Invited lecture/Reflection

Physics of Respiratory Pathogen Transmission Through Droplets and Aerosol

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Abstract:
Recent epidemic of the COVID-19 (CoronaVirus Disease-19), caused by SARS-CoV-2 virus exposed great gaps in the understanding of respiratory transmitted diseases in many public health institutions. Traditionally, respiratory pathogens are believed to spread through: direct physical contact (like spray of droplets onto mucous membrane), indirect contact with contaminated surfaces (known as "fomites") and inhalation of aerosols. Public health has relied on a strict split between heavy falling droplets and lighter air-lingering aerosols. In this review we take a look at this distinction, comment on potential problems of its definition and examine a few basic physical phenomena affecting airborne droplet behaviour. We conclude that droplets smaller than 10 μm tend to linger in the air for extended periods of time and that air circulation has a big impact on the presence of pathogen-carrying particles in the air, which may help craft better public health policy.

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1. Mechanisms of particle generation

There are several mechanisms that generate particles appropriate for pathogen transmission. These include mainly natural human respiratory activities such as talking, breathing, sneezing, and coughing. Studies suggest that breathing generates particles through condensation and high-speed atomization (Jennison, 1942). Warm gas cools down when entering the upper airways and as a result condenses and is expelled in the form of particles during exhalation. Increasingly turbulent airflow during sneezing, coughing, singing or talking results in a further atomization of particles. Recent studies also suggest that during inhalation, re-opening of small airways contributes to particle generation. (Almstrand et al., 2010; Johnson et al., 2009). Some researchers point to energetic vibration of vocal chords as a source of the majority of particle generation (Morawska et al., 2009). Recently developed time-resolved laser-light scattering method showed that far more droplets are generated than could be previously detected (Anfinrud et al., 2020).

2. Distinction between droplets and aerosols

Droplet transmission is defined as transmission of diseases by expelled particles with a propensity to, due to their size, settle quickly, generally within 1 meter of the site of generation (Wells, 1934).

To help us deal with certain diseases that transmit in these ways a distinction of droplets and aerosols is in use. This distinction leans on a few different assumptions: (i) respiratory disease transmission can be viewed in binary manner through larger droplets or smaller aerosols, (ii) this distinction depends on droplet size alone, (iii) the cut off between droplets and aerosols is set at 5 microns and (iv) there is also a strict cut off in distance at which each size of droplets matters.

This definition can be problematic because it assumes a strict exact size (5 microns) at which a droplet is too big to hang in the air and is assumed to fall to the ground or nearby surface in a few seconds. It is also assumed that droplets of size greater than 5 microns travel on average a maximum of 1 to 2 meters from the source (normally a contagious person speaking, breathing, talking, coughing or singing) and are assumed to follow a ballistic trajectory. This is not in accordance with droplet physics where droplets of various sizes, some much greater than 5 microns, can travel much further than 2 meters and can hang in the air much longer, due to various physical phenomena affecting them once surrounded in ambient air. In the case of SARS-CoV-2 the time spent in the air can even reach a few hours. This means that there is no strict discrete point at which droplets hang in the air or fall to the ground. Instead, there is a continuous distribution that depends on various external factors, most importantly relative humidity. Virus transmission is also affected by other factors such as human behaviour (staying indoors in colder seasons), ventilation, ultraviolet radiation and human immune function.

3. Influences on particle size

Many biological factors that are host-specific can influence the size of generated particles. Here we will take a quick look at the physics content, mainly relative humidity, evaporation and aggregation.

