

MODELING THE EFFECTIVENESS OF SELECTED TUBERCULOSIS INTERVENTIONS IN RESOURCE-CONSTRAINED COUNTRIES USING CFD

**Adeel Khalid, Assistant Professor, Systems and Mechanical Engineering, (akhalid2@spsu.edu)
Christina Scherrer, Associate Professor, Industrial Engineering Technology, (cscherre@spsu.edu)
Southern Polytechnic State University**

INTRODUCTION

Tuberculosis (TB) is an airborne bacterial disease that primarily affects the lungs. TB germs are passed through the air when someone who is sick with TB disease coughs, speaks, laughs, sings, or sneezes [1]. People in close proximity to the infected person can breathe TB germs into their lungs and become infected as well. This is especially likely in confined spaces, including waiting rooms of healthcare facilities. Hospitals and clinics are also of great concern because they are likely to contain individuals especially susceptible to infection due to other underlying conditions. Significant progress has been made toward the elimination of TB in the United States, but it continues to be a grave concern in resource-constrained countries. In 2010, 8.8 million people around the world became sick with TB and there were approximately 1.5 million TB-related deaths. 82% of these infections occur in 22 countries [2]. Of growing concern globally is the increasing resistance to first and second line drugs, known as multi-drug resistant (MDR) and extensively drug resistant (XDR) TB.

This research is the first use of computational fluid dynamics (CFD) with practical application for clinic design in resource-constrained countries. The World Health Organization has best practices for clinic design [3] - including high air circulation rates and the use of isolation rooms - that are followed when feasible. But without resources to fully adhere to those recommendations decision makers for clinics in places such as Africa are often at a loss for which design and administrative decisions to make to reduce disease transmission in their clinic. We are working closely with the Centers for Disease Control (CDC) to ensure that the assumptions used in the research are practical and the results are transferrable.

LITERATURE REVIEW

There are many papers, primarily in the medical literature, studying the nosocomial (hospital or clinic-based) spread of infectious disease. One of the most widely used infection models for TB is the Wells-Riley model [4,5], which has been applied to numerous studies that look at TB transmission risk, including Escombe et al. [6], Cooper-Arnold et al. [7] and modified versions of the model in Gammaitoni and Nucci [8] and Beggs et al. [9]. Griffin et al. [10] use stochastic modeling in combination with the Wells-Riley model to study the probability of infection in a resource-constrained clinic waiting area, based on two specific infection control issues. All of the papers rely on the limiting assumption that air is instantaneously and completely mixed in the room once the infected person coughs. Noakes and Sleigh

[11] have shown significant differences in even aggregate results when considering zonal air mixing, rather than the complete air-mixing assumption of the Wells-Riley model. It is for this reason that we are exploring the use of CFD, in combination with stochastic modeling, to relax that assumption.

CFD is a flow modeling technique that solves Navier-Stokes equations to determine the motion of fluid substances. In CFD analysis, equations for the conservation of mass, energy, and momentum are solved simultaneously. These equations form a set of coupled, non-linear partial differential equations. Analytical solutions for these fluid flow models do not exist for most engineering problems. However it is possible to obtain approximate computer based solutions for the governing equations. There are several CFD packages available that could be used to solve this problem numerically. ANSYS Fluent is used in this study. 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 convection mass transfer.

CFD is useful for this problem because it allows tracking of the infectious droplets throughout the room. We are able to precisely estimate risk of disease transmission for patients located at various positions in the room, based on several characteristics of the room and infectious patient. This allows us to consider administrative controls, such as locating potential infectious TB patients in different areas of the room, using screens to block air flow, and segregating high-risk populations.

There is a significant amount of literature related to modeling the spread of infectious droplets similar to TB using CFD. However, the majority of the work comes from enclosed room ventilation researchers and studies particle concentration or movement as a result of very 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 [12-14]. Our work takes this a step further with an objective of modeling the expected number of new infections based on more general instances of people in a clinic waiting area. Niu and Gao [15] 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. [16] who also consider a stochastic version of the Wells-Riley model, but applied to SARS.

