Measurement of Ventilation and Airborne Infection Risk in Large Naturally Ventilated Hospital Wards

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ABSTRACT

Airborne pathogens pose a significant threat to human health and this is especially the case in hospital environments which house patients with weakened immune systems. Good ventilation design can reduce risk, however quantifying ventilation performance and its influence on infection risk is difficult, particularly for large naturally ventilated environments with multiple openings. This study applies a pulse-injection gas tracer method to assess potential infection risk and local ventilation rates in a naturally-ventilated environment. Experiments conducted in a 200 m^3 cross-ventilated Nightingale ward show that local external wind speeds in the range 1-4 m/s lead to indoor ventilation rates of between 3.4 and 6.5 air changes per hour (ACH). Natural ventilation is shown to be effective in open wards with an even distribution of potential airborne infection risk throughout patient locations. Comparison with a partitioned ward highlighted the potential for protecting neighbouring patients with physical partitions between beds, however, higher tracer concentrations are present in both the vicinity and downstream of the source. Closing the windows to represent winter conditions dramatically increases infection risk, with relative exposure to the tracer increased fourfold compared to the scenarios with the windows open. Extract fans are shown to alleviate this problem suggesting that a hybrid

approach utilising the respective strengths of natural and mechanical ventilation may offer the best year-round solution in this and similar settings.

KEYWORDS: Natural ventilation, tracer gas, airborne infection, hospital

1. Introduction

Design of modern hospital wards is driven by several factors including the need to minimize cross-transmission of infection, to maintain patient thermal comfort, ensure patient privacy and dignity, and to enable nursing staff to easily observe patients. In addition energy efficiency is an increasing concern with the need to meet government carbon reduction targets [1,2]. Although UK health policy advocates moving away from the traditional multi-bed layout towards single bed spaces [3], multi-bed spaces, including Nightingale wards, are still commonplace in hospitals throughout the UK and overseas and financial constraints mean they are likely to remain for some time. A recent study [4] has shown that naturally ventilated Nightingale wards can provide good thermal comfort and are more resilient to future climate change than many other ward designs. Such spaces therefore have great potential for retro-fitting low-energy and resilient design solutions [5,6], particularly those that address current issues with privacy and dignity in multi-occupant spaces. However in developing new design solutions it is essential to understand the resilience of such spaces in terms of infection risk and whether retro-fitting may help or hinder infection control.

The notion that airborne pathogens can travel large distances within buildings and remain in the air for long periods of time emerged in the 1930's, demonstrated through a pioneering study by Wells [7] who showed microorganisms sprayed into the basement of a large three-storey building could be recovered in every corridor up to the top floor where the concentration reached approximately one percent of the basement value. Later, the first case of Legionnaires disease was responsible for twenty-six deaths in a Philadelphia hotel in 1976 [8] with airborne transmission being one of the primary transmission routes [9]. Today, airborne infection is well recognized as a significant disease transmission route for a wide range of pathogens [10] and ventilation is acknowledged as a key determinant in infection risk [11]. Studies conducted under full scale conditions [12-15], within laboratory test facilities [16-18] and more recently through computational simulation [19-27] have all improved the understanding of infection risk which is directly influencing building design and ventilation guidance.

Despite this, much of the evidence relating infection risk to hospital ventilation is derived from investigations of controlled, mechanically ventilated environments such as operating theatres [28-32], isolation rooms [10,33-36] and idealized studies conducted in test-chamber environments. The latter

predominately use gas tracers to explore cross-infection risk between patients under different ventilation regimes [17,18,37] although recent studies have used bioaerosol tracers to generate the required airborne concentration distribution within a room [26] and spatial deposition of airborne particles in single and two-bed idealized patient rooms [38]. While results from such studies give valuable insight into the role of ventilation, these do not necessarily apply to naturally ventilated ward environments. The airflow patterns within such spaces are difficult to characterize due to the inherent variability and uncertainty of local outdoor wind conditions [39-41]. In the case of large multi-bed wards, the challenge is often further compounded by air entering and exiting through multiple openings. Baird (1969) [42] conducted one of the earliest studies into air exchange within a "racetrack-style" hospital ward unit using nitrous oxide as a tracer. Global air exchange rates were determined under the influence of both mechanical and natural ventilation. More recent studies conducted in Peru [39] and Hong Kong [41] have implemented similar tracer gas techniques to assess global air exchange. While these studies demonstrate that high ventilation rates are achievable in naturally ventilated hospitals, there is currently little knowledge of the local patient-patient infection risk in such spaces.

This paper presents an experimental study conducted in a cross-ventilated multi-bed Nightingale ward to measure ventilation rates and determine potential cross-infection risk. The study applies a pulse-injection tracer technique to explore airflow characteristics in an "as designed" cross ventilated Nightingale ward. Resulting concentration measurements over time are used to relate ventilation and cross-infection potential to wind conditions and window opening configuration. Comparable experiments are conducted in a modified ward to evaluate the impact of physical partitions and simple extract mechanical ventilation on ventilation and infection risk.

2 METHODOLOGY

2.1 Hospital Layout

The study was carried out in a former Nightingale ward (A-Block) at St. Lukes Hospital, Bradford, United Kingdom. Experiments were conducted over fifty randomly selected days over a five-month period between April and September 2010. The ward which originally contained 14 beds was located on the top floor of a three storey building, shown in Figure 1(a) and (b). With an internal width of 7.25 m, the ward was divided into two zones: (i) an open section and (ii) a custom-built partitioned section (each containing 6 beds for consistency) as illustrated in Figure 1(c).

The ceiling height in the open region and in the central corridor of the partitioned section is 3.36 m (11'0"), whereas each of the six partitioned bays has a height of 2.44 m (8'0"). The length of the open and partitioned ward sections is 8.0 m and 9.75 m respectively, leading to a total volume of ~200 m^3 for each section of the ward. As the building was unoccupied heating was switched off and no heat sources

were included in the experiments. An initial field survey of the building using a thermal camera (Fluke TiR1 Thermal Imager, Fluke Corporation) verified that wall temperatures throughout the test region differed by less than one-degree and thus are expected to have a minimal impact on the airflow patterns.

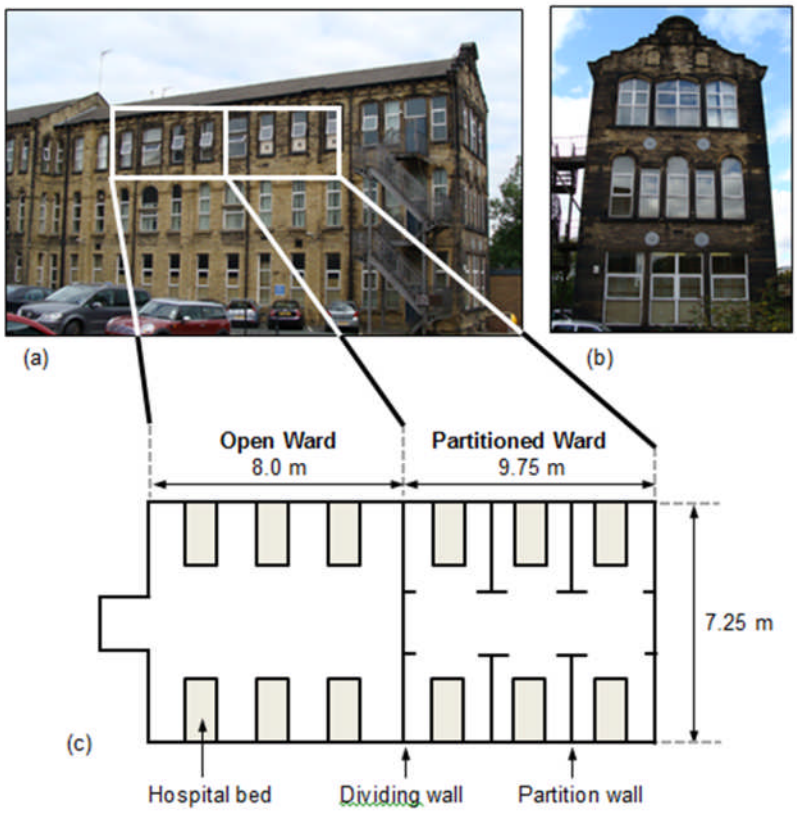

Figure 1 – (a) front view and (b) end view of the experimental facility, St. Lukes Hospital, Bradford, UK and (c) aerial schematic representation of the ward layout, featuring open and partitioned wards.

The building as designed is naturally ventilated, with cross-flow ventilation provided through a row of casement type windows adorning both sides of the building. During experiments with windows open, only one window was opened per bed regardless of the ward layout to ensure consistency. Each window had a locking mechanism that restricted the maximum opening to 0.10 m. In all cases windows were opened to this maximum to ensure the area available for supply/exhaust was constant. The building is orientated such that one row of windows faces south west and the other north east; the prevailing wind is from the south west. Ventilation in the partitioned section was supplemented by six window mounted extract fans (one per bed) so that mechanical ventilation could be compared with the natural regime.

