Redesigning Ventilation to Minimize Airborne Pathogen Transmission in Multiple-Bed Hospital Wards

Matthew Anderson

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ABSTRACT

We investigated how to minimize infection in multiple-bed hospital ward patients from airborne pathogens while maintaining patient thermal comfort and cost-effectiveness. We tried to find the optimal configuration of four ventilation control factors (humidity, airspeed, air change rate, and ventilation regime) that minimize the mean age of air in ward patients' breathing zones using computational fluid dynamics and Taguchi design. We discovered that the optimal configuration of ventilation control factors was: 45% humidity, 1 m/s inlet airspeed, 12 air changes per hour, a supply vent above the patients' bed on the wall, and a return vent to the lower right of the bed/ The mean age of air in this configuration was 93.4% better than the current standard in hospital wards and was 86.8% better than the mean configuration of ventilation control factors. This configuration was also able to maintain cost efficiency and patient thermal comfort.

I. INTRODUCTION

A common feature of the American hospital is the general hospital ward – a centralized location which houses multiple sick patients in close proximity to one another. Such wards have many key benefits, including (1) enhanced surveillance and monitoring of several patients, (2) increased opportunities for teamwork and communication, (3) facilitation of social contact between patients and (4) hospital staff can see patients in quick rotation (Maben et al, 2015).

However, these benefits do not come without cost. Specifically, sick patients in multiple-bed hospital wards breath the same air, which facilitates the spread of airborne pathogens between patients. Patients who are already recovering from ailments that resulted in their hospitalization are now at risk of contracting an additional disease from another source altogether. Research suggests that the scope of this issue is substantial; the CDC (2016) estimated that there were an estimated 721,800 different cases of hospital-acquired infection (HAI). These nosocomial diseases lead to approximately 75,000 deaths, meaning the 2016 death rate for hospital-acquired infection is greater than 10%.

Currently, clinicians only consistently recognize four diseases as being spread nosocomially via the air – Tuberculosis, Pulmonary Aspergillosis, SARS, and Legionnaire's Disease, (Beggs et al, 2008; Leung, 2012). However, additional evidence suggests that *Staphylococcus aureus, Acinetobacter* spp., and *Clostridium difficile*-associated disease (CDAD) can also be dispersed aerially.

Shiamori et al (2002) observed that, especially during bed making, patients were at high risk to inhale airborne methicillin-resistant (MR) *Staphylococcus aureus* and contract that disease. Rutala et al (1993) observed that MR *S. aureus* particles were responsible for 16% of aerial bacterial growth and 31% of bacterial growth on elevated surfaces. Given that clinicians are unlikely to disturb these raised surfaces, it is likely that MR *S. aureus* particles are frequently disseminated through the air. Unfortunately, *S. aureus* is the second leading cause of nosocomially transmitted bacteremia and the primary cause of surgical site infections (Noble and Davies, 1963).

Allen and Green (1987) were the first to note *A. anitratus* in three neurosurgical wards, one medical ward, and two different intensive care units. Also, Houang et al. (2001) observed that 96% of settle plates placed in an ICU contained at least 4 colony forming units (CFUs) of *A. anitratus* and that the majority contained 5-19 CFUs. Houang et al. also put settle plates in a surgical ward, of which 89% contained colonies and 37% had at least 5 CFUs. The evidence collected by Allen and Green (1987) and Houang et al. (2001) supports the conclusion that *A. anitratus* can be spread nosocomially via the air.

A nosocomial outbreak of another disease, *Acinetobacter baumannii* was observed by Bernards et al (1998) in 3 Dutch hospitals. Hospitals that experienced the outbreak isolated patients in non-pressurized rooms. However, a hospital with an infectious patient that isolated its patient in a negatively-pressurized room did not experience an outbreak and settle plates outside of the bedroom were culture-negative. This evidence supports the conclusion that the pathogen *A. baumannii* can be transmitted via the air.

Clostridium difficile-associated disease is a significant problem in elderly care wards (Beggs et al, 2008). Fawley et al (2005) conducted a 22-month survey that discovered that settle plates on elevated, horizontal areas contained *C. difficile*. Since clinicians are unlikely to disturb these areas, it was concluded that *C. difficile* is transmitted aerially.

Because there are 4 recognized airborne nosocomial diseases, and at least four others, we sought to investigate improvement of current hospital ward ventilation by asking – is there a way to reduce the transmission of these potentially fatal diseases, and thus save lives, by redesigning the hospital ventilation systems? But, in doing so, we also want to keep all the stated benefits of housing patients in a general hospital ward and maintain an appropriate level of patient thermal comfort.

