Aerosol Science and Technology

ISSN: 0278-6826 (Print) 1521-7388 (Online) Journal homepage: https://www.tandfonline.com/loi/uast20

What aerosol physics tells us about airborne pathogen transmission

Yannis Drossinos & Nikolaos I. Stilianakis

To cite this article: Yannis Drossinos & Nikolaos I. Stilianakis (2020) What aerosol physics tells us about airborne pathogen transmission, Aerosol Science and Technology, 54:6, 639-643, DOI: 10.1080/02786826.2020.1751055

To link to this article: https://doi.org/10.1080/02786826.2020.1751055

Published online: 13 Apr 2020.

AEROSOL SCIENCE AND TECHNOLOGY
2020, VOL. 54, NO. 6, 639–643
https://doi.org/10.1080/02786826.2020.1751055

Taylor & Francis
Taylor & Francis Group

EDITORIAL

What aerosol physics tells us about airborne pathogen transmission

Modes of transmission of respiratory pathogens: Why are they important?

While a global pandemic by SARS-CoV in 2002–2003 was averted by fast identification, effective surveillance, and quarantine, such measures cannot be easily transferred to new situations, as the case of SARS-CoV-2 demonstrates. Knowledge of the fundamental biological and physical parameters affecting transmission pathways of respiratory pathogens is thus critical for the design of effective non-pharmaceutical intervention strategies. Respiratory pathogens are transmitted via respiratory droplets containing lung fluid laden with infectious pathogens. The generation, transport and eventual fate (deposition, inhalation) of respiratory droplets are key processes in the transmission pathways of respiratory pathogens.

Respiratory droplets are generated within the human respiratory tract, thoracic or extrathoracic, with possibly different pathogen loads, or upon release from an infected person via lung-fluid fragmentation (Bourouiba, Dehandschoewercker, and Bush 2014). They are expelled by expiratory events that include violent events such as coughing or sneezing and quiescent ones such as talking, breathing, or laughing. Respiratory droplets have been associated with three modes of pathogen transmission: in the medical literature, these are referred to as "contact," "droplet," and "airborne" transmission modes (Weber and Stilianakis 2008a).

Contact transmission, be it direct or indirect, occurs via contact with pathogen-laden droplets: transfer of pathogens via physical touch between a susceptible and an infected host (e.g., hand contact) is classified as direct contact transmission, whereas transfer mediated by fomites containing settled droplets is classified as indirect contact transmission. Droplet transmission refers to transmission by large droplets (diameter $d_p > 20$ microns) that are transported by the turbulent air flow generated by a violent expiratory event. They are, subsequently, sprayed and directly deposited upon the conjunctiva or mucus membranes of a susceptible host. Since large droplets gravitationally settle rather quickly, droplet transmission is considered important at close range: in still air, a 50-micron droplet crosses a vertical 1.5 m distance in 20 s (Drossinos and Housiadas 2006). Airborne transmission, also referred to as "aerosol transmission," refers to pathogen transmission via inhalation of small respiratory droplets (typically smaller than 10 microns: a 10-micron droplet settles gravitationally in still air within approximately 9 min). Being relatively small they may deposit deep into the respiratory tract, including the alveolar region. These droplets, often referred to by the confusing term "droplet nuclei," are small enough to remain airborne for sufficient time to transmit the pathogen. Hence, airborne transmission does not require direct face-to-face contact.

The demarcation between the three transmission modes is not clearly specified, as it is not based on well-defined droplet physical properties or their dynamics, often creating confusion. For example, droplets associated with droplet transmission may be transported by a turbulent jet and subsequently inhaled.

