British Council for Offices
Briefing Note
February 2021

THOUGHTS ON VENTILATION DESIGN AND OPERATION POST COVID-19

Supplementary material and bibliography

Wells–Riley risk assessment model

The Wells–Riley model has been used extensively for the quantitative risk assessment of infection with respiratory diseases in indoor premises. It has also been used extensively to analyse ventilation strategies and their association with airborne infections in clinical environments.

Airborne concentrations can be related to infection risk using the Wells–Riley model for specific ventilation rates:[1]

$$N = S[1 - \exp(-\lambda t)]$$

where N is the number of cases affected over time t, S is the number of susceptible people in the space supplied with air at Q m^3/s, and

$$\lambda = Iqp/Q$$

where I is the number of infectious people, p is the pulmonary ventilation or breathing rate of susceptible individuals (m^3/h) and q is a unit of infection (a quantum) that represents the response of susceptible individuals to inhaling infectious droplets (expressed as the number of viral particles per hour).

Elovitz and Elovitz[2] used influenza data to calculate values of p and q. They proposed a value for p of 0.5 m^3/h for adults, and values for q of 10 (sitting and breathing normally), 34 (standing or walking and breathing normally), 320 (sitting and talking) and 1030 (standing or walking and talking) viral particles per hour. While these are not absolute values, and are not based on COVID-19, they can be used to obtain an indication of the rate of infection and the role of ventilation in this process.

Source: Allan Swart | Alamy Stock Photo

The same study also looked at the probability of infection with various air supply rates expressed as the number of air changes per hour (see Table 1 in Elovitz and Elovitz[2]). Besides the airflow rate (Q), the volume of the space (V) is important, because V/Q gives the age of the air. A high value of V/Q indicates stagnant and stuffy conditions, which would mean that the virus remains in the space for longer. The inverse of this ratio (Q/V) gives the air change rate (the number of air changes per hour).

Values of the air-change rate are specified in various guides to ventilation for a variety of spaces, but it should be remembered that these values do not take into account the impacts on the rate of transmission of infection. Elovitz and Elovitz[2] and the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA)[3] have attempted to do this in the results they have reported.

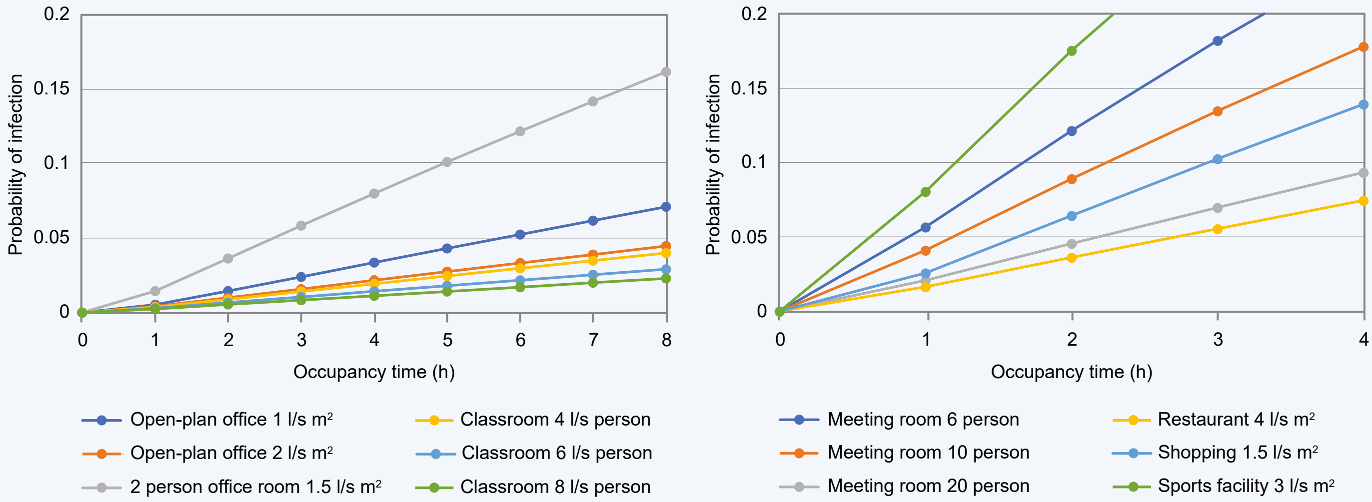

Figure S1
Infection risk assessment for some common non-residential rooms and ventilation rates, calculated using the REHVA COVID-19 ventilation calculator. Ventilation rates used in the calculations: 1.5 l/s per m^2 for two-person 16 m^2 office; 4 l/s per m^2 for a meeting room
Source: REHVA[3]

The Wells–Riley model can be used to calculate infection risk estimates and to compare the effects of ventilation and room parameters. On this basis, REHVA has developed a COVID-19 calculator for designers. Example calculation results for commonly used ventilation rates and rooms are shown in Figure S1. It is assumed that in all the rooms there is one infected person.

