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How airborne transmission of SARS-CoV-2 confirmed the need for new ways of proper ventilation

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Introduction

On January 5th, 2020, the World Health Organization (WHO) published the first Disease Outbreak news about a new virus, including a preliminary risk assessment, and advice, on it. Five days later, this was followed by a technical, comprehensive package of guidance for countries on how to detect, test and manage potential cases, including infection and prevention control guidance, based on experiences with SARS, MERS and other viral infections (WHO, 2020a). Airborne precautions for aerosol-generating procedures (AGPs) (WHO, 2014) conducted by health workers such as tracheal intubation, nebulizer treatment and bronchoscopy were included, but other forms of airborne transmission were ignored. On January 22nd, 2020, a WHO mission to China issued a statement saying that there was evidence of human-to-human transmission in Wuhan, but more investigation was needed to understand the full extent of transmission of the virus.

On March 11th, 2020, COVID-19 (Coronavirus disease 2019) caused by the severe acute respiratory syndrome coronavirus (SARS-CoV-2) was declared a pandemic by the WHO (WHO, 2020a). On April 4th, 2020, 1 million COVID-19 cases were reported by the British Broadcasting Organisation (BBC News, 2021). As numbers rose rapidly, understanding of the mechanisms for transmission of SARS-CoV-2 was more than ever key to preventing further spread. There was no time to waste: all three possible routes of transmission needed urgent investigation, through either:

1 Direct contact between people;
2 Indirect via intermediate surfaces;
3 The air (so-called airborne transmission).

At the end of March 2020, I was approached by Prof. Lidia Morawska to join a group of scientists to petition the WHO. This first letter to the WHO was signed by 36 scientists from around the world, all of whom have worked on the characteristics and mechanisms behind both the transport of droplets expired by humans and airflow patterns in buildings. This letter was sent to Dr. Tedros Adhanom Ghebreyesus, Director General of the WHO on April 3rd,

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2020. In this letter, we made an appeal to recognize the significance of the airborne spread of SARS-CoV-2 (COVID-19), and preventive measures to mitigate its transmission through the air were advocated. A joint publication by the 36 scientists in *Environment International* titled 'How can airborne transmission of COVID-19 indoors be minimized' was published online on May 27th, 2020) (Morawska et al., 2020). Several phone calls and teleconferences with the WHO followed, but it required an open letter signed by 239 scientists to get a more serious response. On July 1st, the invited Commentary MS CID-102575, entitled 'It is Time to Address Airborne Transmission of COVID-19', was accepted for publication in the *Journal of Clinical Infectious Diseases* (Morawska and Milton, 2020). The WHO took several months to acknowledge the fact that poor ventilation in spaces in buildings could increase the risk for building occupants of catching COVID-19, an omission that was finally remedied and expressed in a WHO leaflet advocating that people should 'Avoid the three C's' (WHO, 2020b):

1 **Crowded places**, with many people nearby;
2 **Close-contact settings**, especially where people have close-range conversations;
3 **Confined and enclosed spaces** with poor ventilation.

Airborne transmission was, however, according to the WHO, still only possible during AGPs.

On April 30th, 2021, the WHO finally acknowledged that transmission may occur via aerosols, smaller respiratory particles that can float, as well as via droplets, in poorly ventilated and/or crowded indoor settings; the difference being that aerosols remain suspended in the air, and can travel further than 1 meter (WHO, 2021). Soon after, on May 7th, the US Centers for Disease Control and Prevention (CDC, 2021) also updated their guidance on COVID-19, clearly saying that inhalation of these smaller particles is a key way the virus is transmitted. Then finally, also the RIVM in the Netherlands updated its website (on May 19th, 2021), just after a publication in the Journal *Science* by the scientists with a request to give more attention to ventilation in the fight against indoor respiratory infection (Morawska et al., 2021).

At the time of finalizing this chapter in May 2021, COVID-19 had caused enormous disruption to economies and societies around the world having infected by then nearly 170 million people and caused nearly 3.5 million deaths (BBC, 2021).

The global response to the spread of the coronavirus has been slow, and levels of mortality were affected by the lack of understanding of how this virus is transmitted. As the pandemic has developed over the past year and more researchers have gained invaluable evidence on the way it spreads, the detrimental impact of the WHO's pushing of the three Ws advice to 'Wash your hands, Watch your distance and Wear a mask', that was repeated in many nations, became ever more apparent. Public health campaigns failed to alert people to the dangers of aerosol-borne pathogens that have emerged as being the primary route of infection in this global pandemic. The following chapter provides a clear outline of the emerging science on the pathways of SARS-CoV-2 transmission, a fundamentally important subject to understand, because it profoundly affects the way we will have to think about the provision of safe, healthy and comfortable indoor air conditioning in the future.

Background

Respiratory droplets, aerosols and SARS-CoV-2

It is known that respiratory infections are caused by pathogens exhaled through the nose or mouth of an infected person and transported to receptor sites in the body of a susceptible person. The pathogen, such as the coronavirus, with a size of around 120 nm (0.12 μm) in diameter, is encapsulated in a water-based particle, containing water, salt, protein and other components. The particles are aerosolized from sites within the respiratory tract during breathing, speaking, singing, shouting, sneezing and coughing (Marr et al., 2019; Vejerano and Marr, 2018). These particles, or respiratory droplets, are formed from respiratory secretions and saliva, and have a wide size range, although most of them lie within the size range from sub-micrometres to a few micrometres, thus having a diameter of between <1 μm and >100 μm (Morawska et al., 2009; Papineni and Rosenthal, 1997). When exhaled, these droplets can spread outwards into the environment, depending on their size and weight. The big particles shown in Figure 32.1 (Tang et al., 2021) are larger 'droplets' that typically have a diameter larger than 100 microns, that fall onto the floor under gravity within 2 metre from the source. The small particles are small droplets, also named 'aerosols', typically smaller than 100 microns that, can and do, stay suspended for a longer time, thus potentially spreading further from the body.

