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Zhou, Qi; Qian, Hua; Liu, Li

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Numerical investigation of airborne infection in naturally ventilated hospital wards with central-corridor type

Qi Zhou[1], Hua Qian[1] and Li Liu[2]

Abstract

Natural ventilation is believed to control airborne infection due to high ventilation rates while an undesired flow pattern may cause infection transmission in hospital wards. A computational fluid dynamics simulation was carried out in this study to investigate the impact of airflow pattern on cross infection in a real central-corridor hospital ward with natural ventilation in Nanjing, China. The simulation results demonstrate that the predicted infection risks of the downstream cubicle are up to 10.48% and 11.59% as the index patient is located in the corridor and in the opposite upstream cubicle, respectively. Under this circumstance, the downstream cubicle should be listed on the high-risk list and the central-corridor type is not recommended in a naturally ventilated ward. Measures such as keeping cubicle doors closed should be taken in order to cut off the transmission route. The results not only give direct evidence to strongly support World Health Organization's recommendation but also suggest required amendment of the Chinese standard GB 51039-2014 to improve ventilation arrangement in general hospital wards in China. Our findings are useful for improving the future design of general hospital wards for airborne infection control.

Keywords

Computational fluid dynamics, Infection risk, Cross ventilation, Central corridor, Hospital ward

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Introduction

Ventilation and indoor air quality control in hospital environments have attracted increasing attention, as there is strong and sufficient evidence to demonstrate the association between ventilation, air flow pattern in buildings and the spread of infectious diseases.[1] Beggs et al.'s[2] review on hospital ward ventilation concluded that the clinical role of ventilation of general wards might be underestimated and nosocomial infection rates could be reduced by improving ward ventilation. As one of the ventilation strategies, natural ventilation provides sufficient ventilation rates with energy-efficient and maintenance-free manner. According to field measurement results of naturally ventilated hospital wards and theoretical analyses in Lima[3] and Hong Kong,[4] natural ventilation was shown to be effective in reducing airborne infection risks when both the windows and the doors were open. However, as indicated by Qian et al.,[4] the airflow pattern and the airflow direction were found to be unstable and be difficult to predict and control, which highlighted major disadvantages of natural ventilation.

In general, the architectural design and building elements determine the routes of airflow. For hospital ward design in China, a central-corridor type is extremely common. In this configuration, there is a corridor in the centre of a ward and cubicles on both sides.

[1]School of Energy and Environment, Southeast University, Nanjing, China
[2]Department of Civil Engineering, Aalborg University, Aalborg, Denmark

Corresponding author:
Hua Qian, School of Energy and Environment, Southeast University, Nanjing, China.
Email: keenwa@gmail.com

A cubicle door links to the corridor and windows are located on the wall opposite to the door. When both the windows and doors are kept open, cross ventilation is usually formed. It is easy to image that the contaminated air would probably move from an upstream room to a downstream room under this airflow pattern, which implicates a possible cross infection between hospital wards. Consequently, World Health Organization (WHO)[5] has recommended not to apply the central corridor as a mean of natural ventilation for hospital wards. However, to our knowledge, there is no sufficient evidence to support or negate this recommendation and no more detailed description has been provided by WHO. In addition, since the central-corridor ward is a commonplace in China, there is a need to evaluate the risk associated with this type of hospital ward. Is it a fact or fiction that cross infection in central-corridor hospital wards could occur due to cross ventilation? So far, studies on cross ventilation through full scale measurements,[6–8] laboratory tests[9–11] and computational fluid dynamics (CFD) simulations[12–15] have all improved our understanding of its characteristics. However, few have focused on its effect on infection transmission in a hospital environment. Gilkeson et al.'s[16] measurement on ventilation and airborne infection risk in a cross-ventilation ward did come to reasonable conclusions, but only a limited number of experiments were conducted. Besides, the layout of Nightingale ward investigated in their research is not common in China, thus more specific investigations for Chinese hospital wards are still needed.

With regard to estimating the infection risk, Wells–Riley equation was developed to predict the airborne infection risk[17] on the basis of a concept called quantum.[18] A quantum is the dose of pathogens attached to the droplet nuclei to cause infection. The equation was established with some assumptions, e.g. the well-mixed assumption, which means infected chances are equal within one space. However, airborne transmission is strongly related to local airflow and thus the well-mixed assumption may not always be valid. Qian et al.[19] integrated Wells–Riley equation into CFD program and developed a new model to predict the spatial distribution of infection risk. The model has been verified against the epidemiological data of a severe acute respiratory syndrome (SARS) outbreak in ward 8A in Prince Wales Hospital in Hong Kong.[20]

In this study, the spatial distribution of infection risk of a central-corridor ward with cross ventilation was investigated using CFD method. The simulation configurations were in accordance with a real ward located in Nanjing, China. The impact of airflow pattern of cross ventilation on infection transmission in a central-corridor hospital environment was evaluated and compared.

Methods

The classical Wells–Riley equation was used in evaluating the probability of developing infectious diseases in enclosed spaces. This model is based on a well-mixed assumption which, to some extents, restricts its application. Qian et al.[19] developed a modification that integrated Wells–Riley equation into CFD, thus it could predict spatial distribution of infection risk of airborne diseases. The integrated model is represented by equation (1) as follows

$$\frac{\partial(\rho N)}{\partial t} + \nabla \cdot \left(\rho\left(\vec{V} + \vec{V}_s\right)N\right) = \nabla \cdot (\Gamma \nabla N) - k\rho N + S_N \quad (1)$$

where N is concentration of the quanta (quanta/m^3), ρ is air density, and $\vec{V}$ and $\vec{V}_s$ are air velocity vector and particle settling velocity vector, respectively. Γ is diffusion coefficient and k represents the death rate of organism, and S_N is the source term.