Computational fluid dynamics has gained favor among building and ventilation designers, and it has been applied thoroughly in the analysis of airborne contaminant spread and a room's airflow (Leung, 2012). However, we found little prior research comparing ventilation methodologies for hospital wards. Research had been completed by Beggs et al (2008), but their CFD model did not contain any complex geometries: no beds, humans, chairs, drip bags, curtains or tables nor did not study a variety of different ventilation strategies, airspeeds, or humidities, either. Their research demonstrated that different ventilation strategies can have significant impact on the concentrations of airborne pathogens and that we must take it seriously, but did not lead to any conclusive evidence on what ventilation design is the best at minimizing airborne pathogen spread.

Leung (2012) also completed research on airborne disease spread in hospital wards using CFD. The geometries in his simulation were significantly more accurate; but there were no walls or curtains dividing patients, which is standard in American hospital wards.

II. METHODS

It was clearly impractical for us to attempt an experiment in a working hospital, so we chose to simulate it through computational modeling and computer-aided design of a hospital ward.

We saw the opportunity to complete a simulation that added a level of complexity to what others had done. Using a CAD software called Autodesk Inventor, we constructed our CAD model of the ward. Whereas Beggs et al (2008) only simulated an empty box, our CAD model contained a bed, curtains with a rod, an IV drip brag, a chair, a bedside table, and a human. Leung (2012) did not include curtains, which are standard in American hospital wards.

To simulate airflow and heat transfer, we relied on a tool called Autodesk CFD to handle the computational fluid dynamics aspect of our experiment. Previous research suggested that the main factors that affect contaminant spread, cost efficiency, and patient thermal comfort are humidity, airspeed, air change rates, and the ventilation regime (Beggs et al, 2008; Leung, 2012).

We manipulated those four factors. We compared two different levels each for supply air humidity, inlet airspeed, and air changes per hour.

Factor	Level 1	Level 2
(1) Supply Air Humidity	30%	45%
(2) Inlet Airspeed	1 m/s	0.5 m/s
(3) Air Changes per Hour	6 AC/H	12 AC/H

We chose 30% and 45% as levels for humidity because the ASHRAE thermal comfort guidelines suggest those as two humidity levels that are optimal humidity temperatures for thermal comfort. We chose 1 m/s and 0.5 m/s because, given the size of vents and the AC/H in a standard hospital ward, and the AC/H, we figured these speeds would be, roughly, the current ward standard. In line with current ventilation standards around the world, air change rates of 6 AC/H and 12 AC/H were used (Leung, 2012).

We compared four different ventilation regimes. Our control was the first ventilation strategy, titled “control design.”

Scenario / Ventilation Strategy	Supply Location	Exhaust Location
(1) Control Design	Corridor	Floor by IV Drip Bag
(2) Cubicle Ceiling	In Cubicle, Ceiling	Floor by IV Drip Bag
(3) Cubicle Bedside	In Cubicle, Bedside	Floor by IV Drip Bag
(4) Ducted Return	Corridor	Ceiling Duct

We also accounted for a noise factor, which was outdoor temperature. The outdoor temperature can have an effect on heat transfer and airflow, but it is impossible to control, so it became a noise factor that we examined. We examined four levels of the outdoor temperature – -18ºC, 0ºC, 18ºC, 36ºC.

Now that we had four total factors to manipulate, each with 4 levels of noise, it became clear that we were facing an overwhelmingly complex set of simulation scenarios. There would be 128 total scenarios to study, which, given that it took roughly 3 hours to set up, compute, and collect results from, would be nearly 390 total hours of work combined between the computer and us.

We turned towards Taguchi arrays, which reduces the number of such simulations while still retaining high accuracy. With three 2-level control factors, one 4-level control factor, and one 4-level noise factor, we can only test 8 combinations of those factors, and not all 32. We used a Taguchi orthogonal array to do this.

Run	Control Factors				
	Humidity	Speed	Temperature	ACH	Ventilation
1	30%	1 m/s	22	6	Control Design
2	45%	0.5 m/s	22	12	Control Design
3	30%	1 m/s	22	12	Cubicle Ceiling
4	45%	0.5 m/s	22	6	Cubicle Ceiling
5	30%	0.5 m/s	22	12	Cubicle Bedside
6	45%	1 m/s	22	6	Cubicle Bedside
7	30%	0.5 m/s	22	6	Ducted Return
8	45%	1 m/s	22	12	Ducted Return

Taguchi analyses are robust design methods. In this case, they help researchers find the ventilation design that minimizes variance in the performance, but also has the best mean performance.

