# The Effect of Turbulence on the Spreading of Infectious Airborne Droplets in Hospitals

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**Abstract** The dispersion of droplets plays an important role in the transmission of disease in a hospital environment. The challenge is that as they move, their properties change due to evaporation, the Wells (Am. J. Hyg. 20:611–618, 1934) droplet-nuclei hypothesis. In this paper we examine the effect of evaporation on their movement within a homogeneous turbulent environment. The effect of turbulence is to significantly increase the transmission distance and spread. These numerical results demonstrate that by reducing the level of turbulence, the potential for spreading diseases is reduced. This is in accordance with available experimental/in situ measurements.

## 1 Introduction

A major public health issue at the moment is the spread of airborne disease, as recently documented for severe acute respiratory syndrome (SARS), bird flu and currently swine flu. World Health Organisation (WHO) is currently at a Phase 6 alert which refers to the pandemic stage which is characterised by community level outbreaks in at least one other country (than where the first outbreak started). The risk is real as amply demonstrated by the 1918–1920 Spanish flu (of type H1N1) which was estimated to have killed approximately 50 million people [13]. Only a few diseases are truly airborne, such as *tubercle bacillus* (TB), chickenpox and measles, in the sense that they are created in the respiratory tract and emitted as droplets when we sneeze, breath, shout and talk [20]. But other diseases are recognised to have the potential to be spread in the air (and also by contact), such as the Norwalk virus, methicillin-resistant *S. aureus* (MRSA), *C. difficle* etc.

A cough or sneeze can generate up to 3,000 and 40,000 droplets of saliva/mucus respectively [2]. A typical droplet size distribution has a peak at around 10 μm.

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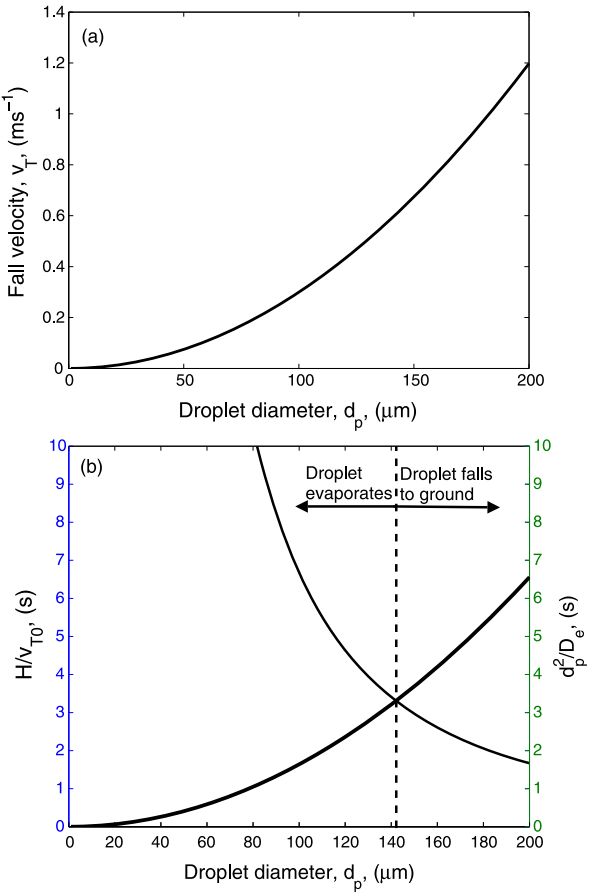


**Fig. 1** (**a**) Variation of droplet fall velocity ($v_T$) with droplet diameter ($d_p$). (**b**) Contrasting the time taken for pure droplets of diameter $d_0$ to evaporate (*thick line*) with the time to fall a height, $H = 2$ m (*thin line*)

Although coughing generates fewer droplets, they tend to be more infectious as the droplets originate from the lungs. Other risks arise from droplets created by projectile vomiting or diarrahea. One well-documented case is of an individual vomiting in a large dining room, and the following day 32 people suffered from vomiting and 19 had fever [15]. Recent analysis has also shown that understanding how droplets move in vortical structures ejected from the nose/mouth can have important implications for forensic science [7, 12].