The overall dose when exposed to a virus (e.g. when sharing a room with an infected person) is equal to the product of concentration and time. To reduce the dose, and thus the risk of infection, ventilation must be increased and the occupancy time reduced. However, the limitations and uncertainties in the calculations due to variations in aerosol emission rates from infected persons, differences in individual risk across the population and the ventilation effectiveness in a given space, make it impossible to predict the absolute infection risk. That said, the model does allow comparison of the effectiveness of different solutions and ventilation strategies in limiting infection risk, enabling informed choices to be made. An example of calculated results of the relative risk of infection in an open-plan office is shown in Figure S2.

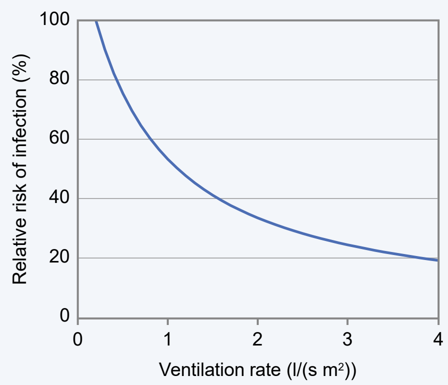

Figure S2
Relative risk of infection in a 50 m^2 open-plan office (reference ventilation rate 2 l/s per person (0.2 l/s per m^2) and a superspreading event with 100% relative risk)
Source: REHVA[3]

Air-cleaning technologies

Air filtration

HEPA (high-efficiency particulate arresting) filters can be used to remove virus particles from air streams.

Air filtration is typically used in the supply air plant of HVAC systems to improve indoor air quality by removing particulate matter such as dust and pollen from the intake air. Air being drawn into the plant from outside should not be contaminated with virus particles, and therefore there is usually no need to install HEPA filters, because normal grade filters would be suitable where the supply plant utilises 100% outdoor air.

It may be beneficial to use HEPA filters in central air handling systems where air is recirculated, but their application needs to be assessed on a case-by-case basis. However, the higher the efficiency of an air-filtration system the higher the pressure drop and space requirements. In addition, they are not easy to retrofit into existing systems, and would normally result in a reduced airflow, which would have a disproportionately negative impact for any perceived benefit.

Portable and fixed room-air cleaners using HEPA filters and recirculating fans can be deployed within an occupied space to remove and inactivate virus particles and other pollutants in the air. However, at this time there is little evidence to demonstrate how effective they would be in mitigating aerosol transmission.

Anti-microbial and anti-viral technology

Manufacturers have responded quickly to the challenge of COVID-19, integrating anti-microbial and anti-viral technology into their products. Some technologies that until now have only been used in the healthcare, food production and pharmaceutical sectors are starting to be considered for use in commercial buildings.

Ultraviolet germicidal irradiation (UVGI) is a disinfection method that employs short-wavelength ultraviolet light (ultraviolet C (UV-C)) to kill or inactivate microorganisms.[4]

Recent research[5] has suggested that a small band of far-UV light (wavelengths of roughly 220 nm) can damage viruses but is still safe for humans. The deployment of UV devices utilising these wavelengths needs to be comprehensively proven before they can be considered for use.

UV lights can be installed within air-handling units and fan coil units to disinfect the airstream and prevent the build-up of biofilms on wet surfaces such as cooling coils. An alternative approach for cooling coils would be to use all-copper coils, which naturally prevent the build-up of biofilms.

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Source: https://www.achrnews.com/articles/131877-ashrae-validates-effectiveness-of-uv-c

Copyright UV Safe Zone and Dakin

However, UV light needs to be used with caution. Prolonged exposure to germicidal wavelengths of UV light can produce rapid sunburn and skin cancer, and exposure of the eyes can produce extremely painful inflammation of the cornea and temporary or permanent vision impairment, including blindness. Another potential danger is the production of ozone, which can be harmful to health. The maximum recommended daily exposure to ozone is 0.1 ppm, as exposure to levels higher than this can directly damage the lungs and olfactory bulb cells.

Several manufacturers offer various types of *ionisation technologies* to distribute high volumes of ions into a space to potentially remove viruses and other pathogens from the breathing zone. These systems can be added to ventilation plant and terminal devices such as fan coil units. They need to be deployed close to the point of use, as the ions lose their charge as they travel through ductwork systems. However, great caution should be exercised in their use, as there is no clear evidence demonstrating the effectiveness of these devices against the SARS-CoV-2 coronavirus.

The potential health benefits of ionisation have been claimed for some time, but these claims have not been proven by research. However, a recent test on a coronavirus surrogate[6] showed a reduction of 99% in airborne virus and 80% in virus on surfaces in 10 minutes, and this has led to growing interest in the use of ionisation technologies.

Even the best ionisers produce a small amount of ozone. There is no scientific consensus on what a 'safe level' of ozone is. In California, for example, all portable indoor-air cleaners must meet an ozone emission concentration limit of 0.050 ppm. Therefore, care needs to be exercised in their use, particularly in unventilated spaces.

Some of the science and understanding of the application of these technologies in this context is still at an early stage, and there is limited research to verify their efficacy against COVID-19. It is therefore important to take a precautionary approach and use only equipment that is suitable for the intended application and that will not result in unintended exposure and alternative health risks in the future.

Useful guidance is given in a publication by SAGE-EMG.[7]

Copyright Conditioned Environment
Source: https://www.conditioned-environment.co.uk/our-sectors/covid-19

Existing system operation

REHVA provides comprehensive practical guidance for the operation of building services systems during a period of pandemic infection. The advice covers 15 main items, most of which relate directly or indirectly to the part played by ventilation in minimising the risk of airborne transmission of disease (Figure S3).