In all of the simulations, we manipulated the factor levels and observed their effect on the response variable, mean age of air in the breathing zone. Both Beggs et al (2008) and Leung (2012) used the mean age of air as a proxy for the spread of airborne pathogens. Although not as accurate as simulating a sneeze and the inhalation of that sneeze, it is the current standard in contaminant dispersal studies.

We used Taguchi signal-to-noise ratios to quantify how good each run was at minimizing the mean age of air in patients breathing zones. To predict which configuration of ventilation design parameters would be the best at reducing the mean age of air, we calculated the mean signal-to-noise ratio for each level of each factor.

To confirm that our prediction was indeed the best configuration at minimizing the mean age of air, we tested the prediction with each of the four levels of the noise factor and compared it to each of the 8 runs in the Taguchi array.

Finally, to ensure that the thermal comfort of patients was maintained while the mean age of air was minimized, we analyzed thermal comfort with Taguchi analysis as well. We wanted to minimize the amount of variance in thermal comfort from bed to bed.

III. RESULTS

We ran each of the runs in the Taguchi designs with 4 noise factors.

The best performing run within the Taguchi design, number 3, had a signal-to-noise ratio of -50.28. This run had 30% humidity, 1 m/s inlet airflow speed, 12 air changes per hour, and the ventilation regime was “cubicle ceiling.” The mean age of air in the patients’ breathing zones was 5:15, which is slightly worse than the mean age of air in the whole room, which was 5:00.

The second best performing run in the Taguchi design was run #6. The mean age of air in the patients’ breathing zones was 6:11, which is slightly better than the mean age of air in the whole room, which was 10:00. However, there was more the mean age of air in this configuration was more variable, which decreased the signal-to-noise ratio to -52.10.

In addition – velocity, air change rate, and ventilation regime explained about 24.5%, 26.5%, and 48% of the variability in the mean age of air, respectively. Although humidity explained about 20% of the variability of the variance in patient thermal comfort, it only explained about 1.3% of the variability in the mean age of air.

According to our Taguchi analysis:

- The mean signal-to-noise ratio of 45% humidity was slightly better than the mean signal-to-noise ratio of 30% humidity (1.28 points better). *See Fig 1.*
- The mean signal-to-noise ratio of 1 m/s inlet airflow speed was about substantially better than the mean signal-to-noise ratio of 0.5 m/s inlet airflow speed (5.61 points better). *See Fig 1.*
- The mean signal-to-noise ratio of 12 ACH was also substantially better than the mean signal-to-noise ratio of 6 ACH (5.83 points better). *See Fig 1.*
- The best ventilation regime was "cubicle bedside," which was 2.73 points higher than "cubicle ceiling." Both "cubicle bedside" and "cubicle ceiling" were substantially better than our control design and "ducted return." *See Fig 1.*

Finally, we tested the combination that Taguchi analysis deemed the optimal combination (45% humidity, 1 m/s airflow rate, 12 ACH, and the "cubicle bedside" ventilation regime). The signal-to-noise ratio of this combination was about 6.86 points higher than the signal-to-noise ratio for the best combination in the Taguchi array. Compared to the solutions in the Taguchi array, the signal-to-noise ratio of the additional run we tested was 2.54 standard deviations above the mean. Furthermore, compared to all of the combinations we tested in the Taguchi array, this one was the best at maintaining patient thermal comfort, and was satisfactory at maintaining cost efficiency. *See Table 3.*

Table 1. Taguchi Orthogonal Array (2^4, 4^1) of mean age of air in patients' breathing areas over four noise factors. The mean age of air is in seconds. VS abbreviates "ventilation strategy."

Run	Humidity	Velocity	ACH	VS*	S/N Ratio	Mean Age
1	30%	1 m/s	6	GW	-67.53	2240
2	45%	0.5 m/s	12	GW	-61.69	1145
3	30%	1 m/s	12	CC	-50.28	315
4	45%	0.5 m/s	6	CC	-64.78	1199
5	30%	0.5 m/s	12	CB	-57.49	773
6	45%	1 m/s	6	CB	-52.10	411
7	30%	0.5 m/s	6	DR	-66.85	2095
8	45%	1 m/s	12	DR	-58.45	814

*GW = General Ward; CC = Cubicle Ceiling; CB = Cubicle Bedside; DR = Ducted Return.