On the critical aspects, at least for droplets, is that their potential to rapidly evaporate reduces their fall velocity, Fig. 1 (a). The effect of this is to significantly increase the droplets residence time which is known as Wells droplet-nuclei hypothesis [23]. This evaporation is quite dramatic as it means that, for example, a solid particle with a diameter of 100 μm will fall to the ground from a height of 2 m in about 6 s, but a similar sized droplet of pure liquid will evaporate in unsaturated air (at 18 °C) in 1.7 s and will not strike the ground, Fig. 1 (b). On the other hand droplets with a diameter of $> 150$ μm will hit the ground before they have time to evaporate. In reality though, droplets ejected from the mouth typically contain about $R_s = 1.5\%$

[4] of solid matter and even when the liquid in the droplet completely evaporates, the pathogens still have the potential for recurrent infection.

Our focus in this paper is on the movement of droplets within hospital rooms and wards. In this environment the chronically sick and immuno-compromised are based which means that airborne and contact driven transmission can occur and is potentially lethal. Ventilation strategies are prescribed for different areas such as the operating theatre, isolation rooms and general ward. Regulations differ from country to country, but amount to roughly the same, pressure differences between rooms/corridors/toilets and room air changes per hour (ACH). Immuno-compromised patients are placed in positively pressured rooms, while those with infectious diseases, in negatively pressured rooms. The pressure difference is maintained using flap valves and having contrasting inlet and exit volume fluxes. The prescribed pressure difference, between the rooms and atrium, or room and toilet, tends to be quite small (minimum of 2.5 Pa and usually 6 Pa) which means that flow reversal occurs when doors are opened and closed. Tang et al. [19] discussed the case of a nurse acquiring chickenpox from a patient in an isolation room, despite the nurse having never entered the room. The minimum ACH varies from 6 for a ward, 10 for a toilet to 12 for an isolation room. Forced ventilation is typically used in urban hospitals where airborne contaminants are removed by a large ACH and high levels of turbulence to promote mixing. For rural hospitals a combination of natural and forced ventilation tends to be used, where the level of turbulence is lower but the ACH is higher.

There is still debate about which type of ventilation is better. The conclusion from a study of eight hospitals in Lima, Peru was that natural ventilation was more beneficial [8]. A more recent study by showed that for naturally ventilated rooms, the transmission was enhanced because hot breathe in a stratified environment can move horizontally over large distances [18]. Increasing the level of turbulence for instance in an isolation room, is beneficial because this leads to contaminants being uniformly mixed and the mean concentration decreases rapidly due to well-mixed air being removed. But, there are potential dangers for wards where turbulence can lead to material spreading to adjacent beds and cross contaminating other patients. The major question is then, what effect does turbulence have on spreading contaminants, such as droplets in the air?

There have been few studies of evaporating droplets in turbulent flows. There have been a number of computational studies of air movement in rooms and buildings (e.g. [11]) which tend to employ a $k - \varepsilon$ formulation (or in a few cases LES). PIV measurements were taken of the flow in a forced ventilated hospital room to characterise the levels of turbulence [22]. Typical values of velocity and lengthscales of $u_* \approx 0.03$ ms$^{-1}$ and $L \approx 0.09$ m were measured in a hospital room. Rather than take into account all these components, we abstract from this a reduced model where the flow is assumed to be homogeneous turbulence and study its effect on spreading droplets whose properties are changing in time.

In Sect. 2, the mathematical model for analysing the motion of droplets in a turbulent flow is introduced. Also, the diagnostics applied to the numerical calculations will be presented. Numerical results are discussed in Sect. 3. Finally, in Sect. 4 conclusions are made.

## 2 Mathematical Model

Simulating the movement of evaporating droplets in a turbulent environment requires two models, the flow field and how droplets move in time. Kinematic simulation (KS) is a popular method of looking at particle dispersion in turbulence [9, 21], because it describes the flowfield as a continuous field which is simply parameterised by a prescribed energy spectrum. We introduce the main elements of the models before describing the diagnostic tools.

### *2.1 Synthetic Model of Turbulence*

Kinematic simulation provides a means of generating a continuous unsteady velocity field over a range of length scales. In the context of the hospital environment the ratio between the largest and the smallest scales is probably about one, or at most, two decades. The essential feature of KS is to express the velocity field in terms of random Fourier components. The velocity is specified to have a r.m.s. velocity scale $u_*$ and the integral lengthscale $L = 2\pi/k_I$ which largely defines the scale at which energy is injected.

