Virus Transmission Modes and Mitigation Strategies, Part 1

Defining Viruses And Droplet Release

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The recent COVID-19 crisis has led to increased concern about the transmission of viruses. One particular area of concern has been the transmission of viruses in classrooms and other spaces served by single-zone HVAC systems. Therefore, it's essential to understand how viruses are commonly transmitted and what mitigation strategies are available, which is the topic of this article. An article in next month's *ASHRAE Journal* will cover airborne virus transmission and the effect of air distribution.

A virus is a small, intracellular parasite consisting of RNA or DNA enclosed in a protein coat that cannot reproduce by itself, but can direct a susceptible host cell to produce more viruses.[1] This virus, consisting of the nucleic acid (RNA or DNA) and an outer shell (capsid), is called a virion.[1] The study of viruses is a relatively recent endeavor with the isolation of individual viruses and their assignment to specific diseases occurring about 1898.[2] With the invention of the electron microscope in 1931, viruses could finally be visualized, and in 1939 the first virus (tobacco mosaic virus) was visualized using electron microscopy.[3]

In 1897 Carl Flügge, a German bacteriologist, showed that droplets from the nose and mouth contained bacteria, and the idea of droplet transmission was born.[4] Then in 1934 William F. Wells released his study "On Air-Borne Infection. Study II. Droplets and Droplet Nuclei."[5] In this study Wells showed the relationship between droplet size, evaporation and falling rate. Since Wells' study, continued research has expanded our understanding on virus transmission and infection mechanisms.

Virus Transmission

Viruses are commonly transferred from an infected person to a susceptible person in two ways:

- Direct Transmission
    - Direct contact: contact between an infected person and a susceptible person (i.e., skin-to-skin contact, kissing, etc.); and
    - Droplet spread: large, short-range droplets produced during sneezing, coughing, talking, etc., that make direct impact with a susceptible person.
- Indirect Transmission
    - Vehicles: food, water, blood and fomites (inanimate objects or materials that can carry pathogens

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from one person to another) can act to passively carry a pathogen;

- Vectors: mosquitoes, fleas and ticks can transfer the pathogen; and
- Short-range and long-range airborne transmission.[6,7,8]

Viruses are not usually specific to one mode of transfer and are often transmitted by multiple modes of transmission.[6] Direct contact and indirect transmission through vehicles and vectors are not directly affected by the HVAC system, so for the purposes of these articles we will focus on airborne transmission modes. Additionally, transmission routes such as through aerosol-generating procedures like intubation, cardiopulmonary resuscitation, surgery and others are not common in a classroom situation and also will not be addressed. Designers working in health-care occupancies should consider all transmission routes and the unique challenges that may be present.

"Infections are a result of the interaction between susceptibility factors in the exposed host, the concentration and virulence of the pathogen in the environment and the extent and nature of the exposure."[6] Evidence also exists that where a respiratory virus is deposited (for example, either as small particles in the lungs or as large particles in the upper respiratory tract) may alter the infection risk and illness severity. Particles deposited in the lungs are thought to carry a greater risk and severity of infection.[9]

As mentioned above, one of the risk factors for infection is the concentration of the pathogen in the environment. Large droplets can contain more virions and, therefore, have a higher potential contagiousness (assuming equal exposure) than smaller droplets.[10] While the smaller droplets have less chance of containing a virus, they can remain suspended in the air for a longer amount of time, increasing the exposure time and the possibility of infection.[10] The probability that a droplet contains one or more virions is proportional to the cube of the initial hydrated droplet's diameter (d^3).[11]

Droplets and Droplet Nuclei

In 1934 Wells carried out experiments showing that droplets greater than 100 microns would fall to the ground in a couple of seconds, while droplets smaller than 100 microns would evaporate before they reach the ground and form droplet nuclei, which could remain airborne for hours or even days.[5] Wells' calculations were based on pure water and didn't account for salinity concentration, surrounding air movement, respiratory jets and other factors,[12] but his work became the foundation for our understanding of droplet transition to droplet nuclei. Much of the early research was concentrated on bacteria, but many of these principles of droplet movement would later be applied to viruses.

