Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 00 (2013) 000–000

Procedia Computer Science

www.elsevier.com/locate/procedia

Conference on Systems Engineering Research (CSER'13)
Eds.: C.J.J. Paredis, C. Bishop, D. Bodner, Georgia Institute of Technology, Atlanta, GA, March 19-22, 2013.

Alternatives for Reducing the Risk of Transmission of Tuberculosis in a Typical Hospital Clinic in Developing African Countries

Adeel Khalid[a*], Christina Scherrer[b]

[a]Assistant Professor, Systems and Mechanical Engineering, Southern Polytechnic State University, 1100 South Marietta Parkway, SE, Marietta, GA. 30060, USA.
[b]Associate Professor, Industrial Engineering Technology, Southern Polytechnic State University, 1100 South Marietta Parkway, SE, Marietta, GA. 30060, USA.

Abstract

In this research, methods are explored to minimize the probability of the spread of airborne aerosols from an infected patient after a cough or sneeze. This work is focused on the spread of Tuberculosis. A hospital clinic is modeled using Computer Aided Design (CAD). The design is based on a typical clinic in a rural African country where resources are limited. The methods to help reduce the spread of Tuberculosis could include the use of masks by the infected patient, use of screens to separate the infected patient, and the use of window mounted exhaust fans for forced air circulation. In this study, the effectiveness of the use of masks of various efficiencies and the window locations are explored. Computational Fluid Dynamics (CFD) is used to model the flow of air and aerosols. Discrete Phase Modeling (DPM) is used to determine the steady state concentration of aerosols at various locations around the room. It is observed that the use of highly efficient masks can greatly reduce the probability of the spread of TB. It is also observed that the window location can have a significant impact on the spread of TB.

Keywords: Airborne; Aerosols; Computational Fluid Dynamics; Tuberculosis

1. Introduction

General infectious respiratory diseases are usually caused by airborne infection. Coughing and sneezing are the prime sources of airborne diseases. They have high velocities and a large quantity of droplets. Indoor environments such as hospitals may have occupants positioned closely for several hours. These environments are confined with low air exchange rates compared to outdoors, thus increasing the chance of infection spread. To be able to determine the ideal room conditions to minimize the risk of airborne disease spread, it is important to study the transport of expiratory droplets in indoor environments. This will help identify the zones under high risk.

There is a substantial and varied literature on the study of airborne disease transmission. Much research on

* Corresponding author. Tel.: +1-678-915-7241; fax: +1-678-915-5527.
E-mail address: akhalid2@spsu.edu.

coughing and sneezing has been performed by Yin et al. [1]. Zhu and Kato studied how air and aerosols are expelled from the mouth and dispersed in the surrounding air as a result of coughing [2]. Effective ventilation in hospital and clinical rooms is important to control respiratory disease transmission through air motion. Beggs et al. conducted a review on designing ventilation systems for hospital wards and other multi-bed rooms [3]. Gammaitoni et al. concluded that administrative control measures e.g. identifying and isolating patients with infectious TB are the most effective means of eliminating transmission because they substantially reduce the rate of infection [4]. Beggs et al. performed a CFD study to evaluate the effectiveness of various ventilation strategies in removing airborne pathogens from hospital rooms [5]. Yin et al. verified through experiments that ventilation systems play a very important role in the contaminant distribution in an impatient room [6].

In this CFD study, the infected patient is modeled as a source of droplet generation. The spread of droplets in a room of given dimensions is measured. This helps determine the concentration of droplets at any given point in the room. The flow through the room is modeled using the airflow rate or the number of air changes per hour. Zhang et al. have modeled various ventilation systems including ceiling and side wall supply systems and an under-floor air distribution system [7, 8].

Mechanical ventilation is prohibitively expensive for some clinics. The objective of this on-going study is to determine cost-effective solutions to contain the hospital and clinic-based spread of TB in such resource-constrained countries. Thus cost-effective building design and placement of wide open windows around the room, and their effect on disease transmission need to be explored. These windows will facilitate open circulation of air through the room. Another method to control the likely spread of the airborne disease is having the infected patient wear a face mask. Airborne aerosol concentrations with the use of masks of different efficiencies are also studied in this research.