Equation (1) was developed on the basis of a drift-flux model which was used for modelling indoor particle movements. In this equation, particle settling is taken into account in the form of settling velocity which can be calculated by the Stokes' law. With regard to particle deposition mechanism, a three-layer deposition model[21] with improved boundary conditions[22] was employed. The detailed description of the model has been given in previous studies.[21,22]

After solving equation (1), the infection risk of a susceptible can be calculated by equation (2), as

$$P = 1 - e^{-pNt} \quad (2)$$

where p is pulmonary ventilation rate (m^3/h) and t is exposure time (h). In this study, the size of particle was assumed to be 5 μm in diameter. The evaporation and coagulation process were neglected.

The computations were carried out by a commercial code ANSYS FLUENT 14.0,[23] which solved the governing equations in a finite volume procedure. The turbulent effect in the flow field was simulated by the renormalization group k-ε model. The user-defined scalar equation was used to solve particle concentration. The convection term was discretized by the second-order upwind scheme and the diffusion term by central difference scheme with second-order accuracy. The air density in the buoyancy term in the momentum equation was treated by the Boussinesq model. Finally, the SIMPLE algorithm was adopted to integrate pressure and velocity.

Validations

The elementary flow characteristics in the present study include flows inside/around a building and indoor particle movements. Both the models and treatments applied in this study were validated against experiment data from literatures.

Airflow inside and around a bluff body

Jiang et al.[24] experimentally investigated the airflow inside/around a building-like model in a wind tunnel. There were two openings with same dimensions fixing on the windward wall and the leeward wall, respectively, which resulted in a cross-ventilation type. The stream-wise air velocities along 10 vertical lines at the middle section were measured in the experiment and 5 of them were selected here to compare with the simulated results. The detailed information of the wind tunnel experiment has been previously reported.[24] As demonstrated in Figure 1, despite a few deficiencies above the roof, the simulation results generally agree well with the experimental data especially inside the building, which is of interest to this study.

Particle distribution in a ventilated chamber

Jin et al.[25] carried out a test in a ventilated chamber to study particle concentration heterogeneity. The chamber had one inlet and one outlet with same rectangular shapes on opposite walls. The room air and particles were well mixed and provided into the chamber via the inlet. Nine measuring points were uniformly distributed at the central plane of the chamber and particle concentration was measured by a laser particle counter. Particles were classified into five groups according to size distribution and concentration of the 5 μm group

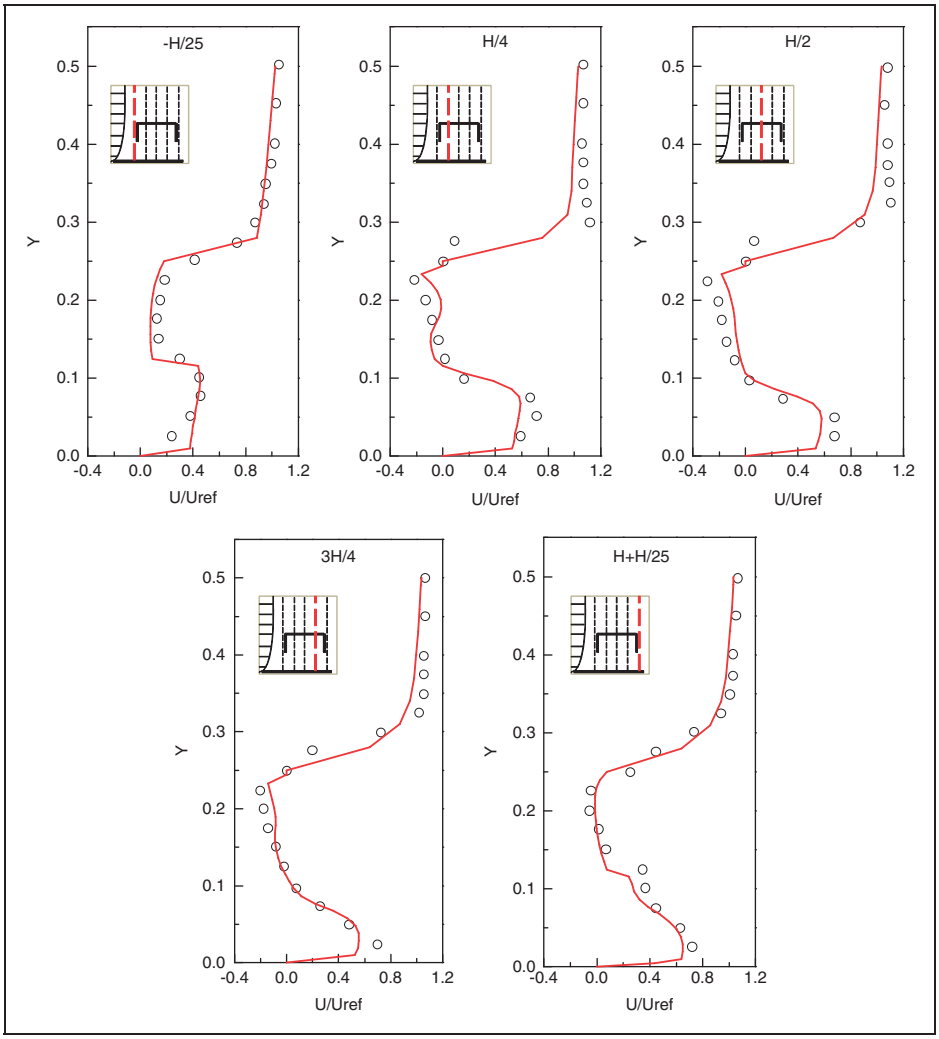

Figure 1. Velocity distribution at the five vertical lines (dot: measured data; line: simulation results).

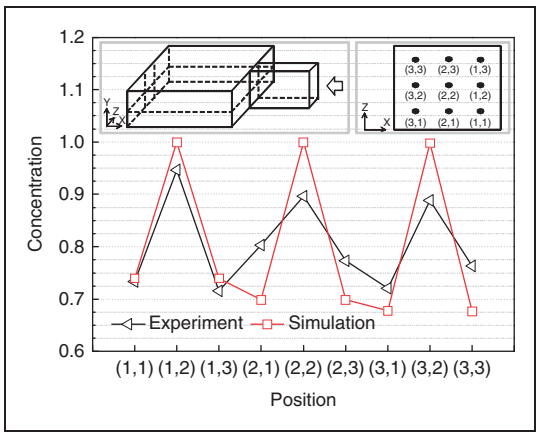

Figure 2. Comparison between measurements and simulations.

was compared with the present simulation. Figure 2 shows that, overall, the simulation results are consistent with the measurement.