Figure 1. Percent contribution towards mean age of air by control factor.

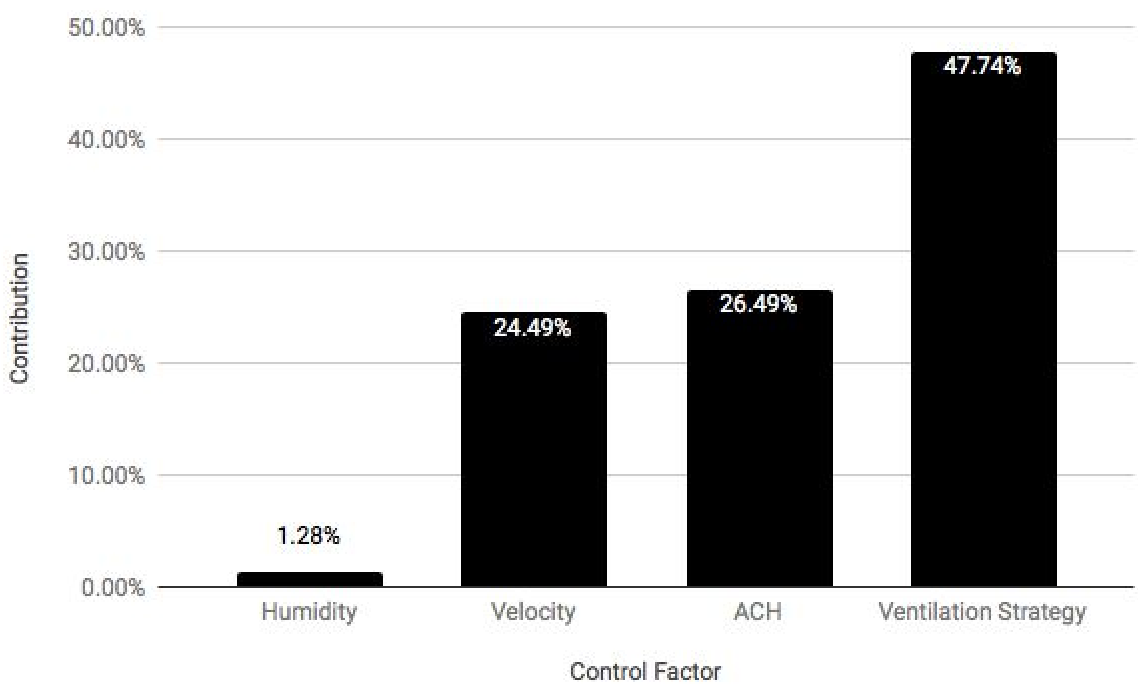

Table 2. Taguchi Orthogonal Array (2^4, 4^1) of variability in temperature of patients' heads. VS abbreviates "ventilation strategy."

Run	Humidity	Velocity	ACH	VS*	S/N Ratio	Mean TD
1	30%	1 m/s	6	GW	-4.35	0.879
2	45%	0.5 m/s	12	GW	4.75	0.492
3	30%	1 ms	12	CC	-5.59	1.466
4	45%	0.5 m/s	6	CC	-7.39	2.138
5	30%	0.5 m/s	12	CB	-9.20	1.350
6	45%	1 m/s	6	CB	-0.82	0.776
7	30%	0.5 m/s	6	DR	-14.71	4.845
8	45%	1 m/s	12	DR	-11.20	3.529

*GW = General Ward; CC = Cubicle Ceiling; CB = Cubicle Bedside; DR = Ducted Return.

Figure 2. Percent contribution towards variability in temperature of patients' heads by control factor.