The amplitudes of the Fourier modes are chosen such that the velocity field is isotropic, statistically stationary and homogeneous. The resulting velocity field is:

$$\boldsymbol{u}\big(\boldsymbol{x}(t),t\big) = \sum_{n=1}^{N_k} (\boldsymbol{a}_n \times \hat{\boldsymbol{k}}_n)\cos(\boldsymbol{k}_n \cdot \boldsymbol{x} - \omega_n t) + (\boldsymbol{b}_n \times \hat{\boldsymbol{k}}_n)\sin(\boldsymbol{k}_n \cdot \boldsymbol{x} - \omega_n t). \tag{1}$$

This form is chosen so that the velocity field is incompressible ($\nabla \cdot \boldsymbol{u} = 0$). $\boldsymbol{k}_n$ is a random vector ($\boldsymbol{k}_n = \hat{\boldsymbol{k}}_n |k_n|$) and $N_k$ is the total number of modes. $\omega_n$ is the unsteadiness associated with each mode which is determined by the eddy turnover time of that node, $\omega_n = \lambda \varepsilon^{1/3} k_n^{2/3}$. $\lambda$ is the unsteadiness parameter of O(1) [17]. The energy dissipation rate $\varepsilon = 1.066 u_*^3 k_I$ [10, Table 1]. $\boldsymbol{a}_n$ and $\boldsymbol{b}_n$ are random, uncorrelated vectors whose amplitudes are determined by integrating the prescribed energy spectrum in close proximity of a specific mode. As in [10], the energy spectrum used is:

$$\frac{E(k)}{u_*^2 k_I} = \begin{cases} \frac{1.196\gamma (k/k_I)^4}{(0.558+(k/k_I)^2)^{17/6}}, & 0 < k < k_\eta, \\ 0, & k > k_\eta. \end{cases} \tag{2}$$

This form of energy spectrum is chosen such that at low wavenumbers $E(k) \propto k^4$ which is the Von Kármán spectrum and at high wavenumbers $E(k) \propto k^{-5/3}$ which is the Kolmogorov spectrum. Integral lengthscale and r.m.s. velocity are defined by:

$$L = \frac{3\pi/4 \int_0^{k_\eta} k^{-1} E(k)\,\mathrm{d}k}{\int_0^\infty E(k)\,\mathrm{d}k}, \qquad u_* = \sqrt{\frac{2}{3}\int_0^{k_\eta} E(k)\,\mathrm{d}k}. \tag{3}$$

A constant is introduced to compensate for the wavenumbers above $k_\eta$, e.g. for $k_\eta = 50k_I$, $\gamma = 1.1$.

## 2.2 Equation of Motion of an Evaporating Droplet

The most general approach to study how discrete elements are dispersed is to use a Lagrangian formulation where each droplet is followed in time using an equation of motion based on considering the balance of forces. In this modelling approach the droplets are assumed to be spherical (of diameter $d_p$, density $\rho_p$) moving with velocity $\boldsymbol{v}$ in an airflow $\boldsymbol{u}$. Since droplets of mucus/saliva are much denser than air ($\rho_p \sim 1000\ \mathrm{kg/m^3}$), the equation of motion describing how they move with time is dominated by a balance of buoyancy and drag forces which can be arranged to give:

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\boldsymbol{v}-\boldsymbol{u}}{t_p} - g\hat{\boldsymbol{z}}, \qquad \frac{\mathrm{d}\boldsymbol{X}}{\mathrm{d}t} = \boldsymbol{v}, \tag{4}$$

where $\boldsymbol{X} = (X, Y, Z)$ is the position at time $t$, $g$ is the gravitational acceleration and $t_p$ is the droplet response time. This model is based on a Stokes drag law, where the viscous drag is proportional to the relative slip between the droplet and air (see [6] for instance). Equation (1) is a second-order linear differential equation with a non-linear forcing caused by the air motion [1]. The ability of a small spherical (rigid) particle to respond to changes in the air flow is characterised by a response time $t_p$ defined by:

$$t_p = \frac{d_p^2 \rho_p}{18\mu}, \tag{5}$$

where $\mu = 18.2 \times 10^{-6}\ \mathrm{Nsm^{-2}}$ is the dynamic viscosity of water and the droplet fall velocity is given by:

$$v_T = t_p g. \tag{6}$$

As the droplet moves it loses mass due to evaporation and for small droplets, the diameter decreases as:

$$\frac{d_p}{d_0} = 1 - \frac{t D_e}{d_0^2}, \tag{7}$$

where $D_e = 6.1 \times 10^{-9}\ \mathrm{m^2/s}$ is the evaporative constant for water in unsaturated air (at 18 °C) [23]. This is considered by varying the Stokes number with time depending on the initial droplet diameter, $d_0$. We nondimensionalise the system of equations using the length $1/k_I$ and the timescale $1/u_* k_I$. Equation (4) is unchanged for droplets which lose mass with time (see [5] for justification):

$$\frac{\mathrm{d}\tilde{\boldsymbol{v}}}{\mathrm{d}\tau} = -\frac{1}{St_0(1-\beta/\tau)}(\tilde{\boldsymbol{v}} - \tilde{\boldsymbol{u}}) - \hat{\boldsymbol{z}}\gamma, \tag{8}$$

where the dimensionless parameters are defined by:

$$St_0 = \frac{u_* t_{p0}}{L}, \qquad \beta = \frac{d_0^2 u_*}{D_e L}, \qquad \gamma = \frac{Lg}{u_*^2}, \tag{9}$$

where $t_{p0}$ and $St_0$ are the initial droplet response time and initial Stokes number respectively. Physically, $St_0$ measures the ability of the droplet to respond to changes in the air flow. For large $St_0$ the droplets move ballistically. $\beta$ is a measure of the time it takes for the droplet to evaporate compared to the eddy turnover time, and $\gamma$ is a measure of the acceleration within the air. $St_0$ and $\beta$ are related since $\beta/St_0 = 18\mu/D_e\rho_p$. Thus the general dynamics are represented by a two parameter family, $St_0$ and $\gamma$. The droplet is assumed to evaporate uniformly with time to the point were only 1.5% of the droplet remains. After this, the droplet equation of motion is

$$\frac{\mathrm{d}\tilde{\boldsymbol{v}}}{\mathrm{d}\tau} = -\frac{1}{St_0(1 - R_s^{2/3})}(\tilde{\boldsymbol{v}} - \tilde{\boldsymbol{u}}) - \hat{z}\gamma, \tag{10}$$

since the droplet Stokes number is constant after the droplet has evaporated to leave a solid residue (i.e. $St_0(1 - R_s^{2/3})$).

## 2.3 Diagnostics

We consider droplets released from a fixed height and examine how they spread in time (on average). One particle is released for each velocity field realisation and the results are averaged over $N_R = 200$ realisations. Averaging over the realisations provides a statistical means of interpreting the results. The focus is on the mean droplet trajectory and the variance of the spread of the trajectories:

$$\langle \boldsymbol{X} \rangle(t) = \frac{1}{N_R} \sum_{i=1}^{N_R} \boldsymbol{X}_i, \qquad R(t) = \frac{1}{N_R} \sum_{i=1}^{N_R} \left\| \boldsymbol{X}_i - \langle \boldsymbol{X} \rangle \right\|_E, \tag{11}$$

where $\| \cdot \|_E$ is the Eulerian norm. The spread can be split into its vertical and horizontal components defined as:

$$R_z(t) = \frac{1}{N_R} \sum_{i=0}^{N_R} \left[ \left( Z_i - \langle Z_i \rangle \right)^2 \right]^{\frac{1}{2}}, \tag{12}$$

and

$$R_{xy}(t) = \frac{1}{N_R} \sum_{i=0}^{N_R} \left[ \left( X_i - \langle X_i \rangle \right)^2 + \left( Y_i - \langle Y_i \rangle \right)^2 \right]^{\frac{1}{2}}. \tag{13}$$

## 3 Numerical Results

The parameters considered were the turbulent intensity ($u_*$) and the initial droplet diameter, ($d_0$). $u_*$ was varied between 0.01–0.05 $\mathrm{ms}^{-1}$. To investigate only the effect of $u_*$ on the droplet spread, the integral lengthscale was assumed to be constant at $L = 0.05$ m. The upper end of the velocity scale and the integral lengthscale were chosen based on the PIV measurements of a typical forced ventilation hospital room [22]. The lower end of the velocity scale represents the turbulence in a naturally ventilated room. The droplet diameter was varied between $d_0 = 20$ µm and $d_0 = 100$ µm. This range of diameters was used as most droplets ejected when coughing and sneezing fall into this range.