Beggs et al [5] indicate that hospital room ventilation could play an important role in controlling the spread of air borne diseases. In developing countries, the room ventilation systems are often specified in terms of providing patient comfort and minimizing energy costs, rather than clinical reasons. There is a need to re-evaluate the basis on which the hospital rooms are designed and configured. In the CFD study, the number of patients in the clinic, breathing rate, air flow rates etc. could be some of the inputs for the simulation code. The outputs are measured in terms of the level of concentration or 3-dimensional concentration map, and velocity field in the room.

CFD is used for modeling fluid flow. It solves Navier-Stokes equations to determine the motion of fluid substances. Equations for the conservation of mass, energy, and momentum are solved simultaneously. For most engineering problems, analytical solutions for fluid flow do not exist. However it is possible to obtain approximate computer based solutions to the governing equations. ANSYS FLUENT CFD Package is used in this study to solve the governing equations. After a numerical solution has been obtained, the results are post-processed for infection concentration visualization. The dispersion of TB droplets submerged in air is modeled using Lagragian, Discrete Phase Model (DPM) mass transfer [20].

Several studies have been done related to modeling the spread of infectious droplets similar to TB using CFD. But the majority of the work comes from enclosed room ventilation researchers and studies particle concentration or movement as a result of specific room set-ups. Balloco and Lio, Chen et al., and Mazumdar et al. have modeled particle transport and distribution in ventilated rooms and have used CFD to simulate the airflow and predict the particle concentration [13-15]. In the current study, the objective is to model the expected number of new infections based on more general instances of people in a clinic waiting area. Niu and Gao [16] also use infection probability (i.e. Wells-Riley model). However, they focus on changes in infection risk between floors of a building based on natural ventilation. The most similar analytical work is from Qian et al. [17] who also consider a stochastic version of the Wells-Riley model, but applied to SARS.

2. Analysis

Two separate analyses are performed in this research. In the first analysis, the effectiveness of face masks is compared in minimizing the spread of TB. In the second analysis, two window locations are compared to determine the level of spread of contamination. The waiting room dimensions of the hospital floor are 30m X 18m X 4m. The seats are located in the middle of the room as shown in Figure 1.

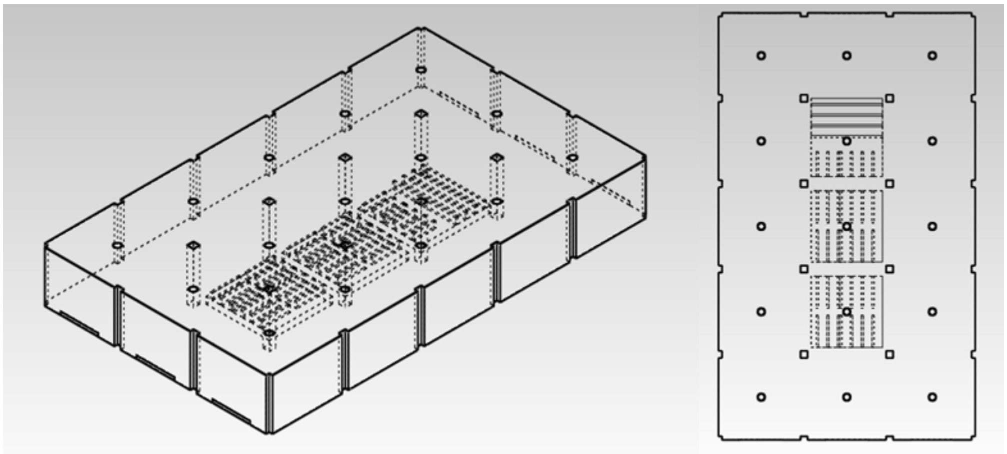


Figure 1: Isometric and top views of the waiting area in a hospital floor

The inlet vents are located in the ceiling of the room. There are 15 equally spaced vents in the room. The circular vents are 0.25m in radius. The outlet vents are located on the north and south walls near the bottom. The rectangular outlets are 3m long and 0.25m wide. Three outlet vents are located on the north and south sides of the room each. A single infected patient is located near the center of the room. A steady state is assumed where the patient is constantly coughing and therefore constantly adding aerosols to the room at the rate of 1Kg/s. For the analysis, the parameters used are summarized in Table 1:

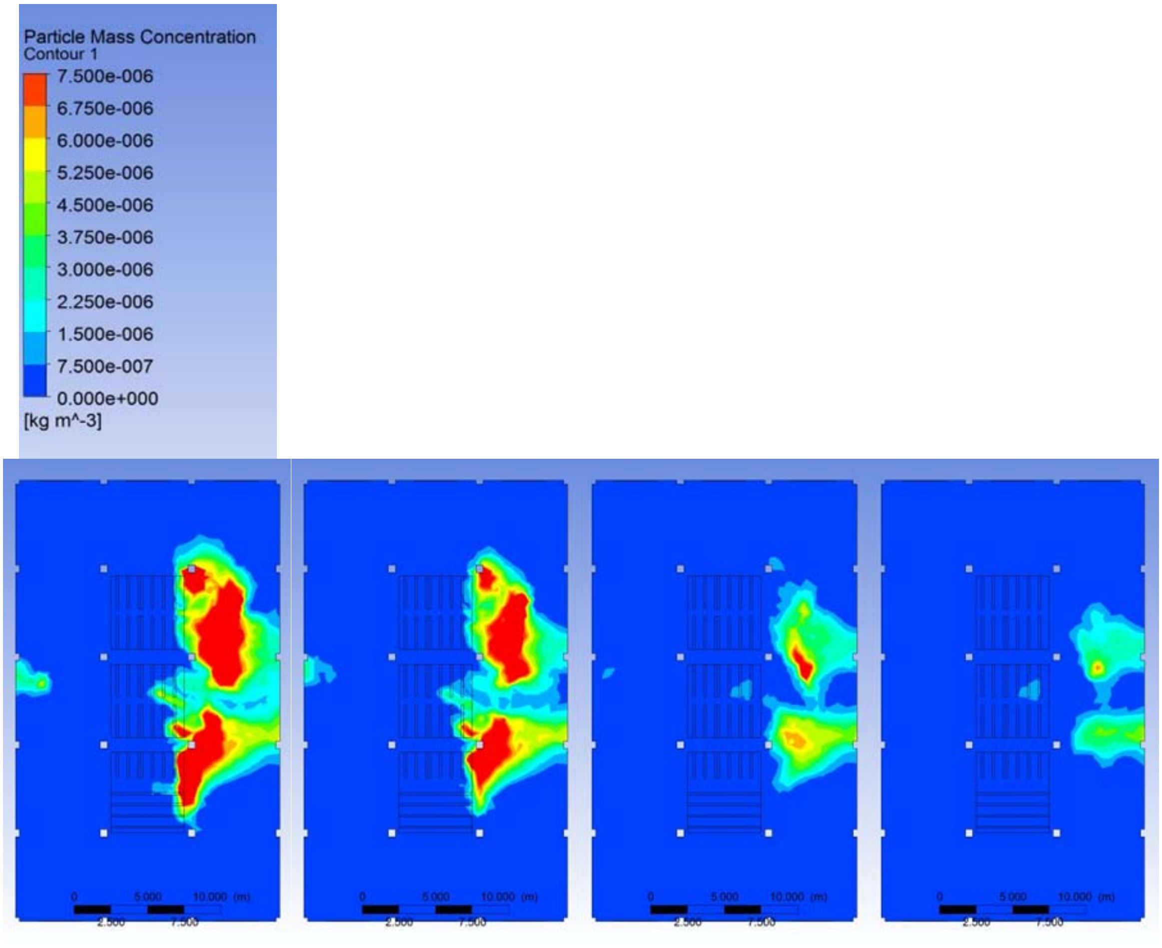
Table 1: Summary of input parameters for CFD analysis

Room Features		
	Room dimensions	18m X 30m X 4m
	Inlet Vent Radius	0.25 m
	Number of inlet vents	15
	Outlet vent dimension	3m X 0.25m
	Number of outlet vents	6
Cough Flow Characteristics		
	Cough material	Liquid water droplets
	Relative velocity of cough	10 m/s
	Particle size	0.31 microns [1]
	Flow rate	1 kg/s
	Number of Parcels	50,000
Air Flow Characteristics		
	Air changes per hour	6 ACH
Patient Location (from origin – top left corner)		
	X	9m
	Y	1.5m
	Z	15.5m
	Standing Plane Height	1.5m
	Sitting Plane Height	1.2m

It is imperative to validate CFD models with real data. The current model is validated against the data from Murakami et al. [17], also used in Zhang and Chen [9]. Full details of our model validation can be found in Khalid and Scherrer [7, 8].