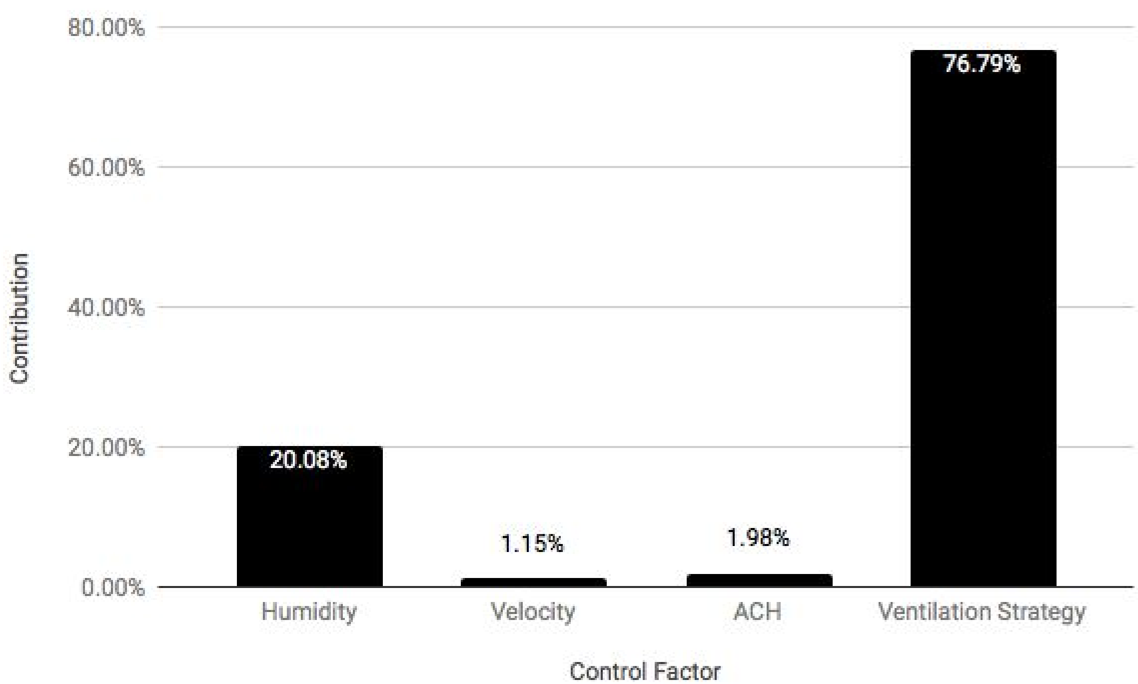

Figure 3. Mean signal to noise ratios for mean age of air by control factor.