The droplet size and local airflow conditions (like air velocity, temperature, humidity and direction) determine how long and how far a droplet can stay or travel in the air (Xie et al., 2007). In a room with little or no airflow, very small droplets can stay airborne for hours (Thatcher et al., 2002), whereas larger (and heavier) droplets are more quickly deposited on the ground or other surfaces due to their weight. In still air, particles of different sizes have different settling times that can be accurately predicted by physical laws, like Stokes' law.

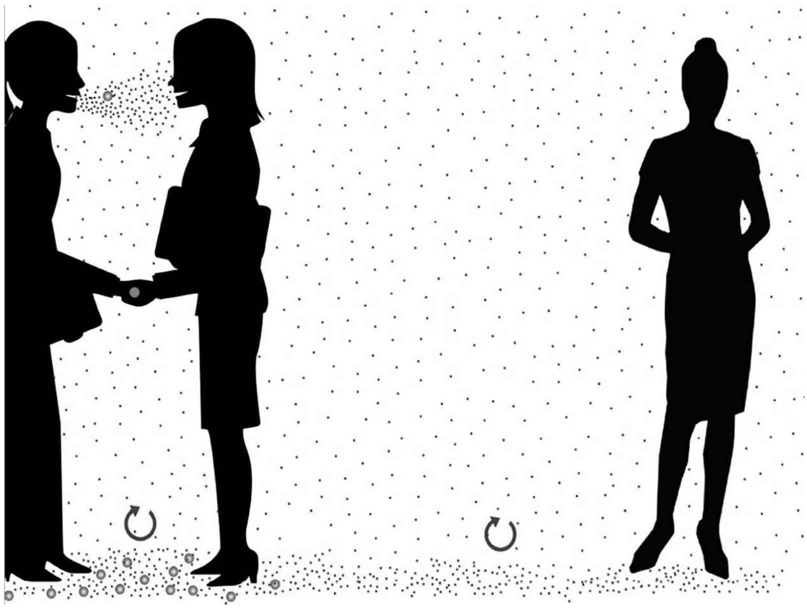

Figure 32.1 Showing the range of respiratory particles and potential spread over distance. Big particles: 'droplets' typically >100 μm diameter that fall to the floor under gravity within 2 m of the source. Small particles: 'aerosols' typically <100 μm that stay suspended for longer, but eventually fall to the ground if the air is motionless for long enough (Reprinted from *Journal of Hospital Infection* 110:89–96, Tang et al., 2021, Dismantling myths on the airborne transmission of severe acute respiratory syndrome coronavirus (SARS-CoV-2)- Narrative review, with permission from Elsevier)

Based on this, calculations show that exhaled particles of diameter 5–10 μm which fall slowly to the floor, on a downward trajectory under the influence of gravity in still indoor air, can take 8–30 minutes from a height of 1.5 m (Tang et al., 2021). Particles with a much larger diameter of around 50 μm will only take about 20 seconds to settle on the floor from a height of 1.5 m (Prather et al., 2020).

But the air indoors is not still (Matthews et al., 1989; Baldwin and Maynard, 1998). Particles that are too small to settle rapidly under gravity can move upwards in a person's thermal plume (Licina et al., 2015a; Licina et al., 2015b), and can be influenced by other airflows, caused, or impeded by, for example, ventilation, movements of persons and warm electrical equipment and intervening obstructions like cubicle curtains or standing equipment (Thatcher et al., 2002). The distance a droplet can theoretically travel was calculated for low indoor air velocities (5 cm/s), and high indoor air velocities (20 cm/s) (Marr, 2020). A particle of a size of 5 micron can in theory travel up to 100 m with low air velocities, while a particle of 10 micron reaches circa 25 m. With high indoor air velocities, these distances can be multiplied by a factor of 4 (Marr, 2020).

Another factor that can affect the travel of a droplet is the humidity of the indoor environment in which the droplet is travelling. As soon as a droplet is expired from a mouth or nose, the water part of it will start evaporating. How much will evaporate depends on the relative humidity (RH) and the temperature of the indoor environment, as well as the chemical composition of the droplet. The larger droplets, larger than 100 μm, have a high probability of landing within 1–2 m of the infected person who emitted it, while smaller droplets rapidly desiccate to 20–40 % of their original diameter (Marr et al., 2019; Tang et al., 2021). For this process, an equation can be applied to approximate the final size of a droplet after travel, the so-called Kohler equation that takes into account the vapour, surface and density conditions of the droplet. For example, a droplet with a size of 10 μm containing physiological levels of salt and protein will shrunk to 40 % of its original size (4 μm) due to evaporation (Marr et al., 2019).

Environmental conditions and viability of SARS-CoV-2

Besides the physics of the formation and evolution, of droplet nuclei forming, RH, temperature and UV-light from the sun can also affect virus viability. Previous studies have shown that coronaviruses are quite resistant to a wide range of changes in their environments, and are mainly susceptible to degradation and inactivation in conditions with a RH higher than 80 %, and an air temperature above 30 °C (Doremalen et al., 2013), which are unacceptable conditions with respect to the thermal comfort of occupants, and the increased risks such conditions provide for microbial growth.

However, in recent studies performed by Morris et al. (2021), SARS-CoV-2 survived the longest at low temperatures and extreme relative humidities, both low and high. They estimated that the median virus half-life was > 24 hours at 10 °C and 40 % RH, while approximately 1.5 hours at 27 °C and 65 % RH.

UV-light from the sun seems very effective at deactivating the virus, especially at high intensities. The virus has shown to have a half-life (50 % decay) of about one hour (at 21 °C and 40 % RH), ten minutes when exposed to a UV-index of 2, and for only two minutes under intense full sun (which equals a UV-index of 10) (Homeland Security, 2021; Schuit et al., 2020). Dabisch et al. (2021) demonstrated the time needed for a 90 % decrease in an infectious virus ranged from 4.8 minutes at 40 °C, 20 % RH in high intensity simulated sunlight at noon, on a clear day, and that time increased to more than two hours under conditions representative of those expected indoors or at night.