2.2 Internal and External Airflow Measurements

Local ambient weather conditions were logged at 2.5 second intervals using a mobile weather station (Vantage Pro2, Davis Instruments, Hayward, CA). This featured a cup-type anemometer and wind vane

to measure wind speed and direction in addition to temperature and relative humidity sensors. Wind measurements were taken at the top of a 7.2 metre mast which was mounted to an external fire escape adjacent to the partitioned ward. This position was considered high enough to measure the free-stream wind conditions local to the ward with acceptable accuracy. The pressure drop across the building was measured manually during each experiment using a low-range (0 to 2000 pa ±5%) manometer (Testo 512, Testo Ltd, Alton, Hampshire, UK). Each reading was determined using an in-built 'damping function' which takes the pressure reading as the average of the greatest 20 consecutive pressure readings throughout the measurement period. Both the high and low pressures were recorded this way, with one measurement taken per second. Internal air velocities were logged at one second intervals using a high-sensitivity (0 to 5 m/s ±0.03 m/s) hot-wire anemometer (Testo 435-2 with comfort level probe, Testo Ltd, Alton, Hampshire, UK). This was placed in the centre of each section for the majority of the experiments.

2.3 Pulse Injection Technique

A carbon dioxide (CO_2) tracer gas approach was used to both measure ventilation rates and simulate pathogen release from a patient source. This method was chosen as it is inexpensive and straightforward to carry out. Laboratory based studies have shown the residence time in air is comparable to small (~2 μm) bioaerosols [37] and its suitability as an indoor air tracer has been demonstrated in many studies [11,37,41,42]. Furthermore, the recent study by Camargo-Valero *et al*. (2011) [37] compared CO_2 to a bioaerosol, *Staphylococcus aureus*, with both exhibiting very similar normalised decay rates within in a mechanically-ventilated room of volume 32m^3.

A pulse injection technique was applied to replicate a discrete release due to actions such as a cough or a sneeze. Given the relatively short timescale of such events, opening and closing a valve on a CO_2 gas cylinder was unsuitable as a controlled release mechanism. An alternative method of inflating and sealing a balloon containing the tracer was employed; a known dose was released in the location of interest by remotely piercing the balloon as required [40,43]. This method of delivery is a better representation of a sudden release due to coughing/sneezing and it has the added advantage of requiring a much smaller volume of the tracer gas. Furthermore, the time taken between inflating the balloons and the beginning each experiment was sufficient for the tracer gas temperature to reach the ambient room temperature, thus minimising potential buoyancy effects.

Laboratory experiments conducted in a mechanically ventilated test chamber confirmed the potential of this technique for a range of ventilation rates [37]. In the hospital ward, scoping tests established that a cluster of three balloons, each 0.4 m diameter, would release 0.1m^3 ±5% of CO_2; a dose large enough to clearly monitor changes in concentration throughout the ward. For each experiment the cluster of

balloons was positioned in a location representative of an infectious patient's head on a table representing a hospital bed, as shown in Figure 2(a). A circular template was used to verify that each balloon contained the same volume of CO_2. Figure 2(b) shows a typical tracer concentration curve measured near source.

Five CO_2 monitors (Telaire 7001Di, Telaire, Goleta, CA) were used to log concentrations (range 0 to 2500 ppm ±50 ppm) at 5 second intervals in locations of interest throughout each experiment. CO_2 sensors were calibrated together against a more precise instrument (Testo 435-2 with IAQ probe [0632 1535] Testo Ltd, Alton, Hampshire, UK) on a monthly basis to ensure comparable readings from all sensors. Readings from the monitors were automatically temperature-compensated and CO_2 concentrations referenced to a standard temperature of 25 °C. Prior to each experiment the ventilation regime was set (i.e. windows opened for natural ventilation, or extract fans activated for mechanical ventilation) and the ward left unattended for a minimum of 15 minutes so the background CO_2 level could be recorded. Next, the balloons were pierced by a researcher using a two-metre triple-pronged pole and the ward immediately vacated to ensure that human activity did not influence the results. Throughout each experiment, CO_2 concentrations were logged in locations of interest. The majority of these lasted 30 minutes with the exception of "no ventilation" cases (see Table 1) which were run over a three hour period due to the slow decay rate of the CO_2 tracer.

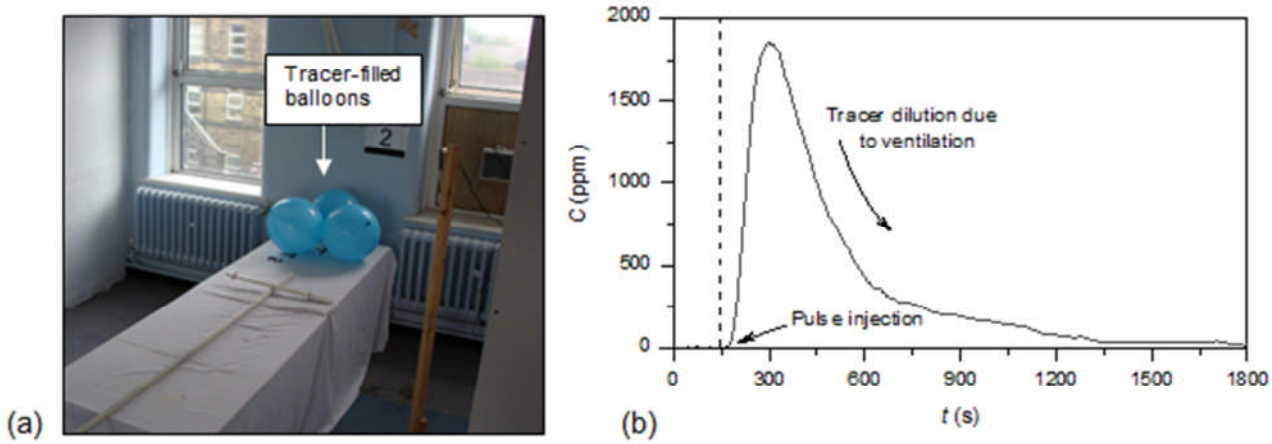

Figure 2 – (a) Photograph of the pulse injection experimental layout and (b) a typical plot of the CO_2 tracer concentration, C, relative to the background level, as a function of time.

2.4 Ventilation Measurements

The pulse injection method is also suitable for measuring ventilation rates provided there is a clear inlet and an outlet to the space of interest []. The enclosed nature of the bays in the partitioned ward allowed ventilation rates to be readily determined since the inlet and outlet are clearly defined. This was achieved by placing three tracer-filled balloons in the window opening (inlet) prior to pulse injection

using the method outlined above. As the tracer advanced through the bay, its concentration was monitored and logged in time via three sensors mounted in the bay entrance (outlet), see Figure 3. An initial scoping study using the aforementioned hot-wire probe ensured that the three sensor locations existed within the bulk airflow region where the air velocity is relatively uniform. Positioning the sensors nearer to the sides of the bay walls would not be appropriate for measuring ventilation rates due to the correspondingly lower air velocities; this should be considered in other studies.

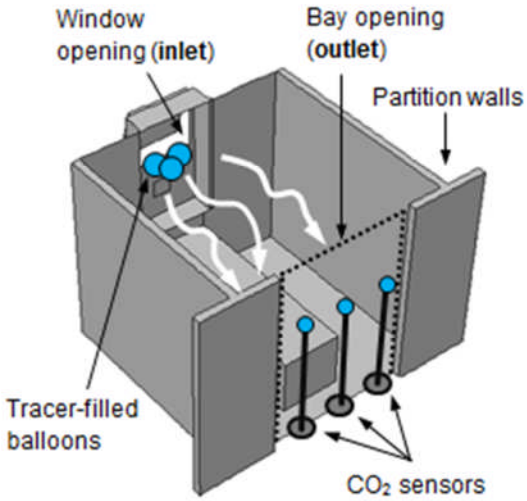

Figure 3 – Experimental set-up used to measure ventilation rates in one of the partitioned bays

Each tracer curve was smoothed using a 12-point moving average to filter out the noise which was present in some instances. Background CO_2 concentration was removed to enable normalisation and comparison between cases. The ventilation rate, V (Air Changes per Hour (ACH)) is found from the following relation:

$$V = \frac{1}{\tau_{mean}} \tag{1}$$

where τ_{mean} is the mean residence time experienced by the air volume. This is given by:

$$\tau_{mean} = \frac{\mu^2}{\mu^1} \tag{2}$$

where μ^1 and μ^2 are first and second order moments of the tracer concentration signal, both of which are found from the general expression:

$$\mu^i = \int_0^\infty C(t) \cdot t^i dt \tag{3}$$

where C is the concentration of tracer recorded as a function of time, t, (hours) for the i^{th} order moment []. The suitability of this approach was confirmed in a separate study in the same hospital ward, giving confidence in the technique [40]. A number of tests were carried out on randomly selected days in one of the central bays which had a volume of 15.4 m^3; this resulted in a relatively large air-to-tracer volume ratio of ~150:1. For all tests where the wind direction was unsuitable or changing, the data was not included in the analysis.

