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A Quantitative Risk Analysis of the Health Effects of Construction Dust on Patients and Workers

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***Abstract*—Aging of the world's population, coupled with improvements in health care management and medical techniques continues to drive the increasing cost of medical treatment for the United States. A secondary and related cost is the Hospital Acquired Infections (HAI) that strike approximately 2 million patients in the USA each year. 100,000 patients will die each year from these secondary infections. A problem that has developed since the 1970s is a rise in secondary fungal infections for immune compromised patients, who are surviving longer. Fungal infections are nasty and very hard to treat, with a high mortality rate. There are several vectors or systems that move fungi into buildings, these include dust from construction sites and the outside space to the hospital. Careful control of dust is needed to minimize the risk to patients and workers during construction at hospitals. This paper represents part of a long running study at our university into dust movement into buildings. The goal is to develop a computational air, dust and fungi movement model for the problem to assist the statistical analysis of fungi movement rates into buildings. The objective of this paper's research is to measure the flow of air through closed doors in a typical institutional building. The long term goal is to provide a mathematical model for air and dust movement through a closed door, to be part of the global model.**

***Index Terms*—Airflow, fungi, hospital acquired infections.**

I. INTRODUCTION

The role of a construction manager is critical to better manage the design, manufacturing, installation and maintenance of building components, particularly in areas requiring clean air. Two major issues intersect at this point in this paper and in time. The first issue is the major change in the development of institutional and commercial buildings. Nash's game theory points clearly the development of a better equilibrium point with specialization of trades in the design and construction environment. Seeking this equilibrium point provides that project managers continue to be pushed to be more remote from the daily work and increasingly rely on experts for all trades. This includes the delivery of clean air, for both the medial gases and ventilation. An increasingly litigious society points to the need to develop accurate models that will model and predict fungal movements with dust particles into hospitals, the HVAC and the corridor systems.

Bassett [1] started this study into dust movements into hospitals from construction sites. Her interest was in investigating the efficiency of plastic dust barriers against the movement of dust particles. She showed it was efficient. Nichols [2] subsequently reanalyzed a 10 year longitudinal study of fungal infections in a French hospital and showed that the infection rate was cyclic with a previously unidentified and troublesome 2 month cycle. Subsequent research strongly suggests that this cycle is related at least in part to the design and operation of the hospital's air conditioning system. Trade specialization is a two edged sword with deficits in institutional memory a serious problem [3].

Two developments in the last decade provide a potentially powerful tool for completing modelling of complex air flow and associated dust movements in hospitals. Space syntax analysis provides a tool [4] to model the connectivity of buildings. The connectivity of buildings provides the pathway model for the movement of air, dust and fungi into the patient areas. Dust movement is complex and can include movement on human vectors, such as shoes. Fungi spore movement will follow a similar pathway, although one has the added complexity of human contamination being the vector. Guo [5] clearly demonstrates connectivity issues in hospitals including the modelling of the HVAC systems with the human pathways. This method provides a simple translation into a flow model for air flow, a concentration model for dust movements and statistical determination of fungal concentrations. Field and Williams [6] provide a framework to develop the air movement model using the kinematic model. Although this was developed for overland flow it is a trivial change to use for the analysis of air flow in a system described using space syntax when coupled with a gradient network analysis algorithm. The method avoids the complexity of three dimensional flow dynamics problems.

Most vulnerable to these infections are the patients who are within the facility for treatment of their pre-existing ailments which have compromised their immune system. Aspergillosis is an example of the problem described here.

This work forms an integral part of the quantitative risk analysis of the health effects of construction dust on patients and workers. Whilst the effect of dust particles is well documented for unprotected workers and adjacent patients, the study of the sources and transport of fungi is at an early stage. It has been shown that construction activities increase the rate of fungal infections in a hospital, all else being equal [7], [8].

The objective of this paper is to consider the mechanics of one of the potential entry points to patient's rooms for the fungi often carried by construction and other dust and to experimentally measure the likely velocity and pressure issues in a typical institutional room. This paper provides a brief literature review, outlines the methodology for the experimental work, presents the results, and provides some conclusions. Finally the paper provides a perspective for a

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project or construction manager in assessing the risks from loose construction dust arising from new construction or refurbishment.