Transmission routes

Based on knowledge from other viruses, and recent work during this current pandemic, SARS-CoV-2 has three possible modes of transmission (Morawska et al., 2020):

1. Direct near-range mode: respiratory droplets infecting others directly when a person is in close vicinity of an infected person by coughing, sneezing or even just talking.
2. Indirect contact mode: when virus-carrying droplets are deposited on surfaces close to where they are expired (and thus lead to surface contamination with the so-called fomites). People touching such surfaces may contaminate themselves, and eventually become infected. A variant of this mode is the contamination of surfaces by touching from infected people who have touched their face or sneezed/coughed in their hands.
3. Far-range airborne mode: virus-carrying small airborne droplets (also named 'aerosols') emitted by infected individuals, may remain suspended and transported in the air for a long time and thus be inhaled by people in the same indoor environment.

The transmission mode or route of respiratory droplets, airborne transmission, can thus be classified as short or near-range or long or far-range (Tang et al., 2006). Although we do not know yet how much each of the different transmission pathways contributes, we do know that close to the face of an infected person the concentration of respiratory droplets of all sizes is the largest (Chen et al., 2020). So, we can assume that the infection risk is the highest there, either by inhalation of aerosols or by deposition of respiratory droplets on the mucous membranes and further inoculation through the mouth, nose or eyes (Prather et al., 2020).

It is important to note that there is little direct evidence for transmission of SARS-CoV-2 via any specific pathway. Moreover, transmission through large droplets has never been directly demonstrated for any respiratory virus infection. Fomites seem to play a small role in overall infection transmission (Chen et al., 2020; UK SAGE, 2020).

Transmission of SARS-CoV-2 by aerosols

Airborne transmission has been potentially the dominant mode of transmission of numerous respiratory infections, including influenza (Tellier, 2006), rhinoviruses (Myatt et al., 2004), tuberculosis (Escombe et al., 2007), measles (Bloch et al., 1985), MERS-CoV (Middle East respiratory syndrome coronavirus) (Kulkarni et al., 2016) and recently SARS-CoV-2 (Azimi et al., 2020; Lu et al., 2020; Miller et al., 2021; Park et al., 2020; Shen et al., 2020).

The transmission characteristics of several outbreaks strongly implied that long or far-range airborne transmission can also play an important role in cross-infections of SARS-CoV-2. For example, during a choir practice in Skagit Valley in the US (Miller et al., 2021), in a poor ventilated restaurant during Chinese New Year's Eve (Lu et al., 2020), on the much-discussed Diamond Princess cruise ship (Azimi et al., 2020), in a call centre in South Korea (Park et al., 2020), on a bus in Eastern China (Shen et al., 2020) and so on. All of these outbreaks implicated aerosols as their main transmission route, because viral spread was harder to explain by other routes of transmission. For all of these outbreaks it can be said that the conditions then were crowded, there were close-contact settings, insufficient ventilation and no masks were worn.

Although the actual viral load of an aerosol shed by an infected person is not known yet, in one modelling study, it was estimated that a person standing and speaking in a room could release over 100 infectious doses (quanta) per hour (Buonanno et al., 2020). Moreover, a further laboratory study reported that these infectious aerosols can remain viable on surfaces up to 72 hours, and in the air for up to 3 hours (van Doremalen et al., 2020), and therefore have enough time to be inhaled by non-infected persons that are in the same space. In field studies, the presence of infectious SARS-CoV-2 viruses has been shown in aerosol samples (Santarpia et al., 2020; Lednicky et al., 2020), and in surface samples from patient rooms (Chia et al. 2020).

Measures to reduce transmission

Physical distancing

To reduce direct transmission from mainly large infectious droplets, physical distancing of individuals has been widely adopted. For indirect transmission, the cleaning of surfaces, washing of hands and sneezing/coughing into the elbow are promoted. For people who need to, or tend to, come close to (possibly) infected persons, personal protective equipment is used (e.g. facial masks and protective gloves), and for public spaces (e.g. airplanes, trains, buses, shops and schools), facial masks are obligatory in more and more countries.

From the information presented above, it is clear that physical distancing of individuals is a good measure to reduce the risk of transmission from the whole range of respiratory droplets expired/emitted. It is also clear that it is false to assume that all droplets larger than 5 μm fall within the typically designated distance of 1–2 m (e.g. 1 m by the WHO; 1.5 m in the Netherlands; 6 feet in the US), and that therefore physical distancing in itself is enough in public spaces to prevent airborne transmission. It clearly is NOT! This 1–2 m social distancing rule originates from a study in 1942 by Jennison in which the majority of droplets in atomized secretions, detected using high-speed photography, were expelled within 1 metre (Qureshi et al., 2020). However, looking at different sizes of droplets/aerosols as well as different air velocities indoors, the distance that a droplet/aerosol can travel in theory from the point it is exhaled can vary considerably, depending on droplet size and local airflow conditions (Xie et al., 2007).

Visualization of aerosols

To visualize the pathway of aerosols, aerosols were mimicked by air-filled-soap bubbles (AFSB), introduced with a breathing system through a manikin head, simulating the exhaling of an infected person in the Experience room of the SenseLab (Bluyssen et al., 2021) (Figure 32.2). From the pathway of the bubbles, monitored by a camera, it was clear that the AFSB can travel further than the 1–2 m social distancing measures recommended to prevent direct transmission via droplets (Figure 32.3).

The use of facemasks

The use of facemasks by the public since the outbreak of COVID-19, obligatory or not, has led to diverse and numerous designs. But which mask should we choose? (Figure 32.4). The ‘surgical’ look-a-like mask, probably the most used mask and by far the cheapest to buy? A KN95 or FFP2 mask that is rather expensive and difficult to buy as a consumer? Or a washable mask made out of cotton or another fabric with, or without, disposable filters that you slide in? Or even a mask you make yourself out of old bedsheets?