2.5 Pathogen Transport Experimental Scenarios

Pathogen transport experiments were conducted between May and September 2010. Six scenarios were considered, as shown in Table 1. A total of 61 experiments were deemed to yield reliable data and are used in the analysis.

			Number of experiments	
Experiment	Ventilation regime	Tracer release location	Open ward	Partitioned ward
1	Natural	Centre	15	14
2	Mechanical	Centre	n/a*	6
3	None	Centre	2	2
4	Natural	Corner	6	8
5	Mechanical	Corner	n/a*	4
6	None	Corner	2	2

* Mechanical ventilation unavailable in the open ward

Table 1 – Summary of the number of tracer experiments carried out.

Two tracer release configurations, central and corner release, were defined as shown in Figure 4. In both cases the source concentration was measured at a height of 1.5 m from the ground beside the source bed as this is representative of the breathing zone of a nearby healthcare worker (HW_S). For central pathogen release cases a sensor simulating another healthcare worker location (HW_C) was positioned in the centre of the ward and the remaining sensors were placed in representative patient head locations on beds opposite to (P_1 and P_3) and adjacent to (P_2) the source (see Figure 4(a)). For the corner release case, only one sensor was used to simulate a healthcare worker (HW_S) with one adjacent patient location (P_4) and three on the opposite wall (P_5, P_6 and P_7), see Figure 4(b).

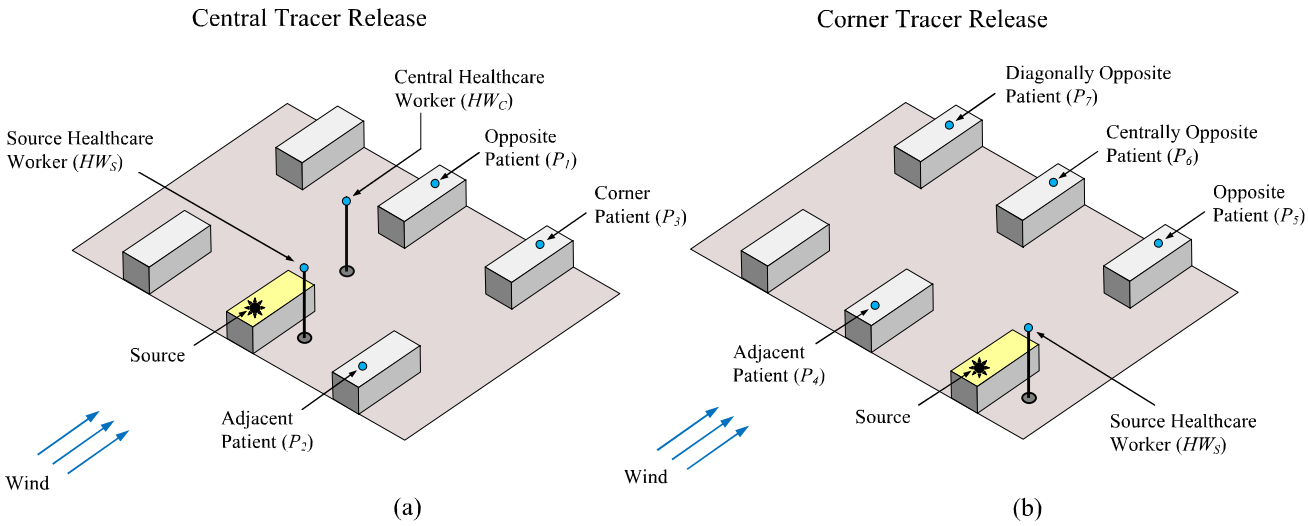

Figure 4 – Illustrations showing sensor locations for (a) central windward and (b) corner windward pathogen release cases with cross ventilation present.

Three ventilation approaches were considered. The natural ventilation scenarios had the windows open to the maximum permissible as described earlier. In these cases the tracer source was located on either the windward or leeward side of the building. Experiments were planned so that equal numbers of windward and leeward cases were considered, however on some occasions results were discarded due to significant variability in the external wind direction, and in others the wind reversed direction, effectively changing the classification of the experiment. This is discussed further in section four. Mechanical ventilation cases were only conducted for the partitioned ward. In these cases all the windows were closed, with ventilation provided solely by the extract fans. Cases referred to as "no ventilation" were conducted with all windows closed and fans switched off; ventilation was by infiltration only.

3 AIRFLOW CHARACTERISTICS

3.1 External Conditions

The mean average external wind speed and direction for each experiment are calculated and plotted in Figure 5. Unsurprisingly, the variability of natural wind leads to significant scatter in the data and the prevailing wind direction can be determined as south-westerly, which is typical for the United Kingdom.

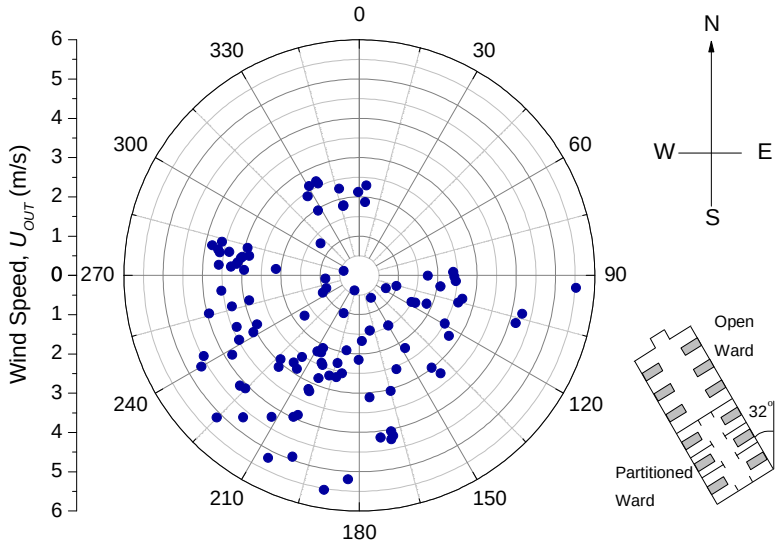

Figure 5 – Scatter plot of the mean average wind speed and direction for each experiment.

Scatter is also evident in the pressure drop, Δ*p*, measured across the building per experiment as shown in Figure 6. The pressure drop across the building generally increases with the wind speed, $U_{OUT,}$ as would be expected considering the building orientation and the predominant wind direction. A mean external temperature of 16.7°C ±1.7°C was observed throughout the experiments with a higher value of 21.3°C ±2.0°C seen within the actual ward. The mean relative humidity was 68% ±7.3% outside the building and 54% ±4.8% within (note: variations in temperature and humidity are calculated from 1 standard deviation).

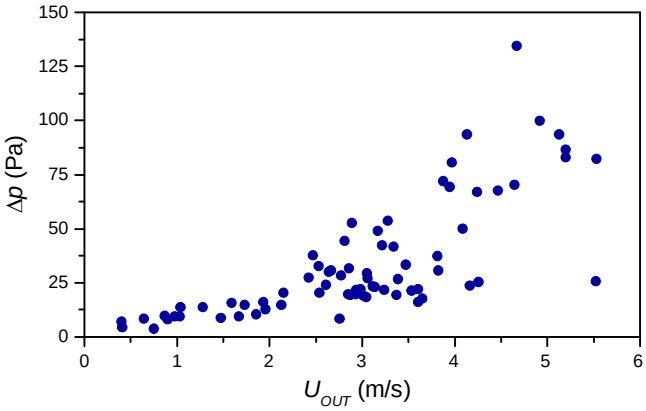

Figure 6 – Scatter plot of the pressure drop across the building for each experiment.

3.2 Internal-External Air Velocity Correlations

The correlations between the measured mean internal air velocity, U_{IN}, and the magnitude of the normal component of the outside wind, $|U_{OUT\text{-}X}|$, are shown for each experiment in Figure 7. Note that $|U_{OUT\text{-}X}|$ is

plotted instead of simply taking the velocity magnitude of the wind, U_{OUT}, because it is the span-wise component which dictates the flow rate through the windows.