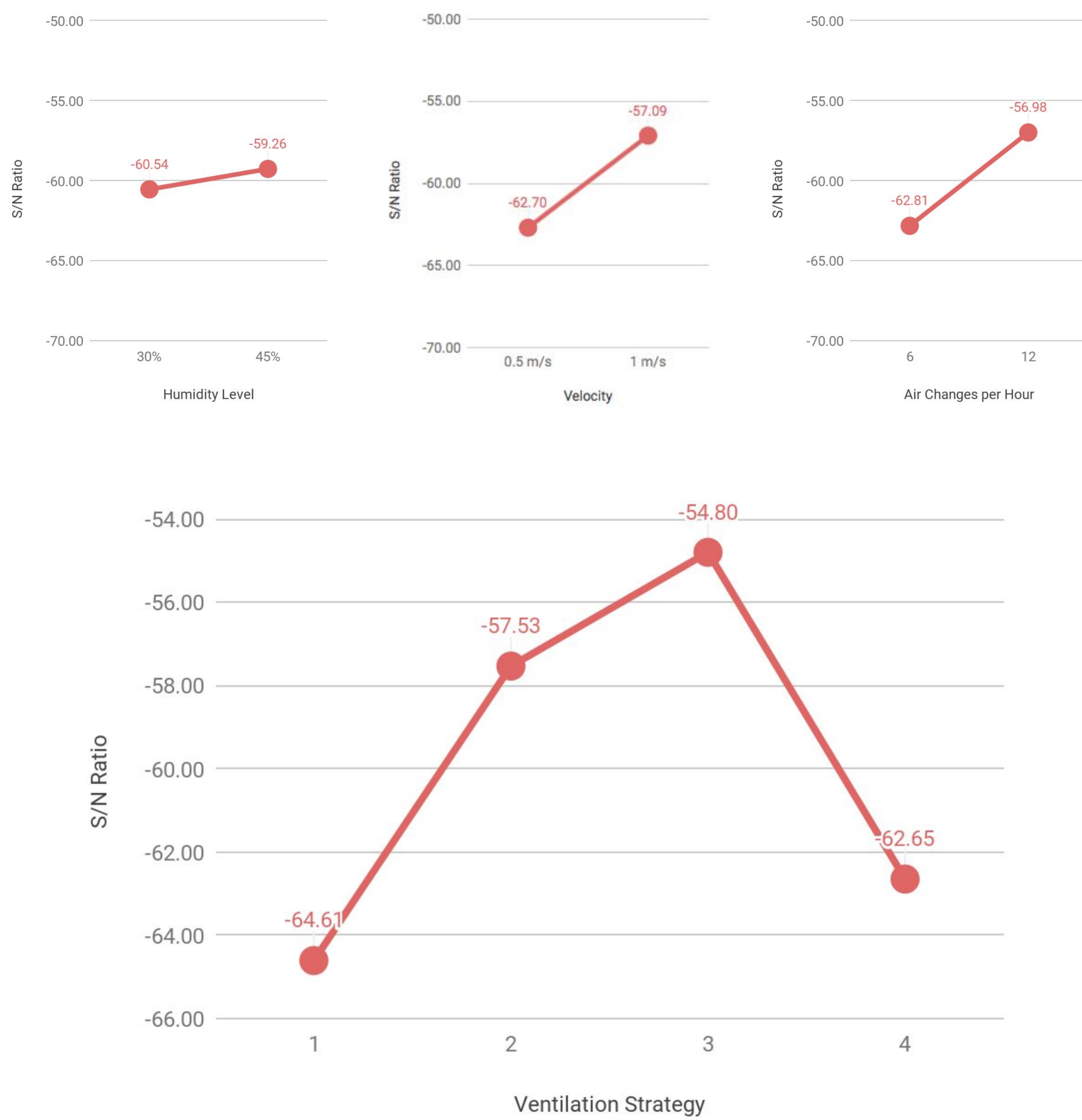

Figure 4. Mean signal to noise ratios for variability in temperature of patients' heads by control factor.

