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CFD modelling of a hospital ward: Assessing risk from bacteria produced from respiratory and activity sources

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SUMMARY
It has been identified that potentially pathogenic bacteria, such as MRSA can be released from the skin during routine activities within hospital wards, such as bed-making, washing patients, dressing and walking. CFD is often used to study airflow patterns and ventilation regimes within hospitals, however such models tend not to consider these types of dispersal mechanisms and concentrate on respiratory transmission, using a point source at the mouth position. A zonal source is demonstrated to represent this release from activity within CFD simulations using both passive scalar and Lagrangian particle tracking. Sensitivity studies are carried out for point and zonal sources. The point source was found to not adequately represent the release of bacteria from a zone and therefore the zonal source is recommended to be used in conjunction with this type of source in order to simulate both respiratory and activity sources of bacteria.

KEYWORDS
Bio-aerosol, CFD, Hospitals, Source definition, Health-care associated infection

INTRODUCTION

Health-care Associated Infection (HAI) is a world wide concern with 2 -3 million people in Europe infected annually (Pittet et al., 2005). Although the most significant route for the transfer of infection is via contact spread there is evidence that the airborne route may also have importance (Brachman, 1970). Infection resulting from airborne transfer of bacteria is not only caused by inhalation of infectious particles, but may also be due to contamination of surfaces by these particles. This contamination may then lead to further infection through transport on health care workers (HCWs) or patient's hands.

Computational Fluid Dynamics (CFD) is a useful tool to understand the dynamics of infectious particles through the air. It has been used successfully to study the effect of different ventilation regimes, and layouts of wards and isolation rooms (Zhao et al., 2004; Noakes et al., 2006; Chang et al., 2007). This can extend to modelling other engineering infection control interventions such as the effect of UV-C irradiation (Noakes et al., 2004).

Modelling the transport of infectious particles in indoor environments tends to focus on respiratory diseases such as SARS and TB and for this reason the source of bio-aerosols is usually taken as being at the head of the patients bed. However this is not the only release mechanism of bacteria that is important for hospital acquired infection. Bacteria such as *Staphylococcus aureus*, including MRSA are known to colonise the skin and can become released into the air on skin flakes due to friction during activity. Noble (1962) found that a patient colonised with *Staphylococci* could rapidly contaminate their environment, and more recently Shiormori et al. (2002) concluded that the process of bed-making resulted in

airborne counts up to 26 times that in the resting period. Within a respiratory ward it has been shown that airborne bacteria sampled over the course of a day fluctuated with activity (Roberts et al., 2006). This type of release from activities such as bed-making will not occur at a single point, as can be assumed when a cough is the release mechanism.

There is currently growing interest in simulating movement directly within CFD models (Shih et al., 2007; Mazumdar and Chen, 2007). Despite the complexity of these models they still only provide limited results for one particular occasion, where as in reality the activities will be enacted differently on every occasion, resulting in different dispersal mechanisms. By modelling the motion directly there is the risk of giving the user, or clients, an incorrect sense of certainty about the results. However it is possible to identify the spatial zones over which an activity occurs, and for this reason the concept of the zonal source was introduced. The zonal source aims to *represent* a time-averaged release from activity within a steady state model. This applies a time averaged concentration for the release which in reality varies in time and space over the entire zone the activity occurs in. A previous validation study (Hathway et al., 2007) showed the time-averaged concentration distribution from a moving source was well represented by a zonal source. However the results from the moving source could differ greatly from the point source depending on the ventilation regime.

This paper aims to demonstrate the application of a zonal source bio-aerosol release model within a hospital side room and compare the risks to patients and staff from a zonal release with a point source. The zonal source will be tested for sensitivity to size and risks from this source compared to that with a point source. A sensitivity study on the location specification of the point source was also carried out to enable a comparison with the possible errors from the zonal source application.

METHODS

Numerical simulations of the air flow pattern and bio-aerosol transport are carried out using the commercial package Fluent 6.2. The simulated side room is mechanically ventilated in accordance with the NHS estates recommendations (2005) with a pressure difference at the extract of –10Pa and a ventilation rate through the room corresponding to 10 ac/h. The air enters the room from a four-way ceiling diffuser as shown in Figure 1, at an angle of 10 degrees to the ceiling. The injected air has a temperature of 20˚C. This is then extracted through a ceiling mounted grille as shown in the Figure. Within the room is a patient, bed, table and sink. The patient is given a heat flux of 60W.m^{-2} and the lights 50W.m^{-2}. Turbulence is modelled using the standard k-ε model with enhanced wall functions. All the walls are adiabatic and set to the no slip condition.