3.1 Relative humidity

A conceptually important start to understanding the relationship between evaporation, particle size and transmission are Wells curves (**Figure 1**). These curves tell us whether a particle will evaporate before reaching the ground or not (Wells, 1934). Of course this is a generalization, as a lot of factors influence particle behaviour and evaporation speed. Since the first publication of Wells curves, corrections have been made and smaller particle sizes were identified to suit the condition of fall time being equal to evaporation time. Particles with radius smaller than 50 microns completely evaporate before reaching the ground (Wan et al., 2007; Nichol et al., 2008). It was found that 95% of all particles generated by human respiratory activity had radii of 50 microns or smaller (Duguid, 1946). Later studies showed that many droplets generated by coughing or speaking fall in the submicron radius range (Papineni et al., 2020). Further, evaporation time can be affected by relative humidity. Generally, higher relative humidity is being responsible for longer time taken to reach equilibrium size. Relative humidity can even affect the equilibrium size itself as well as the travel trajectory of particles. It is indicated that increase in vertical and lateral movement of particles is connected to decreased relative humidity (Wells, 1934; Schaffer et al.,1976).

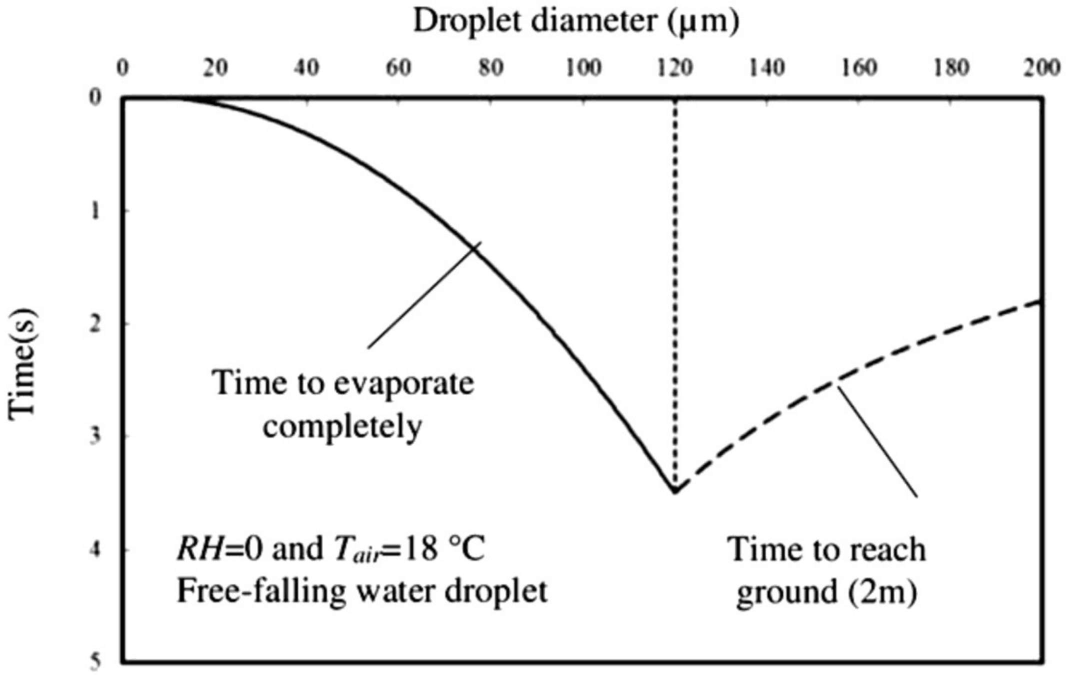

Figure 1. Wells curves showing the relationship between the size of generated particle and evaporation time. Assumed relative humidity of 0%, steady air temperature of 18 degrees Celsius and particle generation at a height of 2 meters and particles modelled as rigid spheres.

Outdoor temperature indirectly influences indoor relative humidity (RH). Especially in winter times, outdoor temperature is lower so heating the buildings dries the cold air that enters into indoor areas, resulting in a drop of RH. This causes that indoor RH in winter times would be between 10% and 40%, compared to summer indoor RH being between 40% and 60% (Božič et al., 2021).

RH influences transmission of infectious material in different ways. First, it impacts how far the droplets can travel through air. Second, stability of winter viruses in droplets is correlated with lower values of RH (between 20% and 50%), while stability of summer viruses is enhanced at higher RH values (around 80%) (Moriyama et al., 2020). Lastly, dry air dries the mucous membrane making it easier for foreign bodies such as infectious viruses to invade the respiratory tract.