Therefore, on the basis of validation results, aforementioned numerical models and treatments could be applied in this study with confidence.

Case description

For investigating the infection transmission in a central-corridor ward, a simplified five-storey hospital building was simulated. The ward is on the third floor (Figure 3). There are three cubicles on each side of the corridor and each cubicle has a dimensions of 8 m (X) × 2.7 m (Y) × 5.5 m (Z), with a door (2.1 m (Y) × 1.3 m (Z)) and a window (1 m (Y) × 1.6 m (Z)) on end walls of a

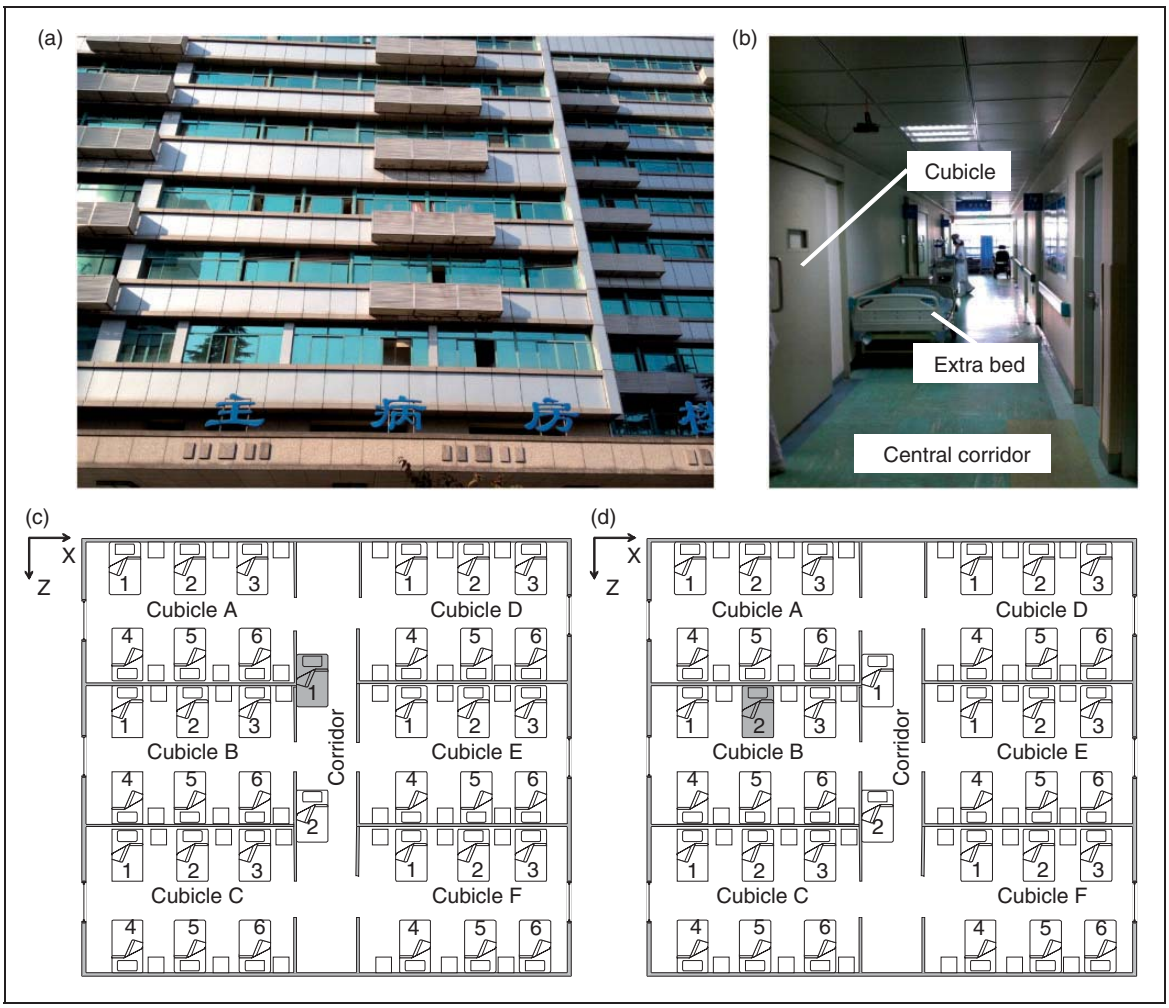

Figure 3. Photos of the prototype ward in Hospital R, Nanjing (a) exterior view and (b) internal view. Illustrations showing index patient locations for (c) corridor and (d) cubicle pathogen release cases.

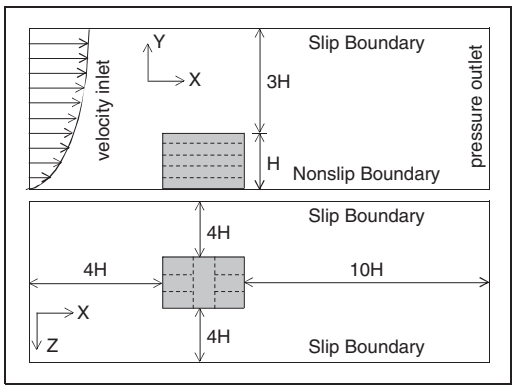

Figure 4. Description of the computational domain.