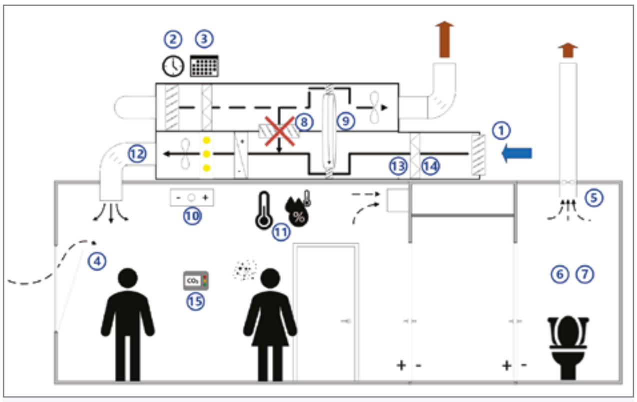

Figure S3
Main items of REHVA guidance for building services operation
Source: REHVA[3]

1. Ventilation rates – increase supply and exhaust ventilation.
2. Ventilation operation times – start ventilation plant 2 hours before occupancy and switch it off or change to a lower setting 2 hours after occupancy.
3. Disable ventilation demand control settings – change CO_2 set points to 400 ppm.
4. Window opening – use windows more, even when this causes thermal discomfort.
5. Toilet ventilation – extend operation times similarly to the recommendations for general ventilation systems.
6. Windows in toilets – avoid the use of windows where mechanical extraction is employed.
7. Flushing toilets – flush with lids closed to minimise air contamination.
8. Recirculation – avoid central air recirculation if possible. Where it cannot be avoided, use HEPA filters in the return air or install disinfection devices such as UVGI.
9. Heat recovery equipment – where rotary equipment is used, ensure that air leakage rates from the exhaust air stream into the supply do not exceed 5%.
10. Fan coils and split units – adjust systems to avoid high air velocities, and maintain units regularly.
11. Heating, cooling, and possible humidification set points – maintain normal settings.
12. Duct cleaning – maintain normal cleaning procedures.
13. Outdoor air filters – there is no need to upgrade or change normal maintenance and replacement procedures.
14. Maintenance works – adopt safe working practices using appropriate PPE when inspecting or replacing filters (especially extract air filters) or working on extraction systems and heat recovery equipment.
15. Indoor air quality monitoring – install CO_2 sensors to warn against underventilation, especially in spaces that are often used for one hour or more by groups of people. ■

References

1. Noakes CJ and Sleigh PA (2008) Applying the Wells–Riley equation to the risk of airborne infection in hospital environments: the importance of stochastic and proximity effects. In: *Indoor Air 2008: The 11th International Conference on Indoor Air Quality and Clean Indoor Air, Copenhagen, Denmark*. Available at: https://eprints.whiterose.ac.uk/7702/1/Noakes-indoorair2008.pdf (accessed 11 February 2021).
2. Elovitz K and Elovitz GM (2020) Assessing the role of HVAC systems in fighting COVID-19. *HPAC Engineering*, 14 August. Available at: https://www.hpac.com/covid-19/article/21138820/assessing-the-role-of-hvac-systems-in-fighting-covid19 (accessed 11 February 2021).
3. REHVA (2020) *REVA COVID 19 Guidance*, version 4. Available at: https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4_09122020.pdf (accessed 11 February 2021).
4. Kostra N (2016) ASHRAE validates effectiveness of UV-C. *ACHR News*, 29 February. Available at: https://www.achrnews.com/articles/131877-ashrae-validates-effectiveness-of-uv-c (accessed 11 February 2021).
5. Cartwright J (2020) The potential of far-ultraviolet light for the next pandemic. *Physics World*, 19 May. Available at: https://physicsworld.com/a/the-potential-of-far-ultraviolet-light-for-the-next-pandemic (accessed 11 February 2021).
6. Taylor A (2020) Unwanted guests: bipolar ionisation in hotel rooms. *CIBSE Journal*, October. Available at: https://www.cibsejournal.com/technical/unwanted-guests-bipolar-ionisation-in-hotel-rooms (accessed 11 February 2021).
7. SAGE-EMG (2020) *Potential Application of Air Cleaning Devices and Personal Decontamination to Manage Transmission of COVID-19*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/939173/S0867_EMG_Potential_application_of_air_cleaning_devices_and_personal_decontamination_to_manage_transmission_of_COVID-19.pdf (accessed 11 February 2021).

Bibliography

Ai Z, Hashimoto K and Melikov AK (2019) Airborne transmission between room occupants during short-term events: measurement and evaluation. *Indoor Air* **29**: 563–576. Available at: https://doi.org/10.1111/ina.12557 (accessed 11 February 2021).

AIVC (2020) *AIVC Newsletter Special Issue: COVID-19*, November. Air Infiltration and Ventilation Centre. Available at: https://www.aivc.org/sites/default/files/AIVC-NL-Special_Issue_Nov-2020.pdf (accessed 11 February 2021).