METHODS

For this study, we model a medium-resource, high-volume outpatient clinic waiting area in Africa, based on input from a researcher at the Centers for Disease Control. All modeling was done using Computer Aided Design (CAD) software called Solid Works and run in ANSYS Fluent version 13. The data used in the CAD and CFD models are listed in table 1.

Table 1: Data used in CFD model

Room Features		
	Room dimensions	30m X 18m 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
Flow Characteristics		
	Cough material	Liquid water droplets
	Relative velocity of cough	10 m/s
	Particle size	0.31 microns [SOURCE]
	Flow rate	1 kg/s
	Air changes per hour	6

It is imperative to validate CFD models with real data. For our model, we relied on the data from Murakami et al. [17], also used in Zhang and Chen [18]. Full details of our model validation can be found in Khalid and Scherrer [19].

To take the most advantage of relaxing the assumption of equal air mixing, this paper focuses on the impact of the location of the infectious source as well as on using room dividers (screens) to prevent the spread of TB. Based on an actual clinic in Africa, we model a single large (360 m²) waiting area with three seating areas with a total of 192 chairs. The room has mechanical ventilation at 6 air changes per hour (ACH). Air enters through 15 circular vents of 0.25m radius in the ceiling. Air is evenly distributed throughout the room and departs through 6 vents at floor level on the north and south walls of the room. (See figure 1.) We assume no other air enters or leaves the room. We also assume that there is exactly one infectious person in the waiting area and study the impact of placing two 6m long floor-to-ceiling screens in the room, separating the three blocks of chairs in the waiting area. We first model the infectious person located approximately in the middle of the room (patient 1) and then model the person seated toward the corner of the seating area (patient 2). The infected person is assumed to be sitting in the chair when the infectious particles are introduced in the room.