II. LITERATURE REVIEW

This literature review provides a brief introduction into the issue of fungi and the infections, air flow analysis and settlement rates of fine dust, using talc as a model particle.

The Center for Disease Control and Prevention (CDC) estimate that approximately 10% of patients who are admitted to hospitals in United States will suffer from healthcare acquired infections. Every year nearly 2 million patients in North America contract a nosocomial infection resulting in 100,000 deaths. The concept of nosocomial infection dates from the mid-19th century. Some of these infection outbreaks in hospitals have been associated with hospital renovation, construction and maintenance. Numerous studies, such as Chen *et al*., in 2013 documented the fatality rates in some patients [9] from this infection source. Control of the infecting source is a better solution than treatment as fungal treatment is debilitating and often not successful.

One of the primary infecting sources is fungi carried with or on dust. Dust disturbance causes transportation of potentially lethal microorganisms like Aspergillus, these in turn can cause lasting impact on the health of patients in a health facility and in some cases cause death from the infection.

Aspergillus flavus is an example of one such fungi, the BCRC number is 32140. Fig. 1 shows a sketch of the fungi from the MycoBank data base.

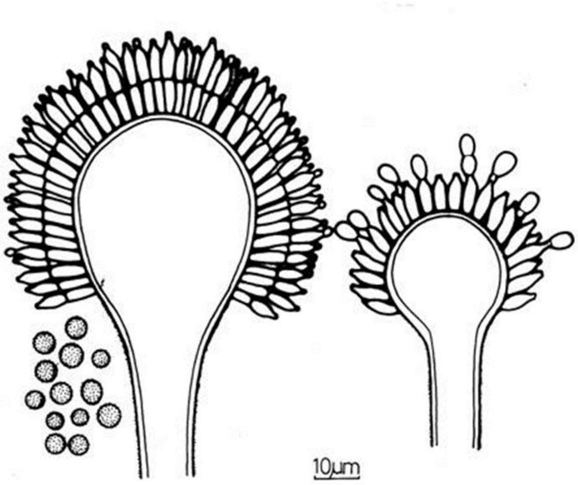

Fig. 1. Aspergillus flavus from MycoBank data base [10].

The note in the database about the fungi is “Colony diameters on Czapek’s Agar 5.0-5.5 cm in 14 days at 25 ℃ “[10]. The rapid growth of the fungi spores at room temperature and the diameter at less than 10 µm provides for relatively easy spread of the infecting agent. Hospital temperature has an impact on the spore counts [11].

Most of the patients who were affected by this microorganism were already suffering from cancer, pulmonary disorder, organ transplant or AIDS, which makes this all the more challenging [12]. Nearly half of the deaths caused by this fungus were construction related according to CDC. This makes it very clear why the construction industry professionals should accept responsibility for construction related dust activities around hospitals and have an awareness of how to minimize the risks to patients and their workers.

Guidelines [13] have been provided for control of the construction activities including:

1) Involvement of infection-control personnel in all phases such as demolition, construction and renovation of Healthcare facilities. This would include risk assessment of construction barriers according to its types, daily monitoring and documenting the negative airflow in construction or renovation area.
2) Monitor and document daily the negative airflow in Airborne Infection Isolation rooms and positive airflow in Physical Education rooms, especially when patients are in these rooms.

Private industry has started to work in this area, Linders Health Institute [14] is one company who have started to layout their own set of practice guidelines in ICRA/PCRA training courses. While research has been conducted in reducing the entry of such particles entering through windows and/or ventilation system and appropriate standards for design and installation have been made, not much is known about their entry through door and corridor system [15]. This is the research interest for this paper as the overall system minimizing risk is considered and the theory developed further.

Air currents within the facility have the potential to transport bacteria, virus and other infectious microorganisms which can affect the health of the staff, patients and visitors adversely. Generally a standard ventilated single room would have 6 (six) air changes per hour by its ventilation system which would provide fresh air into the environment within the building [16]. In a recent study, Guo identified a number of different entry points for air into a hospital room as shown on Fig. 2.