ASHRAE (2017) ANSI/ASHRAE Standard 52.2-2017. Method of testing general ventilation air-cleaning devices for removal efficiency by particle size. Available at: https://www.ashrae.org/File%20Library/Technical%20Resources/COVID-19/52_2_2017_COVID-19_20200401.pdf (accessed 11 February 2021).

ASHRAE (2020) *COVID-19 (Coronavirus) Preparedness Resources*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Available at: https://www.ashrae.org/about/news/2020/ashrae-resources-available-to-address-covid-19-concerns (accessed 11 February 2021).

ASHRAE (2020) *ASHRAE Position Document on Infectious Aerosols*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Available at: https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf (accessed 11 February 2021).

Bedell K, Buchaklian AH and Perlman S (2016) Efficacy of an automated multiple emitter whole-room ultraviolet-C disinfection system against coronaviruses MHV and MERS-CoV. *Infection Control and Hospital Epidemiology* **37**(5): 598–599. Available at: https://dx.doi.org/10.1017%2Fice.2015.348 (accessed 11 February 2021).

Bhagat RK, Davies Wykes MS, Dalziel SB and Linden PF (2020) Effects of ventilation on the indoor spread of COVID-19. *Journal of Fluid Mechanics* **903**: F1. Available at: https://doi.org/10.1017/jfm.2020.720 (accessed 11 February 2021).

Booth CM, Clayton M, Crook B and Gawn J (2013) Effectiveness of surgical masks against influenza bioaerosols. *Journal of Hospital Infection* **84**: 22–26. Available at: https://doi.org/10.1016/j.jhin.2013.02.007 (accessed 11 February 2021).

Brown J, Tang J, Pankhurst L, et al. (2015) Influenza virus survival in aerosols and estimates of viable virus loss resulting from aerosolization and air-sampling. *Journal of Hospital Infection* 91(3): 278–281. Available at: https://doi.org/10.1016/j.jhin.2015.08.004 (accessed 11 February 2021).

BSI (2017) BS EN 16798-7:2017. Energy performance of buildings. Ventilation for buildings. Calculation methods for the determination of air flow rates in buildings including infiltration (Modules M5-5). British Standards Institution, London.

BSI (2017) BS ISO 17772-1:2017. Energy performance of buildings – indoor environmental quality. Indoor environmental input parameters for the design and assessment of energy performance of buildings. British Standards Institution, London.

CDC (2015) *Hierarchy of Controls*. Centers for Disease Control and Prevention. Available at: https://www.cdc.gov/niosh/topics/hierarchy/default.html (accessed 11 February 2021).

CDC/NIOSH (2009) *Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings*. Publication No. 2009-105. Centers for Disease Control and Prevention and National Institute for Occupational Safety and Health. Available at: https://www.cdc.gov/niosh/docs/2009-105/pdfs/2009-105.pdf (accessed 11 February 2021).

Chen W, Zhang N, Wei J and Yen H-L (2020) Short-range airborne route dominates exposure of respiratory infection during close contact. *Building and Environment* **176**: 106859. Available at: https://doi.org/10.1016/j.buildenv.2020.106859 (accessed 11 February 2021).

Chia PY, Coleman KK, Tan YK, et al. (2020) Detection of air and surface contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in hospital rooms of infected patients. Available at: https://doi.org/10.1101/2020.03.29.20046557 (accessed 11 February 2021).

CIBSE (2016) *Guide B0: Applications and activities: HVAC strategies*. Chartered Institution of Building Services Engineers, London.

CIBSE (2016) *Guide B2: Ventilation and ductwork*. Chartered Institution of Building Services Engineers, London.

CIBSE (2020) *COVID-19 Guidance: Ventilation*, version 4. Available at: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q3Y00000HsaFtQAJ (accessed 11 February 2021).

CIBSE (2020) COVID-19 Updates from the *CIBSE Journal*. Available at: https://www.cibse.org/coronavirus-covid-19/covid-19-updates-from-the-cibse-journal (accessed 11 February 2021).

CIBSE (2020) *Healthcare Group Information Note on Coronavirus*. Chartered Institution of Building Services Engineers. Available at: https://www.cibse.org/coronavirus-covid-19/cibse-healthcare-group%C2%A0information-note-on-coronav (accessed 11 February 2021).

Coconuts Singapore (2020) *Look inside Singapore's Exhibition Hall Turned Hospital (Photos)*. Available at: https://coconuts.co/singapore/news/look-inside-singapores-exhibition-hall-turned-hospital-photos (accessed 11 February 2021).

Coleman KK, Nguyen TT, Yadana S, Hansen-Estruch C, Lindsley WG and Gray GC (2018) Bioaerosol sampling for respiratory viruses in Singapore's mass rapid transit network. *Scientific Reports* **8**: 17476. Available at: https://www.nature.com/articles/s41598-018-35896-1 (accessed 11 February 2021).

Darnell ME, Subbarao K, Feinstone SM and Taylor DR (2004) Inactivation of the coronavirus that induces severe acute respiratory syndrome SARS-CoV. *Journal of Virological Methods* **121**(1): 85–91. Available at: https://doi.org/10.1016/j.jviromet.2004.06.006 (accessed 11 February 2021).