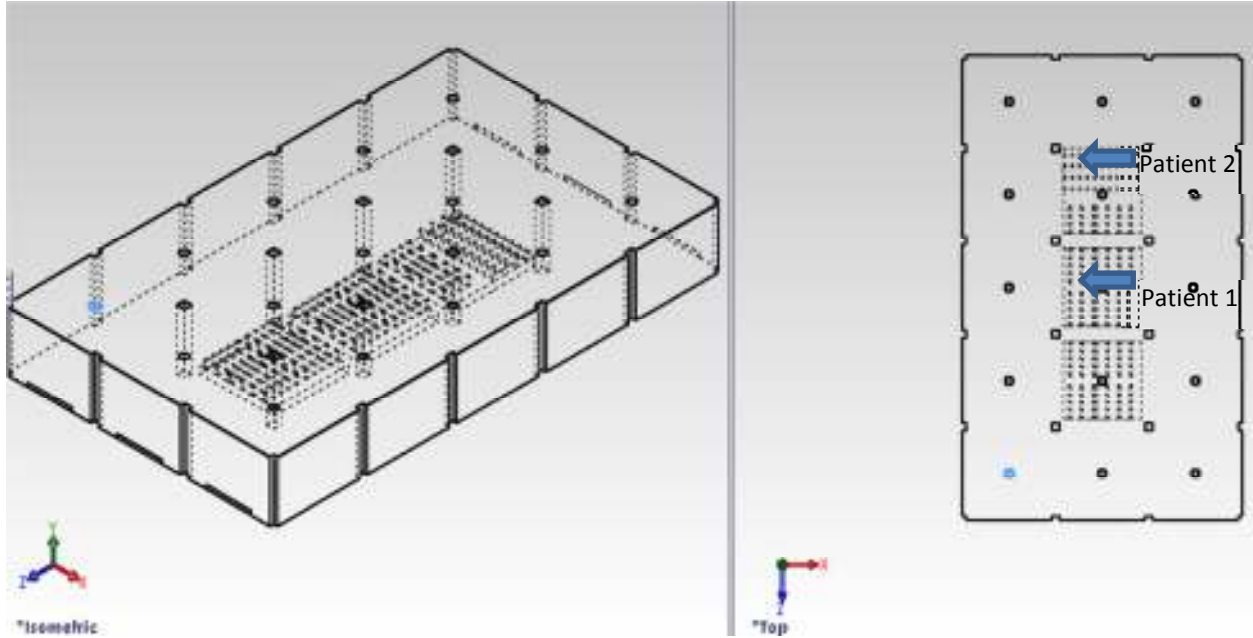


Figure 1: Two views of the waiting room. The arrows represent the direction of the cough (droplet introduction).

RESULTS

The output from fluent is very sophisticated and allows for multiple views of the room. For the purposes of this paper, we have presented the contour maps of TB particle concentration at both the seated height (assumed to be 1.5 meters) and standing height (assumed to be 2 meters). Figure 2 shows the results for the infectious patient in the center of the room. The top two contours are at seated height and the bottom two at standing height. The left two contour maps are without partition screens and the right two are with screens. The concentration scale is the same on all of the figures for ease of comparison. It can be seen that the addition of the screens reduces the area of high concentration, but also causes some eddies with infectious particles carried to the other side of the room around the screens. This could cause a higher risk of infection in a person sitting or standing close to the screen than the one farther away. The infected patient is located in the sitting plane. The concentration in the room is similar at the sitting and standing heights.

