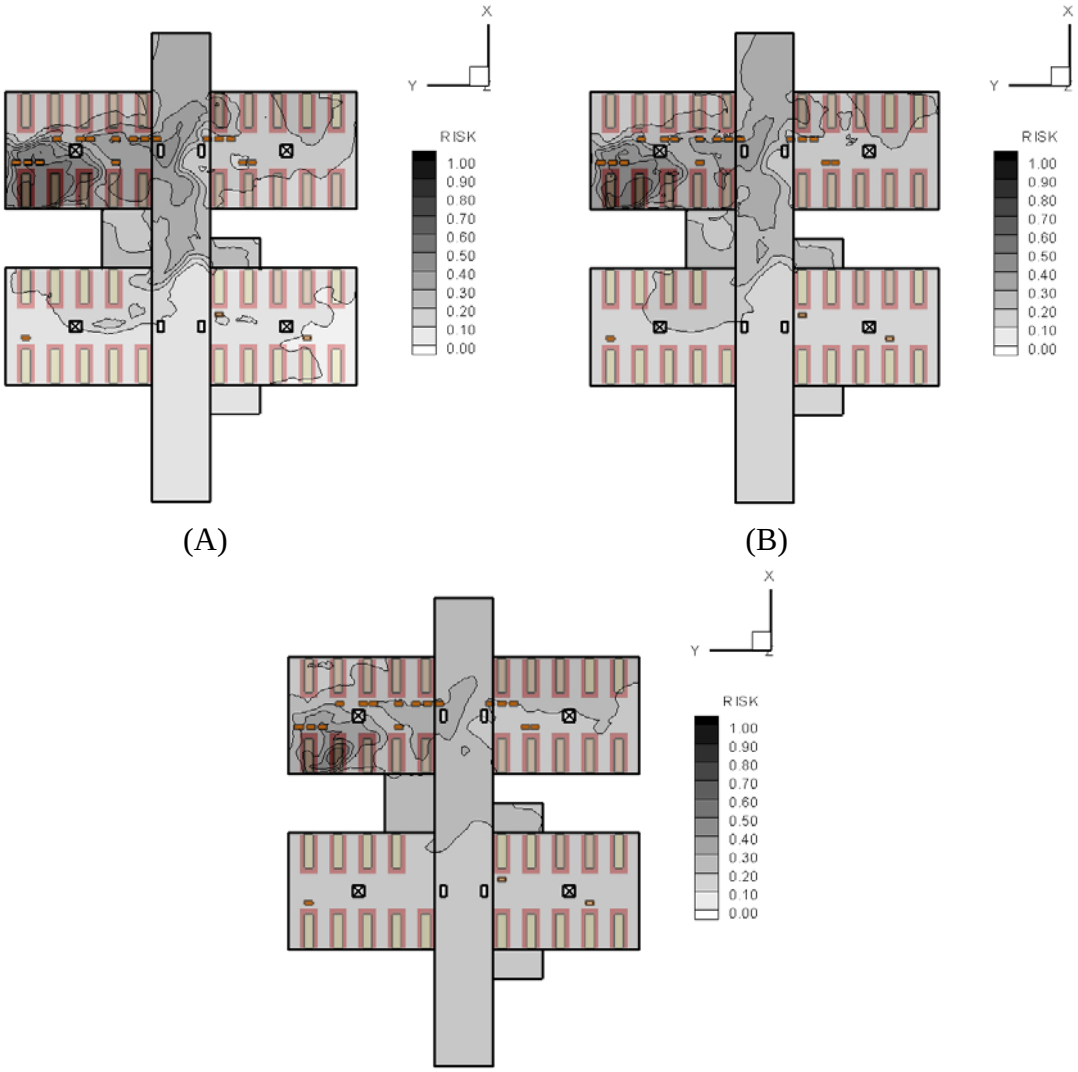

Figure 2 Predicted spatial risk distribution in Ward 8A. (A) Filter Efficiency = 100%, q =148.2 (quanta/min) (B) Filter Efficiency = 50%, q=96.3(quanta /min) (C) Filter Efficiency = 0%, q=44.5 (quanta /min).