The classification of transmission modes depends on the size of the droplets. The size distribution of expelled droplets has been a subject of considerable research and controversy (partly attributable to different instrumentation or collection methods). Nevertheless, it is reasonable to consider that respiratory-droplet diameters vary from 0.5 microns to 1000 microns (Duguid 1946; Loudon and Roberts 1967, Papineni and Rosenthal 1997; Chao et al. 2009; Morawska et al. 2009; Asadi et al. 2019). Care should be exercised in interpreting droplet sizes. Respiratory droplets are generated in a nearly 100% relative-humidity environment. Upon exhalation into the lower-humidity ambient environment they shrink by evaporation (a fast molecular process, of the order of seconds or less, depending on droplet size, composition, and relative humidity) to reach their equilibrium diameter. Some estimates suggest that droplets may shrink to about half their original size (Nicas, Nazaroff, and Hubbard 2005, Parienta et al. 2011).

Not all pathogen transmission modes are relevant for all respiratory infections. The dominant transmission mode will depend on the interplay of a number of factors, including frequency of violent droplet-generating events (coughing, sneezing), droplet size distribution, ambient relative humidity, viral load, virus inactivation rates, deposition location of inhaled droplets in the airway, and infectious dose. The identification of the dominant transmission mode is essential for a proper and efficient strategy to control the spread of an epidemic, including the proper choice of personal protective equipment. The companion *Aerosol Science and Technology* Editorial (Asadi et al. 2020) argues cogently for the

importance of airborne transmission of the SARS-CoV-2 virus, similarly emphasized in the recent analyses of its aerosol and surface stability (van Doremalen et al. 2020). Transmission via settled droplets, direct or indirect contact transmission, albeit important, is beyond the scope of this Editorial. Lastly, we assume that most transmission events occur indoors.

Epidemic theory: Basic reproduction number

The fate of pathogens within a respiratory droplet depends on physical and biological processes. Physical processes determine the droplet (and thus pathogen) airborne lifetime. The dynamics of an expelled droplet is complex depending on environmental and physiological factors: evaporation, and related heat and mass exchanges with the environment for specific droplet chemical compositions (Parienta et al. 2011; Chen and Zhao 2010; Xie et al. 2007); ambient relative humidity and temperature; convection, ventilation (Chen and Zhao 2010); droplet diameter; buoyancy of the expelled multiphase turbulent cloud (Bourouiba, Dehandschoewercker, and Bush 2014); deposition mechanisms (gravitational settling); inertial and drag forces. Brownian motion may be neglected. Biological processes determine pathogen survival within the droplet, i.e., viral inactivation. Inactivation is biologically determined, and it may be influenced by external factors: for example, UV radiation increases the inactivation rate of influenza viruses (Weber and Stilianakis 2008b).

A quantitative measure of the interplay between these processes is encompassed in the basic reproduction number R_0 (Heesterbeek and Dietz 1996; Delamater et al. 2019). The basic reproduction number provides an estimate of how an epidemic may develop. It is defined as the average number of secondary infections caused by a single infected individual introduced in a fully susceptible population. As such, it is used to estimate whether an epidemic will spread ($R_0 > 1$) or die out ($R_0 < 1$). It describes the transmissibility of the pathogen or, in terms of infections, the number of secondary infections (cases) per infectious individual. Dynamically it is a bifurcation point; viewed as a threshold it informs about the potential of an outbreak to be established, and thereby helps to assess the effectiveness of control strategies. In addition, its parameter dependence suggests intervention strategies. In compartmental epidemiological models that analyze the interactions between Susceptibles (S), Infected (I), and Recovered (R), referred to as SIR models, R_0 determines the local stability of the disease-free equilibrium state.

The SIR basic reproduction number for infectious diseases whose pathogen carriers are respiratory droplets, depends on the transmission rate per inhaled droplet β_d, the droplet generation rate κ_d, the droplet removal rate α_d, and the infection recovery rate γ_i (Stilianakis and Drossinos 2010)

$$R_0 = \frac{\beta_d \kappa_d}{\alpha_d} \frac{1}{\gamma_i}.$$

The transmission rate per inhaled droplet is

$$\beta_d = c \frac{B}{V_{cl}} \tau_{ct} p_d q_d \rho_p(d_d) \frac{\pi}{6} d_d^3,$$