FIGURE 1 Wells-Riley equation.[17]

$$P_I = \frac{C}{S} = 1 - exp\left(-\frac{Iqpt}{Q}\right)$$

where

P_I = Probability of infection
C = Number of infection cases
S = Number of susceptible persons
I = Number of infectors
p = Pulmonary ventilation rate of a person
q = Quanta generation rate
t = Exposure time interval
Q = Room ventilation rate with clean air

Studies showing the size and duration of droplet air-carriage by using high speed photography were carried out, and Stokes Law was applied to droplets to calculate the settling velocity.[13] In 1942 Theodore Hatch described dispersion of particulate matter in the air through dynamic projection for large particles and by air carriage for small particles. Large particles, 1.0 mm (0.04 in.) in size, if projected at 46 m/s (152 fps), could travel 4.6 m (15 ft) before reaching the floor if discharged from head height. Smaller particles, less than 0.1 mm (0.004 in.), would not be projected any appreciable distance by their own kinetic energy and must depend on air movement for transport beyond the immediate vicinity of the source. Hatch also noted that particles larger than 5 microns would be primarily removed in the upper respiratory tract, while smaller particles would be deposited by settlement in the alveoli.[14]

In 1978 Edward C. Riley developed an airborne infection model using an epidemiological study of a measles outbreak.[15] Riley worked with Wells at Harvard in the early 1930s, but left to attend medical school. He didn't return to the study of airborne contagion until he retired in 1970, after the death of Wells in 1963.[16] Prior to Riley's model, the Soper equation or Reed-Frost modification was used to model the spread of contagious disease, but what would become known as the Wells-Riley equation (*Figure 1*) would provide a simple and quick calculation to determine the infection risk of airborne transmissible diseases.

Many epidemic modeling studies have used the Wells-Riley equation as part of their mathematical models. Newer research has modified the Wells-Riley equation, developed dose-response models and used numerical modeling techniques to provide more complete risk assessments.[17] There has been a lot of discussion about where the line is between droplet and airborne transmission. The World Health Organization (WHO) and the U.S. Centers for Disease Control and Prevention (CDC) both use 5 microns to make this distinction, considering particles with a diameter greater than 5 microns to be droplets and those less than or equal to 5 microns to be aerosols.[12,18]

Wells showed large droplets would deposit on the ground before total evaporation.[5] The size this occurs at is referred to as the critical size. In 2007 Xie, et al., revisited the Wells evaporation-falling curve and found that for free-falling droplets at a relative humidity (RH) of 0%, 50%, 70% and 90%, the critical sizes were 125 microns, 100 microns, 85 microns and 60 microns, respectively. These values were smaller than those Wells had determined.[12]

As shown above, relative humidity has a great effect on droplet evaporation and falling rate. When relative humidity increases, the critical droplet size decreases. Since large droplets will settle out of the airstream by gravitational forces and small droplets will evaporate quickly, maximum horizontal distance is achieved by droplets of medium diameter.[12] Xie, et al., found that exhaled air carried droplets less than 1 m (3 ft) away during normal breathing (1 m/s [3 fps]) and more than 6 m (20 ft) away during sneezing (50 m/s [164 fps]).[12]

Relative humidity not only plays a role in the evaporation and carriage of the droplet, but it can also affect the survival rate of the pathogen. Research has shown that viruses that have a lipid envelope (influenza, parainfluenza, coronaviruses, etc.) are more stable in dry air (20% to 30% RH), while viruses without a protective envelope (rhino, entero, adeno, etc.) are more stable in moist air (70% to 90%).[19,20] There is also indication that for both lipid-enveloped and non-lipid-enveloped viruses, minimal survival occurs at an intermediate RH (40% to 70%).[20] Some researchers have proposed that at high relative humidity the initial salt concentrations are maintained, and at low relative humidity rapid evaporation causes the salts to crystallize out of solution, yielding low salt concentrations and higher virion stability.[21] Intermediate relative humidity results in increased salt concentrations, resulting in virus inactivation.[21]

Humidity also has an effect on your nasal passages. Mucous membranes lose water through evaporation, and low relative humidity can desiccate the nasal mucosa (altering the mucus viscosity), lead to epithelial damage and reduce mucociliary clearance, increasing susceptibility to infection.[22,23]

TABLE 1 Droplets produced.