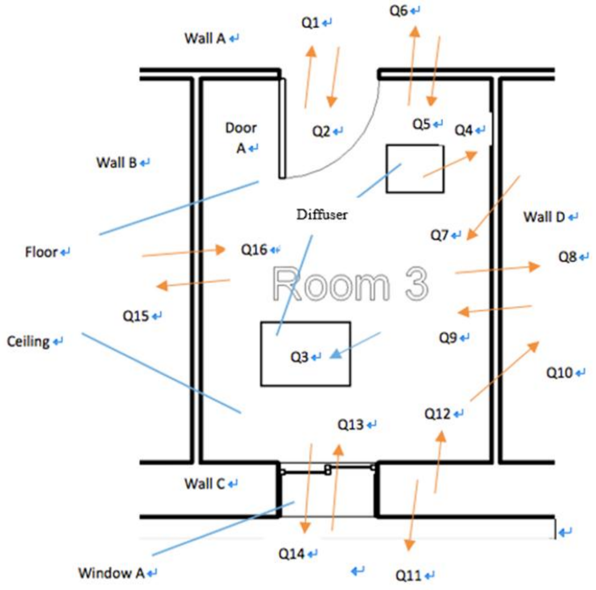

Fig. 2. Air entry points to a hospital room from Guo [5].

Clearly the magnitude of the air flow is not equal for all sources, the critical ones are through the door, whether open or shut and the air handling system. In this paper the interest is in the flow through or around a shut door.

The air handling system and the outdoor environment provide a set of differential pressures to develop and maintain the flow of air into the building rooms. Guo's development of the space syntax to describe the air flow paths is significant in the future study of actual air flows in a real hospital. The simplistic assumptions for air handling design will need to be replaced with a mathematically correct model of the system, the model will need to allow for flow paths, sources and sinks, and for air handling systems. The software tools are available to create this type of system. The difficulty is the fluid mechanics models for all of the elements.

In the case of a closed door, it represents a choke point between two regions of different pressure. If we identify the room pressure as P_i and the corridor pressure in Figure 2 as P_c then the following is possible in thermodynamics terms:

$$P_i > P_c \tag{1}$$

$$P_i = P_c \tag{2}$$

$$P_i < P_c \tag{3}$$

In terms of patient health, equation (1) is preferred. The pressure in the room can be considered constant for our purposes and to be constant at the doorway on the corridor side, also for this analysis. Bernoulli's equation applies to this arrangement

$$P_i + \frac{1}{2}\rho V_1^2 + \rho g H_1 = P_c + \frac{1}{2}\rho V_2^2 + \rho g H_2 \tag{4}$$

where, ρ is the air density, g is gravity on earth, about 9.806 m/s^2, V is velocity in m/s and H is head in m. The heads are likely to be the same and so the following is derived for the door

$$\frac{2(P_i - P_c)}{\rho} = (V_2^2 - V_1^2) \tag{5}$$

where the right hand side of equation (5) reflects the loss in energy in pushing the air through the door openings. The door opening definitions are shown on Fig. 3.

As all widths of door openings, such as G1 are likely to be different to G2, then a standard definition needed to be adopted for this work.

Let us assume that an opening such as a door gap acts as an orifice, allowing for the reality of air flow which is not laminar or inviscid, as shown in equation (6)

$$Q = kA\sqrt{\frac{2(p_i - p_c)}{\rho}} \tag{6}$$

The research interest is in the flow of air at the doors and the flow velocity. The key question is whether there is sufficient velocity in the stream to move or suspend dust particles. A 4 μm particle of talc settles at 1.2 mm/s and 10 μm particle are 7.5 mm/s.

This literature review outlined the key elements in the development of this part of the longer term research question into patient and thus worker safety in a dust environment from construction at a hospital.