In the newly introduced guidelines for public use of masks, material use, comfort of wearing and fit to face are important aspects of the design (AFNOR, 2020; CDC, 2020;

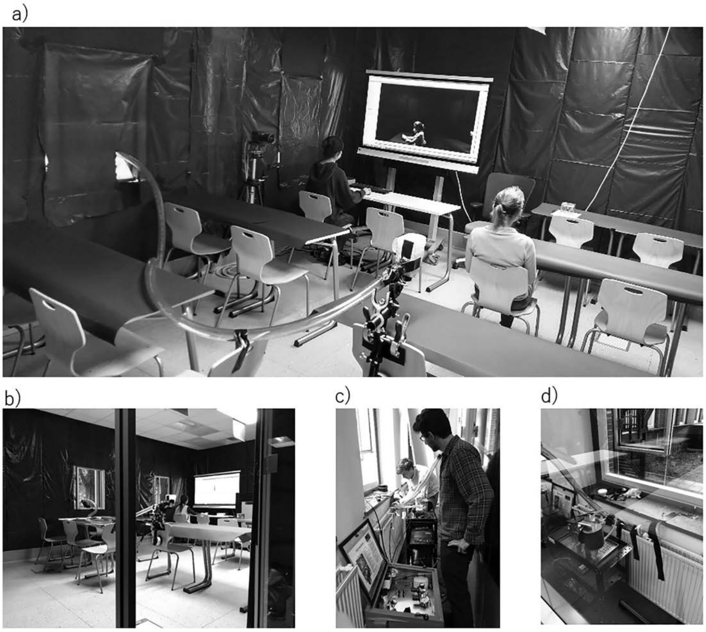

Figure 32.2 (a) Set-up in the Experience room of the SenseLab (Bluyssen et al., 2018); (b) open windows; (c) the soap bubble generator; (d) the ventilator and the PVC-tube. The bubbles were created outside the Experience room (Figure 32.2c), from where the bubbles were led into a 5 m long PVC-tube (external diameter of 48 mm) that was connected on one side to the ventilator (designed by TU Delft project Inspiration (https://www.projectinspiration.nl/specification/) and to the other side to the manikin head that was fixed on one of the chairs in the Experience room (see Figure 32.2a). A camera was installed on a tri-pod so that a measurement volume was located in front of the manikin head (see Figure 32.2a), while existing LED-ceiling lighting illuminated the bubbles. Sequences of 1,000 single-frame images were acquired during 50 seconds at an acquisition frequency of 20 Hz

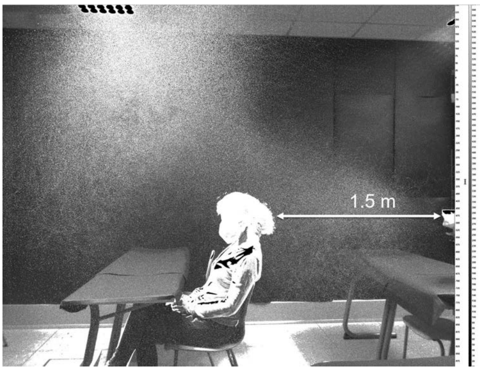

Figure 32.3 An image showing the maximum tracked particles of the first 200 images of each sequence of 1,000 images recorded, while a subject was sitting 1.5 m from the AFSB exhaling mannikin head in the Experience room of the SenseLab

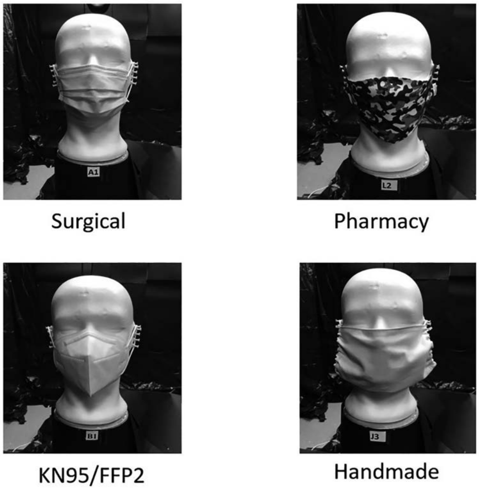

Figure 32.4 Which mask?

CEN, 2020; NEN, 2020; SWiFT, 2020; WHO, 2020c). Tests have been developed and are described for visual inspection, strength, filtration and breathing resistance. Comfort of wearing is of course important; otherwise, no one wants to wear the mask, and so is also the material used, in particular with respect to the content of possible health-threatening chemicals and for the re-use of the mask. But if we consider the purpose of a mask, that is to decrease the risk of spreading of droplets from mouth, and nose, to the environment, and therefore decrease the risk of infecting others, both the outward leakage as a result of a 'bad' fit on the face and the ability to filter 'infectious' droplets and aerosols are important (Asadi et al., 2020; Fischer et al., 2020; Konda et al., 2020; Pan et al., 2020; Tcharkhtchi et al., 2021).