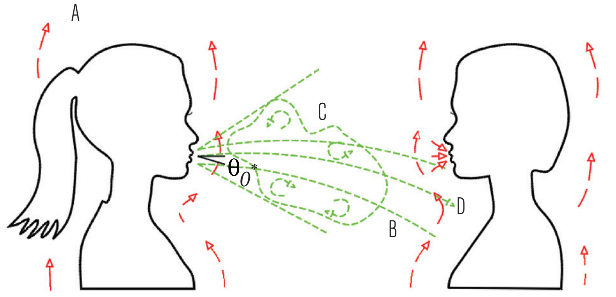
ACTIVITY	NUMBER OF DROPLETS PRODUCED
Projectile Vomiting[35]	3×10^7
Sneeze[25,36]	40,000 to 1 million
Toilet Flush (High Pressure)[37]	145,000 to 287,000
Toilet Flush (Low Pressure Tank)[37]	14,500
Cough[25,36]	3,000 to 5,000
Loudly Speaking (5 min)[38]	3,000
Loudly Speaking (100 words)[36]	250
Breathing (In Through Nose and Out Through Mouth)[39]	98/L

In addition to humidity, temperature also has an effect on the viral survival rate. Lower temperatures (7°C to 8°C [44.6°F to 46.4°F]) are thought to be ideal for airborne influenza survival, with survival decreasing as temperatures increase.[18,24] Moderate temperatures (20.5°C to 24°C [68.9°F to 75.2°F]), and to a greater extent high temperatures (>30°C [>86°F]) are associated with an increase in the rate of protein and nucleic acid inactivation.[18,24] Tang states, “Maintaining temperatures above 60°C [140°F] for more than 60 min is generally sufficient to inactivate most viruses, though this can be very dependent on the presence of any surrounding organic material (e.g., blood, feces, mucus, saliva, etc.), which will tend to insulate the virus against extreme environmental changes.”[20] The effect of low temperatures and low humidity on viruses has led some researchers to conclude that these factors may account for the seasonal nature of the influenza virus.[19,21]

Droplet Formation and Release

Droplets can originate in different parts of the respiratory tract, and the number and size of droplets produced can vary by activity (*Table 1*). During normal breathing and speech, small droplets ($d \leq 1$ µm) can be formed by the bronchiolar fluid film burst mode.[25] In this mode fluids lining the airways of the lungs can form a film across smaller airways at the end of exhalation (much like how a soap solution can form a film across the end of a child’s bubble wand). As the bronchioles reopen during inhalation, these films can burst and release droplets into the alveoli to be expelled.[25,26] Similarly, small

FIGURE 2 Droplet release (uncovered).

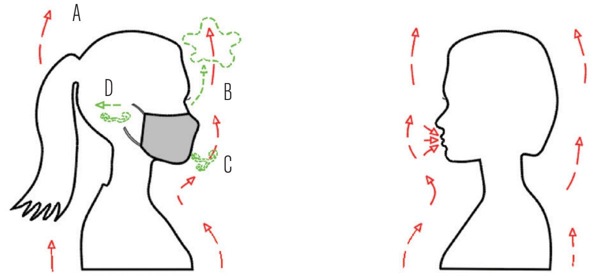


A. Thermal body plume.
B. Large droplets are projected forward, landing on mucous membranes and clothing.
C. Expelled cloud/jet is directed forward.
D. Thermal body plume transports pollutants up.

*Initial angle of cloud trajectory.

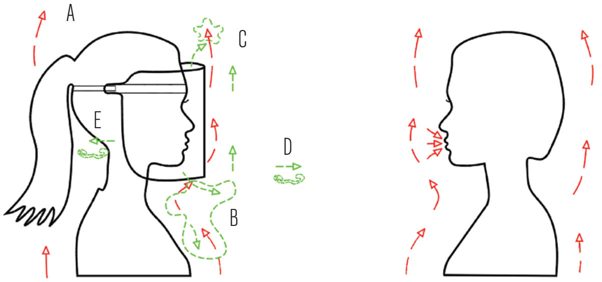
Note: Figures are based on reference imagery of expiratory flow. See References 29, 31 – 33.

FIGURE 3 (TOP) Droplet release (face mask). FIGURE 4 (BOTTOM) Droplet release (face shield).



A. Thermal body plume.
B. Leakage around the top of the mask, crown-ward.
C. Leakage through the mask.
D. Backward leakage from the mask.

Note: Figures are based on reference imagery of expiratory flow. See References 29, 31 – 33.



A. Thermal body plume.
B. Leakage around the bottom of the shield.
C. Leakage from the top of the shield.
D. Horizontal movement of droplet nuclei.
E. Airflow diverted backward from the shield.