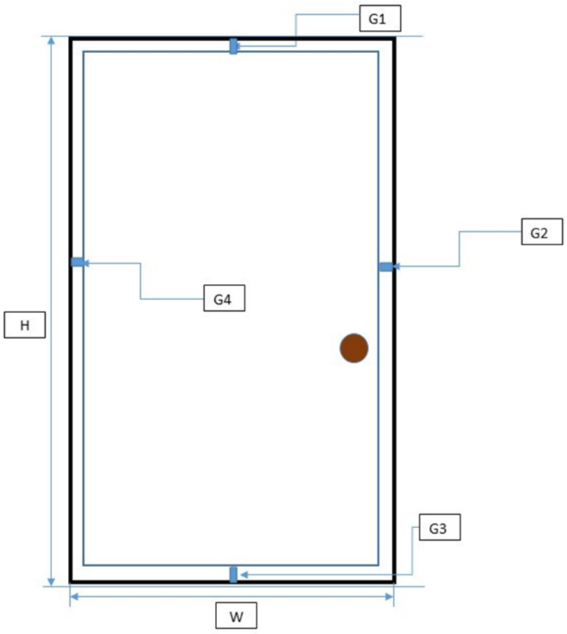

Fig. 3. Door definitions from Bhatt [17].

III. RESEARCH METHOD

This section presents the research methods. The Langford Architectural Complex Building A at Texas A&M University was used for the experimental work. This building dates from the 1970's and represents typical institutional construction for the time.

Experimental work was completed on the ground floor, 1st floor and the third floor using the European convention for floor numbering. Doors were selected at random to study.

The methods were:

Door dimensions were determined using a standard steel tape with a length of 8 m and an accuracy of ± 0.5 mm. All measurements occurred at a constant temperature.

Door gap measurements were made using a Pittsburgh 150 mm Digital Caliper.

Air velocity was measured using a Thermo-Anemometer data logger SD-4214. To accurately measure the air velocity through the door gaps, it is essential to place the white dot on the velocity measuring device perpendicular to the surface from where we are measuring the velocity. This would enable the entire volume of air moving to pass the hot wire which in turn measures its velocity.

Air pressure differentials were measured using a Setra Model 267MR Multi-Range Low Differential Pressure Transducer and a VersaLog DCVC-HR data logger

The measurements are:

1) Height of the door
2) Width of the door
3) Four gaps
4) Four velocities

Two experiments were performed in this experimental study. The first experiment is to measure the door gaps and then determine the average velocity for each of the four gaps.

The second experiment examined a room pressure response in detail.

IV. RESEARCH RESULTS

The research results are summarized in this section of the paper.

The first experiment measured the velocity and the gap measurements for the Langford building. The results for the 18 rooms are presented in Table I.

TABLE I: DOOR MEASUREMENTS

Room Number	Height	Width	Gap G1	Gap G2	Gap G3	Gap G4
3	2286	876.3	1.4	1.6	18.06	1.70
7	2286	876.3	2.2	6.42	17.62	0.30
27	2286	876.3	2.14	1.92	19.33	1.28
22	2286	876.3	2.11	1.72	10.18	0.34
106	2286	977.9	1.96	1.84	13.4	1.22
105	2286	977.9	1.74	1.67	17.12	1.44
117	2286	977.9	2.02	2.11	11.49	1.67
116	2286	1828.8	2.18	3.84	9.89	2.04
313	2286	876.3	0.98	1.12	16.14	1.20
314	2286	876.3	2.11	1.99	4.13	1.04
328	2286	876.3	3.11	3.18	5.07	1.12
329	2286	876.3	3.06	2.04	6.74	1.28
330	2286	876.3	2.04	3.11	8.94	1.18
340	2286	876.3	1.36	3.02	18.14	1.16
341	2286	876.3	3.12	1.04	16.23	1.22
337	2286	876.3	1.11	2.09	6.45	1.14
344	2286	876.3	2.09	1.02	5.43	1.06
343	2286	876.3	1.11	3.04	5.14	1.11

Fig. 4 shows the histogram plot of the door gaps.

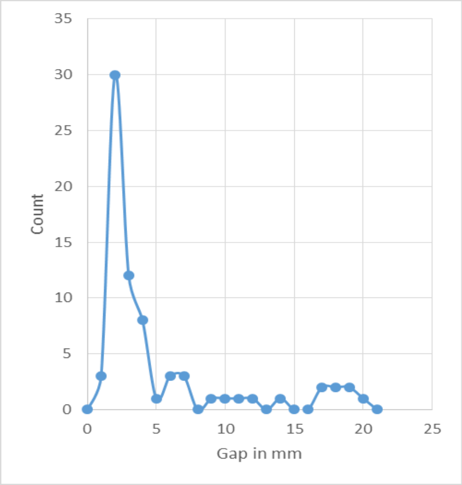

Fig. 4. Door gap histogram.