cubicle. Windows with half size (1 m (Y) × 0.8 m (Z)) are positioned at the end of the corridor and the bottom of the window is 1 m above the floor. All of the doors and windows were kept fully opened except corridor windows in the simulation, and these dimensions were identical with those of a general ward in Hospital R in Nanjing. In reality, the building is slab-like and is extended in the negative and positive Z direction. In addition, in real life each window would have a locking mechanism which would restrict the maximum opening. However, during our field measurement, we found many of these locking mechanisms were out of function and thus in the present simulation we assumed that all the windows were 100% opened. The model building was put into a computational domain (Figure 4) which should be large enough to avoid the influence of domain boundaries.[26]

There are six hospital beds in each cubicle and extra beds will be placed in the corridor if the number of hospital beds in a cubicle is insufficient (Figure 3, this is a common practice in large hospitals in China). In each cubicle, we assumed that all patients lay in their bed. Each patient was simulated by a computer-simulated person (CSP) with rectangular geometry (0.3 m (X) × 0.16216 m (Y) × 1.7 m (Z)).[27] The heat generation of each patient was 76 W[19,28] and half was assumed to be transferred through convection.[29] The heat flux boundary condition was chosen and the corresponding convection heat flux was ~25 W/m^2 with a surface area of 1.62 m^2.[27] The ambient atmospheric air temperature was 20°C.

The surface area of 1.62 m^2 is the total surface area of a CSP rather than the effective exposed surface area of a lying CSP. Since CSP's back is supposed to be connected to the bed in a lying position, the back area should be excluded when the convection heat transfer is taken into consideration. However, due to the fact that the heat transfer mechanism within a human body is relatively complicated and beyond the scope of the present study, the value of convection heat flux calculated here is considered reasonable.[20,29–31]

In urban environment, the wind profile usually follows a power law, which is determined by equation (3)[32]

$$V_Y = V_{ref}(Y/H)^{\alpha} \quad (3)$$

where V_{ref} is the wind speed at the building height (m/s), Y is the height above the ground (m), H is the building height (m) and α is a power law index, 0.25, of urban environment.

Based on meteorological data logged by a weather station on the building roof in Hospital R, four reference wind speeds, e.g. V_{ref} = 0.5 m/s, 1, 2 and 4 m/s were considered in this study so as to cover a wide range of practical situations.

For the prevailing wind condition in this study, two lateral cubicles are aerodynamically identical. Thus, the index patient was supposed to locate in two separate positions, e.g. bed no. 2 in cubicle B and bed no. 1 in the corridor, respectively, see Figure 3(c) and (d). The sensitivity of the source location was checked. In each case, only one index patient was considered, which means infectious particles would be emitted from only one source, via index patient's mouth (1.3 cm^2) through exhalation process. When calculating the infection risk, a quanta generation rate should be given though this could vary with different infectious diseases. A generation rate of 1.3 quanta/min, such as in Influenza,[33] was assumed in the present simulation because this is a common respiratory infectious disease that often occurs in our daily lives. The death rate of airborne organisms could be influenced by many factors and this was assumed zero in our study.

The infection risk was represented by the respiration plane of lying patients at a height of 1.05 m above the floor. The exposure duration for each patient was 4 h and the pulmonary ventilation was 0.36 m^3/h. The exhalation and inhalation process were supposed to be in steady state at a speed of 0.77 m/s, and the exhalant air temperature was 34°C. Eight cases were conducted involving four wind speeds and two index patient locations.

In terms of number of meshes, three mesh systems of 0.6, 1.04 and 2.07 × 10^6 were created. The medium one was selected after the grid independence test. A set of equations of continuity, momentum, energy and turbulence were solved and after the flow field reaches convergence, the particle concentration field was solved solely.

Results

Airflow pattern

The indoor airflow pattern is the key to the dispersion of airborne particles between cubicles in the ward. Cross ventilation generally forms a robust airflow

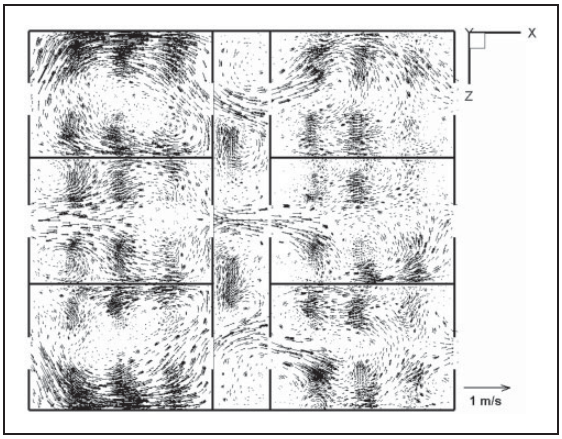

Figure 5. Air velocity vector field on the lying plane.

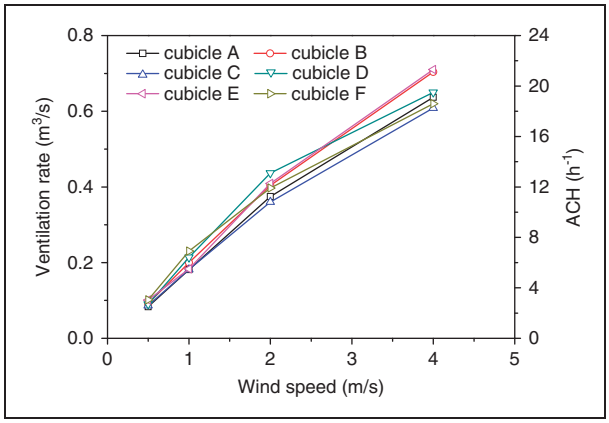

Figure 6. Relationship between ventilation rates and wind speed for each cubicle.

which pours into the room and spreads over the internal space from openings on different faces. However, in the current simulation, the airflow was observed to be disturbed by the internal walls and numerous vortexes (Figure 5). The airflow was shown to deflect when entering the cubicles located on the edge side, i.e. cubicle A and cubicle C. In practice, the airflow pattern around a building contains vertical and lateral separation in the stagnation zone on the windward side, which thus explains the airflow deflection in cubicles on the edge side. Although the downstream flow patterns were less structured, a higher wind speed (>1 m/s) was observed to make the flow stronger while the overall airflow pattern seemed to be similar (Figure 5). Considering infection transmission, the interaction between vortexes and air currents in the corridor would transfer infectious particles entrained in the airflow and thus could be transmitted far from the source.