Department of Health M (2014) *Health Building Note 00-01. General design Guidance for Healthcare Buildings*. UK Government. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/316247/HBN_00-01-2.pdf (accessed 11 February 2021).

Ding Z, Qian H, Xu B, et al. (2020) Toilets dominate environmental detection of SARS-CoV-2 virus in a hospital. Available at: https://doi.org/10.1101/2020.04.03.20052175 (accessed 11 February 2021).

Distasio AJ and Trump DH (1990) The investigation of a tuberculosis outbreak in the closed environment of a US Navy ship, 1987. *Military Medicine* **155**: 347–351.

Eames I, Tang J, Li Y and Wilson P (2009) Airborne transmission of disease in hospitals. *Journal of the Royal Society Interface* **6**(Suppl 6): S697–S702. Available at: https://doi.org/10.1098/rsif.2009.0407.focus (accessed 11 February 2021).

Elovitz K and Elovitz GM (2020) Assessing the role of HVAC systems in fighting COVID-19. *HPAC Engineering*, 14 August. Available at: https://www.hpac.com/covid-19/article/21138820/assessing-the-role-of-hvac-systems-in-fighting-covid19 (accessed 11 February 2021).

Escombe AR, Moore DA, Gilman RH, et al. (2009) Upper-room ultraviolet light and negative air ionization to prevent tuberculosis transmission. *PLOS Medicine* **6**(3): 0132–0323. Available at: https://doi.org/10.1371/journal.pmed.1000043 (accessed 11 February 2021).

Foarde KK (1999) Methodology to perform clean air delivery rate type determinations with microbiological aerosols. *Aerosol Science and Technology* **30**(2): 235–245. Available at: https://www.tandfonline.com/doi/abs/10.1080/713834074 (accessed 11 February 2021).

Gilkeson CA and Noakes C (2013) Application of CFD simulation to predicting upper-room UVGI effectiveness. *Photochemistry and Photobiology* **89**(4): 799–810. Available at: https://doi.org/10.1111/php.12013 (accessed 11 February 2021).

Gilkeson C, Camargo-Valero M, Pickin L and Noakes C (2013) Measurement of ventilation and airborne infection risk in large naturally ventilated hospital wards. *Building and Environment* **65**: 35–48. Available at: https://doi.org/10.1016/j.buildenv.2013.03.006 (accessed 11 February 2021).

Guo Z-D, Wang Z-Y, Zhang S-F, et al. (2020) Aerosol and surface distribution of severe acute respiratory syndrome coronavirus 2 in hospital wards, Wuhan, China. *Emerging Infectious Diseases* **26**(7): 1583–1581. Available at: https://dx.doi.org/10.3201/eid2607.200885 (accessed 11 February 2021).

Jiang Y, Wang, H, Chen Y, et al. (2020) Clinical data on hospital environmental hygiene monitoring and medical staff protection during the coronavirus disease 2019 outbreak. Available at: https://doi.org/10.1101/2020.02.25.20028043 (accessed 11 February 2021).

Jo S, Hong J, Lee S-E, Ki M, Choi BY and Sung M (2019) Airflow analysis of Pyeongtaek St Mary's Hospital during hospitalization of the first Middle East respiratory syndrome patient in Korea. *Royal Society Open Science* **6**(3): 181164. Available at: https://doi.org/10.1098/rsos.181164 (accessed 11 February 2021).

Kim S-H, Chang SY, Sung M, et al. (2016) Extensive viable Middle East respiratory syndrome (MERS) coronavirus contamination in air and surrounding environment in MERS isolation wards. *Clinical Infectious Diseases* **63**(3): 363–369. Available at: https://doi.org/10.1093/cid/ciw239 (accessed 11 February 2021).

Knibbs LD, Morawska L and Bell SC (2012) The risk of airborne influenza transmission in passenger cars. *Epidemiology and Infection* **140**: 474–478. Available at: https://doi.org/10.1017/S0950268811000835 (accessed 11 February 2021).

Kormuth KA, Lin K, Prussin AJ, et al. (2018) Influenza virus infectivity is retained in aerosols and droplets independent of relative humidity. *Journal of Infectious Diseases* **218**(5): 739–747. Available at: https://doi.org/10.1093/infdis/jiy221 (accessed 11 February 2021).

Kujundzic E, Matalkah F, Howard CJ, Hernandez M and Miller SL (2006) UV air cleaners and upper-room air ultraviolet germicidal irradiation for controlling airborne bacteria and fungal spores. *Journal of Occupational and Environmental Hygiene* **3**: 536–546. Available at: https://doi.org/10.1080/15459620600909799 (accessed 11 February 2021).

Kujundzic E, Hernandez M and Miller SL (2007) Ultraviolet germicidal irradiation inactivation of airborne fungal spores and bacteria in upper-room air and HVAC in-duct configurations. *Journal of Environmental Engineering Science* **6**(1): 1–9. Available at: https://doi.org/10.1139/s06-039 (accessed 11 February 2021).

Kulkarni H, Smith CM, Lee DDH, Hirst RA, Easton AJ and O'Callaghan C (2016) Evidence of respiratory syncytial virus spread by aerosol. Time to revisit infection control strategies? *American Journal of Respiratory and Critical Care Medicine* **194**(3): 308–316. Available at: https://doi.org/10.1164/rccm.201509-1833OC (accessed 11 February 2021).