Outward leakage

Several studies have shown that surgical and even home-made masks are somewhat effective in both limiting exhaled droplets and protecting wearers from inhaling droplets from others. KN95/FFP2 masks are of course much better in filtering. But the 'outward' leakage, that is the exhaled particles that escape on the sides of the mask due to a 'bad' fit or 'bad' design, is not necessarily related to the filtration capacity of the mask (see movie: Bluyssen et al., 2020). Next to monitoring the number of particles that are filtrated, visualization of air leakage can be used with the use of lasers and/or camera's in combination with smoke, mist or soap bubbles (Bluyssen et al., 2021; Morawska et al., 2009; Stadnytskyi et al., 2020; Verma et al., 2020; Wölfel et al., 2020). In a study in which the outward leakage of different masks tested on their face seal leakage with water vapour spiked with fluorescence paint was made visible with UV-light, and monitored by a camera, it was shown that, as expected, tighter fitting masks seem to perform better than loose ones (Ortiz and Bluyssen, 2021), that is with respect to outward leakage. If we look closely at the distribution patterns of outward leakage (see Figure 32.5), it can be seen that a mask prevents the exhaled aerosols from going forward, depending on the filtration capacity of the material and number of layers used. Outward leakage can occur on the side (going backwards), with the nose (going upwards) or chin (going down), depending on the size, shape and type of nose clip (if the mask has one). The aerosols that leak on the sides are distributed into the space and reach other persons

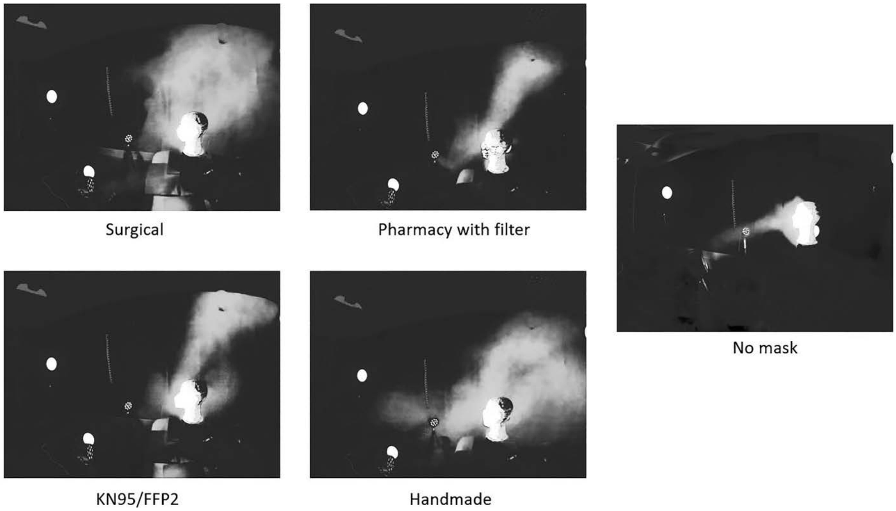

Figure 32.5 Different masks show different patterns of outward leakage taken from the side

on their back or sides, depending on the direction of the leakage. Also, for these 'escaped' aerosols, eventually, ventilation is required. Less outward leakage can be achieved with the right size, shape or nose clip, but it should be said that other important criteria, such as filtration, breathing resistance and possibility for re-use, also need be considered when selecting a mask.

Ventilation as a measure

The use of 'proper' ventilation measures has been recommended to decrease the risk of far-range airborne transmission (ASHRAE, 2020; Morawska et al., 2020; REHVA, 2020). This means first of all to provide sufficient and effective ventilation. Ventilation that ensures the supply of 'clean' air and exhausts polluted ('infected') air from the breathing zones of each individual person, preferable without passing through the breathing zones of other persons, and without recirculation of air. If general ventilation seems not enough or recirculation (re-use of air) cannot be avoided, the advice is to add air cleaning devices.

Ventilation, can be established by simply opening a window (natural ventilation), or can be established by using a mechanical ventilation system varying from exhaust only, to very advanced air conditioning systems that supply and exhaust the air. Mechanical ventilation gives the possibly to control the amount of air supplied, exhausted and/or re-used (recirculated air), while natural ventilation, such as opening a window, is an uncontrolled form – and therefore a less predictable way. Next to the type of ventilation, also different ventilation principles for mechanical systems can be selected (e.g. mixing ventilation, displacement ventilation, cross ventilation, personal ventilation) (Figure 32.6) (Bluyssen, 2019). With mixing ventilation, the air pollutants are diluted, and therefore reducing the number of 'infectious' aerosols in the air. Displacement and cross ventilation move the air horizontally or vertically through a space, replacing polluted air with 'fresh' air. Personal ventilation supplies and/or exhausts air in the breathing zone of each individual person.

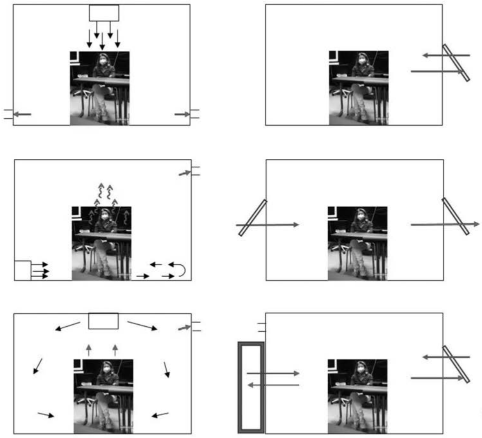

Figure 32.6 Different ventilation strategies/modes

Different ventilation strategies

The effect of different ventilation strategies on the density and distribution of aerosols exhaled by an 'infected person' in a classroom setting was tested with AFSB, introduced with a breathing system through a manikin head, simulating the exhaling of an infected person (Bluyssen et al., 2021) (Figure 32.2): (a) mixing ventilation: 1,200 m^3/h (17.5 ACH (air changes per hour) and 600 m^3/h (8.7 ACH); (b) no ventilation; (c) natural ventilation: opening windows, opening door and finally, opening windows and door. For each test, sequences of 1,000 single-frame images were generated at 1, 5 and 10 minutes and processed in DaVis 10.1.0 9. Figure 32.7 shows an image with the maximum tracked particles of the first 200 images recorded at 10 minutes for each ventilation regime tested (Bluyssen et al., 2021). The type of ventilation regime clearly influenced the density of the bubbles. Mixing ventilation reduced the amount of bubbles as compared to 'No ventilation', while 'Opening a window' had less effect.