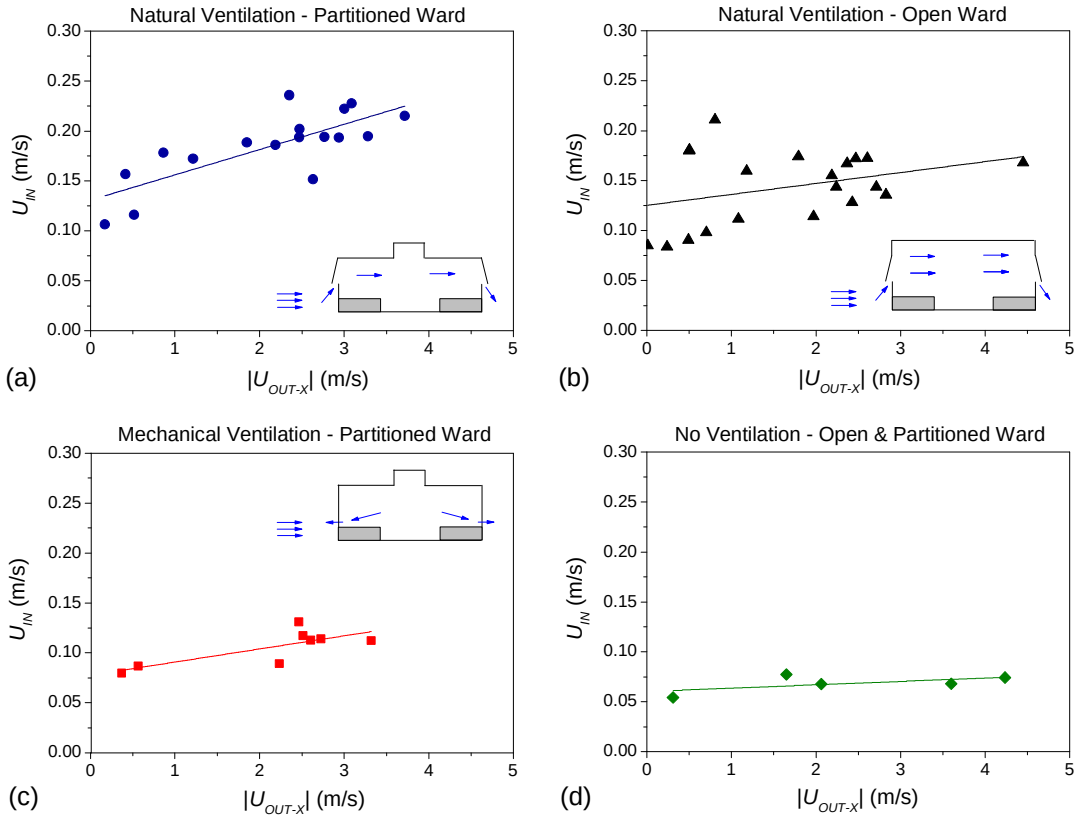

Figure 7 – Plots showing the internal-external velocity correlations for natural ventilation in (a) the partitioned ward and (b) the open ward, and (c) mechanical ventilation in the partitioned ward with (d) no ventilation cases measured in both wards.

In all cases the internal air velocities are more than an order of magnitude lower than those measured externally. Broadly speaking U_{IN} increases linearly with $|U_{OUT-X}|$ whether the hospital is naturally or mechanically ventilated (Figures 7(a)-(c)). For the no ventilation case the influence of the wind is minimal, however the small gradient in the line of best fit (Figure 7(d)) indicates that some leakage/infiltration is present; this was verified visually using smoke sticks (Smoke-Stick™ 3, Hayes Ltd, UK) which indicated air movement in the void above the suspended ceiling. For the natural ventilation cases (Figures 7(a) and (b)) there is sizeable scatter in the data, particularly for low velocities within the open ward. In the partitioned section, greater internal velocities are evident which is due to the reduced ceiling height above the beds; this serves to maintain a greater flow rate due to the smaller available volume. The open section has a higher air volume immediately behind the windows which reduces the incoming flow rate considerably. In comparison to the natural ventilation regimes, mechanical ventilation exhibits a significantly smaller spread of data which is to be expected given that the windows were closed. However, the slope in the line of best fit indicates that the extract fans which

provide mechanical ventilation are also influenced by the pressure drop imparted on the building by the wind.

3.3 Internal Velocity Profiles

To investigate the natural ventilation cases in more detail, span-wise internal velocity profiles were assembled from a series of point anemometry measurements recorded during a prolonged period of steady wind speed (~4.4 m/s) and relatively stable direction (204-240° i.e. SSW-WSW). Each point measurement was taken at 1 second intervals over 2 minutes with a total of 120 samples recorded. As demonstrated in Figure 8, velocities are higher on the supply side of the building (x/L = 0.0) before decaying to a significantly lower value further downstream. In the open ward, the air velocities are generally below 10% of the external wind velocity regardless of the profile height, with the only exception being the near-window region along the upper profile, see Figure 8(a).

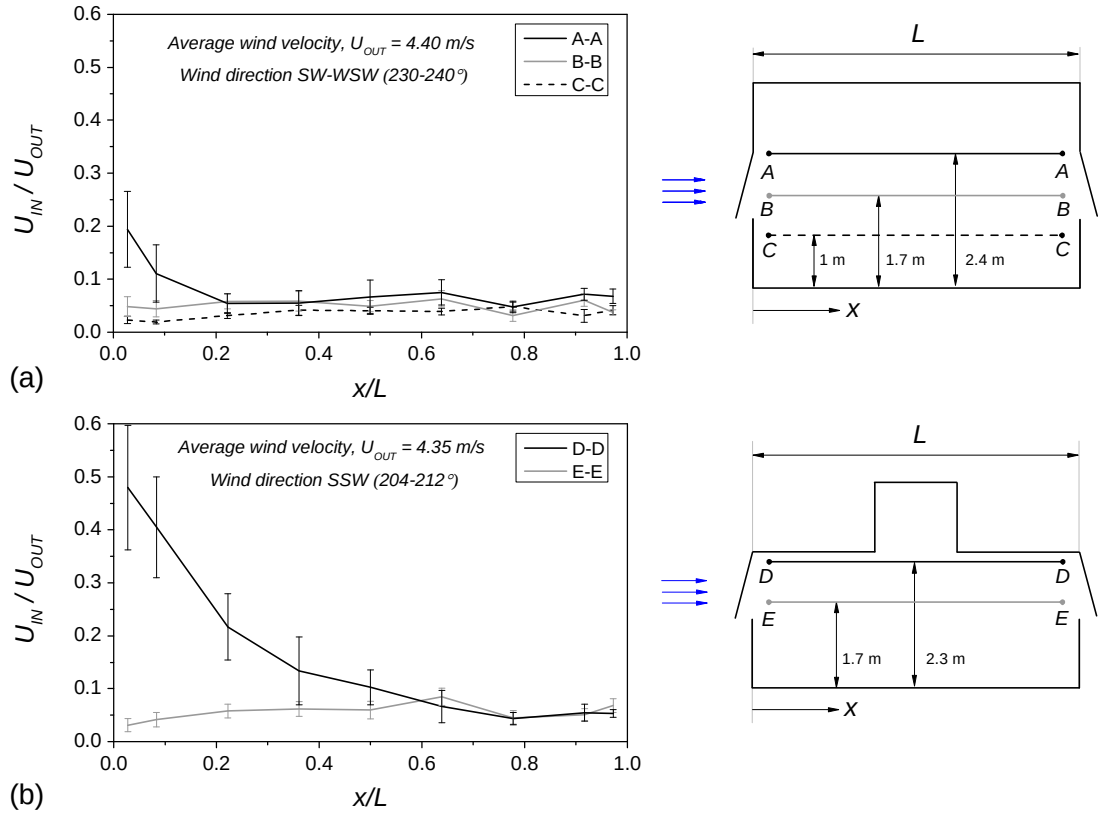

Figure 8 – Internal span-wise velocity profiles in (a) the open ward and (b) the partitioned ward. Error bars show one standard deviation.

It follows that a feature of natural ventilation in large, open spaces, is an inherent uniformity of air velocity in the majority of the space. In contrast, the partitioned section studied here induces far greater

air velocities in the upper breathing zone (y = 2.3 m). As already discussed, this originates from the design of this particular ward which has a lower ceiling height. In terms of the standing breathing zone (y = 1.7 m), the velocity profiles in both the open and partitioned sections are actually very similar with profile-averaged normalised values of 0.050 and 0.056 respectively.

3.4 Ventilation Rates

Figure 9 shows how the ventilation rate, V, and the equivalent flow rate, Q, vary with the external wind velocity, U_{OUT}, in one of the partitioned bays using the procedure outlined in section 2.4. For each experiment, error bars are determined from one standard deviation of V for the three outlet sensors (a total of 8 experiments are shown in Figure 9). Despite the relatively small number of measurements, there is a very clear linearity in the results for which, R^2 = 0.937. The ventilation rates are noticeably high with a range of 13-27 ACH calculated for a corresponding range of external wind speeds of 1-4 m/s. The high ventilation rates are in part due to the small volume of the air space under consideration (15.4 m^2), however they also show the effectiveness of the cross ventilation regime studied.

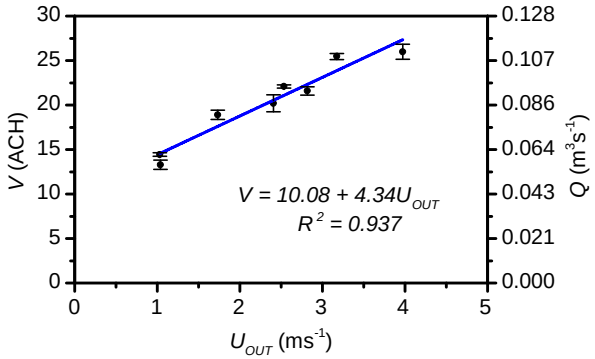

Figure 9 – Relationship between the ventilation rate, V, the flow rate, Q, and the wind velocity, U_{OUT} for a single (15.4 m^3) bay. Error bars show one standard deviation.