2.1. Effectiveness of Mask Efficiency

In this study, the infected patient is modeled with a face mask on. The patient coughs at a constant flow rate of 1kg/s. Green et. al. claim that filtration in general ranges from 48-76% [18]. Mansoor et. al. believe that filtration level of masks is 11% [19]. Since there is uncertainty about the effectiveness of surgical masks as source control, mask efficiencies of 0%, 10%, 50% and 90% are compared in this CFD study. The number of aerosol parcels is reduced by the same percentage as the corresponding increase in the mask efficiency. The concentration levels in the room with masks at various efficiencies, at the sitting plane are shown in Figure 2. The concentration levels at the standing plane are shown in Figure 3. The concentration values are a direct function of the mask efficiency. As shown in Table 3, a 90% efficient mask can help reduce the maximum concentration by up to 98%. These face masks can effectively help reduce the risk of the wearer from transmitting the airborne aerosols. They can reduce the spread of infectious droplets carrying airborne bacteria that are ejected when the wearer coughs or sneezes. They also remind wearers not to touch their mouth or nose, which could otherwise transfer viruses and bacteria after having touched a contaminated surface.



a b c d

Figure 2: Concentration maps at the sitting plane with mask efficiencies of (a) 0%, (b) 10%, (c) 50%, and (d) 90%

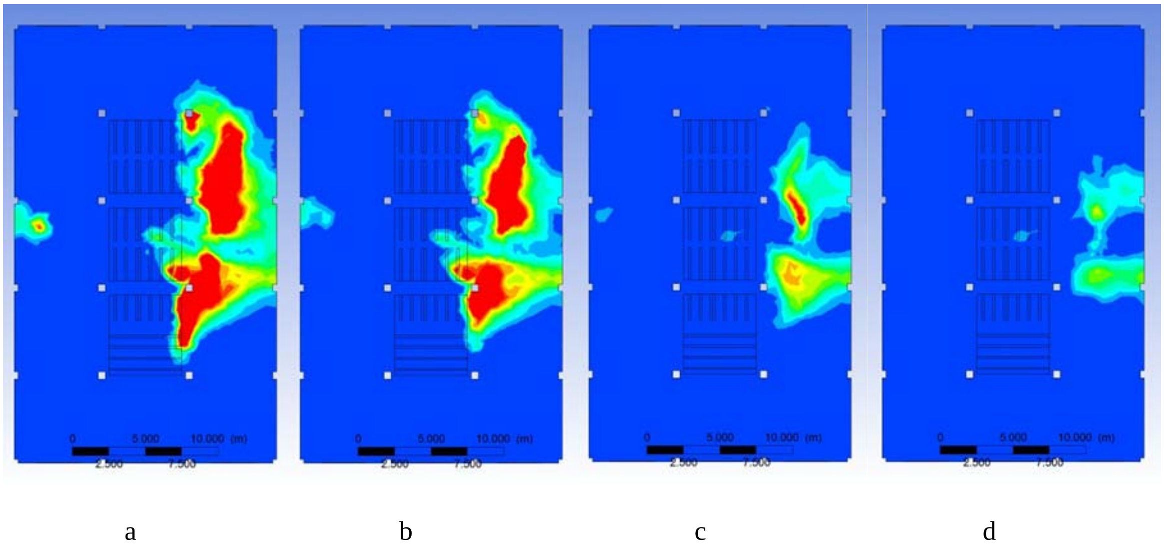


Figure 3: Concentration maps at the standing plane with mask efficiencies of (a) 0%, (b) 10%, (c) 50%, and (d) 90%

As can be seen in Figures 2 and 3, the concentration values decrease as the mask efficiency is increased. These concentrations are determined at the sitting plane, 1.2m meter above the floor, and the standing plan, 1.5m above the floor. The concentrations can also be determined at other planes and locations around the room. The concentration maps can directly be related to the probability of infection.

2.2. Effect of Window Location

In the second study, the effect of the location of windows is analyzed. The window dimensions are 1.5 m X 1.5 m. Three windows on the west side of the room are compared with the equally sized three windows on the south corner of the room. Window configurations are shown in Figure 4. Open doors are also introduced on the north side of the room. These doors help with the cross ventilation in the room. The windows and doors help limit the concentration of aerosols and other airborne pollutants. Due to higher room pressure, and lower outside pressure, air is forced to leave the room through the windows, outlet vents, and the open doors. A steady state condition is obtained with the air exchange rate of 6ACH. The door dimensions are 1m X 3m. The patient is located near the center of the room.