In our study, the airflow patterns on other floors were not calculated because windows on those floors were kept closed. As explained above, since all the windows on the third floor were open, cross ventilation was formed. Under this circumstance, air stream would flow from openings on the windward side to those on the leeward side. This airflow pattern would be completely different from single-sided ventilation. With regard to single-sided ventilation, the opening would serve as inlet and outlet. As a result, the airflow pattern on different floors would thus cause an impact on other floors, e.g. the 'cascade effect'.[34–37] This effect is considered as an important factor in cross transmission between different floors while for cross ventilation this effect may even not happen. Our simulation focused on cross infection due to cross ventilation in a central-corridor ward. Therefore, airflow pattern on other floors may have little effect on the third floor and thus these were not calculated.

In the present study, the ventilation rate of each cubicle could be calculated via integrating the x-velocity across an opening by CFD. The predicted results of CFD method are shown in Figure 6. The ventilation rates were shown to increase linearly with the outdoor wind speed. Ventilation rate of each cubicle was shown to range from ~360 to ~2520 m^3/h (~0.1 to ~0.7 m^3/s) and the corresponding air change rate (ACH) was from ~3 to ~21 h^{-1}.

Spatial distribution of infection risk

In order to estimate the impact of index patient location within cubicle B on the global spatial distribution, a sensitivity test was conducted additionally. When the index patient was in any bed within cubicle B, the corresponding infection risks of each cubicle were found to be almost consistent in any position, excluding cubicle B. In that case, the flow pattern in cubicle B would likely to have contributed to the difference. The spatial distribution of infection risk within the entire ward is of interest in this investigation, thus despite some discrepancies in predicted results of cubicle B, we can confidently choose any bed within cubicle B as an index patient location, e.g. bed no. 2 for our consideration in this paper.

Index patient in corridor

Figures 7 and 8 show the spatial distribution of infection risk with different wind speeds and index patient locations. When the wind speed is 0.5 m/s, cubicle A, the upstream cubicle, would be contaminated. The averaged infection risk of cubicle A would reach 4.37%. The transmission route appears to be bi-directional while the airflow direction of cross ventilation is generally considered to be uni-directional. Under this circumstance, the wind force and buoyancy force would

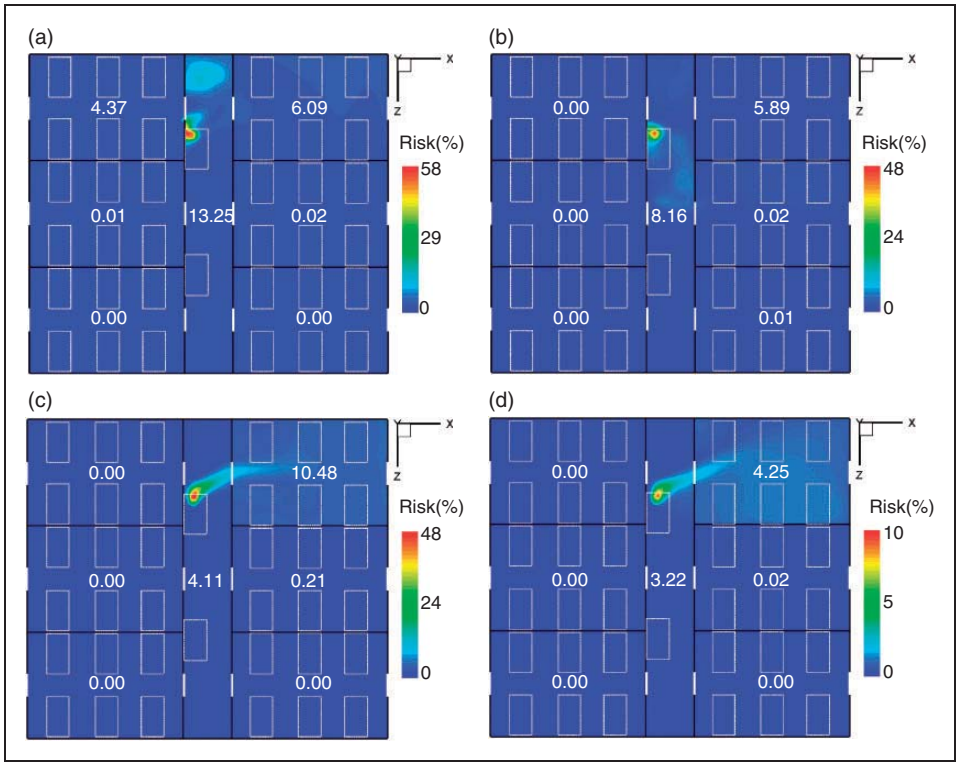

Figure 7. Summary of distribution of risk when the index patient is located in corridor: (a) 0.5, (b) 1, (c) 2 and (d) 4 m/s.