The linear relationship obtained in Figure 9 clearly shows how much fresh air is supplied to one particular bay (through a single window), recall Figure 3. Based on the assumption that the airflow is similar through each open window, the results can be extrapolated to indicate the ventilation rate to the whole ward. As three inlet windows supplied fresh air to each ward (and each ward has the same volume of 200 m^3) an overall mean average ventilation rate, V_{AVE}, can be calculated as a function of the ambient external wind speed. Table 2 shows the expected mean ventilation rates together with an equivalent volumetric flow rate for the range of wind speeds encountered during the experiments.

U_{OUT} (ms^{-1})	V_{AVE} (ACH)	Q (m^{3}s^{-1})
1.0	3.4	0.185
2.5	5.0	0.269
4.0	6.5	0.352

Table 2 – Variation in the average ventilation rate, V_{MEAN}, experienced per ward as a function of the ambient wind velocity, U_{OUT}.

Whilst these ventilation rates are sensible estimates of the equivalent mean value for each ward as a whole, the significantly higher values measured in the small partitioned bay (Figure 9) illustrates that there is distribution of ventilation rates present. As such, the mean ventilation rate serves only as a guide for understanding the total volume of air passing through the space. It should also be noted that the values in Table 2 only assume three windows open on each side of the ward; opening further windows will increase the ventilation rate accordingly.

3.5 Airflow Patterns

In addition to quantitative measurements, flow visualisation using a smoke stick attached to a wand was carried out to qualitatively assess the internal airflow behaviour. Figure 10 illustrates the typical observed flow patterns spanning both ward types. In both cases the angle of air entry followed that of the casement window on the inlet (west) side of the building. The large ceiling height present in the open ward promoted upwash from the incoming wind which effectively drove a recirculating air current near the inlet window, thus keeping this region well mixed. Further downstream the flow patterns were less structured with a slow moving 'stagnant' region of air in the upper level (Figure 10(a)).

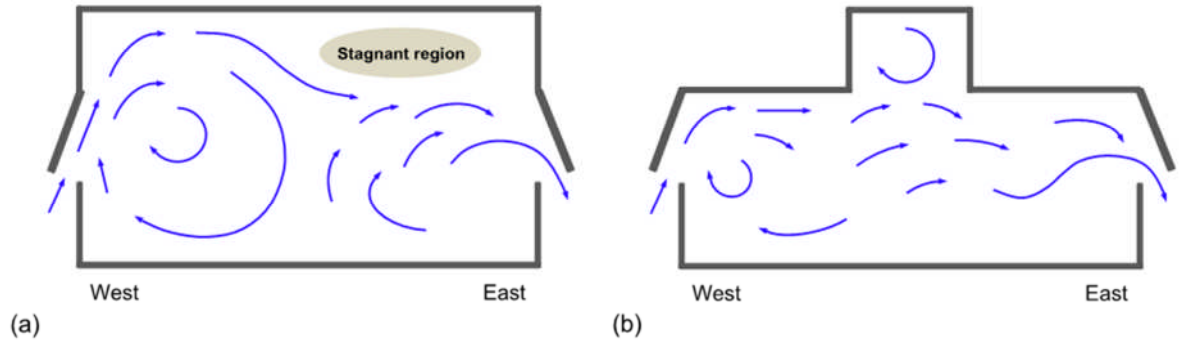

Figure 10 – Span-wise flow patterns observed within (a) the open ward and (b) the partitioned ward (wind direction is west-to-east in both cases).

Observations near the outlet window highlighted a constant extraction current which appeared to be very effective, despite having a low velocity. This constant flow was maintained irrespective of the conditions at the inlet, even when rapid local variations in the wind were present. The reduced ceiling height present in the partitioned ward fundamentally altered the global flow pattern which was dominated by a west-to-east cross-flow with little mixing taking place, Figure 10(b). As mentioned earlier, it is apparent that the lower ceiling above the bays constricts the airflow, increasing its velocity (recall Figure 8(b)) and thus leading to a well-structured cross-ventilation regime. Again the flow near the outlet windows was very similar with steady and constant extraction evident.

4 PATHOGEN TRANSPORT CHARACTERISTICS

4.1 Relative Exposure Index

When considering the temporal tracer distribution at each sensor location, there are two logical parameters which characterise it, namely the peak concentration measured above the background reading, C_P, and the cumulative dose, D, defined as the integral of the tracer with respect to time. As with the ventilation measurement, output from CO_2 sensors was processed using a 12-point moving average to remove noise and values of C_P and D were subsequently determined for each sensor. A relative exposure index, Γ, was defined by:

$$\Gamma = \frac{D_j}{D_{SO}} \tag{4}$$

where D_j is the dose measured at the j^{th} sensor location and D_{S0} is that corresponding to the source location in the open ward for the central release with natural ventilation (experiment 1 in Table 1). Similarly a normalised peak concentration is defined by:

$$\gamma = \frac{C_{Pj}}{C_{PO}} \tag{5}$$

where C_{Pj} is the peak at the j^{th} sensor and C_{P0} is the peak at the source location in the open naturally ventilated ward with central release. This normalisation approach means the peak value and the dose received in any of the sensor locations in any experiment is essentially normalised with respect to the source in an open Nightingale ward experiencing as-designed, cross-ventilation. To ensure consistency D_{S0} and C_{P0} are taken as the mean average of all the doses or peaks respectively for all natural ventilation experiments with an average external wind speed greater than 1 m/s.

4.2 Central Tracer Release

Results for the calculated relative exposure index, Γ, and the normalised peak dose, γ, are presented for the open and partitioned ward in Figure 11. The doses used in the calculation of Γ are based on the first 25 minutes of each experiment only to enable comparison between experiments of different duration. Although Table 1 indicates three ventilation scenarios, analysis of the data showed that four of the natural ventilation experiments (two in the open ward and two in the partitioned ward) were conducted on a hot day (mean indoor temperature 28.8°C) with much lower external wind speeds (0.4-0.9 m/s) than the rest of the experiments (3.04 m/s, standard deviation, σ = 1.04 m/s). Rather than discard these results, they are presented as a separate category labelled "low wind".

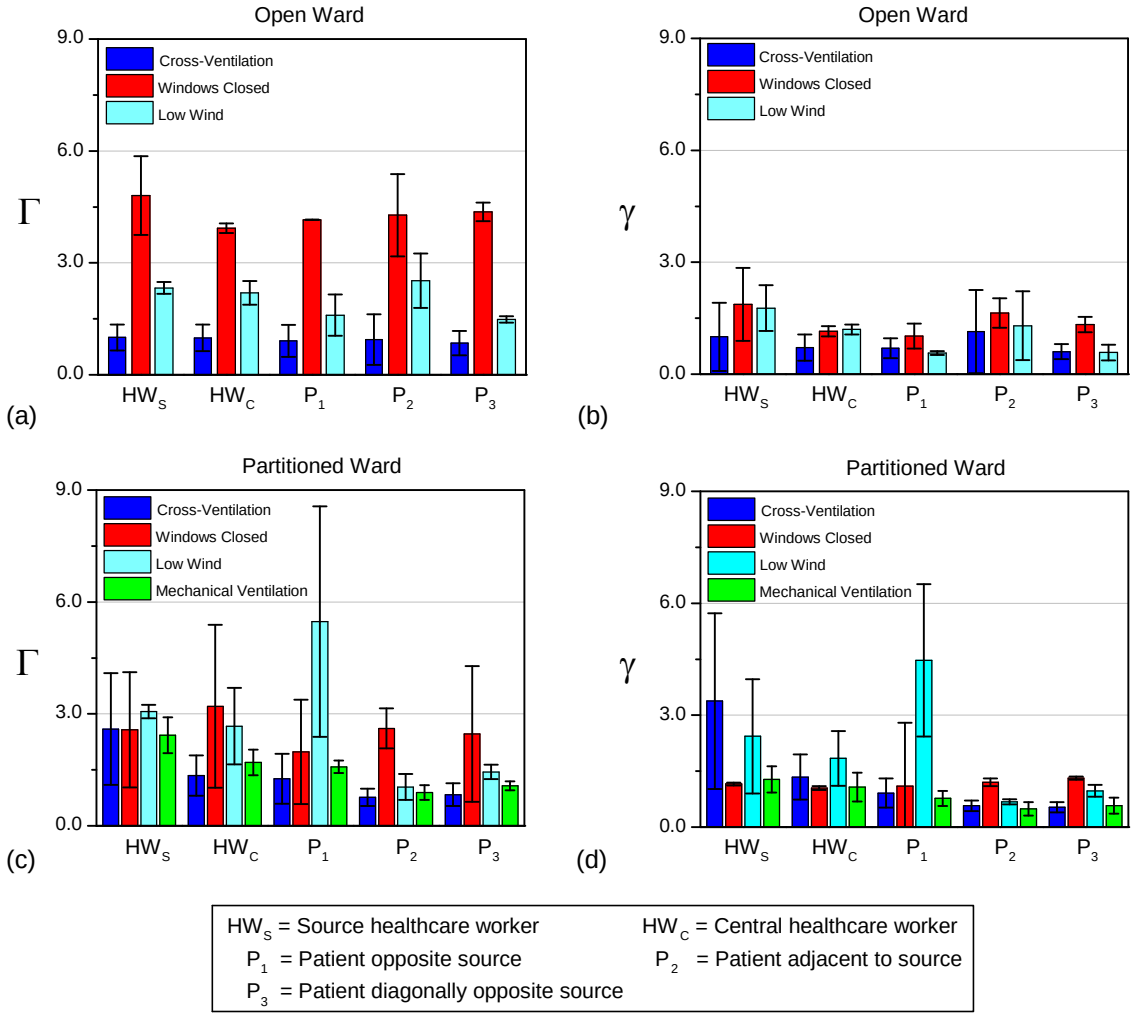

Figure 11 – Plots of the relative exposure index based on dose (Γ) *for (a) open and (c) partitioned ward, and based on peak* (γ) *for (b) open and (d) partitioned ward.*