The average gap is 4.3 ± 5 mm, with a skew of 1.9 and a kurtosis of 2.3. Clearly the gap is not a Gaussian distribution.

The velocity results are shown in Table II. The peak measured velocity is 3.57 m/s. The results for the velocity is an average of 0.5 ± 0.6 m/s. The skew is 2.9 and the kurtosis is 11.7.

Two readings provide a significant skew to the results, this room 7 and room 117, which both have relatively high velocities at the bottom gap of the door, 2.1 and 3.57 m/s respectively.

TABLE II: VELOCITY MEASUREMENTS

Room Number	V1	V2	V3	V4
3	1.06	0.42	1.88	0.48
7	0.21	0.35	2.1	0.15
27	0.24	0.14	1.43	0.2
22	0.32	0.19	0.79	0.31
106	0.25	0.36	1.2	0.14
105	0.18	0.24	0.88	0.24
117	0.24	0.33	3.57	0.19
116	0.11	0.42	1.12	0.24
313	0.02	0.11	0.77	0.14
314	0.19	0.18	0.88	0.21
328	0.06	0.17	0.74	0.14
329	0.14	0.2	0.91	0.21
330	0.14	0.26	0.86	0.14
340	0.19	0.16	0.98	0.11
341	0.21	0.14	1.41	0.12
337	0.21	0.16	1.21	0.21
344	0.12	0.21	0.77	0.28
343	0.24	0.14	0.81	0.2

The velocity measurements are shown in Fig. 5.

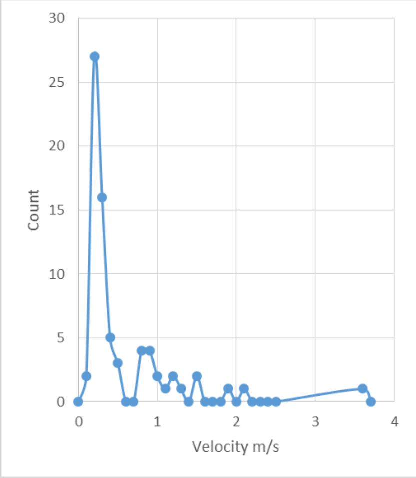

Fig. 5. Door gap velocity histogram.

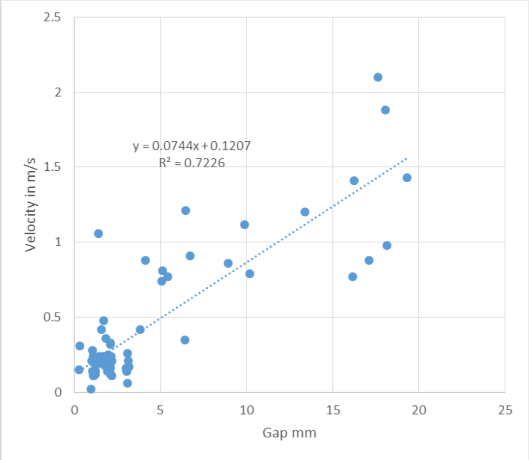

Fig. 6. Door gap plotted against velocity.

The maximum velocity was 3.57 m/s. Fig. 6 shows a plot of the gap against the velocity for the results excluding the maximum velocity which is clearly an outlier.

A linear regression equation is fitted to the results. The results show an intercept of 0.095 ±0.05 and a slope of 0.074 ± 0.008. The results are statistically significant at the 10%

level of the intercept and <5% level for the slope.

The normal probability plot for the results is exponential in shape and not linear.

The second experiment used the pressure manometer to determine the velocity and the pressure for room 7. This room did not lie as far from the regression line as the room 107 and access for the equipment was significantly easier.

The pressure differential across the door in Room 7 was measured for thirty minutes. The findings were:

1) The air pressure shows a cycle pattern
2) The pattern is stable

A cyclic pattern can be investigated using Fast Fourier transforms [18] using a standard program. A FFT provides a set of sine waves that make up the main signal. The results of interest are the cyclic frequency and the amplitude.