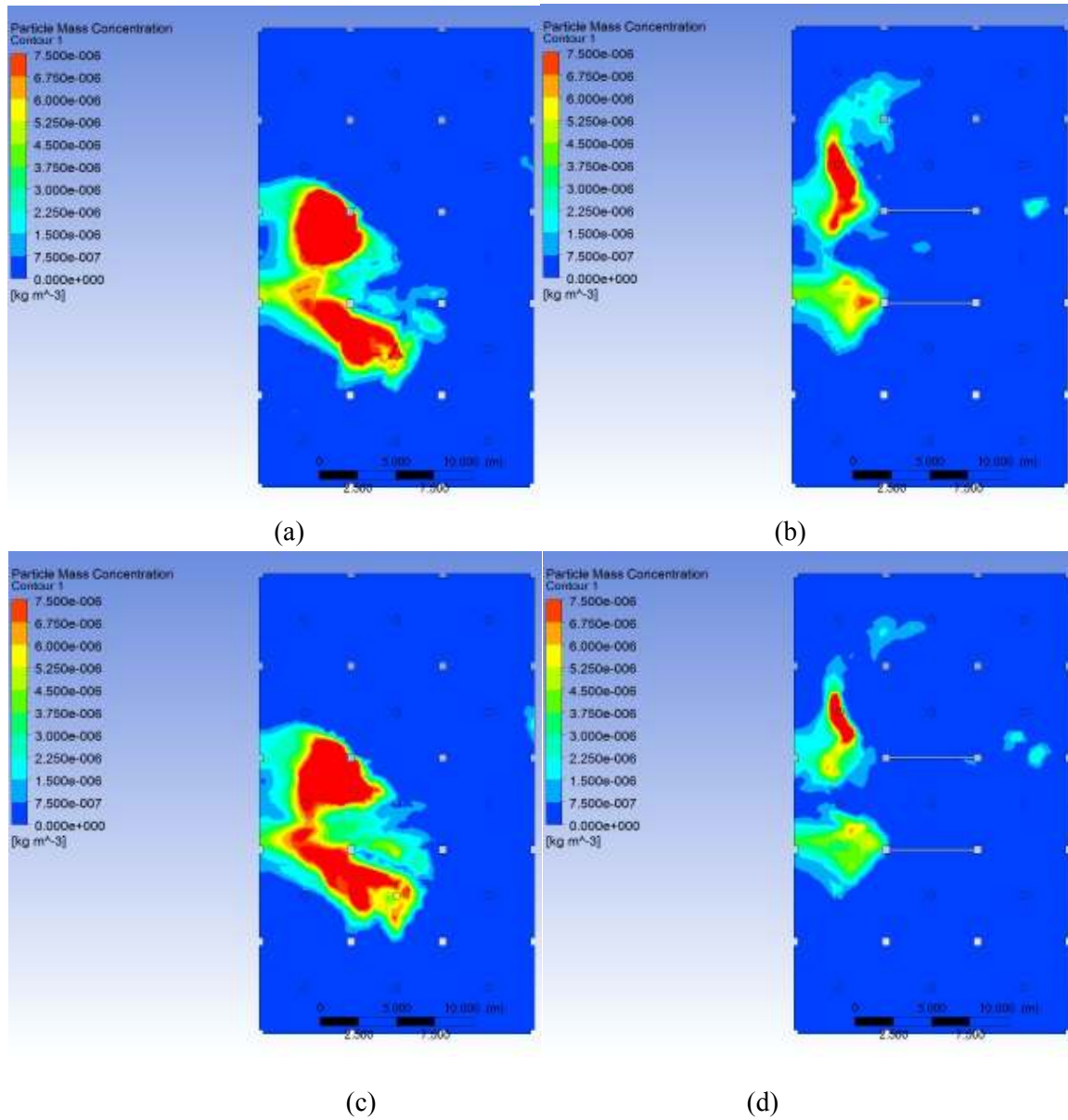
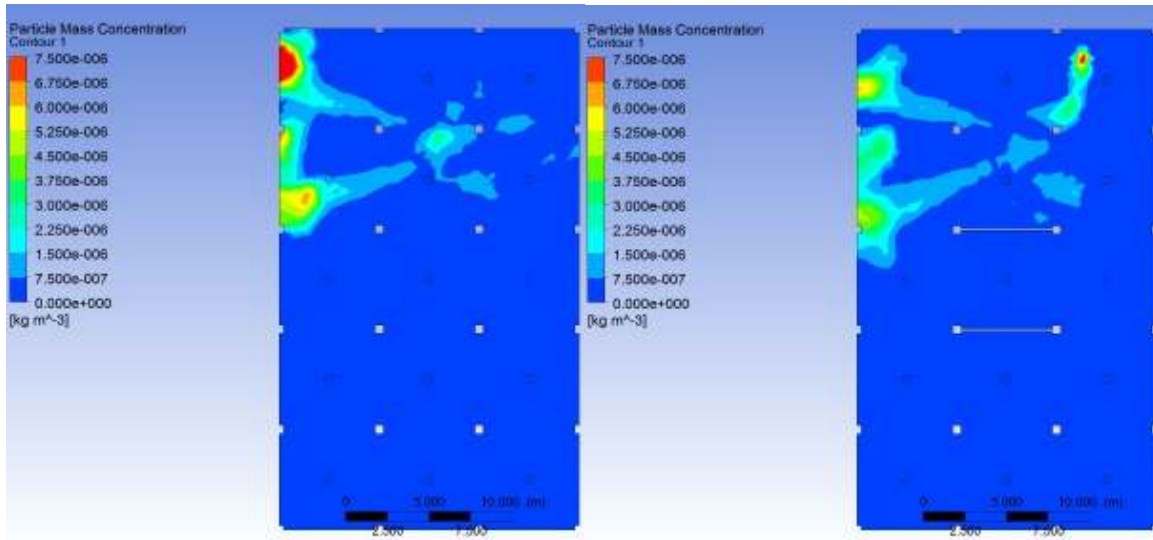