The computational grid is comprised of approximately 600,000 cells using a tet/hybrid automatic meshing scheme. A boundary layer was applied to all walls, resulting in a maximum node distance of 0.01m from the wall. The grid was refined at the inlet and outlet. The airflow was assumed converged when the residuals had dropped by three orders of magnitude and the mass flux within the space was less than 0.1%. The solution for the bio-aerosol sources were run using the converged airflow solutions in order to save time, with the same criteria applied.

Bio-aerosol source

The bio-aerosols were initially assumed to be small enough to stay airborne for long periods of time, and were therefore modelled using a passive scalar. This was extended to a study

using Lagrangian particle tracking to more realistically simulate larger particles that are released from skin.
In the passive scalar study the transport of bio-aerosols (ϕ) was solved using Equation 1.

$$\frac{\partial \phi}{\partial t} + div(\phi \mathbf{u}) - div(\Gamma grad\phi) = 0 \qquad (1)$$

Here **u** is the velocity vector (*u,v,w*) of the air (m.s^{-1}); and Γ is the diffusivity (m^2.s^{-1}). In order to study the sensitivity of a point source location nine injections are defined across the bed as shown in Figure 1. Each of these is represented by a cube of volume 10cm^3 with a source concentration of 500 cfu. The sensitivity of the zonal source to size and location is studied by considering six sources with a plan geometry that ranges between the area of the whole bed to an area just covering the patient. The location and geometry of these sources are given in Table 1. For all the bio-aerosol sources a momentum source of 1N.m^3 is applied in the positive y direction to simulate an upward release.

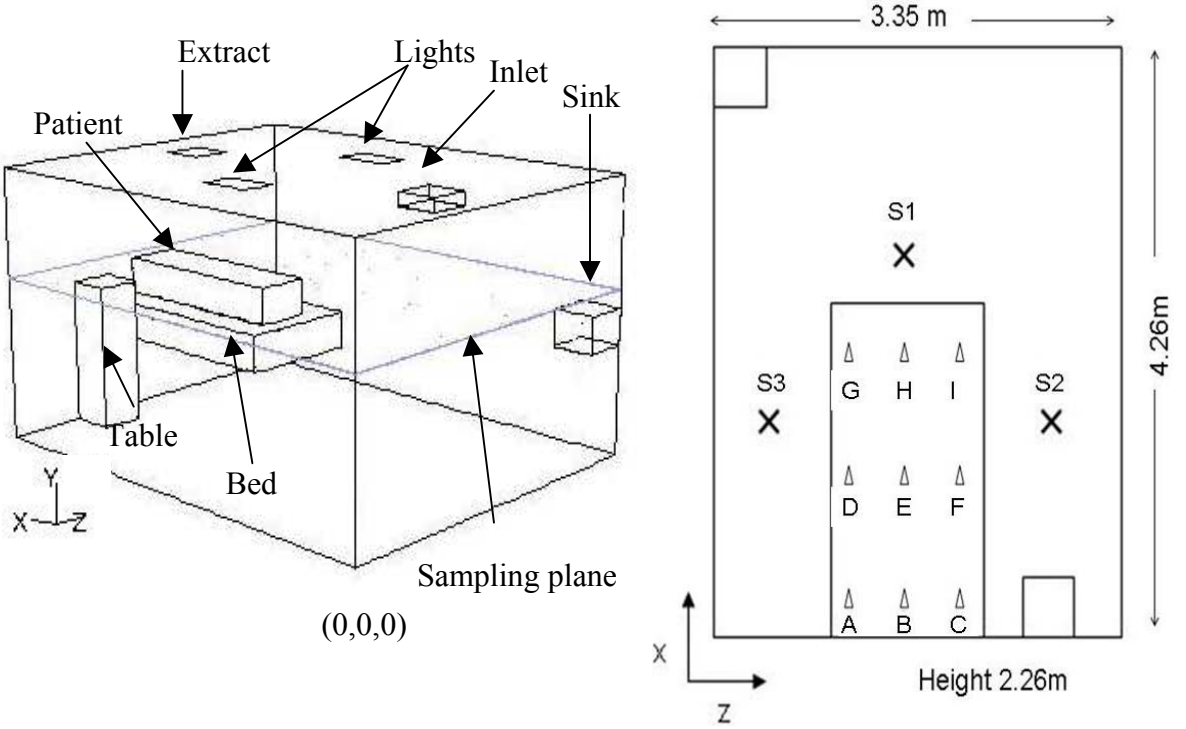

Figure 1. Schematic of the side room (left) Position of sampling points (x) and point source locations (Δ) (right).