where the number of person-to-person contacts per day is c, the average personal breathing rate B, the personal cloud volume V_{cl}, the characteristic breathing (contact) time τ_{ct}, the infection probability per inhaled pathogen p_d, the inhaled droplet lung-deposition probability q_d, and the pathogen concentration in the lung fluid $\rho_p(d_d)$. The droplet diameter is d_d. The droplet removal rate couples biological and physical processes: μ_p is the pathogen inactivation rate while θ_d is the gravitational settling rate,

$$\alpha_d = \theta_d + \mu_p.$$

The importance of each parameter, i.e., whether its value is benign or not, is assessed by evaluating whether it results in R_0 values greater than or less than one. Intervention strategies aim at reducing the basic reproduction number, if possible below the threshold of unity. For instance, the droplet generation rate decreases if an infected individual wears a surgical mask. Surgical masks, usually composed of cotton layers, limit the expulsion of potentially infected biological fluids from an infected person (Milton et al. 2013). They protect nearby susceptibles, but not individuals who wear them for their own protection since some respiratory droplets shrunk by evaporation are small enough to penetrate normal fibrous materials; that is, these surgical masks constitute source control. Alternatively, saline delivery into the lung may limit the number emission of bioaerosols by stabilizing the airway lining fluid/air interface (Watanabe et al. 2007).

The emitted-droplet size may depend on the location of droplet generation because newly generated droplets may deposit within the lung before expiration, and so not be emitted at all (Longest and Vinchurkar 2009). A droplet in a low relative-humidity environment would shrink more than at higher humidity. This change would modify its transport properties and settling rate. A decreased settling rate would decrease the droplet removal rate and thence increase R_0. Pathogen inactivation may be accelerated by exposing droplets to, for instance, ionizing radiation. UV radiation (Weber and Stilianakis 2008b) and the ill-defined "open-air factor" (Hobday 2019) are natural virucidal agents and can contribute significantly to virus inactivation.

However, the most important quantity, and the quantity addressed by most intervention measures, is the transmission rate per inhaled droplet. Social distancing, whether individual or population-based, aims to minimize the number of person-to-person contacts and contact duration. Droplet pathogen load depends on the location

of droplet generation: it is currently accepted that high SARS CoV-2 viral loads are present in the upper respiratory tract (a possible reason for asymptomatic transmission, van Doremalen et al. 2020). The deposition location within the respiratory tract of inhaled droplets and the deposition fraction depend sensitively on droplet composition and droplet diameter: hygroscopic growth within the lung may be important (Mitsakou, Helmis, and Housiadas 2005).

The infection probability per inhaled droplet decreases when susceptibles wear well-fitted respirators, a susceptible control measure. In addition to proper face-seal fit, an important characteristic of a respirator is the filter efficiency. In the U.S., NIOSH certified respirator filters are characterized by their resistance to oil (Non-resistant [N], Partially resistant, Resistant) and the minimum percentage filtration efficiency in standardized test (95, 99, and 100%). In the European Union they are referred to as Filtering Face Pieces 1, 2, or 3 (FFP1/2/3) with a minimum filtration efficiency of 80, 94, and 99%, respectively. Filtering facepiece respirators of at least N95 (CDC 2020) or FFP2 (ECDC 2020a) are recommended to protect the wearer against airborne pathogens. The particle removal efficiency of respirator filters exhibits the standard U-shaped filter efficiency curve, with a minimum at approximately a few hundred nanometers. Larger particles are captured by inertial impaction and interception, while smaller by Brownian motion.

Respiratory droplet transport: How and why it influences transmission

Epidemiological models often assume that the susceptible and infected populations are homogeneously mixed. The basic reproduction number R_0 was calculated assuming populations and droplets are homogeneously mixed. Spatially dependent SIR models where human populations diffuse have been developed, and they have been extended to include droplet diffusion and convection due to indoor ventilation (Robinson, Stilianakis, and Drossinos 2012). These transport mechanisms introduce additional time scales that may be used to define dimensionless numbers to complement the basic reproduction number: for example, the person or droplet diffusive timescales, or a convective time scale. Model results suggest that in closed, ventilated indoor environments a critical ventilation velocity exists such that droplets generated by an infected individual are rapidly transported out of the domain, causing minimal infection as they travel through the susceptible population. For smaller velocities airborne infection is predicted to occur since droplets are transported slowly through the susceptible population, increasing the probability of infection.