Note: Figures are based on reference imagery of expiratory flow. See Ref. 29, 31 – 34.

droplets can be formed by the adduction of the vocal folds and vibration within the larynx during speech.[27] In addition to these smaller droplets, during coughing and sneezing, droplets can be formed by the laryngeal mode where shear stress on the mucus-air interface by the rapid airflow can dislodge mucus from the airways and produce droplets (d ≥1 µm).[25,26,28] However, large droplets from the trachea produced during coughing readily deposit within the oral and nasal cavities and may not be released into the environment.[25]

The oral cavity mode of droplet formation is responsible for most of the large droplets (d ≥100 µm) during speech and coughing.[25] In this mode, movement and contact of the tongue and lips can generate salivary droplets.[26] During a sneeze the soft palate and palatine uvula depress, while the back of the tongue partially closes the passage to the mouth and directs air through the nasal cavity to expel mucus, droplets, and irritants.[28]

When a person coughs, sneezes or exhales, large droplets are projected out of the mouth a short distance following a ballistic trajectory affected by gravity and aerodynamic drag (*Figure 2*). Intermediate and small-sized droplets can be dispersed in a multiphase turbulent gas cloud that traps and carries these droplets and entrains the ambient air around it. The moist and warm local atmosphere within this cloud allows the contained droplets to have a longer evaporation time and can extend the lifetime of the droplets.[29–31]

The turbulence of the gas cloud allows droplets of different sizes to settle out or evaporate based on the cloud dynamics and the space environmental conditions, in addition to the droplet size.[30] As the larger droplets settle out and the average momentum of the cloud becomes comparable to the buoyancy, the cloud will start to rise.[31] As the jet continues to lose momentum, the remaining droplets within the cloud evaporate into droplet nuclei that can remain suspended for hours.[30]

One's body thermal plume also affects the movement of droplets and droplet nuclei. The layer of air closest to the body is warmer and lighter than the surrounding air, causing it to move upward as a thermal plume.[32] The plume starts near the feet as a laminar flow and grows in velocity and thickness as it moves up the body, becoming fully turbulent at the mid-chest level. Maximum velocity (0.2 m/s to 0.3 m/s [0.7 fps to 1 fps]) is reached about 0.5 m (1.6 ft) above the head, and the thickness of the plume can reach 150 mm (5.9 in.) at the breathing zone. This rising plume makes up about two-thirds of the total inhaled air and makes entraining and transporting pollutants near the floor to the breathing zone possible.[25]

The thermal plume can be affected by body position (sitting vs. standing) and clothing, but is still significant while wearing pants and long sleeves.[33]

Droplet Release with Masks and Shields

When looking at face masks (*Figure 3*, page 27), there are all types of masks from commercial to homemade. A study by Viola, et al., found that all of the face covers they tested reduced the frontal jet by more than 90%.[32] A similar study by Verma, et al., found that for a simulated cough a stitched mask limited the frontal respiratory jet to 64 mm (2.5 in.); a commercial mask to 203 mm (8 in.); a folded handkerchief to 381 mm (1 ft, 3 in.); and a bandana to 1 m (3 ft, 7 in.).[29] During normal breathing, when the expelled flow is weak, the air is slowed down by the mask or redirected through the narrow gaps such that air can be captured by the upward convection of the thermal plume without being displaced significantly horizontally.[29,32]

The face shield (*Figure 4*) has been shown to deflect the expelled frontal respiratory jet downward and limit the horizontal travel of large droplets. Smaller droplets, however, can move around the bottom of the shield and leak around the gaps on the sides and top of the shield. As these droplets move forward and laterally, they begin to rise upward after a few seconds, since they are warmer than the ambient air, and have the potential to spread approximately 0.9 m (3 ft) in these directions. Studies also showed that masks, shields and ambient disturbances can cause the airflow to spread toward a person's back.[32,34]

Conclusions

This article has taken a look at what makes up a virus, how it can be released into the space through droplets and aerosols and the effect of certain environmental conditions like temperature and humidity on the droplets. The next article will cover airborne virus transmission and the effect of air distribution.