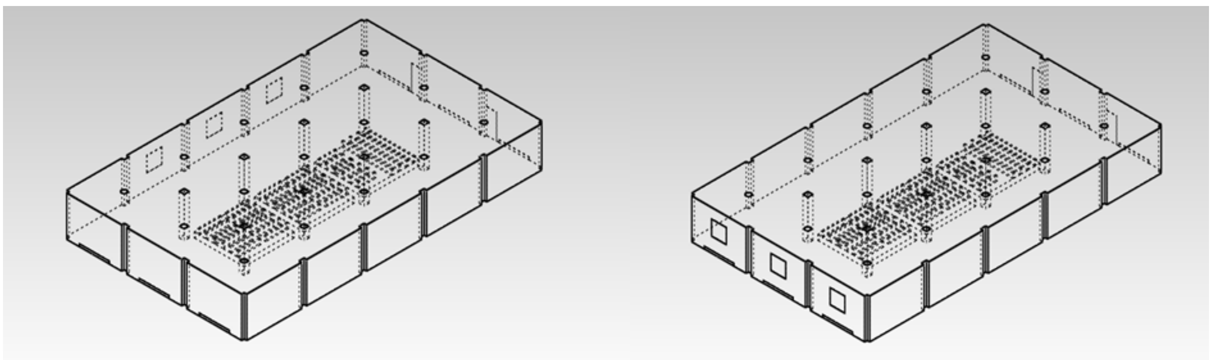


Figure 4: Window locations with open doors. (a) Open windows located on the west side of the room (b) Open windows located on the south side of the room

Table 2. Window and Door Geometry

Geometry	Dimensions
Windows (Open)	1.5m X 1.5m
Doors (Open)	1m X 3m

The results of the concentration distribution for side wall window locations at the sitting and standing planes are shown in Figures 5a and 6a respectively. In this case the patient coughs in the direction opposite to the side wall windows. As can be seen from Figures 5a and 6a, most of the particles tend to accumulate in the direction of the cough. Because of the open doors in the north, some particles are forced towards the exit due to air movement. The concentration results of the windows located in the south of the room are shown in sitting and standing planes in Figures 5b and 6b respectively. Since the direction of the cough is orthogonal to the window location, a much higher concentration accumulation is observed on the east side of the room. Aerosols tend to get removed from the room from the windows in the south and open doors in the north. As shown in Table 3, some locations in the room have a lower concentration with the windows on the south but most locations are served better with the windows towards the west. These results are only valid with the patient coughing towards the east.

The results of cough towards the open west side window are shown in Figure 7 in the sitting and standing planes. When compared with the cough direction away from the open window, it can be seen that the average concentration level is up to 15% lower. This window location comparison indicates that when the cough direction is towards the open window aerosols are quickly removed from the room. This could be directly related to reduction in risk of airborne particles.

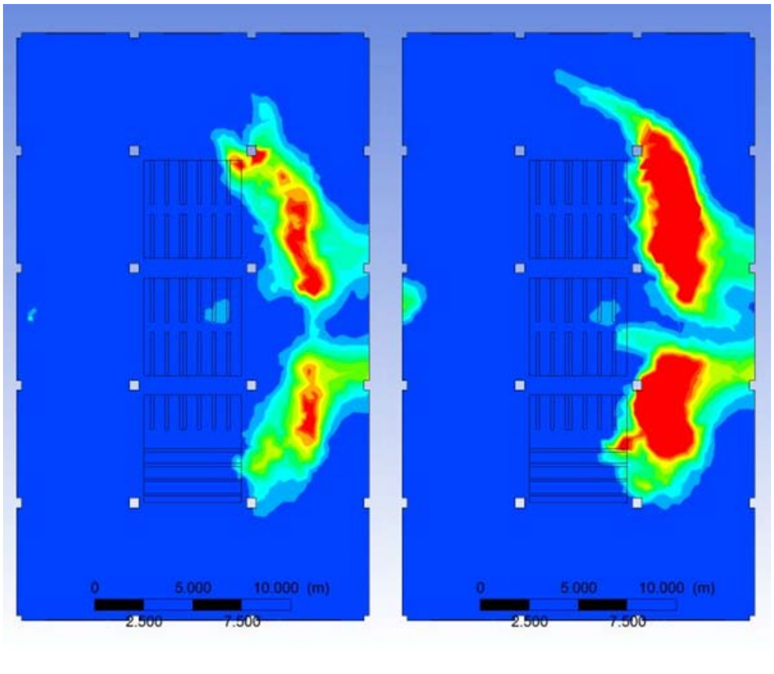


Figure 5: Concentration map at sitting plane and aerosols moving towards the east with (a) Window located on West (left) side and (b) Window located on South (bottom).