1.1 Aggregation

Particles may grow in size due to aggregation with other particles. For this to happen a sufficient concentration of particles is required (Verreault et al., 2008). Aggregation speed depends on multiple factors such as particle size distribution, concentration of aerosol and thermodynamic conditions (Wichmann et al., 2000).

2. Physical phenomena affecting airborne droplets

2.1 Droplet sedimentation without evaporation

A basic equation used for understanding sedimentation times of droplets is

$$\tau_{sed} = C\frac{z_0}{R^2} \qquad (1)$$

where the numerical prefactor turns out to be $C = 0.85 \times 10^{-8}$ m s, z_0 represents the height at which the droplet is initially placed and R represents the droplet radius (Netz, 2020). In standard practice in public health a radius of R = 5 µm is considered the threshold below which droplets are considered relevant for infections as they linger in the air for extended periods of time. The above equation is considered a good estimate for typical sedimentation times for all droplets with $R > 10$ nm. Acceleration effects can be neglected as droplets reach terminal velocity in extremely short times.

2.2 Droplet evaporation without nonvolatile solutes

As droplets evaporate, their radius decreases, which in turn increases sedimentation time. Evaporation of droplet at rest causes time-dependent decrease of droplet radius. This occurs in diffusion-limited evaporation scenario, valid for droplets with radii larger than 70 nm.

$$R(t) = R_0(1 - \theta t(1 - RH)/R_0)^{1/2} \qquad (2)$$

$$\theta = 2D_w c_g v_w \left(1 - \frac{\varepsilon_C \varepsilon_T}{1+\varepsilon_C \varepsilon_T}\right) = 4.2 \times 10^{-10} \ \mathrm{m^2/s} \qquad (3)$$

where R_0 is the initial droplet radius, RH is relative humidity, and $\theta = 4.2\times 10^{-10}$ m²/s at 25 °C. (Netz, 2020) and the meaning and the values of the Equation (3) parameters are given in **Table 1**,

Table 1. Parameters of Equation (3).

D_w	Water diffusion constant in air	2.5×10^{-5} m²/s at 25 °C
v_w	Liquid water molecular volume	3.00×10^{-29} m³ at 25 °C
c_g	Saturated vapor water concentration	7.69×10^{23} m⁻³ at 25 °C
ε_C	Linear coefficient	0.032 K⁻¹
ε_T	Temperature coefficient	55 K

Important factor that affects evaporation time is cooling of droplet surface due to evaporation. Water vapor at droplet surface has a temperature that is lower than the temperature of the surrounding air. Value of this temperature decreases in proportion to relative humidity. At RH = 0, the droplet surface temperature drops for about 20 °C. Even though this effect is significant, droplets do not freeze at ambient temperatures of 20 °C or higher. At lower temperatures however, evaporation cooling can induce freezing and even further slow down evaporation times. Evaporation cooling effect is accounted for with the factor given by

$$\left(1 - \frac{\varepsilon_C \varepsilon_T}{1+\varepsilon_C \varepsilon_T}\right) = 0.36. \qquad (4)$$

If the radius of the droplet becomes smaller than 70 nm, a transition to reaction-rate-limited evaporation regime occurs. Internal mixing due to diffusion can be neglected as it is sufficiently fast for radii below about 100 µm and inhomogeneities in concentration can be neglected. Evaporation time can be approximated by

$$\tau_{ev} = \frac{{R_0}^2}{\theta(1-RH)}. \qquad (5)$$

The important observation is that evaporation time increases quadratically with respect to initial radius R_0 (Equation (5)) while sedimentation time decreases quadratically with respect to R_0 (Equation (1)). For a droplet generated at height of 2 m, at RH = 0.5, critical initial radius below which droplets completely evaporate before reaching the ground is ${R_0}^{crit} = 52$ μm. As RH decreases, critical initial radius increases, with ${R_0}^{crit} = 61$ μm at RH = 0 (**Table 2**).