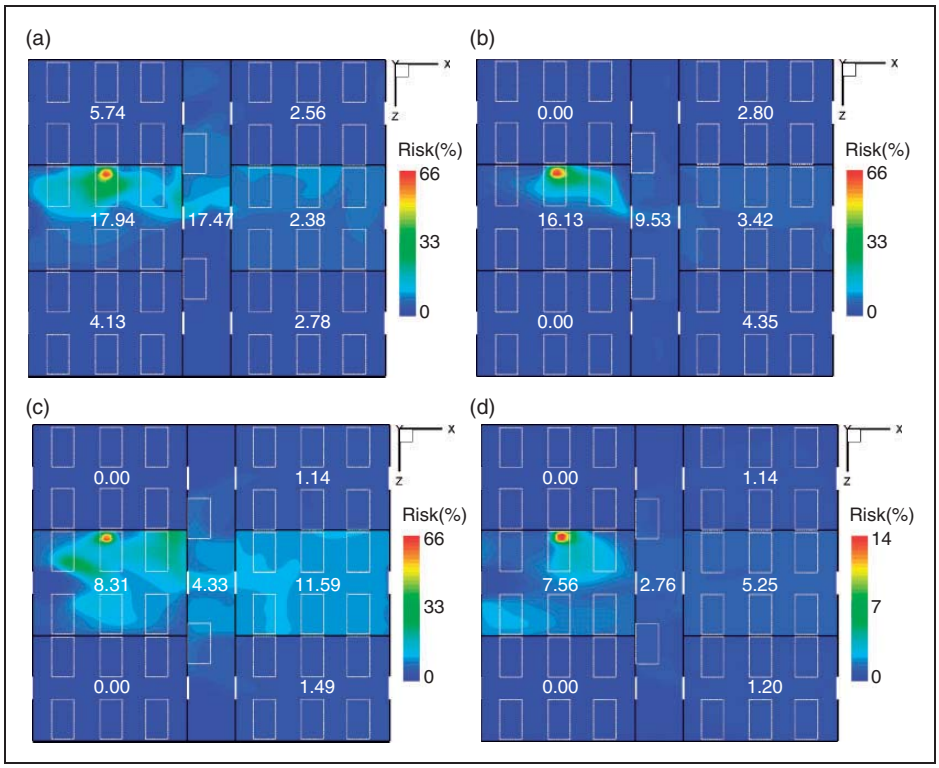

Figure 8. Summary of distribution of risk when the index patient is located in cubicle B: (a) 0.5, (b) 1, (c) 2 and (d) 4 m/s.

be comparable in the inner room, which reinforces the turbulent diffusion of pollutants as the wind speed is low. For cubicle D, the downstream room which is closest to the source location, had a slightly higher value of 6.09%, compared with that of cubicle A. The maximum risk of 13.25% would be in the corridor, and this is a reasonable situation due to the existence of a source in this area. With regard to distant cubicles, cubicles B, C, E and F, risks would be much lower and could be neglected (<0.02%).

As the wind speed is over 0.5 m/s, no infection would be found in windward cubicles, which implies that all pollutants would be carried downstream. The infection risk of the corridor was shown to decrease with an increasing outdoor wind velocity (e.g. from 8.16% to 3.22%). However, a peak value of 10.48% was shown in cubicle D when the wind velocity was increased to 2 m/s. On this occasion, the risk of infection in cubicle B would be even higher than in the corridor where there is a source. The reason for this case is likely due to the effect of airflow pattern in the corridor. As the location of the index patient in the corridor was next to the doorway of cubicle A, the air current from cubicle A to cubicle D would entrain most infectious contaminants released by the index patient and carried them downstream into cubicle D. As a result, the contaminant concentration within the corridor would be transferred away but the contaminants were difficult to be further exhausted by the airflow or be diluted in cubicle D.

When the index patient stays in the corridor, the infection risk in the corridor could reach up to 13.25%. Although the possible cross infection could be prevented by simply closing the cubicle door linking to the corridor, the transmission route was difficult to cut off as the index patient was located in the corridor. If patients closed the cubicle door, the pollutants would float and linger in the corridor space, thus enhancing the risk in the corridor, in comparison to the all-open situation. Our findings have highlighted the need for careful planning of the extra bed location in central-corridor type wards.

Index patient in cubicle B

A symmetrical spatial distribution of infection risk has been observed within the entire hospital ward. When the air speed is 0.5 m/s, the infection risk in cubicle B, where there is an index patient, would be significantly (up to 17.94%) higher than those in other cubicles. The risk of the corridor ranks only second to that of cubicle B and two adjacent cubicles on the windward side would have risk values of 5.74% and 4.13% respectively, which thus illustrates a bi-directional flow in a low air velocity case.

When the air speed increases, the infection risk in cubicle B would be reduced from 16.13% to 7.56%. Remarkably, a peak risk value was shown in the downstream cubicle E when the outdoor wind speed was 2 m/s. This phenomenon is not only similar to that found in the corridor release case mentioned before but also corresponds to that found by Gilkeson et al.[16] In their investigation, the opposite downstream bed showed a higher exposure index than that of a healthcare worker near the source patient in the upstream bed in a low wind case (0.4 ~ 0.9 m/s). Although the possible reason was not given clearly by Gilkeson et al. but the airflow pattern and ventilation rate would be suspected, as previously mentioned.

As wind speed further increases to 4 m/s, the global infection risk would be further reduced. On the one hand, door-to-door air currents would prevent pollutants transmission in span-wise direction in the corridor. On the other hand, higher wind speed could result in higher ventilation rate which means a greater capacity for dilution.

Discussion

The results of this investigation have demonstrated the spatial distribution of infection risk of a cross-ventilated hospital ward with central corridor and effects of the airflow pattern in the hospital ward. Some further discussions are made as follows.

The death rate of airborne organisms was assumed to be zero and as a result the predicted infection risk could be overestimated. This deviation might be a bit larger for distant cubicles (cubicles D and F) because airborne organisms need more time to reach those cubicles and, during this process, more virus death may happen. The death rate of airborne organisms would be influenced by many factors such as disinfection, relative humidity and temperature; therefore, the death rate may vary from case to case. In our study, the airflow pattern was regarded as a dominant factor in infection transmission and thus, even if the death rate was neglected, the results were still reasonable and meaningful.

The quanta generation rate, exposure duration and ventilation rate are key parameters when estimating the infection risk by applying Wells–Riley equation. These parameters vary within a wide range and are strongly dependent on specific cases. In terms of quanta generation rate and exposure duration, a rate of 1.3/min and duration of 4 h was assumed in this study.