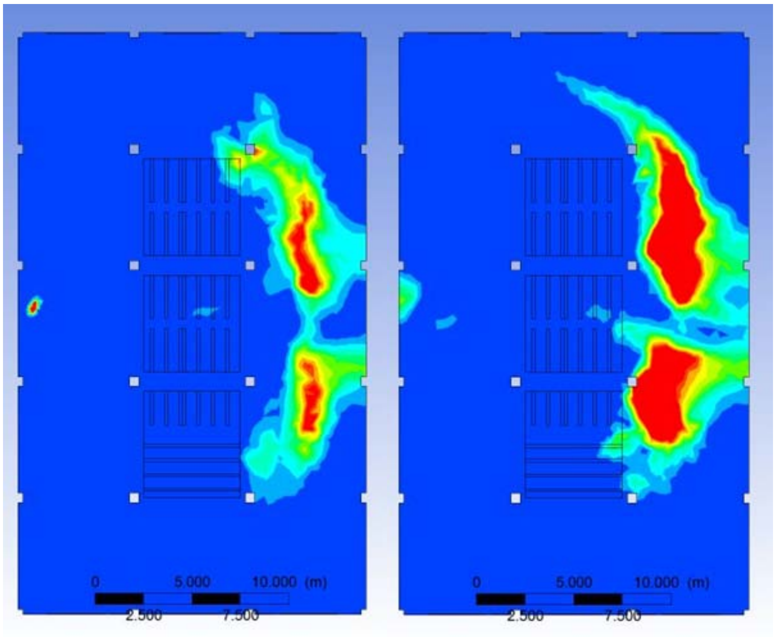


Figure 6: Concentration map at standing plane and aerosols moving towards the east with (a) Window located on West (left) side and (b) Window located on South (bottom).

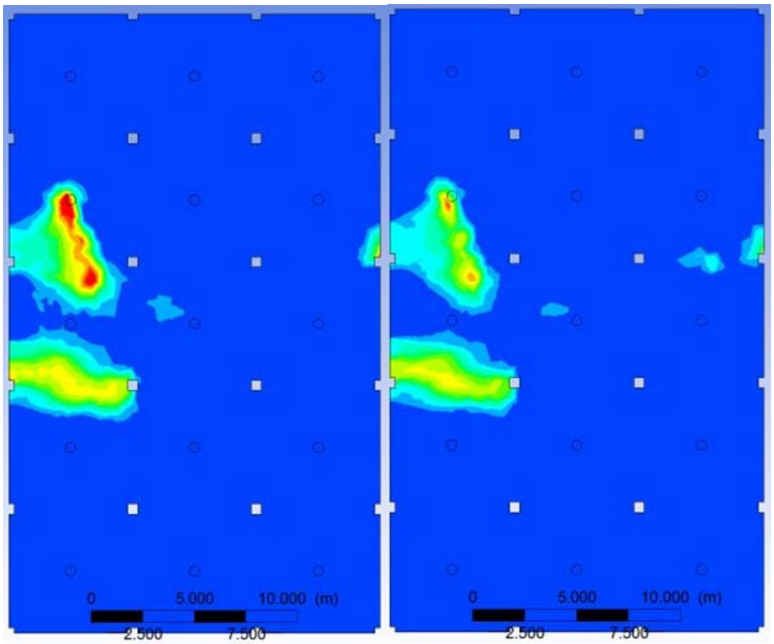


Figure 7: Concentration map with West (left) side window and aerosols moving towards the West (left) at (a) sitting plane, (b) standing plane.

Fifteen locations are evenly selected (three laterally and five longitudinally) in the room right underneath the overhead vents as shown in Fig 8. The concentration values are measured at these locations. These concentration values are normalized with respect to the maximum concentration level of 2.23x10-5 kg/m3. All the results are summarized in Table 3.