Table 2. Sedimentation and evaporation times. (Netz, 2020, [12])

R_0 (μm)	1	2.5	5	10	30	40	55
τ_{sed} (RH = 1)	5 h	45 min	11 min	43 s	19 s	11s	5.6 s
τ_{ev} (RH = 0.5)	0.0048 s	0.030 s	0.12 s	0.48 s	4.3 s	7.7 s	14.5 s
${\tau_{sed}}^{RH}$ (RH = 0.5)	∞	∞	∞	∞	∞	∞	7.6 s
${\tau_{sed}}^{sol}$ (RH = 0.5)	64 h	10 h	154 min	38min	231 s	99.6 s	7.6 s

R_0 represents the initial droplet radius, τ_{sed} (RH = 1) is sedimentation time without evaporation, τ_{ev} (RH = 0.5) is evaporation time at relative humidity of 50% and without any non-volatile solutes, ${\tau_{sed}}^{RH}$ (RH = 0.5) is sedimentation time in absence of non-volatile solutes at relative humidity of 50%, and ${\tau_{sed}}^{sol}$ (RH = 0.5) is sedimentation time at relative humidity of 50% and containing non-volatile solutes inside the droplet of initial volume fraction of 1%. All times are measured from height of 2 meters.

2.3 *Droplet evaporation containing nonvolatile solutes*

Droplets containing non-volatile solutes are unable to completely evaporate. As a result, the amount of reduction of the droplet radius through evaporation has a lower limit. Solutes in water droplets decrease the water vapor pressure and therefore limit the decrease of the droplet radius,

$$R_{ev} = R_0\left(\frac{\Phi_0}{1-RH}\right)^{1/3} , \qquad (6)$$

where Φ_0 is the initial volume fraction of solutes in water droplet. Droplet evaporation all the way to its lower limit of radius is only possible at RH = 0. A good approximation for evaporation time in the presence of nonvolatile solutes in water droplets is

$${\tau_{ev}}^{sol} = \tau_{ev}\left(1 - \frac{{R_{ev}}^2}{{R_0}^2}\right) . \qquad (7)$$

As a result, sedimentation of droplets containing non-volatile solutes (such as pathogens) can be divided in two stages. In the first stage the radius of the droplet shrinks according to the above equations. In the second stage the droplets sediment for a prolonged time at a constant radius. Sedimentation time is given by

$${\tau_{sed}}^{sol} = \frac{Cz_0}{{R_{ev}}^2} - \frac{\tau_{ev}}{2}\left(\frac{R_0}{R_{ev}} - \frac{R_{ev}}{R_0}\right)^2 . \qquad (8)$$

3. Airborne time of aerosol particles

Lifetime of aerosols and air time are important in the context of viability to transmit viral loads. Pathogens capable of surviving a couple of minutes and even a couple of hours, carried in small aerosol particles are capable of circumventing a large portion of public health safety measures such as social distancing.

Since aerosols are incredibly small (typically $< 10\ \mu m$) the turbulent ambient air affects them more than gravity (Somsen et al., 2020) In addition, smaller aerosols have the ability to enter deeper into the respiratory tract and pose a potential risk of a more severe infection. (Somsen et al., 2020) Whether SARS-CoV-2 can transmit by such means is still inconclusive but recent studies suggest a strong possibility for aerosol infections being possible in SARS-CoV-2. (Duval et al., 2022])

In a study on aerosol lifetime in different ventilation conditions (natural home ventilation, common mechanical ventilation and strong mechanical ventilation) (Ding et al., 2021) it was found that aerosols generated by speech decreased exponentially but remained present in the air for up to 9 hours in stagnant air with natural ventilation. For non-stagnant conditions, the number of aerosols from speaking or coughing fell exponentially across all experimental conditions and fell back to near background levels. Half-life of aerosol particles generated by coughing was slightly higher than that of speaking (by about 4% - 38%), independent of measurement methods. Half-life of aerosol particles declined with increase in air change (ventilation) (Ding et al, 2021).
We can see that social distancing is not a sufficient method for stopping the transmission of airborne aerosol-carried viruses. Proper ventilation on the other hand is a viable and effective precaution to combating virus spread.

Conflicts of Interest: The author declares no conflict of interest.

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