Evaluation of Natural Ventilation for Reducing Airborne Infection in General Hospital Wards by Long term Field measurement in Nanjing

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Abstract
Natural ventilation is believed to reduce airborne infection risks in hospital environments. However, a long term measurement is urgently needed to comprehensively evaluate the potential of natural ventilation. In this paper, a long term field measurement was carried out in a hospital ward in Nanjing. The measured CO₂ concentration was used to reveal patients’ behaviors and then the CO₂ data was applied to calculate possible airborne infection risks. The results demonstrate that natural ventilation is capable of maintaining the indoor CO₂ concentration at a low level (<800 ppm) and a night period from 9 p.m. to 7 a.m. is a high risk period due to patient’s behavior, i.e. closing doors and windows. During transition periods, the natural ventilation mode is effective for reducing airborne infection in hospital environments (risk ~0.1). In spite of the fact that mechanical ventilation has irreplaceable advantages in hospital ventilation, e.g. controllable and reliable, natural ventilation has great potential in general hospital wards.

Keywords: Long term; Field-measurement; CO₂ concentration; Hospital wards; airborne infection

1. Introduction
Ventilation in hospital wards affects patients’ and health care workers’ health. As one of the ventilation strategies, natural ventilation provides sufficient ventilation rate with energy efficient manner. Escombe et al.[1] and Qian et al.[2]’s field measurement in hospitals in Lima and HongKong demonstrates that when openings are kept open, natural ventilation can effectively reduce airborne infection risks. Their measurement results provide strong evidence to support using natural ventilation to control and reduce airborne infection. However, natural ventilation is influenced by many factors such as outdoor climate condition and human behaviors. The results of their investigations are based on a short term measurement. Obviously, a long term
measurement is urgently needed to comprehensively evaluate the performance of natural ventilation.

For evaluating the natural ventilation, indoor CO\textsubscript{2} concentration is an alternative\cite{3} and human behaviors, climate and building design are supposed to be determinants \cite{4}. Human behaviors including opening/closing doors and windows, switching on/off air-conditioners have great impact on natural ventilation rates, indoor temperatures and relative humidity. In a previous paper, the effects of human behaviors have been revealed\cite{5}. The purpose of this paper is to estimate the possible airborne infection risk by applying a modified Wells-Riley equation\cite{6} with the measured indoor CO\textsubscript{2} concentration. The results were used to evaluate the potential of natural ventilation for reducing airborne infection in hospital environments.

2. Methods

The field-measurement was conducted in a general hospital ward in Hospital R in Nanjing, China. The ward is on the third floor of a hospital building and it consists of several multi-bed cubicles. There are two types of cubicles, i.e. three-bed cubicle and six-bed cubicle. In this study, we randomly choose one cubicle of each type (namely cubicle A and cubicle B, see Fig.1) for measurement. Cubicle A contains three beds and its dimensions are 3.5(m) \times 7.4(m) \times 2.6(m), while cubicle B contains six beds and its dimensions are 5.8(m) \times 7.4(m) \times 2.6(m). These two cubicles are adjacent to each other and each cubicle holds two openings which are connected to the outside and to the corridor respectively. The opening dimensions are 1.3(m) \times 2.1(m) of a door and 0.8(m) \times 1(m) of a window. There is a locking mechanism on each window which restricts the maximum opening to about 25\% (0.2m). A split-type air-conditioner is installed in each cubicle whereas no ventilation system is equipped. Thus, fresh air supply in each cubicle can only be achieved via infiltration or natural ventilation.

Indoor CO\textsubscript{2} concentration, temperature, relative humidity (RH) and outdoor meteorological parameters such as wind speed, wind direction, temperature and RH were continuously measured and recorded. Indoor parameters were measured using TES CO\textsubscript{2} monitor (1370) (TES Corporation, Taiwan) in which a temperature/RH sensor is also equipped. The measuring range of the CO\textsubscript{2} sensor is from 0 to 5000ppm with the accuracy of 50ppm. Outdoor meteorological data were measured by Vantage Pro2 weather station (DAVIS Inc., Hayward, CA, USA). It was located on the rooftop of the hospital building. The weather station was a wireless device thus its data receiver was located indoor. All the data can be measured and logged automatically. The data log interval for CO\textsubscript{2} monitor and weather station was set to 4min and 30min (later, 60min) respectively.

Before the measurement, all CO\textsubscript{2} monitors were recalibrated using standard gas and calibration curves were plotted. The locations of measurement points are shown in Fig.1. For cubicle A, only one sensor was
installed at the central position while for cubicle B, two sensors were installed on the diagonal. In addition, two other sensors were installed in the corridor. The number and distribution of the sensors were determined on the basis of location sensitivity tests. Sensors were put 2.4m away from the floor in order not to disturb the daily operation of the ward and be affected by patients’ respiratory activities.