The FFT analysis for the data is shown in Fig. 7.

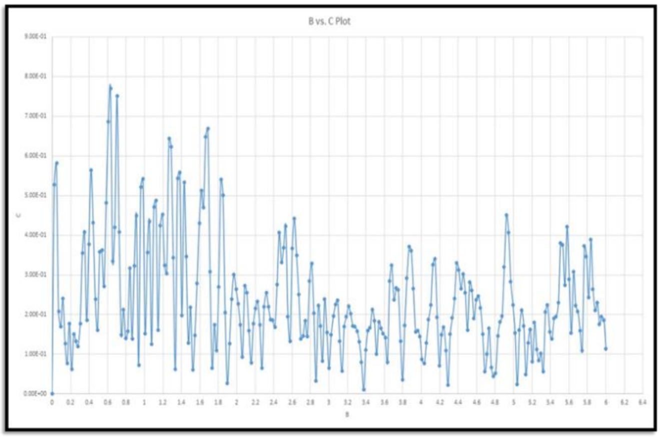

Fig. 7. Pressure profile room 7 – Fast Fourier Transform.

Kordzakhia outlined the development of this method for using FFT to review this type of data when reviewing data on masonry shear panels for the second author [19].

The results shows a peak at 0.6 to 0.8 minutes and a second peak at 1.6 to 1.8 minutes as the two critical examples. This result means that the air in the room and in the hallway are vibrating in a sinusoidal pattern. There is no way to tell at this stage if the pattern arises from the incoming air into the room or the exiting air in the corridor or an interaction between the two.

Clearly this is not an operational method that one would seek in a hospital. Flow reversal could tend to suck air into the room from the corridor, which is less than ideal.

Fig. 8 shows somewhat ideal system for maintaining a clean air flow into a room for an immune compromised patient.

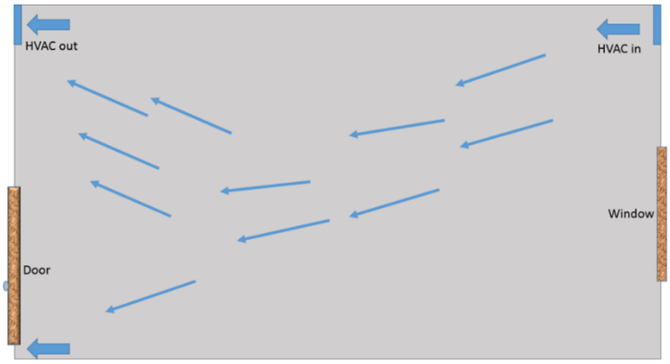

Fig. 8. Cross section of an ideal system for higher pressure to be maintained in the room.

A risk assessment is in reality a Gadankenexperimente to assess a difficult problem that may be impossible to study experimentally or there may be ethical reasons preventing a particular study. One would not run these types of experiments with real immune compromised patients for instance.

Space access diagrams have been invented to provide a guide as to the topological arrangement of human spaces. There are observed cultural differences in space syntax for different regional areas of the world, so a simple first model is used for this work.

Fig. 9 shows a space access diagram for a terminal section of a hospital ward. Figure 10 shows the associated graph.

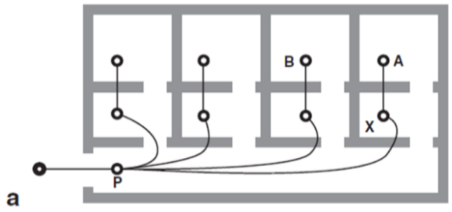

Fig. 9. Space access diagram for a terminal hospital corridor.

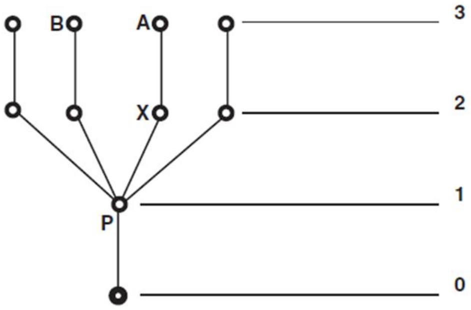

Fig. 10. Space access graph.