Lagrangian particle tracking was used to model particulate release across the same six zonal sources, and point injections were carried out at the centre of the scalar point sources. The velocity of the particles (u_p) was solved using Equation 2.

$$\frac{\partial u_p}{\partial t} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} \qquad (2)$$

Here $F_D(u-u_p)$ is the drag force per unit of particle, ρ density and g the gravitational acceleration. The subscript p refers to particles, whereas the unsubscripted terms refer to the bulk air. Turbulent dispersion was modelled using the stochastic discrete random walk

(DRW) approach. Three diameters of particles were considered; 5, 14 and 20 microns each with a density of 1000 kg.m^{-3}. Ten thousand particles of each diameter were injected and tracked for 50,000 steps. A particle was considered trapped when it hit a surface and escaped when it hit the extract.

Table 1.Geometry of the Zonal Sources showing x,y,z coordinates at max and min positions.

	x		y		z	
	min	**max**	**min**	**max**	**min**	**max**
z(u)1	2.46	4.23	1.3	1.4	1.425	1.925
z(u)2				1.7		
z(u)3				2.0		
z(l)4	2.26	4.26	1.0	1.4	1.175	2.275
z(l)5				1.7		
z(l)6				2.0		

RESULTS

Figure 2 shows the velocity vectors for the airflow across the central x and z planes in the room. The air speed across the patient is less than 0.25m.s^{-1} as required by ASHRAE to provide adequate comfort, and avoid drafts. Figure 2b shows clearly two areas of recirculation down each side of the room.

Contours of bio-aerosol concentration from the passive scalar simulations are shown for three representative point sources and the six zonal sources in Figure 3. These are all plotted on a plane at y= 1.35m, just above the top surface of the patient. In order to compare the results the volume of the room with a concentration greater than 5 cfu.m^{-3} is found for each case and shown in Figure 4. To compare the risk posed by each source to health care workers standing in specific locations the average concentration at three points around the bed (S1, S2, S3 in Figure 1) are given in Figure 5. The error bars indicate the range of values depending on the source position or size.

In the particle tracking results a distinction is made between the lower zonal sources that surround the patient (l), and the upper sources that are immediately above the patient (u) (see Table 1). Figure 6 shows the number of particles extracted as a percentage of those injected for each source. The average value is given for each type of source and the error bars indicate the range of results for the different individual source locations or sizes. The same process is carried out for the results in Figure 7 showing the deposition on different surfaces within the room.

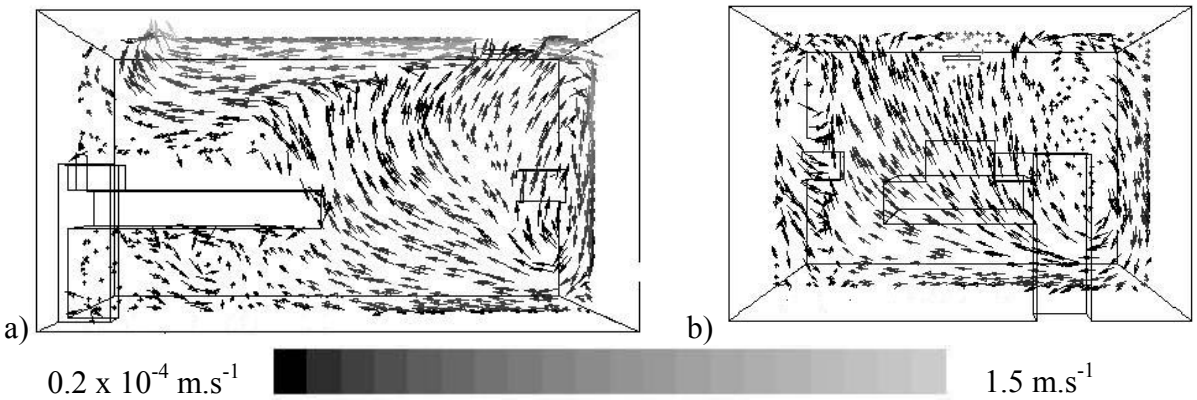

Figure 2. Vectors of velocity on the planes z=1.65 (a) and x=2.13 (b).