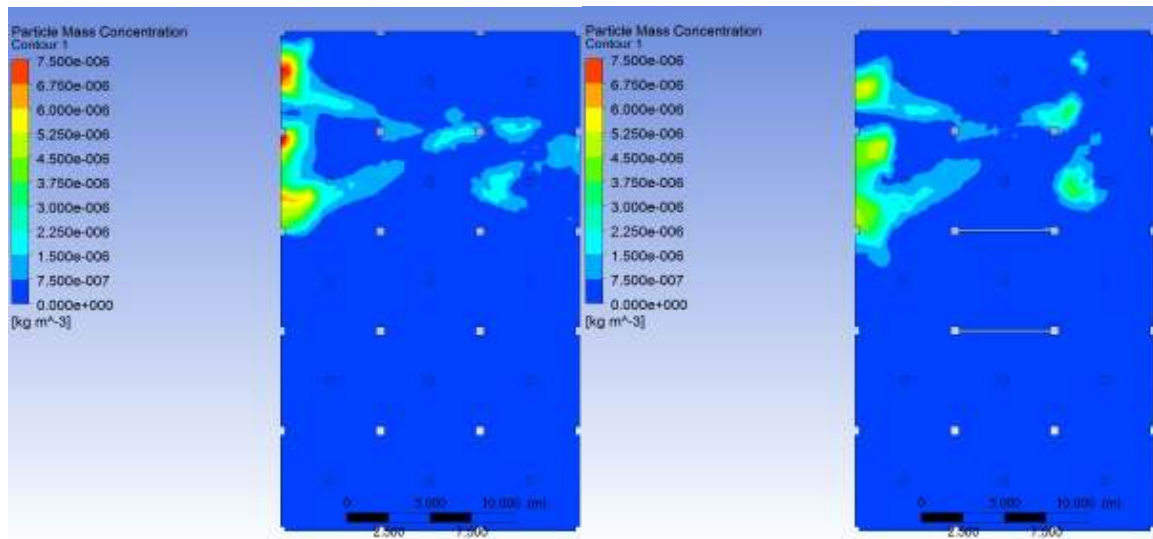
Figure 2: Top view of the concentration contours with the infected patient 1 near the center of the room
(a) seated height (b) seated height, screens added to room (c) standing height (d) standing height, screens added to room

Similar set of contour maps are shown in Figure 3, but for the infectious patient located in the corner of the seating area. The same scale is used for comparison purposes. The proximity of the outlet vent pulls the TB particles out of the room in that direction effectively, reducing overall concentration of TB particles in the room compared with Figure 2.



(a)

(b)



(c)

(d)

Figure 3: Top view of the concentration contours with the infected patient 2 near the top of the room (a) seated height (b) seated height, screens added to room (c) standing height (d) standing height, screens added to room

A 3-dimensional concentration map is shown in Figure 4. This is a 3-D depiction of steady state flow of circulating air through the room and a steady injection of infected particles by the patient. The steady induction of particles is analogous to an infected patient coughing at a constant rate, which is a typical

assumption in the literature. Projections of this concentration map at the sitting and standing level planes are shown in Figures 2 and 3.

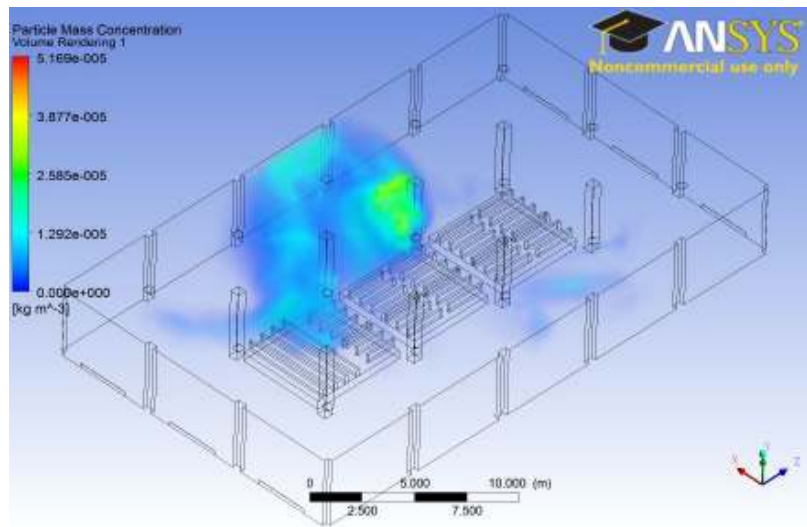


Figure 4: Isometric view of the concentration distribution of the patient sitting near the center of the room, room without screens