It was a long-term measurement that lasted for one year. It began in Oct, 2014. The data from 11 Oct 2014 to 10 Oct 2015 is analyzed in this paper. During the measurement, the whole ward was operated as usual. That means patients’ behaviors and their daily routes were not affected and restricted by the measurement.

Due to the storage capacity limitation, the logged data were output and saved to a laptop once every two weeks. After completing the measurement, all the data were collected and analyzed. It should be mentioned that the measurement were interrupted from 21 Jan to 4 Mar because of a redecoration project. Thus the indoor data were not measured during that period. Besides, the unexpected power supply problem and the accidental sensor fault led to a small number of data lost. Consequently, a total of ~620,000 indoor data and ~52,000 outdoor data were gathered up. The data process was conducted using Excel (Microsoft Inc., USA) and Origin (Microcal Software Inc., USA).

Data process
In this paper, all the data were hourly-averaged before analyzing, which means that the basic unit here is the hourly-averaged value. The parameter of cubicle A is represented by the data logged by the monitor located in cubicle A while the parameter of cubicle B is represented by the average value of two monitors in cubicle B.

The measured CO₂ concentration, temperature and RH were firstly used to determine patients’ behaviors, e.g. when to operate on air-conditioner, when to open windows and doors. Then, for transition periods (natural ventilation), the CO₂ data were used to estimate the infection risk.

Rudnick and Milton[6] developed Wells-Riley equation by directly using indoor CO₂ concentration to estimate airborne infection risk, which avoided calculating the room ventilation rate. The equation can be expressed as follows:

\[
P = 1 - \exp\left(-\frac{\bar{f}Iqt}{n}\right)
\]

Here, \(P\) is infection risk, \(\bar{f} = \frac{(C - C_0)}{C_a}\) (\(C\) is indoor CO₂ concentration, \(C_0\) is outdoor CO₂ concentration and \(C_a\) is the ratio of CO₂ production rate and breathing rate, 0.038) is the re-breathed fraction, \(\bar{f} = \int f dt / t\), \(I\) is the number of infectors, \(q\) is the quanta generation rate, \(t\) is exposure time and \(n\) represents the number of people in the room.
For constant quanta generation rate and number of people, the infection risk can be calculated by the measured indoor CO$_2$ concentration using (1).

![Fig. 1 Schematic plan view of cubicles and distribution of measurement points (red dot)](image)

3. Results and Discussion

In a previous paper[5], patients’ behavior were revealed and five parts of periods were determined, namely transition period 1, heating period, transition period 2, cooling period and transition period 3. The transition period represents a period of time during which air-conditioners are off, while the heating or cooling period stands for a period during which air-conditioners are on. Considering that the purpose of this paper is to evaluate natural ventilation for reducing airborne infection, thus only the data of transition periods were analyzed here. Summary of transition periods of the two cubicles are showed in Table 1.

<table>
<thead>
<tr>
<th>Cubicle</th>
<th>transition period 1</th>
<th>transition period 2</th>
<th>transition period 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubicle A</td>
<td>10/11~11/12</td>
<td>4/15~6/8</td>
<td>9/3~10/10</td>
</tr>
<tr>
<td>Cubicle B</td>
<td>10/11~11/16</td>
<td>4/15~6/6</td>
<td>8/30~10/10</td>
</tr>
</tbody>
</table>

Fig. 2 demonstrates the hourly-averaged CO$_2$ concentration of cubicle A and cubicle B and the adjacent corridor (data logged by monitors located in the corridor adjacent to the doorway of cubicle A and cubicle B). It can be seen from Fig. 2 that in transition period 1 and 3, the variation of concentration of the corridor and the corresponding cubicle showed similar tendency. In transition period 2, the indoor CO$_2$ concentration of the period before 7 a.m. and after 9 p.m. of the two cubicles significantly higher than those of the
corridor. Transition period 1 and 3, which correspond a period from September to mid November, are transferring summer to winter. During this period, patients tend to open doors and windows to keep thermal comfort. Under this circumstance, the cubicle and the corridor are connected. Thus CO\textsubscript{2} disperses freely and as a result the concentration of these two adjacent spaces showed to be similar. Transition 2 represents a period from mid April to early June. At that time, the air-conditioners were off. However, patients may be used to the warm sleeping environment in winter. Therefore, they preferred entirely closing doors and windows when they were sleeping even though the weather was getting warmer. Consequently, indoor CO\textsubscript{2} could only disperse via small gaps between cubicle and corridor, which resulted in the fact that the indoor CO\textsubscript{2} concentration of a period from 9 p.m. to 7 a.m. is remarkably higher than those of the corridor.