Figure 9 provides information about how infection risks of cubicle E are related to different quanta generation rates and exposure duration with the index patient located in upstream cubicle B when the outdoor wind speed is 2 m/s. In Figure 9, the infection risk increases proportionately with the exposure time as

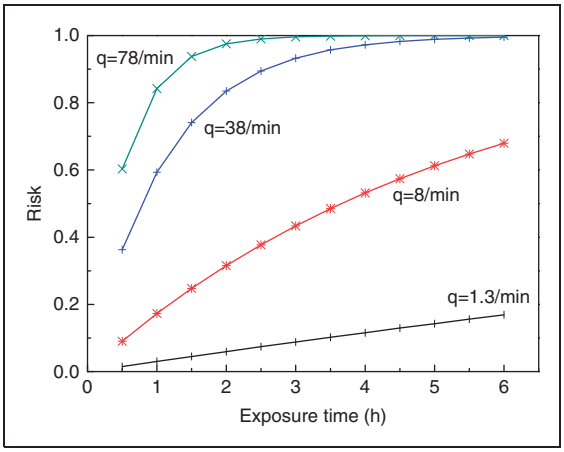

Figure 9. Infection risk of cubicle E with different quanta generation rates and exposure time, $V_{ref} = 2$ m/s.

the quanta generation rate is low. The variation tendency, however, becomes more exponential when the quanta generation rate is high. Given four hours' exposure, the predicted infection risk exceeds 50% at a generation rate of 8/min; and 100% at a generation rate >38/min. Meanwhile, our results suggest the high probability of catching infection when the susceptible stays at the same location in a space.

In terms of ventilation rate, the predicted values ranged from ~360 to ~2520 m^3/h (~0.1 to ~0.7 m^3/s) in the present study. WHO recommends 216 m^3/h/patient for general wards with natural ventilation.[5] If adopted in the hospital ward in this paper, the equivalent ventilation rate would be 1296 m^3/h for each cubicle, which could be obtained when the outdoor wind speed was over 2 m/s. However, under this circumstance, although the risk in the source cubicle could be reduced, the downstream cubicle was seriously polluted, as presented in our results.

The Chinese Standard, GB 51039-2014[38] is the latest standard for hospital design in China, although in this standard, the natural ventilation is a preferred requirement for general hospital wards; minimum ventilation requirement has not been specified. Moreover, considering that China is a country with a vast territory, climate differences between cities should be taken into consideration. Since natural ventilation is widely adopted in Chinese general hospital wards, in addition to referring to WHO, establishing concrete ventilation standards for natural ventilated hospital wards in China is urgently needed.

On the other hand, ASHRAE Standard 170-2008[39] specifies minimum ventilation requirements for types of health care facilities, e.g. 6 ACH for general hospital wards. This value is approximately half of the WHO recommended ventilation rate (~11 ACH) which was adopted in the hospital ward chosen in this study. However, in terms of a ward with mechanical ventilation, when the ACH is maintained at 6 ACH, the infection risk of the source cubicle would be 15.7%, which is comparable to our findings of 16.13% in the present study. Furthermore, in the mechanical ventilation manner, doors and windows of the cubicles are kept closed, which would consequently cut off the transmission route between cubicles. However, it is not easy to maintain the mechanical ventilation in every hospital ward all year round and the energy consumption should be considered.

Natural ventilation is generally applied in mild climate, e.g. during May, June and October in city like Nanjing. The prevailing wind speed measured by the weather station located on the building roof in Hospital R is usually below 2 m/s during these months. As indicated in the previous section, once the cross ventilation is formed, cross infection would be easily occurred between the source cubicle and the downstream cubicle in the central-corridor ward. In consequence, although natural ventilation is capable of reducing airborne infection risk in hospital environments, wards with central-corridor types should still be avoided, or at least, the cross-ventilation route should be cut off. This can be simply achieved by keeping cubicle doors closed or by installing screen or air curtain devices at the doorway.

Conclusions

In this study, the spatial distribution of infection risk of a central-corridor hospital ward with natural ventilation was predicted by applying CFD, taking into account index patient's location and outdoor wind speed. The detailed flow pattern and its impact were then revealed.

Cross ventilation could form a robust airflow pouring into the room and spreading over the internal space from windward openings to leeward openings. On this occasion, pollutants released in the upstream space could be transmitted to downstream rooms, resulting in infection risks as high as 10.48% and 11.59% as the index patient is located in the corridor and opposite cubicle, respectively. The opposite downstream cubicles should thus be included in the high-risk list.

The central-corridor type ventilation route is not only common in hospital wards but also in schools, dormitories and offices. Notwithstanding large ventilation rate provided by cross ventilation could meet the demand of ventilation requirements in guidelines or standards, the cross infection between an upstream room and an opposite downstream room is highly possible to happen. Consequently, as a possible respiratory infectious disease pandemic approaching, the central-corridor type should be avoided in general hospital

wards. Our findings strongly supports WHO's recommendation. Based on our findings, we recommend amendment of the Chinese standard GB 51039-2014 for ventilation arrangement in Chinese hospital wards to ensure adequate ventilation control and to minimize transmission of diseases in the hospital. The present study would help to improve the future design of general hospital wards for controlling airborne infectious diseases.

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Authors' contribution

All authors contributed equally in the preparation of this manuscript.