This set of graphs shows the pedestrian access. A similar graph would show the HVAC points for the room. As an example, Kim and Lee [20] showed that a J-diagram (justified diagram) could be used to effectively simulate movement in a ward area.

Generally the immune compromised patient is located at Level 3 in the space access graph. Fungal contamination can arrive from the Zero Level, the outside of the main corridor or it could arrive through the air handling system. As figure 8 shows the air handling system with direct access to the patient needs to deliver uncontaminated air. Nichols [2] demonstrated a 2 month cycle in the fatalities in a French hospital over a 10 year period. The most probable cause is poor filter changing in the HVAC system, which is outside the scope of this study, but will be the subject of a forthcoming paper.

If the air flow is consistently from Level 3 to Level 0 and if this air has been cleaned of fungi and dust and if the HVAC system is not growing fungi due to poor maintenance and setting aside the two month cycle, the most likely contamination path is from 0 to 3 with human activity causing the main movements in all probability. The human agent is moving against the air stream.

A consideration of the Langford velocity and gap data suggests that wind speeds up to 3.5 metres per second are possible around some doorways in simple institutional buildings. Let us assume a 4 µm particle in the mean velocity air stream of 0.5 m/s, the particle will drop 1.2 mm in a second as it passes under the door. If the door is 35 mm thick then the drop time is 0.07 seconds and it will fall 0.084 mm, about the median thickness of a human hair.

The issue is now of a simple statistical nature, what is the probability for a patient admitted to a hospital who is immune compromised, but not carrying a fungal infection, that they will acquire a fungal infection. The events to consider in a manner analogous to dealing a pack of cards are:

1) The hospital has poor air handling controls, all four patients in Fig. 9 ward would be exposed, the worst possible scenario
2) A person carrying fungi, who is not aware of infection control visits the patient, for the Fig. 9 ward a 1 in 4 chance the visitor is for them. Fungi is delivered to the room, the probability of infection is then the joint probability of a patient contacting a fungal spore and becoming sick, clearly lower risk per patient than scenario 1
3) A higher level of patient access control is practiced in the ward, so that all people are stopped at the door at Level 0. A common practice in ICU units. People will gather and sit at the point of entry, this becomes a collection point for dust, if the visitors walked near a construction site on their way in then there is an increased risk of dust collection. The issue is then what is the probability that air or a human vector will carry one of these particles into a room, with differential pressure levels, possible high velocities and interconnected rooms, the known probability is not zero

Of course the patient faces the potential of all scenarios so the probability becomes an interesting issue to calculate.

So to reduce the probability of fungi entering the room one needs to consider the entry point in detail. The door gap shows the very real issue of construction in the modern setting:

1) Standard sizes, so that door production costs are minimized
2) Standard widths on the door with the gaps on the two sides and the top being well controlled, but the poor placement of concrete on the floor results in a significantly skewed distribution of underdoor gap dimensions. This increased gap results in increased velocity beneath the door as shown in Figure 6. It would take a full research project to determine the actual flow equation format and the parameters, which is well beyond this simple study, but is planned as the next step. The increased velocity provides a higher statistical likelihood that dust may be swept by the air stream. With dust comes fungi.
3) Air pressure handling equipment and design has provided a system with a cyclic load pattern in the room 7. The pattern may be due to the air handling system being faulty, or the large door gap or a multitude of other reasons, but the last thing wanted in a hospital is a cyclic pattern in the room pressure.
4) The two month cycle in the fatality pattern has strongly suggested that a part of the system is allowing fungi to enter in a strange to some extent aperiodic pattern. The 2 month cycle over a 10 year period, strongly suggests a human factor and the most likely factor is air filters. This is a very strong research area for the future.

Computational Fluid dynamics is a very tough subject in three dimensions. Ultimately this will become the normal method, but there is a long way to go before a full hospital can be studied using 3D CFD with any confidence in the results.