Complementary to the Eulerian description of diffusing and convected droplets, Lagrangian tracking of droplets in turbulent jets has been extensively used. Lagrangian tracking considers explicitly droplet inertia (and thus the droplet Stokes number). This is an area of active research. Literature results suggest that the horizontal distance traveled depends on relative humidity dependent droplet diameter, expelled-air velocity and buoyancy. Estimates (Ji et al. 2018; Liu et al. 2017) vary from one-meter horizontal distance traveled by a 100-micron droplet (initial droplet diameter when expelled from the respiratory tract, and jet horizontal cough velocity of 10 m/sec, whereas about 4 m/sec is expected for speaking) to approximately two-three meters for a 60-micron droplet, and more than three to four for a 20-micron droplet. The importance of cloud dynamics was emphasized by Bourouiba, Dehandschoewercker, and Bush (2014) who argue that without cloud entrainment inhalable droplets would settle within centimeters from the ejection location (mouth). Inclusion of cloud dynamics extends the distance traveled to a few meters (2.5 m) for a 30-micron droplet, with considerable upwards (towards the ceiling) movement. Xie et al. (2007) suggest that under many circumstances (droplet diameter larger than 80 microns), the distance crossed is approximately 1.5 m. They also calculate much longer distances (5 to 6 m) for very large exhaled-air velocities (50 m/sec). Parienta et al. (2011) also find long horizontal distances, the minimum distance being approximately 1 m for 100-micron droplets. Similarly, Bourouiba, Dehandschoewercker, and Bush (2014) argue that the competition between droplet momentum and settling rate leads to a non-monotonic dependence of the horizontal distance crossed on the droplet diameter. It is apparent that these estimates are in conflict with the standard demarcation of the three respiratory pathogen transmission modes used in the medical literature, whereby droplet transmission is viewed as distinct from airborne transmission.

Current social distancing recommendation is that a minimum person-to-person distance of at least one meter (ECDC 2020b), and rather 1.5–2 meters (CDC 2020), be maintained. This should be considered as a minimum threshold value: the horizontal distance crossed is a sensitive function of droplet diameter, relative humidity, and respiratory-jet velocity. Current experimental and modeling studies find longer horizontal distances depending on environmental and physiological conditions. Epidemiological and numerical evidence suggests that a one-meter distance (or 1.5 to 2 m) is a reasonable compromise between social and societal needs and current knowledge of droplet transport and dispersion.

Aerosol science and airborne pathogen transmission

The issue of airborne transmission of pathogens holds significant public health implications, as the current

SARS CoV-2 epidemic manifests. Numerous public health decisions (protective equipment, control strategies, communication to the public) depend on quantitative estimates that aerosol scientists, in collaboration with the medical community, are in a position to provide. The emission rates of respiratory droplets, their size distribution, their generation mechanism within and outside the infected host, and their dispersion and transport in still air and ventilated indoor spaces are all topics upon which aerosol scientists are especially equipped to offer critical data in order to contribute to informed public health choices and the well-being of our society.

Acknowledgments

We thank Panos Cavoulacos, Thomas Weber, and Anthony Wexler for insightful comments.

Disclaimer

The views expressed in this article are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

ORCID

Yannis Drossinos http://orcid.org/0000-0002-8059-9636

References

Asadi, S., A. S. Wexler, C. D. Cappa, S. Barreda, N. M. Bouvier, and W. D. Ristenpart. 2019. Aerosol emission and superemission during human speech increase with voice loudness. *Sci. Rep.* 9(1): 2348. doi: 10.1038/s41598-019-38808-z.