In the open ward layout the relative exposure, Γ, (Figure 11(a)) shows that the spatial distribution of the tracer over time is relatively uniform for both the natural cross ventilation and no ventilation scenarios (windows closed), indicating good mixing in the space. Although the "no ventilation" results are based on a small number of experiments, the results clearly indicate that with the windows closed the level of tracer exposure in all locations is significantly increased, with up to a four-fold increase. For the "low wind" cases a two-fold increase is also apparent, although these are again based on a small data set.

Comparison with peak concentrations (Figure 11(b)) highlights less uniformity between locations and greater variability between experiments as indicated by the proportionately larger error bars. As would be expected the largest peaks occur nearest the source (HW_S and P_2) with progressively smaller peaks in the centre of the ward (HW_C) and very low peaks furthest downstream (P_1). Furthermore, the mean peak concentration close to the source (HWs and P_2) is over 40% higher than the mean peak concentration at P3 for the cross-ventilation scenarios. It is also noticeable that while the relative exposure is substantially increased with low ventilation rates, the increase in peak concentration is less pronounced than that of the dose (Figure 11(a)).

Results for the partitioned ward clearly indicate that the partitions strongly influence the spatial distribution of Γ and γ as shown in Figure 11(c) and (d). In the cross ventilated case (Figure 11(c)), the dose exposure close to the source (HWs) is significantly higher than in the open ward (Figure 11(a)), however the dose experienced in the other locations comparable to the open ward results and in fact the exposure is notably less for the patients situated at the other side of the partitions (P2 and P3) which illustrates the benefit of barrier nursing. The mechanically ventilated scenarios also show similar results, with the measured dose only marginally higher than the cross-ventilated cases. As with the open ward, cases with low ventilation rates (windows closed and low wind) show higher levels of exposure across the ward.

In terms of the peak concentrations (Figure 11(d)), the results follow a similar trend to the relative dose exposure for most cases and again marked variability between experiments is evident in some cases. The one notable exception is the partitioned cross ventilation case, where the relative peak concentration is higher than the increase in relative exposure over 25 minutes. Interestingly, the low-wind peak values are significantly higher than the equivalent no-ventilation values in the centre of the ward (HW_S, HW_C and P_1). Whilst this result may appear to be non-intuitive, the central portion of the partitioned ward had a very clearly defined cross-ventilation flow pattern due to the partition walls (Figure 10(b)) and it is likely that the low-velocity wind transported the tracer downstream and towards the sensors (they were all located downstream of the source), thereby increasing the peak values. This observation is supported by the concentrations measured behind the partitions (P_2 and P_3) where the tracer concentration is shown to be higher in the no-ventilation case compared to low-wind

one; with no-ventilation, diffusion dominates tracer transport towards locations P_2 and P_3, whereas cross-ventilation (whether strong or weak) prevents this.

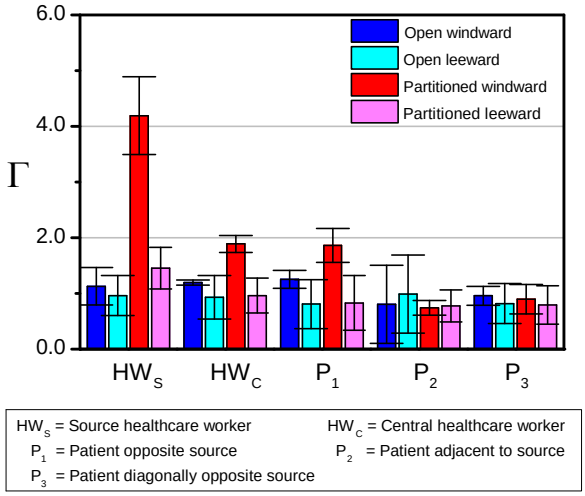

Figure 12 – Comparison of the exposure index, Γ, at various locations, for combinations of ward type (open or partitioned) and source location (windward or leeward side of building).

Figure 12 separates out the cross ventilation results for the two ward layouts by source release location which was either on the windward or leeward side of the building (refer to Figure 5 for sensor configuration). With the exception of location P_2, the relative exposure is lower when the source is released from the leeward side compared to equivalent windward release scenarios. This suggests that the flow direction in the vicinity of the source is a key factor; releasing the tracer near the outlet window (i.e. leeward release) serves to extract a significant proportion of the contaminant before it mixes and diffuses throughout the room. This trend is particularly noticeable in the partitioned case, where concentrations are markedly higher in the central zone (HWs, HWc and P_1) for the windward release case. To further illustrate the importance of the location of the source in relation the wind entry point, Figure 13 shows typical measured tracer concentration curves in the partitioned ward for windward and leeward tracer releases for comparable natural ventilation regimes (i.e. similar wind velocity and direction). In all five measurement locations the tracer concentration is significantly lower for the leeward release case.

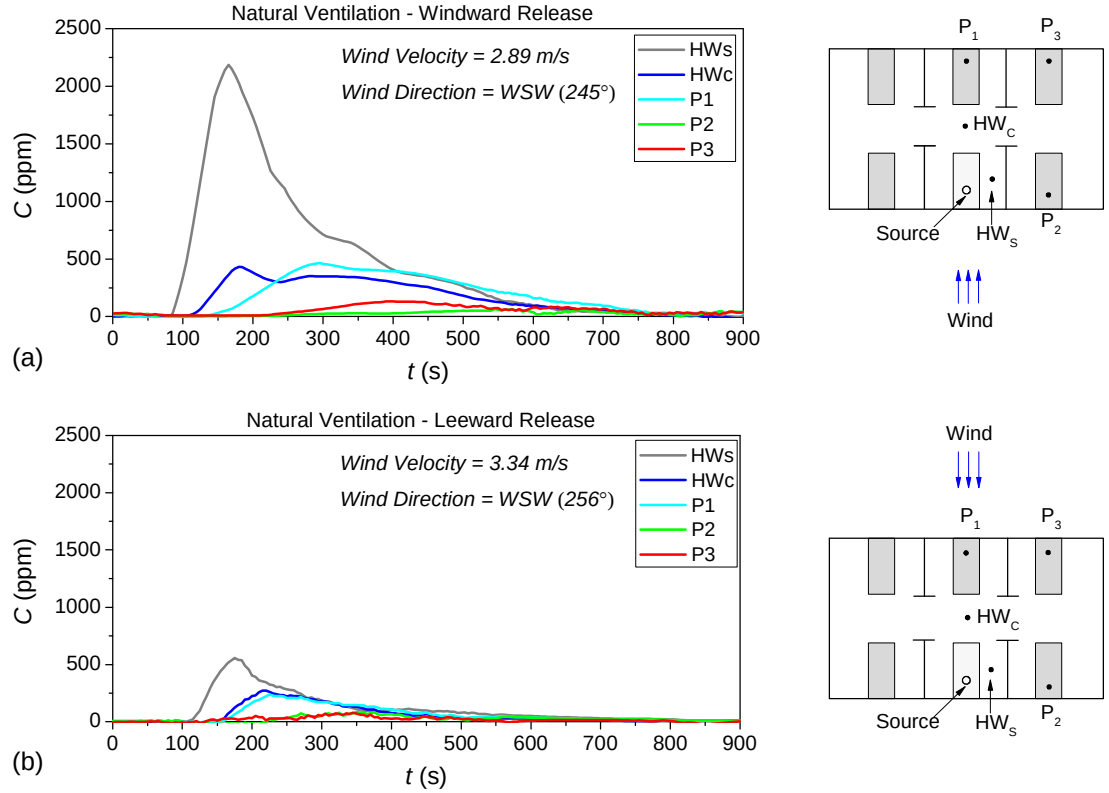

Figure 13 – Plots showing the variation in tracer concentration level, C, above the background value, with time, t, for (a) windward and (b) leeward tracer release in the partitioned ward.