Cross-ventilation

Additionally, a test was performed starting with no ventilation, then the production of the soap bubbles was stopped, simulating that the infected person is leaving the room, while opening windows and door – creating cross ventilation. The density of the bubbles reduced until zero in less than a minute, showing the effectiveness of this source control measure (Figure 32.8) and confirming a recent study reported by Melikov et al. (2020) that concluded opening windows and door to be an effective control measure. This method appears to provide a good alternative to the recommended increase of room ventilation in cases where only natural ventilation options are present.

Displacement and vertical ventilation

Vertical ventilation, used in operating theatres to keep the patient area clean, and in aeroplanes, supplies the air from the ceiling with a high air velocity, creating a downward jet,

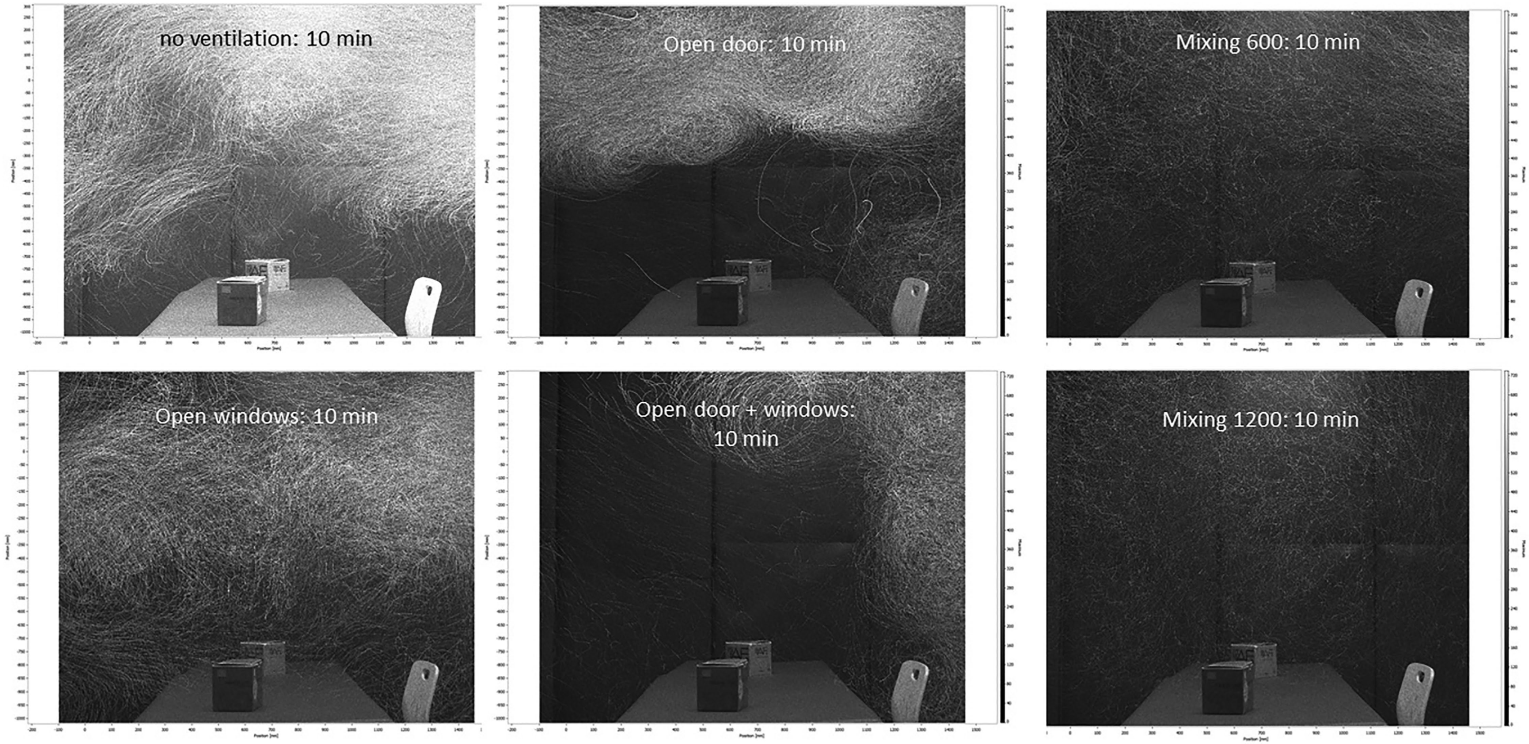

Figure 32.7 An image showing the maximum tracked particles of the first 200 images recorded at ten minutes for each ventilation regime tested (Bluyssen et al., 2021)

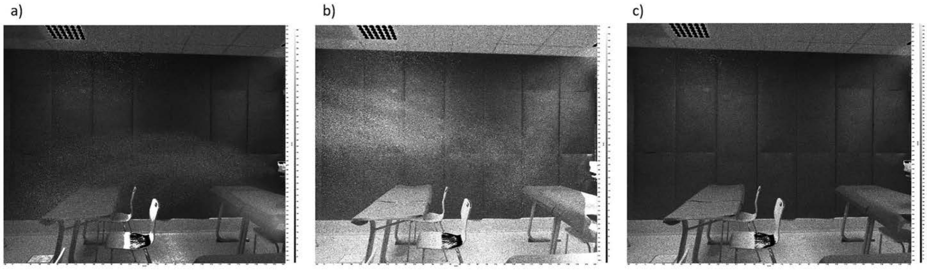

Figure 32.8 An image showing the maximum tracked particles of the first 200 images of each sequence of 1,000 images recorded (a) in first minute after start production, (b) in first minute after stop production and (c) five minutes after stop production

and exhausts the air above floor level. With displacement ventilation, the air is supplied with a low air velocity nearby the floor, and is drawn upwards by the natural plume of heated air around human bodies, where it is exhausted then at ceiling level (Melikov, 2015; Nielsen et al., 2008). For displacement ventilation to work properly, therefore, occupants are required. Unfortunately, due to the corona crisis lab studies could not be performed with more than one occupant at the time, but the expectation is that exhaled droplets on their way down, evaporate and might be moved upwards again by the displacement flow principle. The upward moving shrunken droplet or aerosol might then be inhaled by another occupant in the same room. The vertical ventilation principle is then a much better way of removing 'infected' aerosols and droplets.