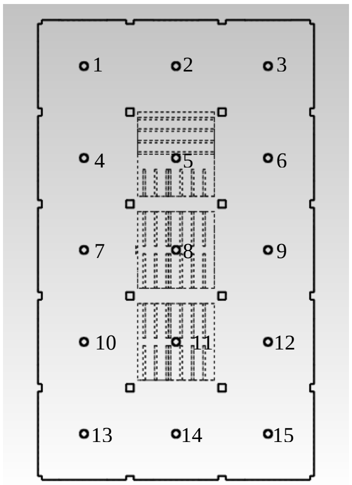


Fig. 8. Evenly spaced locations where the particle concentrations are measured

Table 3. Concentration Contents for various room configurations

Location	Mask Ƞ=0%	Mask Ƞ=10%	Mask Ƞ=50%	Mask Ƞ=90%	West Window, Flow direction East	West Window, Flow direction West	South Window
1	0	0	0	0	0	0.185	0
2	0	0	0	0	0	0.185	0
3	0	0	0	0	0	0	0
4	0.262	0.153	0.022	0.005	0.262	0.131	0.198
5	1.000	0.726	0.244	0.244	1.000	0.009	0.591
6	0	0	0	0	0	0	0
7	0.106	0.075	0.020	0.016	0.013	0.016	0.039
8	0.091	0.064	0.071	0.071	0.028	0.020	0.048
9	0.005	0.005	0.005	0.005	0.002	0.004	0.005
10	0	0	0.001	0	0.076	0	0.071
11	0	0	0	0	0.038	0	0.049
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
Room Average C (Kg/m3)	2.27×10^{-6}	2.12×10^{-6}	1.44×10^{-6}	9.5×10^{-7}	1.38×10^{-6}	1.64×10^{-6}	1.87×10^{-6}

As can be seen from Figures 2-6, and Table 3, the location of windows and the direction of cough can significantly affect the concentration contents in a room. Depending on the orientation of the hospital chairs in the waiting room, the level of concentration and therefore the risk of airborne disease transfer can be reduced.

3. Conclusions

In this study, the mask efficiencies are compared and their effect on the concentration of airborne aerosols is analyzed. It is observed that a high efficiency mask can significantly reduce the concentration value and therefore the probability of spread of Tuberculosis. The concentrations are compared at the sitting and standing planes. In the second study, the location of windows is compared in terms of the corresponding aerosol concentration levels under the given conditions at the sitting and standing levels. When the windows are on the west side of the room, and the centrally located infected patient coughs towards the east, the infection spread is lower than when the windows are on the south side of the room. Additionally, when the patient coughs towards the west with open windows towards the west, the risk of airborne infection spread is significantly reduced. These results can help the architects and engineers to design the windows on a given floor plan. These results can also help the hospital management to orient the seating according to the location of the windows to minimize the spread of the airborne disease.

Other low-resource methods to help reduce the spread of Tuberculosis could include the use of screens to separate the infected patient and the use of window mounted exhaust fans for forced air circulation. In the future studies, economic analysis can be performed to compare the cost of implementing the masks, screens or fans. From a systems engineering perspective, this research is one step towards a complete and well-rounded study on the investigation of methodologies that can be used to prevent the spread of Tuberculosis, their effectiveness and the corresponding costs. The study will help the systems engineers, designers, architects, and hospital management to make important decision to improve the overall healthcare system.

Acknowledgements

This work was partially supported by the Center for Disease Control (CDC) under grant number CRDF #CO-31096-12 and the National Science Foundation (NSF) under grant number BRIGE #0927095. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the CDC or NSF. The authors would also like to thank Michele Pearson, MD from the Centers for Disease Control for her insights into the project.