4.3 Corner Tracer Release

Results for both ward layouts are presented in Figure 14(a)-(c) for cases where the tracer was released from a corner bed (i.e. cases 4-6 shown in Table 1). Here, the sensor configuration considers four patients (P_4 – P_7) and the source healthcare worker (HW_S), as shown in Figure 14(d). For consistency Γ and γ are again determined relative to the source for a central release case in the naturally ventilated open ward.

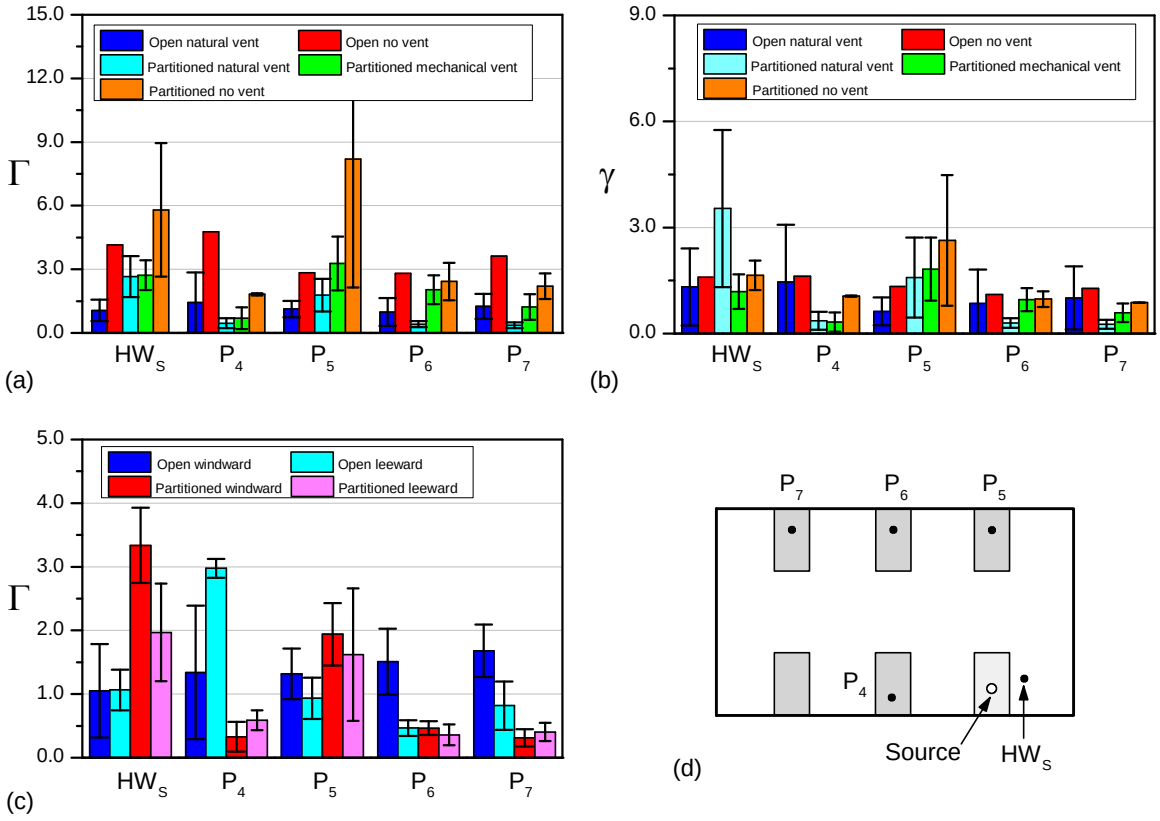

Figure 14 – Plots of the relative exposure index based on (a) dose [Γ] *and (b) peak* [γ]*; breakdown of dose as a function of release location for the corner tracer release case with sensor layout shown in (d).*

Figure 14(a) shows the relative exposure follows similar trends to the experiments with a central tracer release. In the open ward the exposure index with natural ventilation is between 1.0 and 1.4 for all five sensor locations. The exposure is marginally higher than with the central tracer release, but results still suggest a good degree of mixing within the ward. As with the central tracer release, the inclusion of partitions again changes the distribution pattern, with higher relative exposure close to the source and at the opposite bed (P_5), but much lower measured doses beyond the partitions (P_4, P_6 and P_7). In both ward configurations, closure of the windows results in a substantially increased exposure across the ward space. Measured peak concentrations (Figure 14 (b)) show similar trends to the central release; relative increase in peak concentration is lower than relative increase in dose for the majority of cases, with the notable exception being the concentration close to the source (HW_s) following addition of partitions.

Figure 14(c) considers the influence of source location on relative exposure. As with central tracer releases, locating the source on the leeward side of the building tends to reduce the overall exposure in

the open ward, with the exception of location (P_4). The increase seen in this location is likely to be due to the airflow direction acting to retain the contaminant on the leeward side of the ward. In the case of the partitioned ward bays adjacent to the source (P_4, P_6 and P_7) are relatively insensitive to either windward or leeward natural ventilation conditions. Leeward ventilation appears to reduce exposure at the other two locations (HW_s and P_5), but the exposure (dose) is still greater than for those patients who are protected by the partitions.

5 DISCUSSION

The results from this investigation demonstrate that pulse injection of a tracer gas is a feasible approach for measuring ventilation rates and assessing the potential for airborne pathogen transport in naturally ventilated hospital wards. Both of these tasks were carried out with very small tracer doses on the order of $0.1m^3$ thereby making the procedure inexpensive.

5.1 Ventilation Rate

In terms of measuring natural ventilation rates, the pulse injection technique was repeatable and accurate for a range of external wind characteristics. Although the focus of this aspect of the investigation was on a small, 15.4 m^3 air volume that could be assumed to be representative of the whole space, the technique was also implemented in an entire ward (volume 195 m^3). The results are not presented as there are too few experiments where the wind direction remained consistent for confidence, however the approach did appear to work. The key assumption which must be satisfied for the technique to be valid is for the tracer to be released at the inlet and its decay monitored in the outlet of the space of interest. As such, the method is limited to situations where a steady and constant cross-ventilation regime is present; single-sided ventilation cannot be analysed.

Experience from the present study showed that the tracer concentration should be monitored by a minimum of three sensors and these should be placed slightly upstream of the outlet, otherwise fresh air in the vicinity of the outlet can interfere with the tracer signal, introducing significant levels of noise in the data. Another important parameter is the magnitude of the dose; a very small tracer volume does not register with the sensors and too large a volume can lead to multiple peaks due to large-scale recirculation in the flow field – a single, clearly-defined peak must be obtained for the pulse injection formulae to give a valid result. In this investigation a dose of 0.1 m^3 per inlet window was sufficient to obtain ventilation rates. Overall the results suggest mean ward ventilation rates of between 3 and 7 ACH for an ambient wind velocity of 1 to 4 m/s. This is comparable to Department of Health recommendations of 6 ACH for ward environments [3]. However, the ventilation rate obtained in one particular bay varied between 13 and 27 ACH (for the same conditions) and so the *local* ventilation rate is an important consideration which deserves attention in naturally ventilated spaces.

5.2 Ward Layout

While the ventilation rate gives a feel for how well the overall ventilation compares to other spaces, the results from the experiments measuring the spread and distribution of a tracer provide much more relevant insight into the airflow pathways in this healthcare setting and the potential infection transmission risk. Results clearly show that the "as designed" cross-ventilated open ward performs well; the air is well mixed and therefore the measured ventilation rates are a realistic parameter to gauge performance. Results showed an even distribution of dose (Γ) whether the tracer was centrally released or released from the corner of the ward and that peak concentrations broadly followed exposure. Locating the infectious source close to a window on the leeward side of the building was shown to reduce the risk of cross transmission. As many Nightingale-type wards are positioned to take advantage of a clear prevailing wind, this may be a feasible management action with a patient deemed to present a higher risk. However, as seen in this study, this cannot be done with 100% certainty as the wind speed and direction is variable. The cross-ventilated partitioned ward also performed well, but the layout led to a heterogeneous tracer distribution as its progress was either encouraged or impeded depending on location. The partitions were very effective at containing the source which has the potential to protect patients either side of the partition walls. This concurs with early studies in real hospital environments [45,46], laboratory studies with biological aerosols [38] and recent numerical modelling work [20,47].

However the results do show that partitions can increase the risk close to the source, and potentially in opposite bays. In particular the results suggest that a tracer released by an inlet window (windward release) can lead to elevated exposure levels in the vicinity of the source and immediately downstream. Numerical studies [20] and Nielsen's recent investigation into the feasibility of using a partition between two beds also suggested that partitions could increase infection risk as well as minimise it [18]. This aspect must be considered in context in future design. Where the airborne transmission risk is very small, the increase due to partitions will remain small, and the advantages in terms of patient privacy and potential for reducing environmental contamination [38] will likely outweigh disadvantages. However in environments where there is a substantial airborne risk, considering the ventilation flow in conjunction with the partition will be essential.