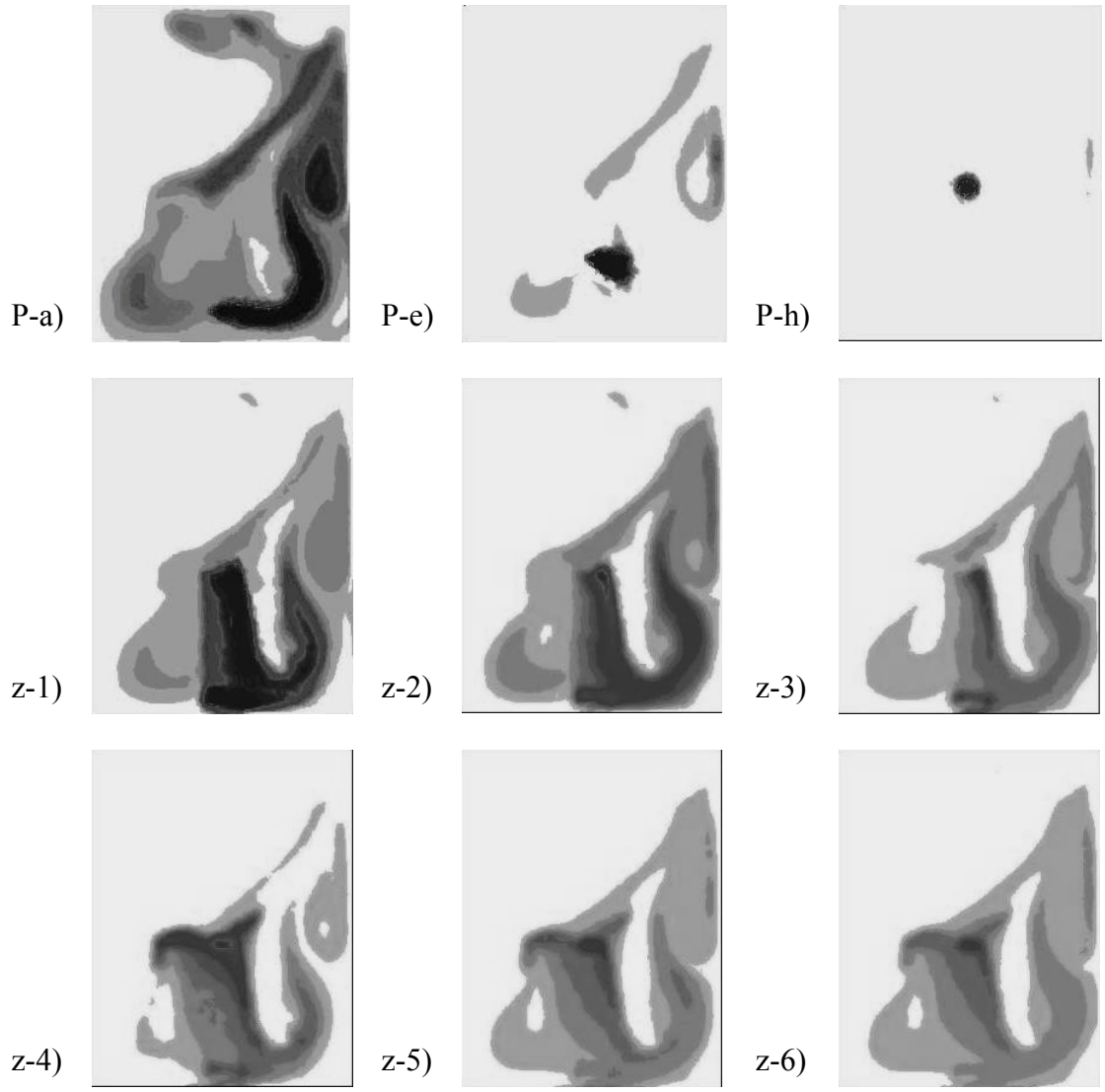

Figure 3. Contours of bio-aerosol concentration on the plane y=1.35m for point sources (P) as shown in Figure 1, and zonal sources (z) described in Table 1. The colours are equivalent for each plot with light areas showing the highest contamination. Orientation as in Figure 1b.