Space syntax developed for human movements provides a very powerful took to consider the air flow problem in a manner akin to monitoring of water supply systems. The problem is isolated with the space diagram and each element of the space diagram can be modelled using a standard element. It is good first step to understanding the problem. The developments in kinematic and gradient models can then be used to determine likely flows, dust levels and then be moved to fungi movement issues. Whilst there is a long way to go, the recent excellent work by Reboux [8] provides the quality of data needed to allow the engineering community to ask the correct questions. Of course the ultimate question is “When do we achieve zero deaths from secondary fungal infections?”

V. CONCLUSIONS

Hospitals are dangerous places for immune compromised patients. Work sites with excess dust are dangerous places for all, but particularly for workers with a lowered immunity level. The issue of nosocomial infections is one that is being raised by the community and the Center for Disease Control and Prevention as the community increases the level of accountability required of our medical facilities. Whilst the joint danger of nosocomial infections caused by fungi riding on dust particles has become a significant problem as there are increased numbers of immune compromised patients living longer lives so the issue is tagged with the incidence of dust particles from construction sites. There are no simple answers for this problem. The project manager for a hospital construction has to first be aware of the problem and determine the best method to address the issue. The infection control officer and the facilities management team have to address how to monitor and control for the presence of fungi in the hospital areas, but particularly in the areas for the immune compromised patients.

The research reported in this paper forms part of a larger body of work at TAMU into the fungal and dust movement into hospitals, both with and without construction activities. The best solution for the patient is to minimize the exposure to fungi spores, this is of course difficult to monitor. The next best course is to limit the exposure, but in that case the facilities manager and infection control officer needs a sound model of the air, dust and fungi movement. Like all such models it will be statistically based, but given enough time and the new deep learning algorithms one would expect that improved evidence (i.e. statistically driven data) will be used to manage the hospital infection control system which will have the potential to manage the HVAC and other systems using sensor technology to minimize the risk to the patient.

Research in reality is usually about small steps, whilst everyone loves the large steps forward, Einstein or Nash’s famous theories being two examples. In this case the research uses brief research studies that can quickly address the changing research needs. This research builds on the first author's study of air flow rates around doors in an institutional building dating from the early 1970s and being of a similar vintage to a large number of existing hospitals. The building has many of the characteristics that make operational of an older HVAC system challenging for all concerned. The work also builds on the space syntax work of Guo who demonstrated the application of this technique in assisting in infection control. Space syntax is not just about human movement, it can be applied to fungi movement in the long run. The ultimate goal is clearly visible, the research steps are straightforward, the technology exists or can be developed, and the issue is only will and money.

The purpose of this work was to investigate the air flow around doorways in an institutional building. The results show that for the studied building, Langford Building A at TAMU, the door gaps ranged from 2 to 20 mm, with the distribution being non Gaussian and highly skewed. The air velocity was shown to be proportional to the door gap, with a regression co-efficient of 0.7. This matter now becomes a quality control matter for construction, the clear problem is the poor control on door installation. This is a project manager's problem, a wind velocity of 3.47 metres per second or 8 miles per hour is clearly unacceptable.

The second part of the study looked at the differential pressures in one of the high velocity doors. The pressure distribution in the room with time, showed a cyclic pattern with a time period of about 1 minutes in reality. Periodic patterns in air flows have been of recent research interest in hurricanes with intense damage due to window breaches and the formation of Helmholtz resonators, but the same problem exists in this studied room, although it is not damaging to the building it may affect the patients exposure to harmful materials from the corridor floors.

In summary, this work showed that a peak under door air velocity of 3.47 m/s was measured in the Langford Architectural complex in one of 18 measured rooms, 10% of the rooms had flow velocities in excess of 2 m/s. A 4 μm fungal spore will drop 84 μm in an average air stream velocity of 0.5 m/s as it passes beneath a closed door.

The space syntax work undertaken at the same time in this research program provides a model to build a sound flow model for the air, a statistical model for the movement of fungi and a method to assess real patient risk. The long term goal must be a deep learning system that monitors all of the systems and results in a hospital continuously to minimize the risk to patients. This work forms part of this long term aim.

Hospital designers and managers can address some of these risks, but unfortunately some of the problems are built and will require a major effort to fix.

ACKNOWLEDGMENT

Thanks to Aimee Bassett who commenced this interesting study and to the professors at TAMU who have given of their time to assist these students. Never ask for whom the bell toll.

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