Air cleaning

If general ventilation seems not enough to protect people from cross-infection, or recirculation (re-use of air) cannot be avoided, then air cleaning devices can be added in spaces. Air cleaning in most mechanical systems involves the filtering the air of particles (dust: 0.01–200 μm), using air filters like cassette filters or absolute filters that remove mainly coarse particles (PM10: < 10 μm), and bag filters that remove fine particles (PM2.5: < 2.5 μm), which can reach the lung cells. Additionally, for cleaning of ultrafine nanoparticles (< 0.1 μm) such as bacteria and viruses, that can even pass through the membrane of our lung cells, HEPA (High-Efficiency Particulate Air) and ULPA (Ultra-Low Particulate Air) filters can be used (Bluyssen et al., 2021). Another air cleaning technique that is used to 'clean' the air of viral, bacterial and fungal particles, is Ultraviolet Germicidal Irradiation (UVGI-light), in particular the UV-C part of the UV-spectrum (Martin et al., 2008). Since the outbreak of Corona both cleaning techniques have been used in mobile form, as an additional measure indoors, especially in buildings where natural ventilation is the only option, and in enclosed spaces with several occupants.

Effect of a mobile HEPA filter system

The 'air cleaning' effect (with the AFSB) as well as the effect on sound and air velocity (draught risk) of a mobile HEPA filter system with a filter class H14, was demonstrated to ensure that 99.995% of the particles with a diameter of 0.1 to 0.3 μm were filtered out of the passing room air, when tested for different airflow settings (600, 800, 1,000, 1,200 and 1,500 m^3/h), and in two positions in the Experience room of the SenseLab (Bluyssen et al., 2021).

The HEPA filter system had the additional possibility of being able to heat up the HEPA filter to 100 °C when not activated as a filter, to kill the viruses caught in passing by the filter. Room air was sucked in on two sides in the lower part of the system, and the 'cleaned' air is supplied into the room from all sides of the upper part of the system and directed towards the ceiling.

A separate experiment was undertaken with six subjects to assess the impact of the sound/noise created by the mobile HEPA filter system at different settings, while the sound level was monitored with a Norsonic Nor 140 sound analyser. The percentage of people dissatisfied with the noise was determined for each of the settings assessed by combining the answers 'bad' and 'very bad' to the question: 'What is your assessment of that noise?' Additionally, the air velocity was monitored at 6 locations (the same as the 6 subjects for the sound evaluation) in the Experience room for different settings, different heights (0.2 m, 1.10 m and 1.80 m) and for different positions of the mobile HEPA filter system. From the air velocity measurements, for each test the draught rating (DR), which is the predicted percentage of dissatisfied occupants resulting from draught, was calculated using the following equation (ISO, 2005):

$$DR = \left(34 - T_l\right)\left(v_1 - 0.05\right)^{0.62}\left(0.37 v_1 Tu + 3.14\right)[\%]$$

With:

T_l = local air temperature (= 23) [°C]
v_1 = local average air velocity [m/s]
Tu = local turbulence intensity [%]

From both the noise assessments by a panel of subjects and sound monitoring, it was concluded that the mobile HEPA filter system causes an unacceptable background sound level in the tested classroom setting (Experience room). With respect to the air velocity measurements and DR calculations, it was concluded that they both depended on the position and the setting of the HEPA filter system as well as on the position and height of the measurements. For the removal of aerosols simulated by AFSB in front of the subject, the mobile HEPA filter system performed better as compared to the 'No ventilation' regime, for all settings and both positions, and for some settings, even better than all the tested mixing ventilation regimes. The use of a mobile HEPA filter system seems, therefore, a good additional measure when only natural ventilation options are available. Moreover, for cleaning of air close to the vicinity of people, where most of the cross-infection takes place, a mobile HEPA filter system is more effective than a HEPA filter embedded within duct systems.

UV-C cleaning

UV-C cleaning has been used in 'in-duct' application within an air-conditioning system and ventilation ducts, in particular in cases where it is not possible to stop recirculation (Kujundzic et al., 2006). Upper-room ultraviolet applications have been considered for use in crowded, poorly ventilated environments where aerosol transmission could occur and where the ability to increase ventilation is limited (Morawska et al., 2020). In the 'upper-room' system, lamps are placed in the upper part of the room, either on the walls or mounted on the ceiling, directing the UV-C light into the upper zone with louvers and limiting UV-exposure in the occupied space (Xu et al., 2006). Also, small devices to disinfect products and robots to disinfect surfaces of entire spaces with UV-C light are available.

UV-C radiation, the part of UV-radiation from the sun that does not reach earth has been found effective in the inactivation of pathogens such as SARS-CoV and MERS-CoV. In particular, UV-C light with a wavelength of 254 nm and 222 nm (Hessling et al., 2020). Because UV-C of 254 nm can be a health hazard to skin and eyes, UV-C light of 222 nm, not hazardous to human tissues has been applied in such UV-C cleaning systems (Buonanno et al., 2020). Most commercially available devices are, however, still based on UV-C of 254 nm, and can therefore not be used in the vicinity of people. Additionally, it should be noted that UV-lights can only deactivate the pathogens that they 'see' and that in dusty ducts, or rooms, and particular in air, passing pathogens may be shielded from the UV-rays.

Future directions

Risk-based ventilation guidelines

To be effective in controlling respiratory infection transmission, it is necessary to adopt risk-based, rather than absolute ventilation guidelines and standards.