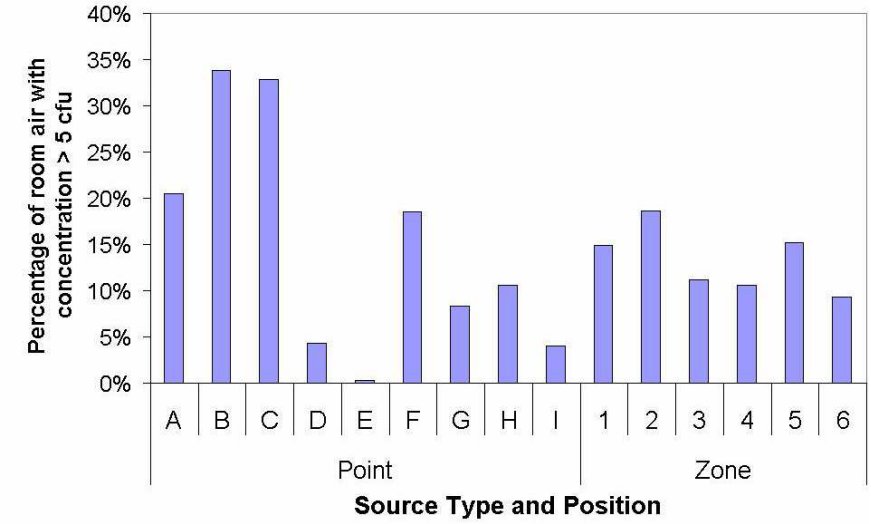

Figure 4. The percentage by volume of the room air with a scalar concentration > 5cfu.m^{-3}.

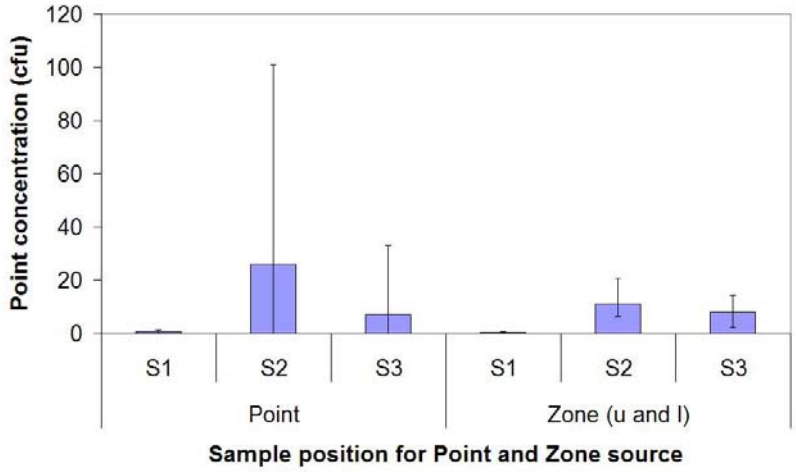

Figure 5. Average concentration at three HCW locations (shown in Figure 1) based on mean of all 9 point source results and all 6 zonal source simulations. The error bars indicate the range of values for each type of source.

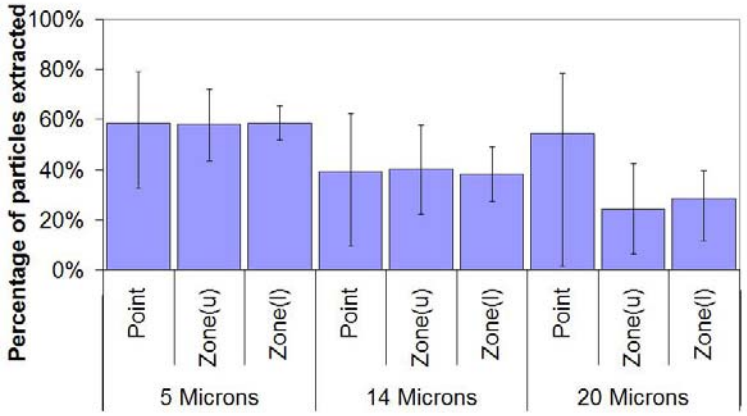

Figure 6. The average number of particles extracted from the space as a percentage of those injected, based on mean of 9 point source, 3 (u) zonal source and 3 (l) zonal source simulations. The error bars show the range of values found for the different types of source.