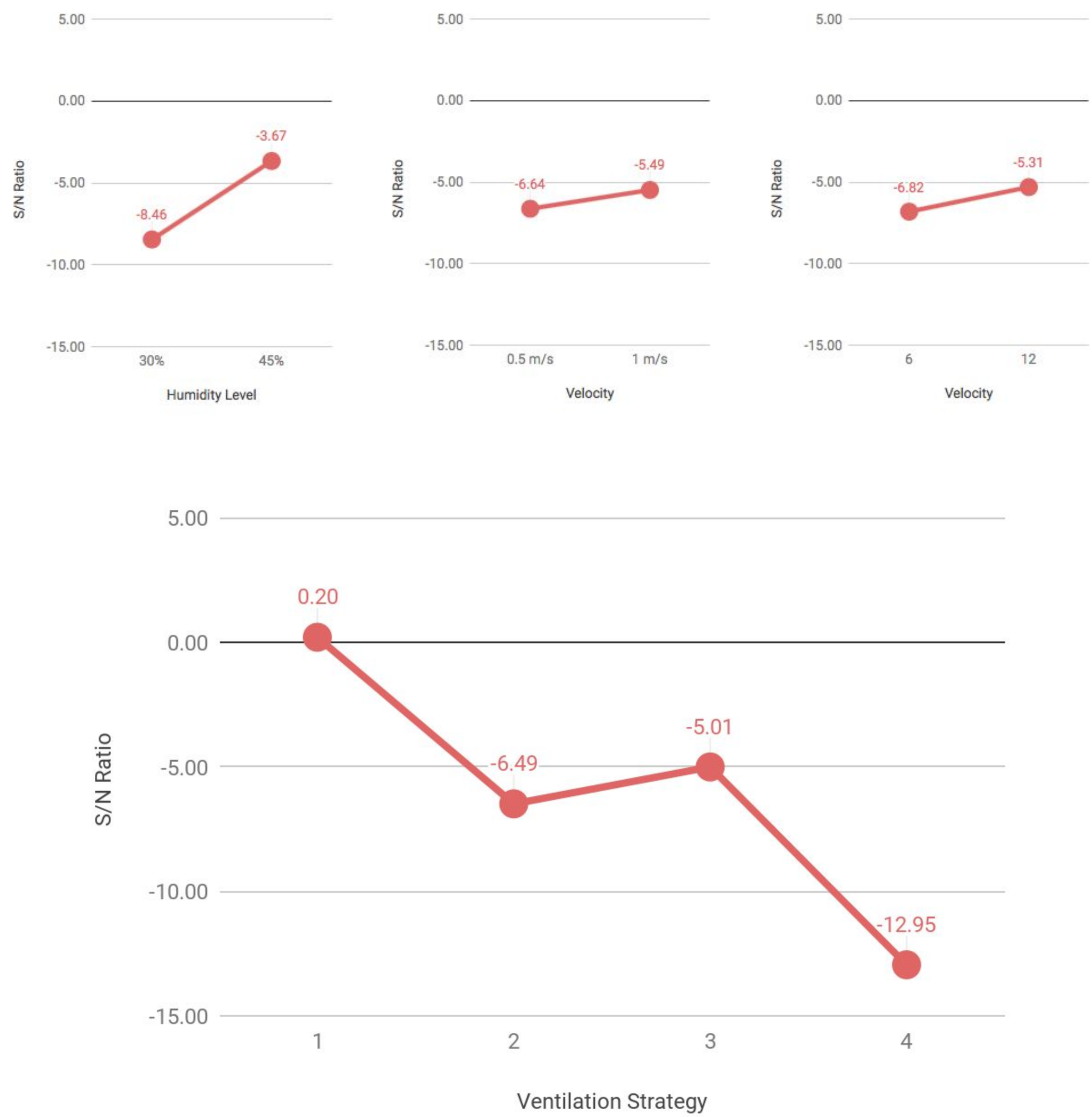

Table 3. S/N Ratio for the optimal ventilation strategy as predicted by the Taguchi designs (humidity, 45%; velocity, 1 m/s; 12 air changes per hour; cubicle bedside ventilation design).

Category	S/N Ratio	Z-Score*	Added Performance†
Mean Age of Air	-43.42	+2.54	+6.86
Thermal Comfort	6.40	+0.99	+1.65

*Z-score compares to all other signal to noise ratios in that category.

†Added performance is the difference between new S/N ratio and the best S/N ratio in the design.

IV. DISCUSSION

The Taguchi analysis suggested that the optimal settings to minimize disease transmission were as follows:

Humidity	45%
Inlet Air Velocity	1 m/s
Air Changes per Hour	12
Supply Vent Location	2ft Above Bed
Return Vent Location	Lower Right Corner of Cubicle

Even though this combination of settings was not a part of the Taguchi array, we tested it, and it performed nearly 6.9 points higher than the best configuration in the array. The mean age of air with these settings was about 2.5 minutes, which is about 52.4% better than the best configuration in the array. It was also able to maintain patient thermal comfort and cost-effectiveness.

Although the settings for air change rates were consistent with what Beggs et al (2008) and Leung (2012) concluded, the optimal locations of the supply and return vents were different from previous experiments. Leung (2012) suggested that the best ventilation strategy consisted of a ceiling inlet and a ducted ceiling return. We tested this ventilation strategy, and, in our experiment, performed marginally better than the control design. Although Beggs et al (2008) did not test any of the experimental ventilation strategies we did, they suggested that the best ventilation strategy was when air was supplied and extracted from the ceiling.

The evidence presented by Leung (2012) could be more accurate than our simulation. Whereas we simulated a half-sized 3-bed hospital ward, he simulated a full 6-bed hospital ward. However, Leung (2012) did not simulate curtains, which are standard in American hospital wards, and have major impacts on airflow.

We could not find any other public experiments that suggested varying humidity or inlet airspeed. We tested 30% and 45% humidity. Only 1.3% of the variability in mean age of air can be explained by humidity, so it is most likely not worth regulating. However, 45% humidity performed better for both pathogen spread and patient thermal comfort, so it may be worth recommending a 45% humidity level. We also tested inlet airspeeds of 0.5m/s and 1 m/s. Differences in airspeed explained 24.5% of the variability in the mean age of air, so airspeed should certainly be regulated. We recommend 1m/s because it performed substantially better for both pathogen spread and patient thermal comfort.

Ultimately, this study will help us choose what ventilation parameters to regulate and how we should regulate them. Percent contribution results can be employed in choosing what ventilation parameters we want to regulate, and signal to noise ratios for specific control factors can help us choose how we should regulate them.

We are not to say that this study cannot see further improvements. Because this study was completed computationally, on a mesh, and with residuals that did not equal 0, there is both error and uncertainty in the results of this study. Although the results of our CFD design study converged, there were still slight errors (residuals) in turbulence, temperature, velocity, and humidity. However, for the results, these were mostly negligible. Furthermore, the mesh for this study was slightly coarse. The mesh was able to perfectly capture the geometry, but the mesh was not fine enough for there to be a negligible amount of uncertainty.

Statistically, the accuracy of our measurements would be increased if we considered a greater number and level noise factors. The accuracy of our measurements would also benefit from the use a full factorial experimental design. Nonetheless, given the cost of a full factorial design, this was not reasonable for our study.

Additionally, the CAD models lacked absolute detail. For instance, human heads were simply rectangular prisms. However, if we made our geometry complicated than that, the computational complexity would be increased by several orders of magnitude. The CFD designs did not have any clinicians in it either, and they would typically be present.