References

1. Lodish, H., A. Berk, Zipursky, S.L., et al. 2000. *Molecular Cell Biology, 4th edition*, "Section 6.3, Viruses: Structure, Function, and Uses." New York: W. H. Freeman. https://tinyurl.com/yyofaa67
2. Oldstone, M.B.A. 2014. "History of virology." *Encyclopedia of Microbiology* 2014:608–612. http://doi.org/10.1016/B978-0-12-801238-3.00078-7
3. Goldsmith, C.S., S.E. Miller. 2009. "Modern uses of electron microscopy for detection of viruses." *Clin Microbiol Reviews* 22(4):552–563. https://doi.org/10.1128/CMR.00027-09
4. Eames, I., J.W. Tang, Y. Li, P. Wilson. 2009. "Airborne transmission of disease in hospitals." *J. R. Soc. Interface* 6(Suppl6):6S697–S702. http://doi.org/10.1098/rsif.2009.0407.focus
5. Wells, W.F. 1934. "On air-borne infection. Study II. Droplets and droplet nuclei." *American Journal of Epidemiology* 20(3):611–618. https://doi.org/10.1093/oxfordjournals.aje.a118097
6. Luongo, J.C., K.P. Fennelly, J.A. Keen, Z.J. Zhai, et al. 2016. "Role of mechanical ventilation in the airborne transmission of infectious agents in buildings." *Indoor Air* 26(5):666–678. https://doi.org/10.1111/ina.12267
7. Kutter, J., M. Spronken, P. Fraaij, R. Fouchier, et al. 2018. "Transmission routes of respiratory viruses among humans." *Current Opinion in Virology* 28:142–151. https://doi.org/10.1016/j.coviro.2018.01.001
8. HHS. 2012. *Principles of Epidemiology in Public Health Practice: An Introduction to Applied Epidemiology and Biostatistics*. Atlanta: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. https://tinyurl.com/y3jb3t96
9. Bischoff, W.E., K. Swett, I. Leng, T.R. Peters. 2013. "Exposure to influenza virus aerosols during routine patient care." *J Infect Dis*. 207(7):1037–1046. https://doi.org/10.1093/infdis/jis773
10. Giovanni, A., T. Radulesco, G. Bouchet, et al. 2020. "Transmission of droplet-conveyed infectious agents such as SARS-CoV-2 by speech and vocal exercises during speech therapy: preliminary experiment concerning airflow velocity." *Eur Arch Otorhinolaryngol*. https://doi.org/10.1007/s00405-020-06200-7
11. Stadnytskyi, V., P. Anfinrud, C. Bax, A. Bax. 2020. "The airborne lifetime of small speech droplets and their potential importance to SARS-CoV-2 transmission." Zenodo.org. http://doi.org/10.5281/zenodo.3770559
12. Xie, X., Y. Li, A.T. Chwang, P.L. Ho, et al. 2007. "How far droplets can move in indoor environments—revisiting the Wells evaporation-falling curve." *Indoor Air* 17(3):211–225. https://doi.org/10.1111/j.1600-0668.2007.00469.x
13. Jennison, M.W. 1942. "Atomizing of mouth and nose secretions into the air as revealed by high-speed photography." In *Aerobiology*, F. R. Moulton (Ed.), pp. 106–128. American Association for the Advancement of Science. https://tinyurl.com/y57vxtxs
14. Hatch, T.F. 1942. "Behavior of microscopic particles in air and the respiratory system." In *Aerobiology*, F.R. Moulton (Ed.), pp. 102–105. American Association for the Advancement of Science. https://tinyurl.com/y57vxtxs
15. Riley, E.C., G. Murphy, R.L. Riley. 1978. "Airborne spread of measles in a suburban elementary school." *American Journal of Epidemiology* 107(5):421–432. https://doi.org/10.1093/oxfordjournals.aje.a112560
16. Riley, E.C. 1980. "The role of ventilation in the spread of measles in an elementary school." *Annals of the New York Academy of Sciences* 353(1):25–34. https://doi.org/10.1111/j.1749-6632.1980.tb18902.x
17. Sze To, G.N., C.Y.H. Chao. 2010. "Review and comparison between the Wells–Riley and dose-response approaches to risk assessment of infectious respiratory diseases." *Indoor Air* 20(1):2–16. https://doi.org/10.1111/j.1600-0668.2009.00621.x
18. Fernstrom, A., M. Goldblatt. 2013. "Aerobiology and its role in the transmission of infectious diseases." *Journal of Pathogens* 2013:Article ID 493960. https://doi.org/10.1155/2013/493960
19. Morawska, L. 2006. "Droplet fate in indoor environments, or can we prevent the spread of infection?" *Indoor Air* 16(5):335–347. https://doi.org/10.1111/j.1600-0668.2006.00432.x
20. Tang, J.W. 2009. "The effect of environmental parameters on the survival of airborne infectious agents." *Journal of the Royal Society Interface* 6(Issue Suppl_6):S737–S746. https://doi.org/10.1098/rsif.2009.0227.focus
21. Nikitin, N., E. Petrova, E. Trifonova, O. Karpova. 2014. "Influenza virus aerosols in the air and their infectiousness." *Advances in Virology* 2014:859090. https://doi.org/10.1155/2014/859090
22. Bolashikov, Z.D., A.K. Melikov. 2009. "Methods for air cleaning and protection of building occupants from airborne

pathogens." *Build. Environ* 44(7):1378–1385. https://doi.org/10.1016/j.buildenv.2008.09.001