References

1. Yin, Y., et al., ‘Experimental study on displacement and mixing ventilation systems for a patient ward,’ 2009, ASHRAE HVAC&R Research, Vol. 15, No. 6, pp. 1175-1191
2. Zhu, S., Kato, S., Yang, J-h., ‘Investigation into airborne transport characteristics of airflow due to coughing in a stagnant indoor environment,’ 2006, ASHRAE Transaction, Vol. 112, Part 1, pp. 123-133
3. Beggs, C.B., Noakes, E. J., Sleigh, P. A., Fletcher, L. A., Siddiqi, K., ‘Transmission of Tuberculosis in confined spaces: an analytical review of alternative epidemiological models,’ 2003, International Journal of Tuberculosis and Lung Disease, Vol. 7, Issue 11, pp. 1015-1026
4. Gammaitoni, L., Nucci, M. C., ‘Using a mathematical model to evaluate the efficacy of TB control measures,’ Emerging Infectious Diseases, Vol. 3, No. 3, 1997
5. Beggs, C. B., Kerr, K. G., Noakes, C. J., Hathway, E. A., Sleigh, P. A., ‘The ventilation of multiple bed hospital wards: review and analysis,’ 2008, American Journal of Infection Control, Vol. 36, Issue 4, pp. 250-259
6. Yin, Y., Gupta, J. K., Zhang, X., Liu, J., and Chen, Q., ‘Distribution of contaminant exhaled out by a patient with different postures and exhaling modes in a single bed patient room,’ Buildings and Environment, 46(1), pp. 75-81
7. Zhang, Z., Chen, Q., ‘Experimental measurements and numerical simulations of particle transport and distribution in ventilated rooms,’ 2006, Atmospheric Environment, 40 (18), pp. 3396-3408
8. Zhang, Z., Chen, Q., ‘Particle dispersion in a room with under-floor air distribution,’ 2005, Proceedings of Indoor Air, Vol. III, pp. 2373-2378
9. Murakami, S., Kato, S., Nagano, S., Tanaka, Y., ‘Diffusion characteristics of airborne particles with gravitational settling in a

convection-dominant indoor flow field,' 1992, ASHRAE Transactions, Vol. 98, part 1, pp. 82-97.

10. Zhu, S., Kato, S., Yang, J-h., 'Investigation into airborne transport characteristics of airflow due to coughing in a stagnant indoor environment,' 2006, ASHRAE Transaction, Vol. 112, Part 1, pp. 123-133
11. Khalid, A., Scherrer, C., 'Study of Tuberculosis spread in Hospital Rooms in Developing Countries using Computational Fluid Dynamics (CFD),' American Society of Mechanical Engineers (ASME), The Twelfth Annual Early Career Technical Conference (ECTC), November 2-3, 2012, Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.
12. Khalid, A., Scherrer, C., 'Modeling the Effectiveness of Selected Tuberculosis Interventions in Resource Constrained Countries using CFD,' Institute for Operations Research and the Management Sciences (INFORMS), Southeastern Chapter 2012 Conference, Oct 4-5, Myrtle Beach, SC
13. Balocco, C. and Liò, P. (2010) Modelling infection spreading control in a hospital isolation room. Journal of Biomedical Science and Engineering, 3, 653-663.
14. Chen C, Zhao B., Indoor Air. 2010 Apr;20(2):95-111. Some questions on dispersion of human exhaled droplets in ventilation room: answers from numerical investigation.
15. Mazumdar, Sagnik; Yanggao Yin; Guity, Arash; Marmion, Paul; Gulick, Bob; Qingyan Chen. Impact of Moving Objects on Contaminant Concentration Distributions in an Inpatient Ward with Displacement Ventilation. HVAC&R Research Sep2010 Volume: 16 Issue: 5 Pages: 545(19).
16. Niu, J. L.; Gao, N. P. 'CFD Simulation of Spread Risks of Infectious Disease due to Interactive Wind and Ventilation Airflows via Window Openings in High-Rise Buildings'. AIP Conference Proceedings, May 21, 2010.
17. Qian, H., Li, Y.G., Nielson, P.V. and Huang, X.H. (2009) Spatial Distribution of Infection Risk of SARS Transmission in a Hospital Ward. Build. Environ. 44, 1651-1658.
18. Christopher F. Green; Craig S. Davidson; Adelisa L. Panlilio; Paul A.; Jensen; Yan Jin; Shawn G. Gibbs; Pasquale V. Scarpino, 'Effectiveness of selected surgical masks in arresting vegetative cells and endospores when worn by simulated contagious patients,' Infection Control and Hospital Epidemiology 2012;33(5):487-494
19. M. M. Mansour, K. T. Diaz, G. C. Smaldone, 'Protection From Inhaled Infectious Aerosols:importance Of Source Control,' Stony Brook University Hospital, Stony Brook, NY, SUNY At Stony Brook, Stony Brook, NY, Am J Respir Crit Care Med 183;2011:A4778