Lewis D (2020) Is the coronavirus airborne? Experts can't agree. *Nature* **580**: 175. Available at: https://media.nature.com/original/magazine-assets/d41586-020-00974-w/d41586-020-00974-w.pdf (accessed 11 February 2021).

Li Y, Huang X, Yu I, Wong T and Qian H (2005) Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. *Indoor Air* **15**(2): 83–95. Available at: https://doi.org/10.1111/j.1600-0668.2004.00317.x (accessed 11 February 2021).

Li Y, Leung GM, Tang J, et al. (2007) Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systematic review. *Indoor Air* **17**(1): 2–18. Available at: https://doi.org/10.1111/j.1600-0668.2006.00445.x (accessed 11 February 2021).

Lipinski T, Ahmad D, Serey N and Jouhara H (2020) Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings. *International Journal of Thermofluids* **7-8**: 100045. Available at: http://doi.org/10.1016/j.ijft.2020.100045 (accessed 11 February 2021).

Liu L, Li Y, Nielsen PV, Wei J and Jensen RL (2017) Short-range airborne transmission of expiratory droplets between two people. *Indoor Air* **27**: 452–462. Available at: https://doi.org/10.1111/ina.12314 (accessed 11 February 2021).

Liu Y, Ning Z, Chen Y, et al. (2020) Aerodynamic characteristics and RNA concentration of SARS-CoV-2 aerosol in Wuhan hospitals during COVID-19 outbreak. Available at: https://doi.org/10.1101/2020.03.08.982637 (accessed 11 February 2021).

Marr LC, Tang JW, Van Mullekom J and Lakdawala SS (2019) Mechanistic insights into the effect of humidity on airborne influenza virus survival, transmission and incidence. *Journal of the Royal Society Interface* **16**: 20180298. Available at: https://doi.org/10.1098/rsif.2018.0298 (accessed 11 February 2021).

McDevitt JJ, Lai KM, Rudnick SN, Houseman EA, First MW and Milton DK (2007) Characterization of UVC light sensitivity of vaccinia virus. *Applied and Environmental Microbiology* **73**: 5760–5766. Available at: https://doi.org/10.1128/AEM.00110-07 (accessed 11 February 2021).

McDevitt JJ, Rudnick SN and Radonovich LJ (2012) Aerosol susceptibility of influenza virus to UV-C light. *Applied and Environmental Microbiology* **78**: 1666–1669. Available at: https://doi.org/10.1128/AEM.06960-11 (accessed 11 February 2021).

McLean R (1961) The mechanism of spread of Asian influenza: general discussion. *American Review of Respiratory Disease* **83**(2P2): 36–38. Available at: https://www.atsjournals.org/doi/abs/10.1164/arrd.1961.83.2P2.29 (accessed 11 February 2021).

Melikov AK (2011) Advanced air distribution. *ASHRAE Journal* **53**: 73–77.

Melikov AK (2016) Advanced air distribution: improving health and comfort while reducing energy use. *Indoor Air* **26**: 112–124. Available at: https://doi.org/10.1111/ina.12206 (accessed 11 February 2021).

Miller-Leiden S, Lohascio C, Nazaroff W and Macher J (1996) Effectiveness of in-room air filtration and dilution ventilation for tuberculosis infection control. *Journal of the Air & Waste Management Association* **46**: 869–882. Available at: https://doi.org/10.1080/10473289.1996.10467523 (accessed 11 February 2021).

Miller SL, Clements N, Elliott SA, Subhash SS, Eagan A and Radonovich LJ (2017) Implementing a negative-pressure isolation ward for a surge in airborne infectious patients. *American Journal of Infection Control* **45**: 652–659. Available at: https://doi.org/10.1016/j.ajic.2017.01.029 (accessed 11 February 2021).

Morawska L and Cao J (2020) Airborne transmission of SARS-CoV-2: the world should face the reality. *Environment International* **139**: 105730. Available at: https://doi.org/10.1016/j.envint.2020.105730 (accessed 11 February 2021).

Morawska L, Tang JW, Bahnfleth W, et al. (2020) How can airborne transmission of COVID-19 indoors be minimised? *Environmental International* **142**: 105832. Available at: https://doi.org/10.1016/j.envint.2020.105832 (accessed 11 February 2021).

Moser MR, Bender TR, Margolis HS, Noble GR, Kendal AP and Ritter DG (1979) An outbreak of influenza aboard a commercial airliner. *American Journal of Epidemiology* **110**: 1–6. Available at: https://doi.org/10.1093/oxfordjournals.aje.a112781 (accessed 11 February 2021).

Nishiura H, Oshitani H, Kobayashi T, et al. (2020) Closed environments facilitate secondary transmission of coronavirus disease 2019 (COVID-19). Available at: https://doi.org/10.1101/2020.02.28.20029272 (accessed 11 February 2021).

Noakes CJ and Sleigh PA (2008) Applying the Wells–Riley equation to the risk of airborne infection in hospital environments: the importance of stochastic and proximity effects. In: *Indoor Air 2008: The 11th International Conference on Indoor Air Quality and Clean Indoor Air, Copenhagen, Denmark*. Available at: https://eprints.whiterose.ac.uk/7702/1/Noakes-indoorair2008.pdf (accessed 11 February 2021).