Asadi, S., N. Bouvier, A. S. Wexler, and W. D. Ristenpart. 2020. The coronavirus pandemic and aerosols: Does COVID-19 transmit via expiratory particles? *Aerosol Sci. Technol.* doi: 10.1080/02786826.2020.1749229.

Bourouiba, L., E. Dehandschoewercker, and J. W. M. Bush. 2014. Violent expiratory events: On coughing and sneezing. *J. Fluid Mech.* 745:537–63. doi: 10.1017/jfm.2014.88.

Chao, C. Y. H., M. P. Wan, L. Morawska, G. R. Johnson, Z. D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, Y. Li, X. Xie, et al. 2009. Characterization of expiration air jets and droplet size distributions immediately at the mouth opening. *J. Aerosol Sci.* 40 (2):122–33. doi: 10.1016/j.aerosci.2008.10.003.

CDC, US Centers for Disease Control. 2020. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/prevention.html.

Chen, C., and B. Zhao. 2010. Some questions on dispersion of human exhaled droplets in ventilation room: Answers from numerical investigation. *Indoor Air* 20 (2):95–111. doi: 10.1111/j.1600-0668.2009.00626.x.

Delamater, P. L., E. J. Street, T. F. Leslie, Y. T. Yang, and K. H. Jacobsen. 2019. Complexity of the basic reproduction number (R_0). *Emerg. Infect. Dis.* 25 (1):1–4. doi: 10.3201/eid2501.171901.

Drossinos, Y, and C. Housiadas. 2006. Aerosol flows. In *Multiphase flow handbook*, ed. C. T. Crowe, 6-1–6-58. Boca Raton, FL: CRC Press.

Duguid, J. P. 1946. The size and the duration of air-carriage of respiratory droplets and droplet-nuclei. *Epidemiol. Infect.* 44 (6): 471–9. doi: 10.1017/S0022172400019288.

ECDC, European Centre for Disease Prevention and Control. 2020a. https://www.ecdc.europa.eu/sites/default/files/documents/Infection-prevention-control-for-the-care-of-patients-with-2019-nCoV-healthcare-settings_update-31-March-2020.pdf

ECDC, European Centre for Disease Prevention and Control. 2020b. https://www.ecdc.europa.eu/en/covid-19/questions-answers.

Heesterbeek, J. A. P., and K. Dietz. 1996. The concept of Ro in epidemic theory. *Stat. Neerland.* 50 (1):89–110. doi:/10.1111/j.1467-9574.1996.tb01482.x. doi: 10.1111/j.1467-9574.1996.tb01482.x.

Hobday, R. A. 2019. The open-air factor and infection control. *J. Hosp. Infect.* 103 (1):e23–e24. doi.org/10.1016/j.jhin.2019.04.003 doi: 10.1016/j.jhin.2019.04.003.

Ji, Y., H. Qian, J. Ye, and X. Zheng. 2018. The impact of ambient humidity on the evaporation and dispersion of exhaled breathing droplets: A numerical investigation. *J. Aerosol Sci.* 115: 164–72. doi: 10.1016/j.aerosci.2017.10.009.

Longest, P. W., and S. Vinchurkar. 2009. Inertial deposition of aerosols in bifurcating models during steady expiratory flow. *J. Aerosol Sci.* 40 (4):370–8. doi: 10.1016/j.aeroasci.2008.11.007.

Loudon, R. G., and R. M. Roberts. 1967. Relation between the airborne diameters of respiratory droplets and the diameter of the stains left after recovery. *Nature* 213 (5071):95–6. doi: 10.1038/213095a0.

Liu, L., Y. Li, P. V. Nielsen, J. Wei, and R. L. Jensen. 2017. Short-range airborne transmission of expiratory droplets between two people. *Indoor Air* 27 (2):452–62. doi: 10.1111/ina.12314.

Milton, D. K., M. P. Fabian, B. J. Cowling, M. L. Grantham, and J. J. McDevitt. 2013. Influenza virus aerosols in human exhaled breath: Particle size, culturability, and effect of surgical masks. *PLoS Pathog.* 9 (3):e1003205. doi: 10.1371/journal.ppat.1003205.