In addition to the visual representation of the concentration, it can be output numerically at all of the grid points in the mesh. We use this to populate an Excel-based model of the room for further analysis. First, we subdivide the room into 0.5 meter by 0.5 meter blocks to represent possible locations for susceptible patients to stand or sit in the room. (See Figure 5.) Note that this is an approximation of the more accurate CAD rendering (Figure 1). Each of the chairs in the room is represented by a block (squares), shaded regions represent places that patients cannot be (because they are between chairs, they are nurses' stations or equipment is located there in the actual clinic in Africa), and we assume that standing patients in the open spaces will be located in one of the 0.5X0.5m blocks. The location of infectious patient 1 is represented by the chair with the red horizontal lines and patient 2 by the chair with green vertical lines.

The concentration measurements from Fluent at seated height and standing height is exported to Excel. Because Fluent uses a mesh grid, these thousands of points from the grid are scattered throughout the room. A Visual Basic script was written to select sample concentrations for each of the 0.5m x 0.5m Excel boxes. Using a variant of the Wells-Riley model, the relative risk is estimated for a susceptible patient located at each of the locations in the Excel grid. If it is a chair location, the risk is selected at seated height and if it is an open location, at standing height. Red locations are the highest risk, yellow are moderate risk, and blue are low risk. The process is repeated for each of the four cases outlined above, using the same risk scale for all four cases. Results are shown in Figure 5.