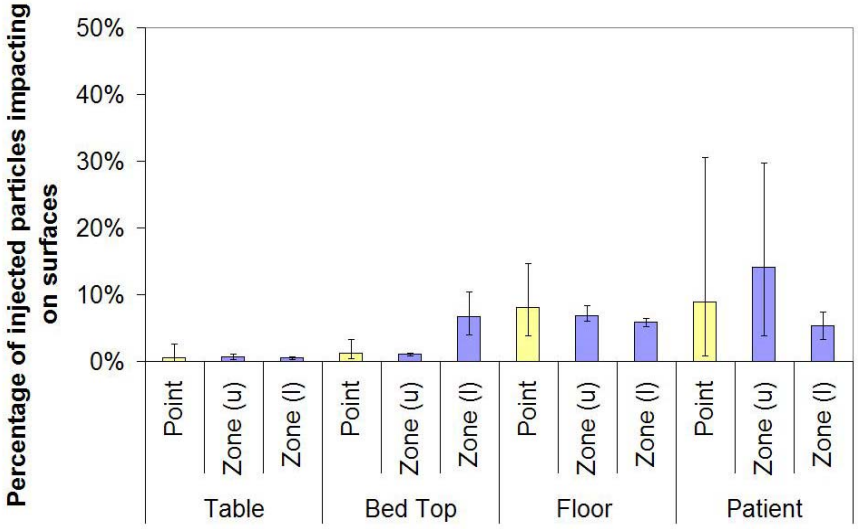

Figure 7. The average percentage injected of 5μm particles impacting on surfaces within the room, based on mean of 9 point source, 3 (u) zonal source and 3 (l) zonal source simulations. The range of values for each type of source is shown by the error bars.

DISCUSSION

Figure 2 shows quite clearly that the dispersal pattern changes as the point source location moves away from the wall, with the resulting contour plot very dependant on the original source location. These patterns are quite different to those that occur due to release from a zonal source. In the latter case there is very little difference between the dispersal patterns when the source dimensions change, with greatest difference in concentration, when the source is thin resulting in a much higher concentration at the source.

Comparing these concentration patterns quantitatively, Figure 4 shows the percentage of the room with concentrations above 5 cfu.m^3. For the point source simulations this volume varies greatly depending on location with the largest differences between points B and E despite them being only 64 cm apart. The zonal source simulations result in percentage values between the extremes of the point source simulations, with only a small variation with size of the source. The results shown in Figure 5 aim to quantify the potential risk to a HCW located at three positions around the bed. The results show immediately how the risk at a particular location depends very much on the nature and location of the source. In particular the variation at position B for point sources is very large, as depending on the position of the point source the bio-aerosols are immediately extracted, or recirculate around the room. These results show how important it is to locate a point bio-aerosol source correctly as incorrect positioning can give very false results when calculating the risk to HCWs.

These findings are also reflected in the Lagrangian particle tracking results (Figures 5 and 6). Although particle tracking is more susceptible to the size of a zone, particularly for the upper zone (u) results which have a smaller plan area. The depth of the zone for these models greatly influences the level of deposition on the patient and the bed. Lai and Chen (2006) showed how the incorrect assumption of isotropic turbulence in the k-ε model can result in over deposition and when a large number of particles are injected close to a surface, as with the thin sources, this effect may have a greater effect. They also showed that Lagrangian particle tracking is more sensitive to the grid size than the simulation of the bulk air flow. For this reason over deposition with thin sources may be reduced by a finer grid. However since the zone thickness does not otherwise have a great effect on the dispersal pattern it may be more appropriate to consider a thicker zone so less particles are injected in the area close to the surface.

As discussed in the introduction, the release of bacteria from activity can significantly affect the concentration of bio-aerosols and these may be pathogenic. It is therefore important to consider the type and location of activity when simulating hospital wards. To model the release of bacteria from an activity such as bed-making, dispersion will occur in varying amounts over the length of the bed. From the results shown here it is clear that a point source at the head of the bed could give misleading results, but equally a point source located at another position on the bed would also be incorrect. When using CFD to research the effect of airflows on the risk of transmission of infection, incorrectly assuming a point source release could lead to erroneous results. Therefore when using CFD simulations to study bio-aerosol transport it is important to understand the types of sources that may exist in the space and the purpose of any interventions. It may then be necessary to consider both respiratory and activity based bio-aerosol sources, and to achieve this by using a combination of point and zonal sources to build a realistic simulation of the risks in a space.

CONCLUSIONS

When using CFD simulations for research or design of hospital isolation or side rooms it is important to consider the type of infection that a bio-aerosol transport model is intending to represent. Pathogens that contaminate the skin, and can therefore be released from the skin due to friction during activity will have different dispersion characteristics to respiratory aerosols. It is therefore important to consider the pathogen source when researching the design of ventilation and engineering infection control interventions in side rooms, isolation rooms and hospital wards. The dispersion patterns from point and zonal sources are different and it may be necessary to use both to represent the release from respiratory and activity based sources of infection. The results of this study also highlight the importance of specifying a realistic location for the source of a pathogen and understanding the limitations in the model created by making this choice.

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