Figure 2 shows how a packet of particles spreading with time as they sediment. In the absence of evaporative and turbulence effects, the trajectory is shown by a thin full line (derived analytically from (4) with $\boldsymbol{u} = 0$). The inclusion of evaporation (but no turbulence) leads to the droplet diameter decreasing by factor of $R_s^{-2/3}$, thereby decreasing the fall velocity by a factor of $R_s^{1/3}$ ((4) and (10) solved numerically, again $\boldsymbol{u} = 0$). The effect of turbulence (made of random Fourier modes) has a rather weak effect on the mean settling velocity which is consistent with [16], however the residence time for $d_0 = 100$ µm approximately doubled, Fig. 2 (a). More striking is the effect of turbulence on how clouds of particles spread in time. Figures 2 (a), (b) and (c) show graphically the size of spread from the mean position as a function of time. This spread is represented in the figure as a spherical possibility region for the droplet. Figures 3 (a) and (b) presents these results in a dimensionless time with $R/L$ increasing with $u_*t/L$ for $d_0 = 50$ µm and $d_0 = 100$ µm respectively. The droplet spread was found to be independent of the droplet diameter. This is because after evaporative effects the droplets' Stokes number is sufficiently small such that the droplets (irrespective of $d_0$) will follow the fluid streamlines closely. For short time (and $R/L < 1$), $R/L$ increases according to $(u_*t/L)^{3/2}$ which is consistent with Richardson dispersion ([3, p. 277], [10]). For $R/L > 1$, $R/L \sim 0.8(u_*t/L)^{1/2}$, indicating that transport is ultimately diffusive with an effective dispersivity:

$$D_E = \frac{1}{2}\frac{\mathrm{d}R^2}{\mathrm{d}t} = 0.32u_*L. \tag{14}$$

Also, this radius has been split into its horizontal and vertical components, $R_{xy}$ and $R_z$ respectively, Fig. 3 (c) and (d). This shows that the horizontal spread is greater than the vertical spread. This would be expected as the influence of gravity will have the effect of reducing the variance in the vertical direction. Therefore, the spheres in Fig. 2 are a simplification, as they assume $R_{xy} = R_z$ (in fact $R_{xy}/R_z \approx 1.25$).

The influence of turbulence on the average fall velocity is negligible to leading order so that the average fall velocity depends on the droplet diameter after evaporation:

$$\langle v_T \rangle = R_s^{2/3} \langle v_{T0} \rangle. \tag{15}$$

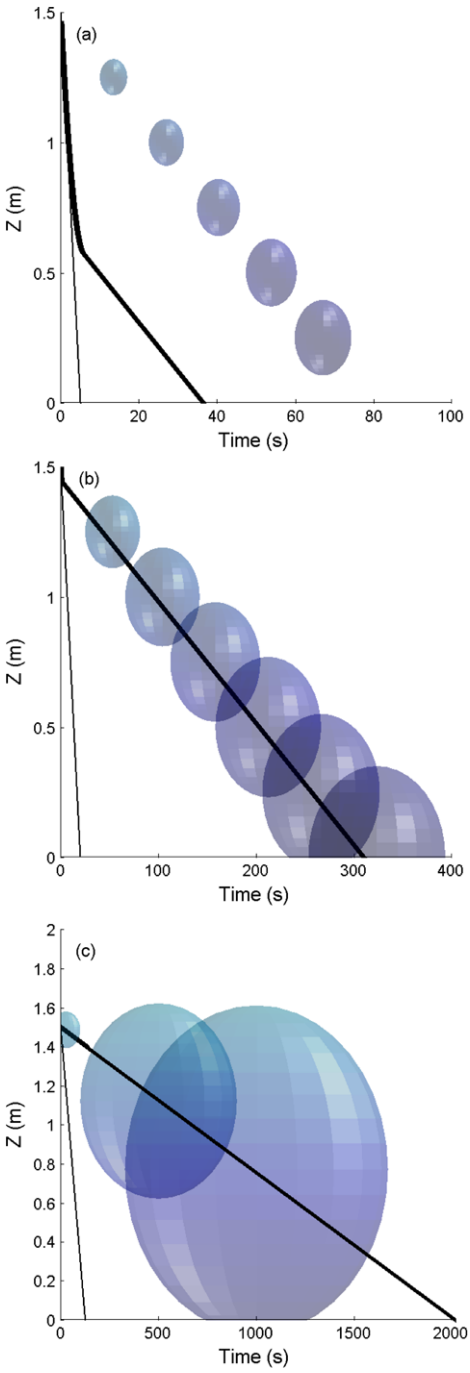


**Fig. 2** Evaporating droplet in turbulence: (**a**) $d_0 = 100$ µm, (**b**) $d_0 = 50$ µm and (**c**) $d_0 = 20$ µm. *Spheres*: numerical; evaporating with turbulence ($u_* = 0.01$ ms$^{-1}$ and $L = 0.05$ m). *Thin line*: analytical; non-evaporating with no turbulence. *Thick line*: numerical; evaporating with no turbulence

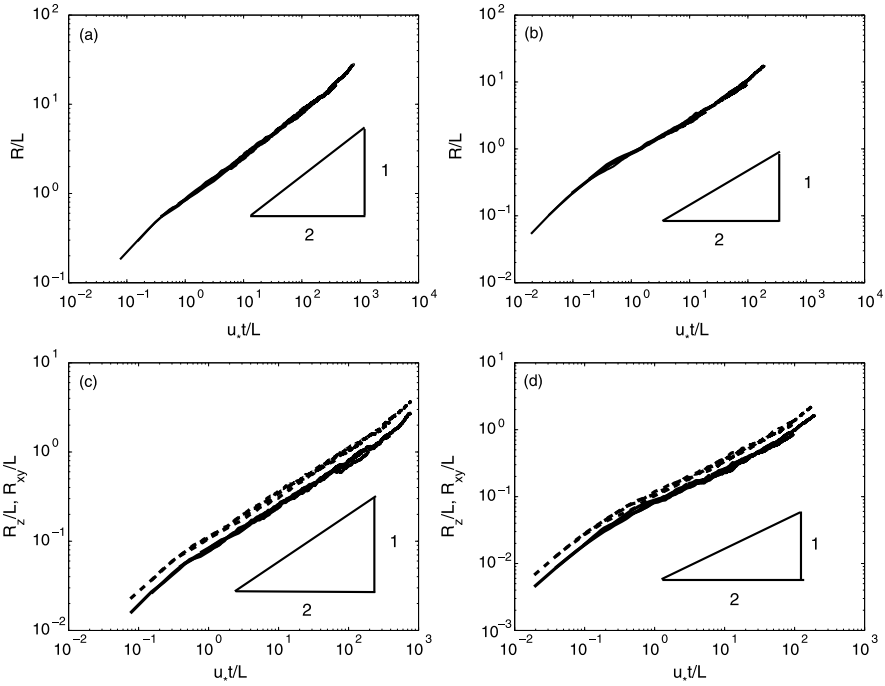


**Fig. 3** Variation of $R/L$ with $u_* t/L$ for (**a**) $d_0 = 50$ μm and (**b**) $d_0 = 100$ μm. Variation of $R_{xy}/L$ and $R_z/L$ with $u_* t/L$ for (**c**) $d_0 = 50$ μm and (**d**) $d_0 = 100$ μm. In these calculations $L = 0.05$ m and $u_* = 0.01, 0.02, 0.05$ ms$^{-1}$

The average time taken to fall through a vertical distance $H$ is:

$$t \sim \frac{H}{R_s^{2/3} \langle v_{T0} \rangle}. \tag{16}$$

The radius of the clouds shown in Fig. 2 (when their centre meets the ground) can be estimated from (14), (15) and (16) to be:

$$R_c \sim 0.8 \left( \frac{u_* H L}{R_s^{2/3} \langle v_{T0} \rangle} \right)^{1/2}. \tag{17}$$

Figure 4 shows this variation of the cloud radius with droplet diameter for two contrasting values of $u_* = 0.01$ ms$^{-1}$ and $u_* = 0.05$ ms$^{-1}$. Also included in this figure is an estimation of the cloud radius with $u_*$ and $L$ from [22].