5.3 Ventilation approach

The pathogen transport tests also give a good insight into the risks posed by poor ventilation. Ventilation was a prime factor in the original design of Nightingale wards, with high ceilings, large casement and/or sash-type windows, orientation to maximise the cross-flow and use of low level vents and central chimneys to enable trickle ventilation and stack effect flows which were featured in many designs [48]. However, safety concerns have restricted window openings and energy reduction

measures have prompted many hospitals to remove wall vents and chimneys and replace original windows with sealed double-glazed units. While this increase in air-tightness is beneficial from a thermal comfort and energy perspective, in many wards ventilation relies on window opening, supplemented only by the small amount of infiltration present in all buildings due to flow through penetrations and via doorways from other spaces.

While the present study clearly shows the effectiveness of cross ventilation when the windows are open, the detrimental effect of closing all the windows is clear from the results, with up to a four-fold increase in tracer exposure across the whole ward. Given that calculated ventilation rates with windows open are typically around 4-5 ACH (Table 2), this increase in exposure implies an equivalent ventilation rate of around 1 ACH with the windows closed, substantially below guidance recommendations. Moreover, the total exposure due to a release with windows closed is likely to be higher than presented here for two reasons. Firstly, to enable direct comparison between experiments exposure was calculated over the 25 minutes following tracer release. In the majority of experiments, the concentration had almost returned to background levels over this time, however for the cases with no ventilation the time taken to return to background levels was considerably longer with timescales of 2-4 hours. Secondly, the experiments in this study were conducted in a disused ward that was not well maintained. An occupied ward is likely to have a higher air-tightness, and potentially even lower infiltration rates. Results also show an increased risk on warm still days. Although this finding is based on a very small number of experiments, it is clear that for very low external wind conditions, the ventilation patterns within the room fundamentally changed (from the cross-ventilation regime), leading to notably different tracer distribution, and in some cases significantly higher concentrations.

Although the results demonstrate the potential risks of poor ventilation, they do also show an effective solution. The addition of extract fans to each bay of the partitioned ward reduced relative exposure compared to the case with no ventilation, and in the central release scenario yielded average exposure results only marginally higher than the cross-ventilation case. A hybrid ventilation approach of supplementing the natural cross-ventilation with mechanical extraction may offer a cost effective approach to ensuring year-round ventilation without substantially increasing energy costs. The fans installed here were a simple retrofit aimed solely at the experiments. With careful design it is likely that such an approach may be even more effective than measured during this study. Similarly, reinstating original features such as low level vents and central chimney extracts present in many Nightingale ward designs may also mitigate poor ventilation, by encouraging flows due to stack effects in addition to the wind-driven cross ventilation.

5.4 Infection Risk

While the results clearly show the variability of tracer gas concentration with ventilation and ward layout, they do not provide a direct measure of infection risk. However, carbon dioxide and other tracer gases (e.g. nitrous oxide or SF_6) have been shown to give comparable distributions to small particle bioaerosols [37,49] and hence offer a realistic representation of airborne pathogens and thus infection risk. The action of piercing tracer-filled balloons is an effective method for simulating the sudden delivery of pathogenic material such as a cough or a sneeze; the results presented are therefore representative of the exposure due to a single discrete event. As all results are normalised it is possible to infer relative risk between scenarios although absolute risk cannot be determined.

It is also worth commenting on the two measures used to analyse the results, namely peak concentration, γ, and exposure over a time period, Γ. In the evaluation presented here more emphasis is placed on the exposure, mainly because this parameter had less variability and it was cumulative which reduced uncertainties due to inherent differences between experiments. However, either measure may be significant depending on the infection concerned; risk may be a function of total exposure, increasing with time, or peak exposure when the concentration crosses a threshold dose. Although some infections such as norovirus and influenza are believed to have a threshold dose, for most pathogens this data is uncertain or unknown.

As well as the internal contaminants considered in this study (i.e. tracer released from patient beds) there are of course other contaminant sources present in a real environment including those from adjoining wards and ingress from outdoors. Clearly these sources will add to the risk within a given ward, but their contribution will be dependent on the source type and location. In terms of respiratory diseases such as influenza and TB, and healthcare associated infections transmitted from patient to patient such as *Clostridium difficile* and norovirus, internal sources in close proximity to other patients will pose the biggest risk; hence this is the primary focus in this study. Outdoor sources are a possible issue with naturally ventilated environments, although poor outdoor air quality is generally a greater concern than infectious disease transmission particularly in urban environments. A direct comparison between the wards studied here and protection offered by single-patient rooms is difficult to draw as the infection risks will depend on the specific configuration and ventilation of a particular ward. It is likely that the risk of airborne cross-infection between patients in a single-room ward environment will be less than in Nightingale wards due to the complete physical segregation of patients. However providing single-rooms to all patients incurs a cost that is beyond many hospitals and hence understanding the performance and potential adaption of multi-bed wards is a necessary reality.

5.5 Replicability and Reliability

Finally, discussion of the limitations of investigation are also necessary. As displayed in Table 1, only a limited number of experiments were carried out for some configurations. Whilst this is undesirable from a statistical viewpoint, inevitably some data had to be discarded due to experimental issues and so the number of useful experiments was correspondingly reduced. The experimental set up was also constrained by the physical condition of the building. The heating system was switched off as the building was unoccupied and almost all medical equipment had been removed. As such the thermal environment within the ward did not have the heat loads that would be present in a real ward. Introducing heated manikins to represent patients was considered, however it was not feasible to release the tracer in a pulse from a manikin and without the wider room thermal control this heat load would also be unrealistic. Although this is a limitation with the current study, it was noted that while pathogen transport experiments were conducted over a three month period where the outdoor temperature ranged between 12 and 22 ˚C, there does not appear to be any correlation between indoor or outdoor temperature and tracer exposure; external wind speed and window opening appear to be the dominant factors.

In undertaking this investigation a total of fifty days were devoted to preparing the hospital wards for experimentation, to develop the techniques and to conduct the actual experiments. Unfortunately the hospital ward was demolished in September 2010, which ultimately ended the test programme. In spite of this, the conclusions gained are reinforced by the data presented and they are, on the whole, logical, which is a satisfying outcome to a difficult and challenging problem. It should also be noted that, with the exception of thermal control, the data collected is for a real ward under real conditions. While in most cases it was possible to group experiments by layout, ventilation regime, tracer release location and broad wind speed and direction, unlike a study conducted in a test chamber (or even a mechanically ventilated ward) it is impossible to carry out genuine “replicate” tests. Even though some of the findings are based on a small number of experiments they are real; the high concentrations seen in some cases with low ventilation rates are evidence of events which did happen and could again in an occupied ward.

Gas tracer experiments in empty wards and other simulation approaches such as computational fluid dynamics models are the most convenient approaches for investigating pathogen transport, both for obvious ethical reasons and for the insight they give into the relationships between design variables and risk. However they are surrogate methods and infection risk can only be inferred rather than calculated. Nevertheless, the findings from such studies have been shown to concur with data from other laboratory studies and from outbreaks. The results in this study agree with other studies in more controlled laboratory environments and computational simulations that show the benefits of using

partitions between beds to restrict airborne pathogen movement [18,20,38,40,45-47]. In terms of outbreaks, Gustavson's study [50] shows that tracer gas concentrations measured in a children's ward correlated to varicella transmission, while analysis of the 2003 SAR's outbreak in Hong Kong showed that actual transmission patterns compared well to simulations of both indoor [51] and outdoor [52] airflow paths.

6 CONCLUSIONS

The cross ventilated ward was shown to perform well in all configurations, with ventilation rates in line with Department of Health recommendations and proportional to external wind conditions. With an open ward layout, the air is well mixed and dilution determines the exposure of occupants to airborne contaminants. The position of the source has an influence on spatial distribution, with a leeward release reducing risk. Partitions can be effective at reducing infection risk to patients who are situated behind partition walls, however the airborne exposure is consequently higher close to and downstream of the source; this should be considered in design with additional controls implemented if the risk of airborne transmission in a particular ward space is believed to be a concern.

Results clearly demonstrate the consequences of poor ventilation either through actively closing ventilation openings, or not accounting for conditions such as low external wind speed during design. At ward level the risk may be increased four-fold, with local patient exposure up to eight times higher in some cases. These results show the importance of considering year-round ventilation, and in particular considering whether ventilation is adequate during cold winter months when windows are likely to be closed for comfort reasons. During this period, opportunistic infection rates are generally higher, including influenza and norovirus which have both been associated with aerosol spread. Mechanical ventilation in the form of extract fans is shown to be effective at reducing exposure risk. A hybrid ventilation approach may therefore offer a viable method of controlling pathogens and ensuring adequate ventilation during conditions where natural ventilation schemes are less effective.

Despite the study being conducted in a ward that was constructed over 100 years ago, the results show that the Nightingale design is well ventilated and that the positioning of the building to utilise the prevailing wind direction is an effective design strategy. With such wards also potentially offering good thermal resilience, adapting these spaces to provide better levels of patient privacy, such as through the installation of partitions, is clearly a viable option. Combining old and new technology to ensure good year-round ventilation may also ensure an appropriate balance between energy efficiency and maintaining good environmental quality.

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