Noakes C, Beggs C and Sleigh P (2004) Modelling the performance of upper room ultraviolet germicidal irradiation devices in ventilated rooms: comparison of analytical and CFD methods. *Indoor and Built Environment* **13**: 477–488. Available at: https://doi.org/10.1177/1420326X04049343 (accessed 11 February 2021).

Noakes CJ, Khan MAI and Gilkeson CA (2015) Modeling infection risk and energy use of upper-room ultraviolet germicidal irradiation systems in multi-room environments. *Science and Technolology for the Built Environment* **21**: 99–111. Available at: https://doi.org/10.1080/10789669.2014.983035 (accessed 11 February 2021).

Ong SWX, Tan YK, Chia PY, et al. (2020) Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from a symptomatic patient. *JAMA* **323**(16):1610–1612. Available at: https://doi.org/10.1001/jama.2020.3227 (accessed 11 February 2021).

Persily A, Chapman RE, Emmerich SJ, et al. (2007) *Building Retrofits for Increased Protection against Airborne Chemical and Biological Releases*. National Institute of Standards and Technology, Gaithersburg, MD, USA. Available at: https://www.nist.gov/publications/building-retrofits-increased-protection-against-airborne-chemical-and-biological (accessed 11 February 2021).

Public Health England (2015) *The Green Book, Chapter 4: Varicella*. Available at: https://www.gov.uk/government/publications/varicella-the-green-book-chapter-34 (accessed 11 February 2021).

Pyankov OV, Bodnev SA, Pyankova OG and Agranovski IE (2018) Survival of aerosolized coronavirus in the ambient air. *Journal of Aerosol Science* **115**: 158–163. Available at: https://doi.org/10.1016/j.jaerosci.2017.09.009 (accessed 11 February 2021).

REHVA (2020) *REVA COVID 19 Guidance*, version 4. Available at: https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4_09122020.pdf (accessed 11 February 2021).

Roy CJ and Milton DK (2004) Transmission of communicable infection – the elusive pathway. *New England Journal of Medicine* **350**: 1710. Available at: https://doi.org/10.1056/NEJMp048051 (accessed 11 February 2021).

Rule AM, Apau O, Ahrenholz SH, et al. (2018) Healthcare personnel exposure in an emergency department during influenza season. PLOS ONE, 13. Available at: https://doi.org/10.1371/journal.pone.0203223 (accessed 11 February 2021).

SAGE-EMG (2020) Role of Ventilation in Controlling SARA-CoV-2 Transmission. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/928720/S0789_EMG_Role_of_Ventilation_in_Controlling_SARS-CoV-2_Transmission.pdf (accessed 11 February 2021).

Santarpia JL, Rivera DN, Herrera V, et al. (2020) Transmission potential of SARS-CoV-2 in viral shedding observed at the University of Nebraska Medical Center. Available at: https://doi.org/10.1101/2020.03.23.20039446 (accessed 11 February 2021).

Settles GS (1992) An overview of planar laser scattering for the visualization of high-speed airflows. In: Tanida Y and Miyashiro H (eds), *Flow Visualization VI*. Springer, Berlin.

SHASE (2020) *Role of Ventilation in Control of COVID-19 Infection*. Society of Heating, Air-conditioning and Sanitary Engineers of Japan.

Shaughnessy R and Sextro R (2006) What is an effective portable air cleaning device? A review. *Journal of Occupational and Environmental Hygiene* **3**: 169–181. Available at: https://doi.org/10.1080/15459620600580129 (accessed 11 February 2021).

Sornboot J, Aekplakorn W, Ramasoota P, Bualert S, Tumwasorn S and Jiamjarasrangsi W (2019) Detection of airborne Mycobacterium tuberculosis complex in high-risk areas of health care facilities in Thailand. *International Journal of Tuberculosis and Lung Disease* **28**(4): 465–473. Available at: https://doi.org/10.5588/ijtld.18.0218 (accessed 11 February 2021).

Stopera M and Stopera D (2020) 19 Pictures of the Most dangerous places in New York City right now. *BuzzFeed*, 1 April. Available at: https://www.buzzfeed.com/mjs538/pictures-of-one-of-the-most-dangerous-places-in-new-york (accessed 11 February 2021).

Sung M and Kato S (2010) Method to evaluate UV dose of upper-room UVGI system using the concept of ventilation efficiency. *Building and Environment* **45**: 1626–1631. Available at: https://doi.org/10.1016/j.buildenv.2010.01.011 (accessed 11 February 2021).

Taipei Times (2004) Hong Kong hotel is eliminating memories of SARS. *Taipei Times*, 23 February. Available at: https://www.taipeitimes.com/News/world/archives/2004/02/23/2003099824 (accessed 11 February 2021).

Tang JW (2009) The effect of environmental parameters on the survival of airborne infectious agents. *Journal of the Royal Society Interface* **6**(Suppl 6): S737–S746. Available at: https://doi.org/10.1098/rsif.2009.0227.focus (accessed 11 February 2021).

Tellier R, Li Y, Cowling BJ and Tang JW (2019) Recognition of aerosol transmission of infectious agents: a commentary. *BMC Infectious Diseases* **19**: 101. Available at: https://doi.org/10.1186/s12879-019-3707-y (accessed 11 February 2021).