Considering the above in a hospital environment. As stated, turbulence can have the effect of shortening or lengthening a droplets residence time, Fig. 2. From [2] a cough or a sneeze has a droplet distribution peak at around 10 μm. The closest droplet size from these numerical experiments (i.e. 20 μm), after approximately 1000 s or 20 minutes a droplet might have hit the floor or may still be at a height of 1.5–1.6 m, Fig. 2 (c). This is quite remarkable as not only could a droplet be

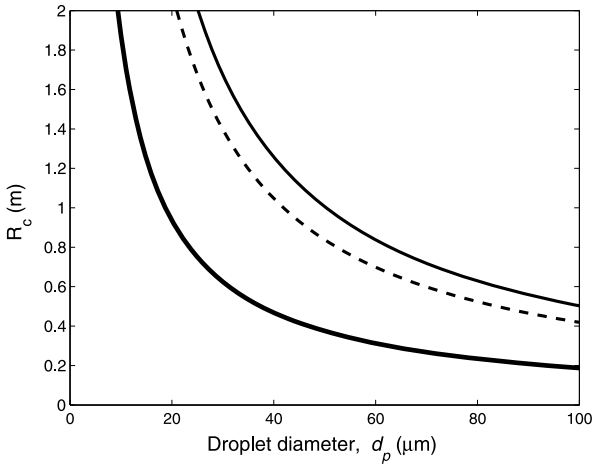


**Fig. 4** Variation of $R_c$ with droplet diameter ($d_p$), according to Eq. (17). $H = 2$ m assumed. *Full thick* and *dashed line* indicates $u_* = 0.01$ ms$^{-1}$ and $u_* = 0.05$ ms$^{-1}$ respectively ($L = 0.05$ m). *Thin line* indicates $u_* = 0.03$ ms$^{-1}$ and $L = 0.12$ m (estimated values from [22])

inhaled/ingested by other patients it is likely that staff clothes will come into contact with any remaining droplet aiding indirect (person-object-person) transmission. It should be noted that not all inhaled/ingested droplets will result in disease [24]. However, as it is estimated that a cough or a sneeze has between 3,000–40,000 droplets the risk is certainly there. Figure 4 shows that for values of $u_*$ and $L$ measured in a hospital [22], a droplet of $\approx 30$ μm will move nearly 2 m. Considering that these calculations have also been carried out without a mean flow present which is likely to be present in a hospital, they represent quite conservative estimates on droplet spread. Therefore, the concept of bed-spacing, currently recommended to be at least 1–2 m apart [25], though some more recent guidelines recommend 2.5–3.6 m apart [14], as being sufficiently well-separated enough to significantly reduce the likelihood of infectious agents transmitting between patients in neighbouring beds via coughed or sneezed droplets, is therefore also probably unreliable.

The limitations of the model applied need to be highlighted. Firstly, this formulation does not include the kinematic effect of boundaries on a flow. KS makes the assumption that there is homogeneous turbulence. Also, other sources of turbulence in the hospital as a result of people moving, doors opening/closing and thermal plumes cannot be ignored in most healthcare settings.

## 4 Conclusion

The effect of a synthetic homogeneous turbulence on droplet spread in the context of the hospital environment was studied. Homogeneous turbulence was simulated using the well known technique kinematic simulation. The flow was characterised by $u_*$ and $L$ (using typical values found in a hospital environment). Three different configurations were considered; no evaporation/no turbulence, evaporation/no turbulence and evaporation/turbulence. Although the first two models have been

studied extensively, the third (the effect of turbulence) has not. The effect of turbulence was to significantly increase residence time for larger droplets $d_0 = 100$ μm. The droplet spread from the mean position showed that droplets can move large distances and that this, together with increased residence time can lead to increased disease (direct or indirect) transmission. Therefore it is not only evaporation but also turbulence which is responsible for the long residence time of the droplet in the air. Taking this into consideration, increased turbulence should be welcome in isolation rooms where there is no risk of infecting other patients and the increased mixing (due to the turbulence) helps decrease the mean contaminant concentration. However, turbulence levels in general wards should be strictly monitored to avoid cross contamination between patients. Therefore this study urges a conceptual shift in how infection control should be approached in modern healthcare settings, particularly in the current global pandemic influenza situation. Hence, perhaps true physical barrier isolation is the only reliable means of isolating an individual infected with an aerosol- or airborne-transmissible infectious agent.

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