In addition, except for the period of 9 p.m. to 7 a.m. in transition period 2, the CO\textsubscript{2} concentration of the two cubicles was kept below 800 ppm in other periods. In transition period 1, minimal value of CO\textsubscript{2} concentration appeared at 8 a.m. and 1 p.m. while in transition period 3, the minimal value appeared only at 1 p.m.
Fig. 2 Hourly averaged CO₂ concentration of cubicles and corridor

Fig. 3 Predicted infection risk of cubicle A and cubicle B

Fig. 3 shows predicted infection risks of the two cubicles in accordance with indoor CO₂ concentration. Here, the quant generation rate is assumed to be 1.3/min[7], which represents Influenza, one of the most common airborne diseases. The number of infector is one and the exposure period is one hour.
for each period. The number of people in cubicle A is five while in cubicle B is ten (including the infector in each cubicle). It should be noted that during the long term measurement we found the number of people in the cubicle (including patients, caretakers and health care workers) went through drastic changes within a short period. Thus it is difficult to determine a specific number of people in every hour. However, from a perspective of statistics (considering the regularity of patients’ daily routine and health care workers’ schedule), the number of people in different period can be considered to be constant. In the present study, the stay duration of health care workers were shortest thus they were excluded when accounting for the number of people. On the other hand, the number of patients can be determined by the number of hospital beds in the cubicle (the measured hospital is one of the largest hospital in Jiangsu thus the wards are always full load). Besides, considering that each patient may not be necessarily with a caretaker (only one caretaker for a patient is permitted for 24h duration in the cubicle), we assumed that the 3-bed cubicle A held 5 people while the 6-bed cubicle B held 10 people when estimating the infection risk.

For cubicle A, the average infection risks of the three transition periods are about 0.1. The maximum risks dramatically changed, of which the variation range is from ~0.1 to ~0.5. Similar to the changing rule of indoor CO$_2$ concentration, in transition period 2, the maximum risk curve demonstrated significant high risk period i.e. from 9 p.m. to 7 a.m. The peak value is up to 0.47 though the average risk is less than 0.2 during this period. In this case, the windows and doors were kept entirely closed and after 10-hour exposure (9 p.m.-7 a.m.), the cross infection is highly possible to burst during the night. The result reminded us that although during transition period the windows and doors are kept opened for most time of a day, the closed room during the night time is still a place with high risk.

The predicted risk of cubicle B is similar to that of cubicle A but the risk value seems to be slightly lower. This may be because that the volume of cubicle B is larger and thus is beneficial to gas diffusion.

On the other hand, the green line in Fig. 3 represents the infection risk estimated by the classical Wells-Riley equation for two imaginary mechanical ventilation rooms. It is assumed that the room volumes are identical to those of cubicle A and cubicle B and the quanta generation rate is still 1.3/min. The air change rates of the two rooms are set as 2 ACH, which correspond to the minimum value of Ventilation of Health Care Facilities[8]. The predicted risks are 24.3% (volume$_{room}=$volume$_{cubicleA}$) and 15.4% (volume$_{room}=$volume$_{cubicleB}$) respectively. It is found that the average risks of cubicle A and B were lower than those of the two mechanically ventilated rooms. In most cases, only the maximum values of night duration were higher in cubicle A and B. This again illustrates that the night time of a cubicle is a high risk period. Meanwhile, the result demonstrates that during transition periods, the natural ventilation mode is effective for reducing airborne infection in hospital environments. In spite
of the fact that mechanical ventilation has irreplaceable advantages in hospital ventilation, e.g. controllable and reliable, during the transition period, natural ventilation has great potential in general hospital wards.

Last but not least, although the field measurement was carried out in Nanjing, the configuration and operating pattern of the hospital in this study is very common in China. Besides, the climate type of Nanjing is ‘hot summer and cold winter’, to which a large number of cities are similar. Consequently, the result of this paper is considered to be general and be used for reference. It also provides basis and evidence when designing and applying natural ventilation in general hospital wards.

4. Conclusions

In this paper a long-term field-measurement of indoor CO₂ level in a general hospital ward in Nanjing was reported. The measured CO₂ concentration of transition periods were analyzed and used to estimate the possible airborne infection risk. The following conclusions could be drawn.

1. Natural ventilation is capable of maintaining the indoor CO₂ concentration at a low level, e.g. <800 ppm in the present study. It implies that using natural ventilation is able to meet the demand of indoor air quality standard (<1000 ppm).

2. A period with extremely high CO₂ concentration (9 p.m.-7 a.m.) results in extremely high infection risks. Although during transition period the windows and doors are kept opened for most time of a day, the closed room during the night time is still a high-risk place.

3. During transition periods, the natural ventilation mode is effective for reducing airborne infection in hospital environments. In spite of the fact that mechanical ventilation has irreplaceable advantages in hospital ventilation, e.g. controllable and reliable, natural ventilation has great potential in general hospital wards.

Acknowledgment

The work described in this paper was funded by the Natural Science Foundation of China under the Project no.51378103.

References