Thatiparti DS, Ghia U and Mead KR (2016) Assessing effectiveness of ceiling-ventilated mock airborne infection isolation room in preventing hospital-acquired influenza transmission to health care workers. *ASHRAE Transactions* **122**: 35. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5438175 (accessed 11 February 2021).

Thatiparti DS, Ghia U and Mead KR (2017) Computational fluid dynamics study on the influence of an alternate ventilation configuration on the possible flow path of infectious cough aerosols in a mock airborne infection isolation room. *Science and Technology for the Built Environment* **23**: 355–366. Available at: https://doi.org/10.1080/23744731.2016.1222212 (accessed 11 February 2021).

van Doremalen N, Bushmaker T, Morris DH, et al. (2020) Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *New England Journal of Medicine* **382**:1564–1567. Available at: 10.1056/NEJMc2004973 (accessed 11 February 2021).

Walker CM and Ko G (2007) Effect of ultraviolet germicidal irradiation on viral aerosols. *Environmental Science and Technology* **41**: 5460–5465. Available at: https://doi.org/10.1021/es070056u (accessed 11 February 2021).

WHO (2009) Natural Ventilation for Infection Control in Health-care Settings. WHO Guidelines 2009. Available at: https://www.who.int/water_sanitation_health/publications/natural_ventilation/en (accessed 11 February 2021).

WHO (2020) *Shortage of Personal Protective Equipment Endangering Health Workers Worldwide*. News Release, 3 March. Available at: https://www.who.int/news/item/03-03-2020-shortage-of-personal-protective-equipment-endangering-health-workers-worldwide (accessed 11 February 2021).

WHO (2020) *Infection Prevention and Control during Health Care when Novel Coronavirus (nCoV) Infection is Suspected*. Interim Guidance, 19 March. Available at: https://www.who.int/publications/i/item/10665-331495 (accessed 11 February 2021).

WHO (2020) *Modes of Transmission of Virus Causing COVID-19: Implications for IPC Precaution Recommendations*. Scientific Brief, 29 March. Available at: https://www.who.int/news-room/commentaries/detail/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations (accessed 11 February 2021).

Xu P, Fisher N and Miller SL (2013) Using computational fluid dynamics modelling to evaluate the design of hospital ultraviolet germicidal irradiation systems for inactivating airborne mycobacteria. *Photochemistry and Photobiology* **89**: 792–798. Available at: https://doi.org/10.1111/php.12062 (accessed 11 February 2021).

Xu P, Peccia J, Fabian P, et al. (2003) Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivating airborne bacterial spores and mycobacteria in full-scale studies. *Atmospheric Environment* **37**(3): 405–419. Available at: https://doi.org/10.1016/S1352-2310(02)00825-7 (accessed 11 February 2021).

Xu P, Kujundzic E, Peccia J, et al. (2005) Impact of environmental factors on efficacy of upper-room air ultraviolet germicidal irradiation for inactivating airborne mycobacteria. *Environmental Science and Technology* **39**: 9656–9664. Available at: https://doi.org/10.1021/es0504892 (accessed 11 February 2021).

Yang Y, Chan WY, Wu C, Kong R and Lai A (2012) Minimizing the exposure of airborne pathogens by upper-room ultraviolet germicidal irradiation: an experimental and numerical study. *Journal of the Royal Society Interface* **9**(77): 3184–3195. Available at: https://doi.org/10.1098/rsif.2012.0439 (accessed 11 February 2021).

Young L and Wormser G (1994) The resurgence of tuberculosis. *Scandinavian Journal of Infectious Disease Supplement* **93**: 9–19. Available at: https://pubmed.ncbi.nlm.nih.gov/8047859 (accessed 11 February 2021).

Zhu S, Srebric J, Rudnick SN, Vincent RL and Nardell EA (2014) Numerical modelling of indoor environment with a ceiling fan and an upper-room ultraviolet germicidal irradiation system. *Building and Environment* **72**: 116–124. Available at: https://doi.org/10.1016/j.buildenv.2013.10.019 (accessed 11 February 2021).

ABOUT THE BCO

The BCO is the UK's leading forum for the discussion and debate of issues affecting the office sector. Established in 1990, its membership base comprises organisations involved in creating, acquiring or occupying office space, including architects, lawyers, surveyors, financial institutions and public agencies.

The BCO recognises that offices don't just house companies, they hold people and so what goes on inside them is paramount to workplace wellbeing.

ABOUT THE AUTHORS

The Technical Affairs Committee (TAC) is the voice for the BCO on technical aspects of the built environment. It is responsible for the organisation's globally recognised best practice guides on office specification and fit-out, and acts as a forum for new ideas and discussion to address the technical challenges facing the workplace sector. This briefing note has been based on a technical paper prepared for the BCO TAC by Derek Clements-Croome, Professor Emeritus at University of Reading and Visiting Professor at Queen Mary University London. Derek is a member of the TAC and a key contributor to the 2019 BCO *Guide to Specification*. Derek was also one of the 239 signatories to the letter to WHO, and a contributor to the WHO report *Natural Ventilation for Infection Control in Health-care Settings* (2009).

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