Existing ventilation guidelines and standards are aimed at controlling odour and carbon dioxide (CO_2) exhaled by occupants. For indoor spaces in which the main pollution source is the occupant, those regulations include limit values for the CO_2 concentration in air (ASHRAE, 2019; CEN, 2007). CO_2, in principle a relatively benign chemical, is used as an indicator of the presence of people, with every breath we take, we exhale CO_2 (see Box on the next page). Additionally, the WHO provides health-based guidelines for specific chemicals in the air based on the duration of exposure (WHO, 2010), such as benzene, carbon monoxide and formaldehyde, for which no ventilation guidelines or standards are available to control for the concentration of these pollutants indoors. Also, for mitigating bacteria or viruses in indoor air, originating from breathing, talking, singing, coughing and sneezing, design recommendations, regulations or standards simply do not exist.

To cope with the risk of airborne transmission, the most common calculation approach has been to use the Wells-Riley equation to relate infectious cases to human and environmental parameters (Noakes and Sleigh, 2009; Wells, 1955) (see Box on the next page). Based on this equation, it is theoretically possible to calculate the infection risk for a certain ventilation rate and the number of persons present, assuming one infected person. There are, however, several limitations to this approach. First, Quantum, the unit of infection introduced by Wells to express the response of susceptible individuals to inhaling infectious aerosols, and defined as the number of infectious aerosols required to infect 63% of susceptible people, is based on the available information and it is therefore not easy to determine how it relates in reality to current conditions. The calculation does not account for the differences between persons (Noakes and Sleigh, 2009). Moreover, the Wells-Riley model assumes that the concentration of infectious aerosols is homogeneous in indoor spaces, or in terms of ventilation: a mixing situation. Also, it is assumed that over time this uniform concentration is constant, and therefore the ongoing inhalation of the concentration is constant as well, over time. Nevertheless, the Wells-Riley equation is useful in gaining insights into generalized infection risk for a range of certain situations, and in terms of ventilation, these may possibly best relate to measures to reduce that airborne risk at a larger population scale. Crude assumptions necessary to be made to apply the model, with regard to quanta rate and distribution of air, however, limits its use to those seeking workable solutions at building level that reduce cross-infection through improved building design and ventilation measures.

Ventilation equation

With the equation the following equation, it is possible to calculate the required ventilation rate per person in a space to keep below the allowed CO_2 concentration:

$$Q = P / (C_i - C_o)E_v \; [1 / s]$$

with: Q = ventilation rate [l/s]
P = total emission of CO_2 [l/s]
C_i = concentration limit indoors [-]
C_o = concentration outdoors [-]
E_v = ventilation effectiveness [-]

Wells-Riley equation

$$N_C = S(1 - e^{-1qpt/Q})$$

with: N_c = number of new infected cases [-] in exposure time t [h]
S = number of persons that possibly can be infected in the indoor space studied [-]
I = number of infected persons in the indoor space [-]
q = quanta that are produced in the indoor space by one infected person [quanta/h]
p = breathing rate of person that might get infected [m^3/h]
Q = ventilation of the indoor space studied [m^3/h]

Re-thinking ventilation

There is a need for a new generation of ventilation systems that is able to respond to the different cooling, heating and air quality challenges occupants may well encounter, over time (Bluyssen, 2020).

Assuming airborne transmission of SARS-CoV-2 is a route of transmission that seriously needs our attention, it is clear that the question is not only ‘What ventilation rates, and strategies, are required to protect building occupants against infection transmission?’, but also ‘How would it be best to ventilate for different situations’?

The specific problem of indoor airborne transmission requires knowledge of several characteristics of a particular space:

1 The source(s) of pathogens determines the loading of the air with infectious aerosols;
2 The thermo-fluid-dynamic conditions of the environment (e.g. temperature, humidity and airflow velocity) that are important for the lifetime and pathway dynamics of the droplets/aerosols;
3 The physical boundaries of the indoor environment, such as its volume, height and shape, that determine location-specific pathways and regimes (e.g. distribution, direction of airflow, ventilation effectivity and natural vs. mechanical);
4 The presence of people and activities taken place over time, and the changing environmental conditions, including the location of physical obstacles to airflow in the space.

To account for all of these changing conditions, the new generation of ventilation systems should not focus on the ventilation of a (complex and dynamic) space, but would more effectively be targeted at providing a range of ventilation options, to meet the changing demands of the occupants in that space over time, whether related to health, safety or comfort.

Flexibility is therefore the key.

This presents a real problem: most existing ventilation systems are obsolete and far from flexible. Additionally, most existing mechanical ventilation systems require energy to heat/cool the outdoor air to maintain both indoor air quality and thermal comfort. The challenge therefore lies in creating new thinking of how to provide 'ventilation' that is both flexible and energy-efficient; and, in some cases do not require energy at all.

The urgency of this new thinking on the ventilation of indoor spaces with high densities of people relates in particular to educational settings, offices, hotels, restaurants, cruise ships, hospitals, care homes, theatres and gyms. It is clear that natural ventilation (such as opening a window) is not a universally suitable way of ventilating such spaces at all times. It may be that at certain times of the day and year it may provide acceptable levels of comfort, and during extreme events such as power outages or future pandemics, it can provide invaluable fresh air to such spaces. Also, in those settings, increasing the ventilation rate to the point of reducing the risk to below the acceptable level, is just not possible if we want to keep using the 'mixing'-based ventilation regimes. For these settings, next to cleaning of the air as an additional measure, ventilating people not spaces is an exciting new prospect.

The future is unpredictable, but COVID-19 has placed a lens onto the complexity of the challenges ahead in designing ventilation systems that will keep building occupants safe, healthy and comfortable, with more frequent events like pandemics and power supply challenges. What COVID-19 has shown us is that we desperately need to get a better understanding of how pathogens spread within buildings, and how we can affordable, efficiently and effectively reduce transmission rates through flexible and well-informed ventilation design in buildings, to provide pathogen safe and comfortable buildings in the future. What is also clear is that the current ventilation regulations are written for the few, and not the many. This will have to change if we want to live in a safer world for all. COVID-19 has proved that no one is safe, until all of us are safe.

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