V. CONCLUSION

This study identified the optimal configuration of humidity levels, airspeeds, air change rates, and ventilation designs to minimize the spread of airborne pathogens from patient to patient in multiple bed hospital wards. In conclusion, we recommend regulating airspeeds, air change rates, and ventilation designs. Our study suggests that to minimize the age of air in patients' breathing zones, the following ventilation settings should be set:

- 1 m/s inlet airspeed
- 12 air changes per hour
- supply vent above the bed
- return vent in the lower right corner

In addition, our study suggests that a humidity level of 45% is slightly better than a humidity level of 30%, but the effects are small and it may be a matter of chance. This study will help us decide how to better regulate ventilation in hospital wards.

ACKNOWLEDGMENTS

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WORKS CITED

Allen, K. D., & Green, H. T. (1987). Hospital outbreak of multi-resistant Acinetobacter anitratus: an airborne mode of spread? *Journal of Hospital Infection, 9*(2), 110-119. doi:10.1016/0195-6701(87)90048-x

Beggs, C. B., Kerr, K. G., Noakes, C. J., Hathway, E. A., & Sleigh, P. A. (2008). The ventilation of multiple-bed hospital wards: Review and analysis. *American Journal of Infection Control, 36*(4), 250-259. doi:10.1016/j.ajic.2007.07.012

Bernards, A. T., Frénay, H. M., Lim, B. T., Hendriks, W. D., Dijkshoorn, L., & Boven, C. P. (1998). Methicillin-resistant Staphylococcus aureus and Acinetobacter baumannii: An unexpected difference in epidemiologic behavior. *American Journal of Infection Control, 26*(6), 544-551. doi:10.1053/ic.1998.v26.a84555

Fawley, W. N., Parnell, P., Verity, P., Freeman, J., & Wilcox, M. H. (2005). Molecular Epidemiology of Endemic Clostridium difficile Infection and the Significance of Subtypes of the United Kingdom Epidemic Strain (PCR Ribotype 1). Journal of Clinical Microbiology, 43(6), 2685-2696. doi:10.1128/jcm.43.6.2685-2696.2005

Klein, E., Smith, D. L., & Laxminarayan, R. (2010, July 06). Hospitalizations and Deaths Caused by Methicillin-Resistant Staphylococcus aureus, United States, 1999–2005 - Volume 13, Number 12-December 2007 - Emerging Infectious Disease journal - CDC. Retrieved January 09, 2018, from https://wwwnc.cdc.gov/eid/article/13/12/07-0629_article

Houang, E. T., Chu, Y. W., Leung, C. M., Chu, K. Y., Berlau, J., Ng, K. C., & Cheng, A. F. (2001). Epidemiology and Infection Control Implications of Acinetobacter spp. in Hong Kong. *Journal of Clinical Microbiology,39*(1), 228-234. doi:10.1128/jcm.39.1.228-234.2001

Leung, Y. P. (2012). *Rethinking ventilation design for reducing airborne respiratory disease transmission in general hospital wards* (PhD thesis, City University of Hong Kong, 2012) (pp. 2-109). Hong Kong: Department of Manufacturing Engineering and Engineering Management.

Maben, J. et al (n.d.). Staff experiences of the advantages and challenges of single rooms: adaptations to work patterns. In *Evaluating a major innovation in hospital design: workforce implications and impact on patient and staff experiences of all single room hospital accommodation* (1st ed., Vol. 1). Health Services and Delivery Research

Noble, W. C., & Davies, R. R. (1965). Studies in the dispersal of Staphylococci. *Journal of Clinical Pathology,18*(16), 16-19. Retrieved September 11, 2016, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC472825/pdf/jclinpath00354-0022.pdf.

Rutala, W. A., Katz, E. B., Sherertz, R. J., & Sarrubi, F. A., Jr. (1983). Environmental study of a methicillin-resistant Staphylococcus aureus epidemic in a burn unit [Abstract]. *Journal of Clinical Microbiology, 18*(3), 683-688. Retrieved September 13, 2016, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC270875/.

Shiomori, T., Miyamoto, H., Makishima, K., Yoshida, M., Fujiyoshi, T., Udaka, T., . . . Hiraki, N. (2002). Evaluation of bedmaking-related airborne and surface methicillin-resistant Staphylococcus aureus contamination. *Journal of Hospital Infection, 50*(1), 30-35. doi:10.1053/jhin.2001.1136

Yam, R., Yuen, P., Yung, R., & Choy, T. (2011). Rethinking hospital general ward ventilation design using computational fluid dynamics. *Journal of Hospital Infection, 77*(1), 31-36. doi:10.1016/j.jhin.2010.08.010