Mitsakou, C., C. Helmis, and C. Housiadas. 2005. Eulerian modelling of lung deposition with sectional representation of aerosol dynamics. *J. Aerosol Sci.* 36 (1):75–94. doi: 10.1016/j.aerosci.2004.08.008.

Morawska, L., G. R. Johnson, Z. D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C. Y. H. Chao, Y. Li, and D. Katoshevski. 2009. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. *J. Aerosol Sci.* 40 (3):256–69. doi: 10.1016/j.jaerosci.2008.11.002.

Nicas, M., W. W. Nazaroff, and A. Hubbard. 2005. Toward understanding the risk of secondary airborne infection: Emission of respirable pathogens. *J. Occup. Environ. Hyg.* 2 (3):143–54. doi: 10.1080/15459620590918466.

Papineni, R. S., and F. S. Rosenthal. 1997. The size distribution of droplets in the exhaled breath of healthy human subjects. *J. Aerosol Med. Pulm. D.* 10 (2):105–16. doi: 10.1089/jam.1997.10.105.

Parienta, D., L. Morawska, G. R. Johnson, Z. D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C. Y. H. Chao, Y. Li, and D. Katoshevski. 2011. Theoretical analysis of the motion and evaporation of exhaled respiratory droplets of mixed composition. *J. Aerosol Sci.* 42 (1):1–10. doi: 10.1016/j.aerosci.2010.10.005.

Robinson, M., N. I. Stilianakis, and Y. Drossinos. 2012. Spatial dynamics of airborne infectious diseases. *J. Theor. Biol.* 297: 116–26. doi: 10.1016/j.jtbi.2011.12.015.

Stilianakis, N. I., and Y. Drossinos. 2010. Dynamics of infectious disease transmission by inhalable respiratory droplets. *J. R. Soc. Interface* 7 (50):1355–66. doi: 10.1098/rsif.2010.0026.

Watanabe, W., M. Thomas, R. Clarke, A. M. Klibanov, R. Langer, J. Katstra, G. G. Fuller, L. C. Griel, J. Fiegel, and D. Edwards. 2007. Why inhaling salt water changes what we exhale. *J. Colloid Interface Sci.* 307 (1):71–8. doi: 10.1016/j.jcis.2006.11.017.

Weber, T. P., and N. I. Stilianakis. 2008a. Inactivation of influenza A viruses in the environment and modes of transmission: A

critical review. *J. Infect.* 57 (5):361–73. doi: 10.1016/j.jinf.2008.08.013.

Weber, T. P., and N. I. Stilianakis. 2008b. A note on the inactivation of influenza A viruses by solar radiation, relative humidity and temperature. *Photochem. Photobiol.* 84 (6):1601–2. doi.org/10.1111/j.1751-1097.2008.00416.x. doi: 10.1111/j.1751-1097.2008.00416.x.

van Doremalen, N., T. Bushmaker, D. Morris, M. Holbrook, A. Gamble, B. Williamson, A. Tamin, J. Harcourt, N. Thornburg, S. Gerber, et al. 2020. Aerosol and surface stability of SARS-CoV-2 compared to SARS-CoV-1. *N. Engl. J. Med.* 1–3. doi: 10.1056/NEJMc2004973.

Xie, X., Y. Li, A. T. Y. Chwang, P. L. Ho, and W. H. Seto. 2007. How far droplets can move in indoor environments - revisiting the wells evaporation-falling curve. *Indoor Air* 17 (3):211–25. doi: 10.1111/j.1600-0668.2007.00469.x.

Yannis Drossinos
European Commission, Joint Research Centre, Ispra (VA), Italy
yannis.drossinos@ec.europa.eu
ORCID http://orcid.org/0000-0002-8059-9636

Nikolaos I. Stilianakis
European Commission, Joint Research Centre, Ispra (VA), Italy
Department of Biometry and Epidemiology, University of Erlangen-Nuremberg, Erlangen, Germany
nikolaos.stilianakis@fau.de