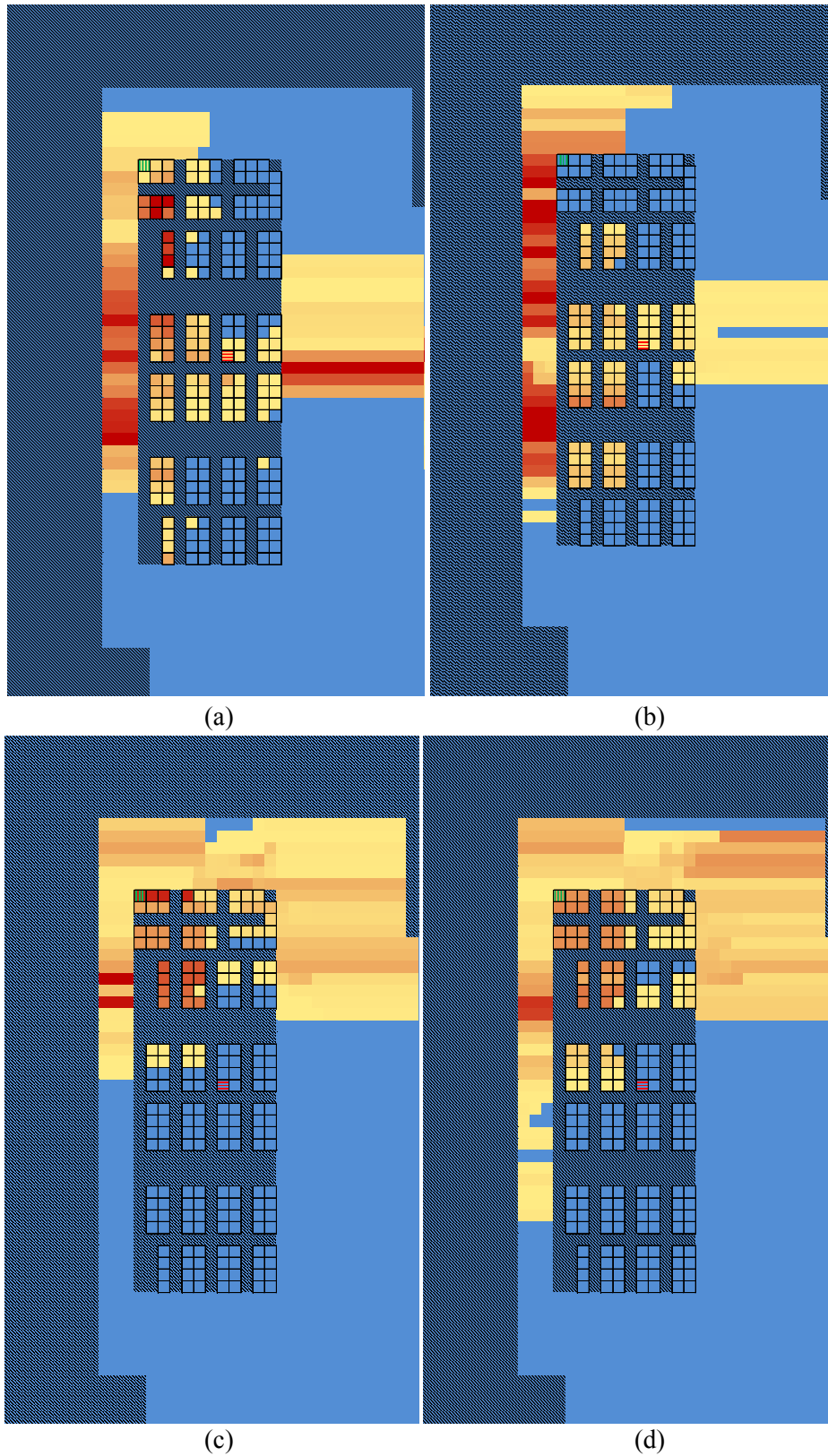


Figure 5: Relative estimate of risk of infection for patients in the case of patient located at (a) center of room, (b) center of room with screens, (c) top of room, (d) top of room with screens

These results give some insight into the spread of disease in a medium sized clinic. Due to the air flow in the large space, and vent location, locations of high risk are not necessarily where one might assume. Areas of high risk are found a significant distance from the infectious patient. The direction of the infectious patient's cough has a huge impact on the risk. Also, as seen in the concentration contours, the screens cause the concentration of particles to behave differently. In the case of the patient located in the center of the room (a and b), the partitions move the high risk area from the seats to the open area. With the infectious patient in the corner (c and d) the risk is also moved away from the seated area. Careful placement of screens, taking into account vent locations, could be an effective strategy to reduce risk in patient areas.

It is notable that in all cases, large areas of the room have very little risk of infection. This is in sharp contrast to the equal mixing of air assumption typically used in the literature, and gives motivation for further study in this area.

CONCLUSIONS AND FUTURE WORK

The research presented here is just the beginning of many opportunities to use operations research paired with CFD for clinic design as well as administrative decisions within existing clinics. Currently we are working on ways to accurately pair the Wells-Riley disease model with the output from the CFD model to obtain a realistic measurement of risk. Rather than using concentration of infectious particles, such as the output of CFD, the Wells-Riley model requires an estimate of the number of “quanta” emitted by the infectious patient, which is the number of infectious droplet nuclei required to infect $(1 - 1/e)$ susceptible people [4]. In the literature, these are estimated based on actual cases of disease, but under the exact assumption of equal mixing of air that we are relaxing in our work. Pairing the widely accepted Wells-Riley model with our model should lead to broader support in the medical community.

We next would like to expand the interventions that we are studying, including different configurations and sizes of screens, the impact of vent and window locations, changes in ventilation rate, use of ultraviolet radiation, and patient masks. Also important will be including the cost-effectiveness aspect. Clinics in resource-constrained countries are in need of better understanding of which combinations of interventions will give them the most return on their investment. We would also like to look at expanding the model to include different types of layouts, multiple rooms and multiple infectious persons in the room.

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