23. Wolkoff, P. 2018. "Indoor air humidity, air quality, and health—an overview. *International Journal of Hygiene and Environmental Health* 221(3):376–390. https://doi.org/10.1016/j.ijheh.2018.01.015

24. Marr, L.C., J.W. Tang, J. Van Mullekom, S.S. Lakdawala. 2019. "Mechanistic insights into the effect of humidity on airborne influenza virus survival, transmission and incidence." *J. R. Soc. Interface* 16(150):20180298. http://dx.doi.org/10.1098/rsif.2018.0298

25. Wei, J, Y. Li. 2016. "Airborne spread of infectious agents in the indoor environment." *Am J Infect Control* 2016;44(9,Suppl):S102-S108. https://doi.org/10.1016/j.ajic.2016.06.003

26. Mittal, R., R. Ni, J. Seo. 2020. "The flow physics of COVID-19." *Journal of Fluid Mechanics* 894(F2). https://doi.org/10.1017/jfm.2020.330

27. Asadi, S., A.S. Wexler, C.D. Cappa, et al. 2019. "Aerosol emission and superemission during human speech increase with voice loudness." *Sci Rep* 9:2348. https://doi.org/10.1038/s41598-019-38808-z

28. Dhand, R, J. Li. 2020. "Coughs and sneezes: their role in transmission of respiratory viral infections, including SARS-CoV-2." *Am J Respir Crit Care Med* 202(5):651–659. https://doi.org/10.1164/rccm.202004-1263PP

29. Verma, S., M. Dhanak, J. Frankenfield. 2020. "Visualizing the effectiveness of face masks in obstructing respiratory jets." *Phys. Fluids* 32(6):061708. https://doi.org/10.1063/5.0016018

30. Bourouiba, L. 2020. "Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19." *JAMA* 323(18):1837–1838. https://doi.org/10.1001/jama.2020.4756

31. Bourouiba, L., E. Dehandschoewercker, J. Bush. 2014. "Violent expiratory events: on coughing and sneezing." *Journal of Fluid Mechanics* 745(537–563). https://doi.org/10.1017/jfm.2014.88

32. Viola, I.M., B. Peterson, G. Pisetta, G. Pavar, et al. 2020. "Face coverings, aerosol dispersion and mitigation of virus transmission risk." arXiv.org. ePrint. https://tinyurl.com/yy622y5j

33. Bhagat, R.K., M.S. Davies Wykes, S.B. Dalziel, P.F. Linden. 2020. "Effects of ventilation on the indoor spread of COVID-19." *Journal of Fluid Mechanics* 903:F1. https://doi.org/10.1017/jfm.2020.720

34. Verma, S., M. Dhanak, J. Frankenfield. 2020. "Visualizing droplet dispersal for face shields and masks with exhalation valves." *Physics of Fluids* 32(9):091701. https://doi.org/10.1063/5.0022968

35. Barker, J, D. Stevens, S.F. Bloomfield. 2001. "Spread and prevention of some common viral infections in community facilities and domestic homes." *J Appl Microbiol* 91(1):7–21. https://doi.org/10.1046/j.1365-2672.2001.01364.x

36. Duguid, J.P. 1946. "The size and the duration of air-carriage of respiratory droplets and droplet-nuclei." *The Journal of Hygiene* 44(6):471–479. https://doi.org/10.1017/s0022172400019288

37. Lai, A.C.K, T.F. Tan, W.S. Li, D.K.M. Ip. 2018. "Emission strength of airborne pathogens during toilet flushing." *Indoor Air* 28(1):73–79. https://doi.org/10.1111/ina.12406.

38. Qian, H., X. Zheng. 2018. "Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings." *Journal of Thoracic Disease* 10(Suppl 19):S2295–S2304. https://doi.org/10.21037/jtd.2018.01.24

39. Bake, B., P. Larsson, G. Ljungkvist, et al. 2019. "Exhaled particles and small airways." *Respir Res* 20(8). https://doi.org/10.1186/s12931-019-0970-9 ■

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