Declaration of conflicting interests

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References

1. Li Y, Leung GM, Tang JW, Yang X, Chao CYH, Lin JZ, Lu JW, Nielsen PV, Niu J, Qian H, Sleigh AC, Su HJJ, Sundell J, Wong TW and Yuen PL. Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systematic review. *Indoor Air* 2007; 17: 2–18.
2. Beggs CB, Kerr KG, Noakes CJ, Hathway EA and Sleigh PA. The ventilation of multiple-bed hospital wards: review and analysis. *Am J Infect Control* 2008; 36: 250–259.
3. Escombe AR, Oeser CC, Gilman RH, Navincopa M, Ticona E, Pan W, Martinez C, Chacaltana J, Rodriguez R, Moore DAJ, Friedland JS and Evans CA. Natural ventilation for the prevention of airborne contagion. *PLoS Med* 2007; 4: 309–316.
4. Qian H, Li Y, Seto WH, Ching P, Ching WH and Sun HQ. Natural ventilation for reducing airborne infection in hospitals. *Build Environ* 2010; 45: 559–565.
5. WHO. *Natural ventilation for infection control in health-care settings*. Geneva: World Health Organization, 2009.
6. Lo LJ and Novoselac A. Cross ventilation with small openings: measurements in a multi-zone test building. *Build Environ* 2012; 57: 377–386.
7. Park JS. Long-term field measurement on effects of wind speed and directional fluctuation on wind-driven cross ventilation in a mock-up building. *Build Environ* 2013; 62: 1–8.
8. Faggianelli GA, Brun A, Wurtz E and Muselli M. Natural cross ventilation in buildings on Mediterranean coastal zones. *Energy Build* 2014; 77: 206–218.
9. Karava P, Stathopoulos T and Athienitis AK. Airflow assessment in cross-ventilated buildings with operable façade elements. *Build Environ* 2011; 46: 266–279.
10. Ji L, Tan H, Kato S, Bu Z and Takahashi T. Wind tunnel investigation on influence of fluctuating wind direction on cross natural ventilation. *Build Environ* 2011; 46: 2490–2499.
11. Chu C-R and Chiang B-F. Wind-driven cross ventilation in long buildings. *Build Environ* 2014; 80: 150–158.
12. Ramponi R and Blocken B. CFD simulation of cross-ventilation for a generic isolated building: impact of computational parameters. *Build Environ* 2012; 53: 34–48.
13. Ramponi R and Blocken B. CFD simulation of cross-ventilation flow for different isolated building configurations: validation with wind tunnel measurements and analysis of physical and numerical diffusion effects. *J Wind Eng Ind Aerodyn* 2012; 104–106: 408–418.
14. Chu C-R and Chiang B-F. Wind-driven cross ventilation with internal obstacles. *Energy Build* 2013; 67: 201–209.
15. Shetabivash H. Investigation of opening position and shape on the natural cross ventilation. *Energy Build* 2015; 93: 1–15.
16. Gilkeson CA, Camargo-Valero MA, Pickin LE and Noakes CJ. Measurement of ventilation and airborne infection risk in large naturally ventilated hospital wards. *Build Environ* 2013; 65: 35–48.
17. Riley EC, Murphy G and Riley RL. Airborne spread of measles in a suburban elementary school. *Am J Epidemiol* 1978; 107: 421–432.
18. Wells WF. *Airborne contagion and air hygiene; an ecological study of droplet infections*. Cambridge: Harvard University, 1955.
19. Qian H, Li Y, Nielsen PV and Huang X. Spatial distribution of infection risk of SARS transmission in a hospital ward. *Build Environ* 2009; 44: 1651–1658.
20. Li Y, Huang X, Yu ITS, Wong TW and Qian H. Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. *Indoor Air* 2005; 15: 83–95.
21. Lai ACK and Nazaroff WW. Modeling indoor particle deposition from turbulent flow onto smooth surfaces. *J Aerosol Sci* 2000; 31: 463–476.
22. Gao NP and Niu JL. Modeling particle dispersion and deposition in indoor environments. *Atmos Environ* 2007; 41: 3862–3876.
23. Fluent. *ANSYS FLUENT 14.0 user's guide*. Canonsburg, PA: ANSYS Inc., 2011.
24. Jiang Y, Alexander D, Jenkins H, Arthur R and Chen Q. Natural ventilation in buildings: measurement in a wind tunnel and numerical simulation with large-eddy simulation. *J Wind Eng Ind Aerodyn* 2003; 91: 331–353.
25. Jin H, Li Q, Chen L, Fan J and Lu L. Experimental analysis of particle concentration heterogeneity in a ventilated scale chamber. *Atmos Environ* 2009; 43: 4311–4318.
26. Allocca C, Chen Q and Glicksman LR. Design analysis of single-sided natural ventilation. *Energy Build* 2003; 35: 785–795.
27. Brohus H. *Personal exposure to contaminant sources in ventilated rooms*. PhD Thesis, Aalborg University, Aalborg, 1997.
28. Nielsen PV, Li Y, Buus M and Winther FV. Risk of cross-infection in a hospital ward with downward ventilation. *Build Environ* 2010; 45: 2008–2014.
29. Hang J, Li Y, Ching WH, Wei J, Jin R, Liu L and Xie X. Potential airborne transmission between two isolation cubicles through a shared anteroom. *Build Environ* 2015; 89: 264–278.
30. Hang J, Li Y and Jin R. The influence of human walking on the flow and airborne transmission in a six-bed isolation room: tracer gas simulation. *Build Environ* 2014; 77: 119–134.
31. Zhu S, Kato S and Yang J-H. Study on transport characteristics of saliva droplets produced by coughing in a calm indoor environment. *Build Environ* 2006; 41: 1691–1702.

32. Etheridge D and Sandberg M. *Building ventilation: theory and measurement*. Chichester: John Wiley & Sons, 1996.
33. Qian H. *Ventilation for controlling airborne infection in hospital environments*. PhD Thesis, The University of Hong Kong, Hong Kong, China, 2007.
34. Gao NP, Niu JL, Perino M and Heiselberg P. The airborne transmission of infection between flats in high-rise residential buildings: tracer gas simulation. *Build Environ* 2008; 43: 1805–1817.
35. Gao NP, Niu JL, Perino M and Heiselberg P. The airborne transmission of infection between flats in high-rise residential buildings: particle simulation. *Build Environ* 2009; 44: 402–410.
36. Ai ZT, Mak CM and Niu JL. Numerical investigation of wind-induced airflow and interunit dispersion characteristics in multistory residential buildings. *Indoor Air* 2013; 23: 417–429.
37. Niu J and Tung TCW. On-site quantification of re-entry ratio of ventilation exhausts in multi-family residential buildings and implications. *Indoor Air* 2008; 18: 12–26.
38. GB 51039-2014. *Code for design of general hospital*. Beijing, China: Ministry of Housing and Urban-Rural Development of the People's Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2014.
39. ANSI/ASHRAE/ASHE Standard 170-2008. *Ventilation of health care facilities*. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers, 2008.